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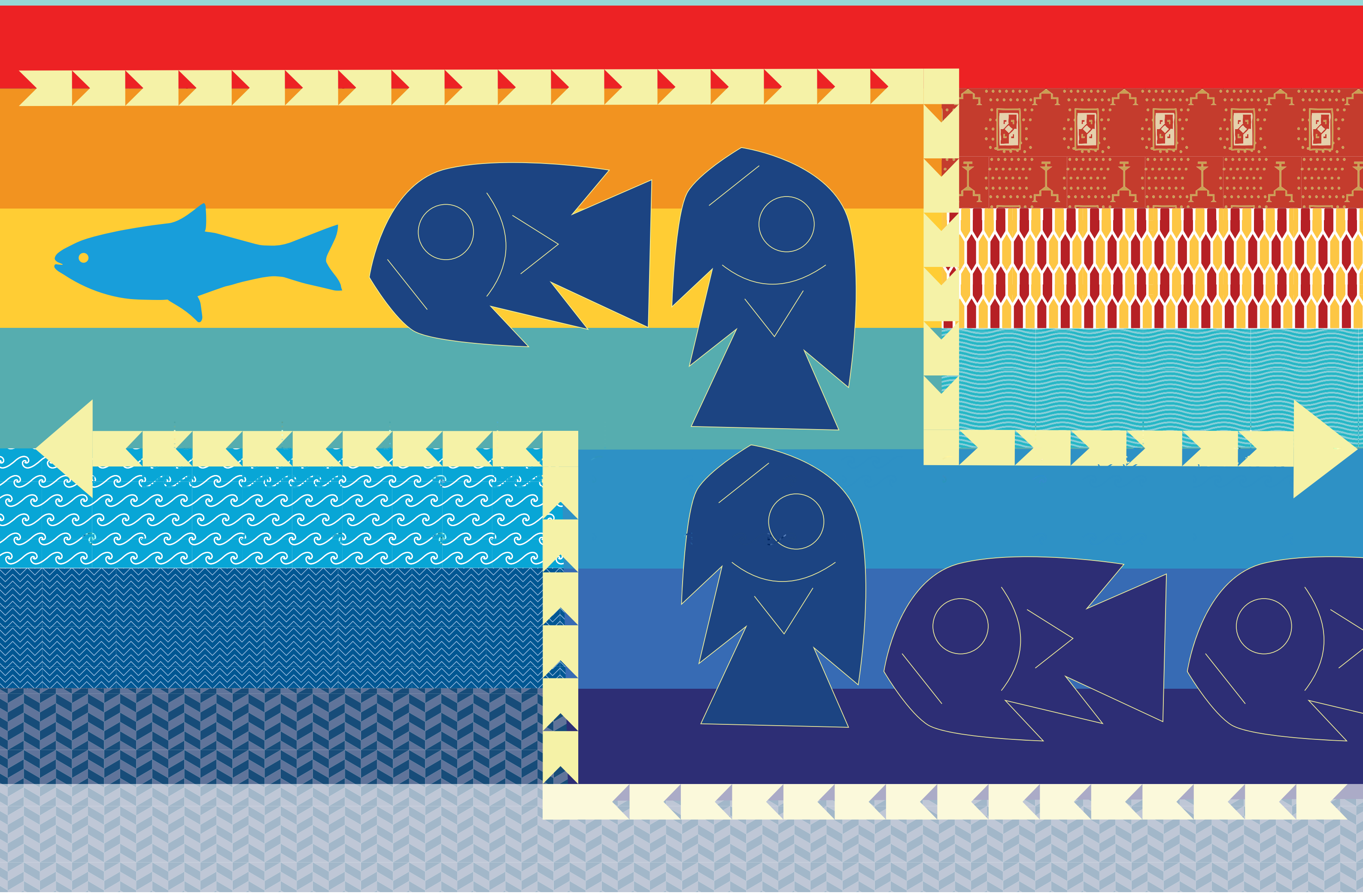

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Preparation of this document

Climate variability related to El Niño–Southern Oscillation (ENSO) affects many sectors such as agriculture, water and aquatic resources. In 2016, the Emergency and Rehabilitation Division of the Food and Agriculture Organization of the United Nations (FAO) requested the FAO Fisheries and Aquaculture Department to investigate further the impacts of ENSO on the fisheries and aquaculture sector and to suggest (disaster) planning strategies and mitigation measures. A first paper was prepared by Mr Neil Handisyde, followed by this Technical Paper prepared by the present authors, with contributions from, and under the overall direction of Manuel Barange and Florence Poulain (FAO Fisheries and Aquaculture Department), with the aim to synthesize current knowledge on the impact of the variety of ENSO events on fisheries and aquaculture in the context of a changing climate, and to identify existing and recommended coping and adaptation strategies. This Technical Paper was edited by Claire Ward and laid out by Wendy Worrall (Fishmedia, South Africa). Thanks are also due to Marianne Guyonnet (FAO) for her role in preparing the document for publication.

Abstract

The survival of pre-industrial societies was tightly connected to climatic variation. The prominent global driver of year-to-year variation in the climate system is the El Niño Southern Oscillation (ENSO), a basin-scale phenomenon involving a coupling between the atmosphere and the ocean. The El Niño phenomenon was first recognized by South American fishers during the 1600s and was described as an unusual, warm ocean current off the coast of Peru. During strong El Niño events, tropical species arrive from the north while native fish species either migrate southwards or collapse, the most famous case being that of the Peruvian anchovy or anchoveta, populations of which typically collapse during these events. Seabirds and mammals along the Peruvian coast that largely depend on anchoveta for their food, as well as those occurring on the nearby Galapagos Islands, can also decline dramatically. The unusually warm water also causes heavy rain that can result in the coastal desert undergoing a floral bloom, while also being destructive to crops, property and infrastructure.

In the course of the twentieth century, it was recognized that El Niño was not only a tropical coastal current but a large-scale phenomenon that affects weather patterns across the globe. The last five millennia have witnessed about 20 major El Niño events, which have radically affected the history of many societies in different parts of the world. ENSO impacts on climate, fisheries and aquaculture have recently been the focus of numerous scientific works but also stimulated considerable (and often overly-sensational) media coverage. It should, however, be recognized that no two El Niño events are quite alike and that this diversity results in a variety of ecological as well as institutional and socio-economic responses. The recent discovery that ENSO is far more diverse than previously recognized highlights a pressing need to synthesize the impact of the different ENSO types on fisheries and aquaculture, two key components of the global food supply system. In addition, the possible effects of climate change on these sectors can be partly illustrated from the current effects of ENSO events, which are themselves affected by climate change. This document aims to synthesize current knowledge on the impact of the variety of ENSO events on fisheries and aquaculture in the context of a changing climate, and to identify existing and/or recommended adaptation/coping strategies to address ENSO-related events.

After introducing the context of this document (Chapter 1), Chapter 2 describes the diversity of ENSO events. This document considers five types of ENSO events: Extreme El Niño, Moderate Eastern Pacific (EP) El Niño, Moderate Central Pacific (CP) El Niño, Coastal El Niño and Strong La Niña events. Chapter 3 discusses our current capability to predict ENSO events. It highlights that operational forecasts can provide accurate ENSO predictions up to nine months before the ENSO peak, but are currently unable to predict the type of El Niño that will occur, even at short lead-times. Chapter 4 discusses ENSO events in the context of climate change and shows that, although current climate model projections point towards a robust doubling of the frequency of extreme ENSO events, these models do not allow us to confidently assess if and how the overall ENSO activity (amplitude, frequency and pattern) will change in the future. Chapter 5 provides a global overview of ENSO impacts on ocean conditions, storms, climate and marine capture fisheries, indicating that ENSO alters climate, weather patterns and tropical cyclones (TCs) as well as oceanic conditions and productivity across the globe through atmospheric and oceanic teleconnections. These ENSO impacts are, however, sensitive to ENSO flavour. Global marine landings are reduced during extreme El Niño (–3.2 million tonnes) and EP El Niño (–0.7 million tonnes), increase during La Niña

(+1.3 million tonnes) and remain stable during CP El Niño and normal years. ENSO impacts also drastically vary as a function of the region considered, with more stringent negative (extreme and CP El Niño) and positive (La Niña) impacts in the Eastern Pacific than in any other marine region.

Chapter 6 proposes a regional assessment of ENSO impacts for FAO Major Fishing Areas affected by ENSO events, and includes a series of actions recommended or implemented to address these events. Since ENSO has significant impacts on TCs, storms and floods, the consequences in terms of safety at sea and potential damage to fisheries facilities and livelihoods, are addressed regionally by ENSO type. In the tropical Pacific Ocean, ENSO is undoubtedly the main driver of interannual variations in sea surface temperature, sea level, precipitation and TC activity. ENSO impacts on fisheries are strong in the Pacific Ocean as a whole, with production anomalies of approximately 1 million tonnes associated with El Niño (negative) and La Niña (positive), albeit with large regional disparities in effects. Marine heat waves (MHWs) associated with ENSO have a devastating effect on coral reefs. The effects of MHWs also impact the supply chain and markets, as a result of change in abundance, mortality, growth and phenology of fish species. Outside the Pacific, ENSO events impact both the Atlantic and Indian Ocean through remote atmospheric teleconnections. For instance, El Niño events act to warm the tropical north Atlantic in the boreal spring following its peak, but marginally impact the equatorial Atlantic. ENSO categories and types have no significant impact on fisheries landings over the Atlantic Ocean as a whole. In the Southwest Atlantic, all El Niño types have some negative impact on coastal species, but fish landings are only negatively impacted after extreme El Niño events. Similarly, all El Niños have a negative impact on small pelagic fish in the western central Atlantic, but only extreme El Niño events induce negative capture anomalies in this region. There is currently no robust evidence of any impact of ENSO on fish and fisheries of the eastern central and southeast Atlantic Ocean. In the Indian Ocean, ENSO-induced changes in the circulation often lead to a sea surface temperature dipole pattern called the Indian Ocean Dipole (IOD), but this dipole can occur independently of ENSO. El Niño-related MHWs and El Niño events in 2016, combined with increased human pressure and local threats, prevented the recovery of coral reefs in the Indian Ocean to their pre-1998 state. While ENSO events are known to affect tuna fisheries in the Indian Ocean, fisheries landings over the Indian Ocean as a whole are not affected by ENSO, whatever the category or type of fishery. The recruitment of targeted tropical fish species in western Australia, however, depends on ENSO, with La Niña conditions associated with higher recruitment.

Chapter 7 further synthesizes the impact of ENSO on coral bleaching, damage to reefs and related fisheries. High sea temperatures associated with El Niño events cause bleaching, which reduces coral growth or increases coral mortality: in recent years, ENSO activity has devastated many tropical reefs that provide important ecological goods and services to human populations. In addition to direct or indirect effects of ENSO on reef fishes, positive correlations have been observed between the annual incidence of ciguatera fish poisoning in Pacific islands that experience warming during El Niño conditions. The repetition of strong El Niño events in a warmer ocean, and the resulting loss of productive habitat, will likely diminish fish catches for coastal communities and reduce protection from storms and rising seas, putting coastal communities in peril.

In Chapter 8 we examine ENSO impacts on aquaculture, the largest source of fish and seafood for human consumption, which is seen by many as a means of adding resilience to the global food supply system. Using FAO production statistics, we examine whether ENSO variation affected production at global, regional and national (top 10 producers in 2016) levels, as well as in the species/categories that dominated aquaculture worldwide between 1950 and 2016. Results showed that there were no obvious large-scale differences in production between different ENSO categories or El Niño event types. However, certain ENSO conditions (La Niña and Extreme El Niño) were more often associated with larger variations in production anomalies, indicating that they have more scope to produce shocks in the aquaculture sector. The most commonly cultured species showed relatively limited variation associated with ENSO, but unfed taxa (plants and molluscs) were the most affected groups. Of the different El Niño event types, CP El Niño (plants, molluscs) and Extreme El Niño (molluscs, crustaceans, fish) were associated with the largest production anomalies.

In Chapter 9, we follow a similar approach and examine potential effects of ENSO on inland fisheries production at a number of different levels, including global, subregional and national levels, as well as at the level of the most commonly captured species. Comparison of annual inland fishery production anomalies between 1950 and 2016 showed no statistical effect of ENSO variation in any of the cases examined. There was clear evidence of considerable temporal shifts in the taxonomic structure of the global inland fishery catch but this was not affected by ENSO. ENSO event category or El Niño event type had no statistical effect on inland fisheries production in any of the subregions, but percentage anomalies associated with the different ENSO conditions and El Niño event types varied considerably (between −18.8 percent and +34.9 percent).The sign or strength of production anomalies differed for many subregions under ENSO, including those that provide the bulk of inland fishery production, and as with the aquaculture sector, La Niña was associated with more extreme production anomalies than neutral or El Niño events. Comparison of mean annual inland fisheries production values during the different El Niño event types indicated quite distinct responses, with switches in the sign and scale of anomalies at a subregional, and extra-subregional scale.

Extreme El Niño saw particularly large numbers of inland fisheries subregions with negative production anomalies. Considerable (−14.4 percent to +8.3 percent) production anomalies at the country level were associated with the different El Niño event types, indicating that certain El Niño conditions have the potential to shock inland fisheries production in the key countries supporting inland fisheries. Analyses were limited due to the low level of taxonomic resolution in many national production data. Where highly detailed catch composition data were available from Uganda, the impact of the Extreme El Niño of 1983 on inland fisheries in that country was very clear, with production shifting markedly to drought-resistant species. Given the well-reported impacts of ENSO variation on freshwater ecosystems and on fisheries production at a local level, we suggest caution before it is definitely concluded that ENSO does not affect inland fishery production. We suggest that the way that inland fisheries data are typically reported (annually, national level, low taxonomic resolution) may limit our ability to identify effects of ENSO-derived variation in inland fisheries production and we provide suggestions for future studies.

Finally, in Chapter 10 we synthesize the lessons learned and the perspectives for ENSO preparedness in a warmer ocean. This document first highlights that while the physical impacts of the various ENSO types are relatively well documented, their consequences on fish and fisheries remain poorly understood. The existing literature and data, however, suggest that ENSO impacts on fisheries and aquaculture are weak globally but can be severe regionally (e.g. in the Humboldt Current System). ENSO types can have very diverse effects on fish and fisheries, and the communities dependent on these resources. Consequently, coping/adaptation measures should be adapted to ENSO event types in a given region supporting capture fisheries or aquaculture, and build on or develop existing capacity. ENSO early warning should document the expected type of event, and as far as possible the expected regional impacts to inform adaptation. To date, warning mostly concerns El Niño events but our work indicates that La Niña has a similar ability to shock the food supply system. ENSO events may affect food security, but mostly because of their impacts on agriculture rather than on marine capture fisheries or aquaculture (NB impacts on the inland fisheries sector are still unclear). ENSO events generally worsen the effects of climate change on fish and fisheries. The combination of global warming and ENSO events shall dramatically impact coral reefs.

Contents

Foreword

Capture fisheries is the only major food production system that relies entirely on the natural fluctuations of wild biodiversity, and yet, global capture production has remained largely stable for the last three decades. However, this stability masks very significant fluctuations at regional and national level, often driven by climate variability and its consequences on the ecosystems that support fishery resources.

El Niño-Southern Oscillation (ENSO) is the most important mode of climate variability in the Pacific Ocean, but its impacts are felt across all production sectors and all over the world. ENSO is often simplified to reflect two mains phases: an anomalous warming phase in the central and/or eastern equatorial Pacific Ocean named El Niño ("little boy" or "Christ child", so named because it usually occurs around Christmas), and the opposite cool phase called La Niña. During the warm phase the thickness of the top layer of the eastern Pacific ocean classically increases, preventing cold and nutrient-rich deep waters to reach the surface, dampening production on which fish depend for food. This pseudo-cyclical phenomenon also influences air temperature, precipitation patterns, and even tropical cyclones (TCs) across the globe. The consequences are felt worldwide in agriculture, inland fisheries, aquaculture, and as a result affect food security, malnutrition and hunger.

But ENSO is not just a binary phenomenon (either warm or cold). Every ENSO event is different in signal, intensity, duration, and so are its consequences. Taking into account the diversity of types of ENSO is essential to improve our understanding, predictive capacity, and societal preparation to cope with these events. In this publication, the authors identify five types of ENSO as follows: Extreme El Niño, Moderate Eastern Pacific (EP) El Niño, Moderate Central Pacific (CP) El Niño, Coastal El Niño and Strong La Niña events. Each has a different impact on the fisheries and aquaculture sector.

The analysis of these five types also recognizes they are not static. In particular, there are strong indications that climate change affects ENSO events, probably both in terms of their frequency and intensity, but the evidence is not yet conclusive enough.

This Technical Paper brings together a team of international experts with the intent to synthesize the current state of knowledge on the impacts of ENSO-types on fisheries and aquaculture with a specific focus on their impacts on food security. The Paper also explores a range of adaptation and risk management responses already available to strengthen local and national capacity to anticipate, respond to and reduce ENSO impacts on fisheries and aquaculture. This work will contribute to FAO's efforts to reduce the impact of climate on the sector by bridging the gap between researchers and policymakers. The overall goal is also to contribute to ongoing efforts to implement the Sustainable Development Goals, the Sendai Framework for Disaster Risk Reduction 2015–2030 and the Paris Agreement on Climate Change.

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Abbreviations and acronyms

AMO	Atlantic Multidecadal Oscillation
BoB	Bay of Bengal
CCS	California Current System
CFP	ciguatera fish poisoning
CP El Niño	Central Pacific El Niño event
CPUE	catch per unit effort
DO	dissolved oxygen
DRR	disaster risk reduction
EAA	ecosystem approach to aquaculture
EAF	ecosystem approach to fisheries
EEZ	exclusive economic zone
ENSO	El Niño Southern Oscillation
EP El Niño	Moderate Eastern Pacific El Niño event
FAD	fish aggregating device
HCS	Humboldt Current System
GLM	general linear models
IOB	Indian Ocean Basin
IOD	Indian Ocean Dipole
IOTC	Indian Ocean Tuna Commission
ITCZ	intertropical convergence zone
GAO	global atmosphere oscillation
LOESS	locally weighted scatterplot smoothing
LIFDCs	low-income food deficit countries
MHW	marine heatwave
NAO	North Atlantic Oscillation
nei	not elsewhere included
NOAA	National Oceanic and Atmospheric Administration (United States of America)
NPGO	North Pacific Gyre Oscillation
NPO	North Pacific Oscillation
ONI	Oceanic Niño Index
PDO	Pacific Decadal Oscillation
PICTs	Pacific island countries and territories
SIDS	small island developing states
SOI	Southern Oscillation Index
SPCZ	South Pacific convergence zone
SSB	Southern Brazilian Bight
SSF	small-scale fisheries
SSH	sea surface height
SST	sea surface temperature
SSTA	sea surface temperature anomaly
TAC	total allowable catch
TC	tropical cyclone
USA	United States of America
WIO	Western Indian Ocean

1 Introduction

The El Niño phenomenon was originally recognized by fishers in South America in the 1600s as an unusual, warm ocean current off the coast of Peru. The name (meaning "little boy" or "Christ child" in Spanish) was chosen according to the time of year (around December) when these warm-water events tended to occur. The Peruvian scientists who first analysed the El Niño phenomenon considered it to be a local event (Grove and Adamson, 2018). During these events, tropical species move from the north, while native fish species either migrate southwards or collapse. The most famous example is that of the Peruvian anchovy or anchoveta (*Engraulis ringens*), populations of which conspicuously collapsed during the 1972 and 1982/83 El Niños (Barber and Chávez, 1986; Chavez *et al*., 2008). Seabirds and mammals around the Peruvian coast, which depend mainly on the anchoveta, as well as those occurring on the nearby Galapagos Islands, can also undergo dramatic declines during El Niño events. Evaporation of the unusually warm water causes heavy rainfall that can result in the coastal desert undergoing a floral bloom, while also being destructive to agricultural crops, property and infrastructure. The 1957/58 El Niño led to the realization that the phenomenon was more than just the intensification of a tropical coastal current but was linked to a basin-scale phenomenon involving a coupling between the atmosphere and the ocean, referred to as the El Niño Southern Oscillation (ENSO). This phenomenon is the most prominent interannual fluctuation of the tropical climate system, which affects weather patterns across the globe. For instance, Indonesia and northern Australia experience drought and often forest fires, while Peru and Ecuador suffer serious floods. TC frequency increases in the Pacific but reduces in the Caribbean region and North Atlantic in relation to ENSO.

ENSO originates in the tropical Pacific and consists of two opposite phases: an anomalous warming phase in the central and eastern equatorial Pacific called El Niño, and an anomalous subsequent cooling phase called La Niña. The warm sea surface temperature (SST) anomaly associated with El Niño in the central Pacific induces a large-scale east–west sea level pressure seesaw, termed the Southern Oscillation, which represents the atmospheric manifestation of the coupled ENSO phenomenon. It results in enhanced deep atmospheric convection and westerly wind anomalies in the central Pacific. The eastward surface current and deeper thermocline[1] response to this wind anomaly in turn reinforces the initial warming. ENSO events last for six to 12 months and are usually phase-locked to the annual seasonal cycle: SST anomalies develop over the eastern equatorial Pacific during boreal summer, peak during winter and recede in the following spring. These events occur irregularly every two to seven years, making their prediction difficult (Barnston *et al*., 2012). It is a pseudo-cyclical phenomenon.

ENSO has affected humans since prehistoric times. The survival of pre-industrial societies was closely associated with climate and the abrupt climatic shock of a global El Niño or La Niña was probably more important than processes of climatic change or variability that operated more slowly. Extreme weather events such as those associated with El Niño or La Niña could plunge a society into great difficulty, radically reduce population numbers, or even destroy it altogether (Grove and Adamson, 2018). Large or recurrent El Niños may have triggered significant disruption and in some cases even contributed to political change. During the last five millennia, about 20 major El Niño

[1] Thermocline: the physical boundary in the water column separating the warm surface layer from the deeper, colder layers.

events appear to have radically affected the history of many societies in quite distinct parts of the world (Grove and Adamson, 2018). As a result, some societies developed adaptations to El Niño. In central Peru, for example, the people of Manchay Bajo built an 800 m stone dam during the second millennium BCE (Before the Current Era) to protect themselves against landslides and maintained it for six centuries. The Moche Valley's Chimú civilization (Figure 1.1) built their agricultural system around the natural irrigation provided by "periodic" El Niño rains (Grove and Adamson, 2018).

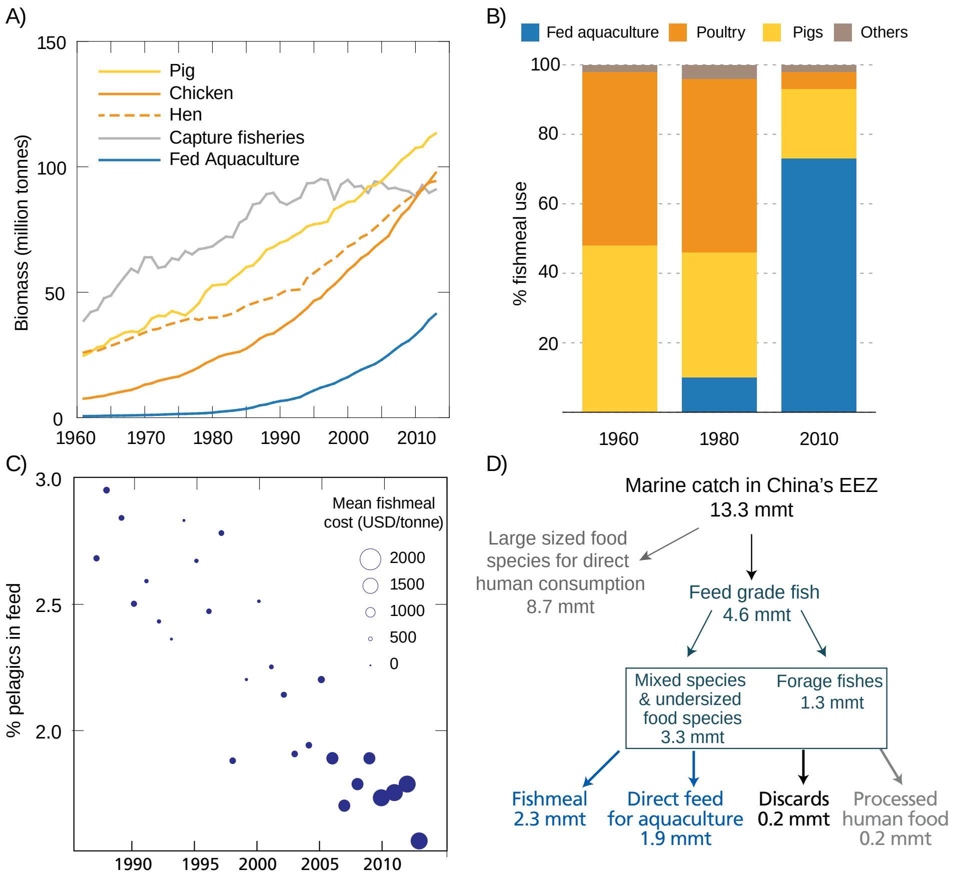
FIGURE 1.1
Bas-relief from the Chan Chan city located at the mouth of the Moche Valley in Peru

More recently, ENSO impacts on climate, agriculture, fisheries and aquaculture have been the focus of numerous scientific works but have also resulted in widespread, and often sensationalist, media coverage. El Niño events have typically been considered as being similar, and having archetypal consequences. Following the extremely strong 1982/83 event, the 1997/98 El Niño was noticeable because it saw an extreme SST anomaly in the eastern equatorial Pacific, with temperatures exceeding 28 °C in this region (McPhaden, 1999). This resulted in intense rainfall in the eastern part of the basin, which is characteristically dry and cold. The first El Niño of the twenty-first century in 2002/03 was also very unusual relative to previous events, with the largest SST anomalies restricted to the central equatorial Pacific (McPhaden, 2004). This form of atypical El Niño became increasingly frequent during the following decade. Finally, although most of the equatorial Pacific experienced climatological values, an intense coastal warming, referred to as a "coastal El Niño", produced severe flooding in Peru in 2017 (Takahashi, Karamperidou and Dewitte, 2019). These very marked event-to-event differences over the past two decades led the scientific community to pay more attention to the diversity in ENSO events, including their description and underlying mechanisms (Timmerman *et al*., 2018).

Wyrtki (1975) noted almost 50 years ago that "No two El Niño events are quite alike". This diversity results in a variety of ecological responses. The recent discovery that ENSO presents a high diversity of characteristics (Timmermann *et al*., 2018) highlights the pressing need to synthesize the impact of different ENSO types on fisheries and aquaculture, given their key role in supporting human populations (FAO *et al*., 2019). This is further complicated by interactions between the different sectors that together provide food for the global human population. For instance, modern agriculture and aquaculture have both been reliant on marine capture fisheries for the provision of fish by-products for feed, e.g. fishmeal from pelagic fishes (Figure 1.2). Recent years have seen shifts to alternative sources, including agricultural crops, resulting in a decreased reliance on pelagic forage fishes, but have also seen increased use of low-value marine species and juveniles of high-value fisheries species to satisfy the demand from the fed-aquaculture sector. Given that all sectors (terrestrial agriculture of crops and animals, marine fisheries for forage and non-forage fishes and aquaculture) are potentially individually susceptible to ENSO impacts, there is clearly a pressing need for a detailed examination of how different ENSO events affect these key parts of the human life-support system.

FIGURE 1.2

Production in major fed-livestock sectors (e.g. poultry and pigs) as well as fed-aquaculture is reliant on by-products from wild-capture fisheries, typically forage fish



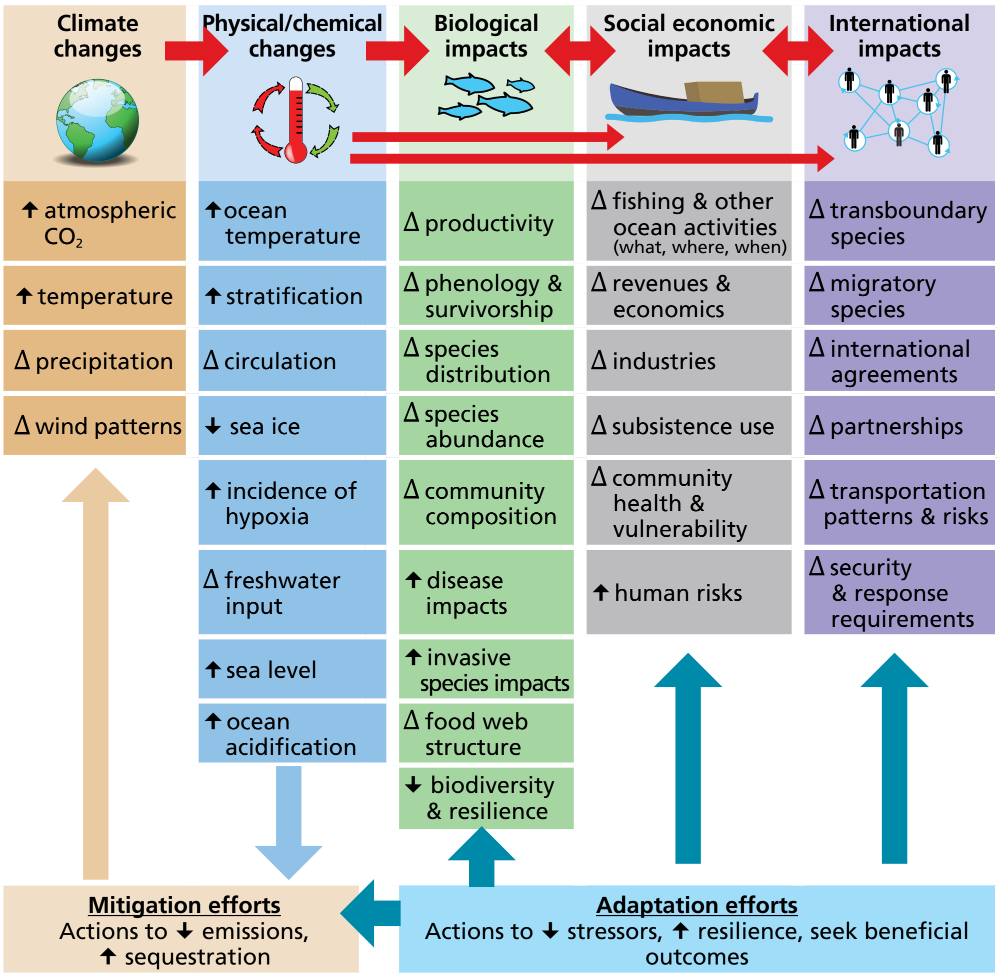
These sectors are potentially susceptible to ENSO effects. Although production in the fed-aquaculture sector is currently low compared to that of fed livestock (A) the relative use of fishmeal is higher in the aquaculture sector than the agricultural sectors (B), heightening its sensitivity to potential shocks. Both the increased cost of fishmeal, and concerns about the ecological impacts of industrial fisheries, have seen reductions in the percentage of pelagic fish in animal feed over recent decades (C). The fed-aquaculture sector has greatly increased the use of non-animal products (e.g. terrestrial crops such as soy and maize) to provide the energetic and nutritional demands of cultured species, which raises issues with regard to potential shocks associated with ENSO (e.g. impacts of extreme weather on crop production). However, growing demand for aquaculture feed has also resulted in increased use of products from non-forage fishes. For instance, Zhang *et al*. (2019) recently showed that China, by far the leading global aquaculture producer (See Chapter 8) is increasingly reliant on non-forage fishes to produce fishmeal and for direct feeding of cultured species. These non-forage fishes include low value species as well as large numbers of juvenile fishes of species targeted by marine fisheries. As ENSO can affect aquaculture species as well as terrestrial crops, forage fishes and (increasingly) non-forage fishes exploited by capture fisheries to feed aquaculture, this highlights the potential for ENSO to have wide-ranging impacts on these key sectors.

Source: A–C: Froehlich *et al*. (2018) ; D: Zhang *et al*. (2019).

However, there is limited information on the impacts of a specific type of event and so far, adaptation and risk management have not considered the diversity of ENSO types. In addition, the possible effects of climate change on fisheries can be partly illustrated by the current effects of ENSO events, which are themselves affected by climate change (Barange *et al*., 2018). This document aims to synthesize knowledge on the impact of the variety of ENSO events on capture fisheries and aquaculture in the current context of climate change. It also identifies adaptation and/or coping[2] efforts implemented or recommended to address ENSO-related events. The impacts of climate change on aquatic ecosystems and fisheries (Figure 1.3) will not be directly addressed, but only indirectly via the specific impacts associated with ENSO.

FIGURE 1.3

Impacts of climate change on marine ecosystems and fisheries



Source: NOAA (2015).

Note that this document will focus on the impact of ENSO events originating in the Pacific, and will not address climate events that originate in other basins, which also include the term "El Niño" in their definition (e.g. the "Benguela Niño" in the Atlantic or the "Ningaloo Niño" in the Indian Ocean). In addition, robust information on the impact of ENSO on fisheries and aquaculture varies in number and quality between ocean regions. This variety demonstrates the fact that ENSO impact is not equal in all

[2] In most cases adaptation and coping are used interchangeably in this publication.

ocean areas and also indicates, in some cases, a lack of specific research based on fair databases or models. In this document, we therefore focus on regions and cases for which the most reliable information is available.

This document is organized into ten chapters:

- In Chapter 2 we describe and define the diversity of ENSO events.
- In Chapter 3 we describe how ENSO events are forecast and identify the current prediction limits on the type, intensity and duration of a given ENSO event.
- In Chapter 4 we synthesize the knowledge on the evolution of the ENSO in the context of climate change.
- In Chapter 5 we describe the impact of ENSO on ocean conditions and marine fisheries at a global scale.
- In Chapter 6 we describe the impact of ENSO on ocean conditions and marine fisheries in different world regions.
- In Chapter 7 we focus on the impact of ENSO on coral reefs and associated ecosystems.
- In Chapter 8 we examine evidence for ENSO impacts on aquaculture at global, regional and national levels.
- In Chapter 9 we examine potential ENSO impacts on inland fisheries at global, regional and national scales.
- Finally, in Chapter 10 we summarize the lessons learned during the analysis of the body of knowledge on ENSO and provide ideas for adaptation options, with a focus on three main domains of intervention: institutional adaptation, livelihoods adaptation and risk reduction and management measures.

2 Diversity of ENSO events

KEY MESSAGES

No two El Niño events are alike, nor are the resulting ecological responses. In this document we define five types of ENSO events:

- Extreme El Niño events: intense warming over most of the equatorial Pacific with the strongest oceanic signature located in the eastern part of the basin.
- Moderate Eastern Pacific (EP) El Niño events: modest warming over most of the equatorial Pacific with the strongest oceanic signature located in the eastern part of the basin.
- Moderate Central Pacific (CP) El Niño events: modest equatorial Pacific warming located near the dateline with weak oceanic signature along the west coast of South America.
- Coastal El Niño events: warm conditions along the west coast of South America, but normal or cool conditions elsewhere in the Pacific.
- Strong La Niña events: large-scale cooling over most of the equatorial Pacific with the strongest oceanic signature located in the central part of the basin.

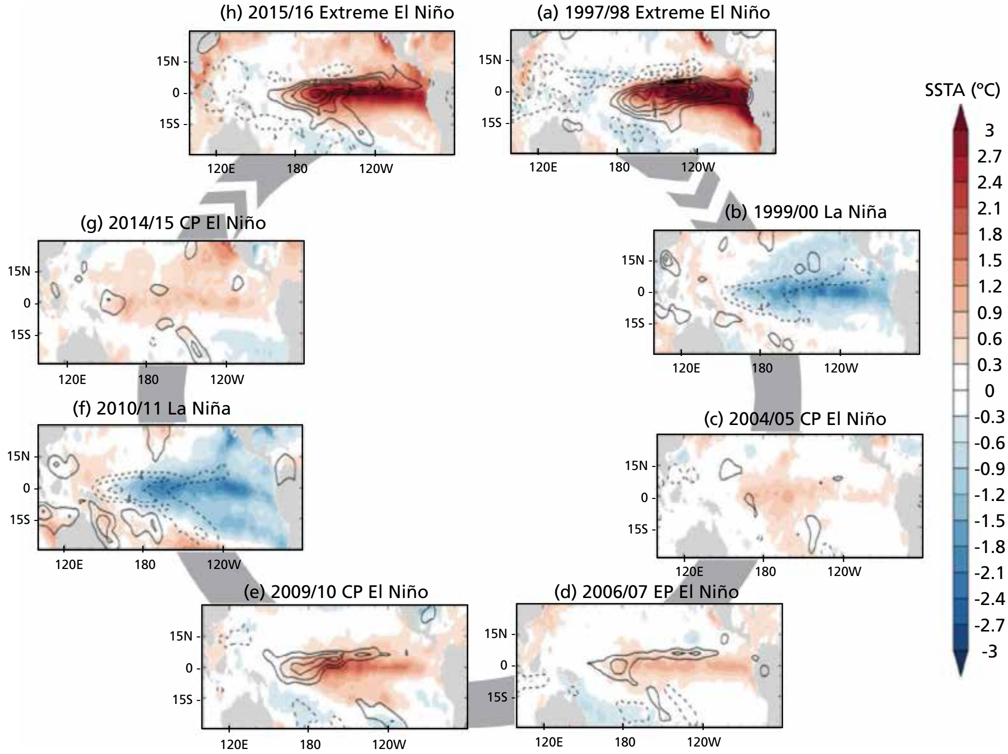
As mentioned in Chapter 1, the concept of El Niño evolved at the turn of the twentieth century, from a canonical description to one that accounts for the phenomenon's spatiotemporal diversity. In spite of some prominent common features, El Niño events indeed differ considerably from one event to another in terms of magnitude, spatial pattern, temporal evolution and predictability. A common way to highlight ENSO diversity is to contrast sea surface temperature anomaly (SSTA) patterns at the height of different ENSO events. Figure 2.1 shows boreal winter SSTAs for different El Niño and La Niña events over the past two decades.

The 1997/98 and 2015/16 El Niño events exhibited exceptionally large SSTAs, peaking along the coasts of Peru and Chile and extending westwards along the equator with decreasing amplitude (McPhaden, 1999). These events featured a pronounced eastward extension of the West Pacific warm pool and the development of atmospheric convection, and hence a huge rainfall increase in the usually cold and dry equatorial central/eastern Pacific, which enhances the ocean–atmosphere coupling that leads to further growth of the event (Takahashi, Karamperidou and Dewitte, 2019). These events will be referred to as **"extreme" El Niño events** hereinafter. This massive reorganization of atmospheric convection severely disrupts weather patterns at the global scale, inducing numerous natural disasters worldwide. For instance, Ecuador and northern Peru experienced catastrophic floods, while the Galapagos Islands witnessed the disappearance of a variety of marine species and the decimation of native bird populations. Severe bleaching of corals occurred in the Pacific and beyond. The recent period culminated with the intense 2015/16 El Niño event, which displayed similar SSTAs to those of the 1997/98 event, but shifted further west than in 1997/98.

Some other El Niño events, like those in 1991/92 or 2006/07, displayed a maximum warming in the eastern Pacific, as for extreme El Niño events, but with a considerably weaker amplitude. We will refer to these events as **"moderate Eastern Pacific" (EP) El Niño** events. Both EP and extreme El Niños are somewhat reminiscent of the "canonical" El Niño pattern described by Rasmusson and Carpenter (1982). Another type of El Niño event started to be noticed at the turn of the twenty-first century. The 2002/03, 2004/05 and 2009/10 El Niños displayed moderate positive SSTAs, with a maximum warming near the International Dateline, and a weak or insignificant warming along the coast of South America. These later events will be referred to as **"moderate Central Pacific" (CP) El Niño** events (Kao and Yu, 2009). In contrast, **La Niña events** (Figure 2.1b,f) exhibit subtler differences in their spatial patterns, with cold SSTAs peaking in the central Pacific with more limited longitudinal excursions (Kug and Ham, 2011). In addition, La Niña events never achieve the exceptionally large amplitudes reached during extreme El Niños. This amplitude asymmetry between positive and negative ENSO phases represents another important aspect of ENSO diversity.

While CP and EP El Niño definitions will be used in this document as shorthand for a synthetic description, there is now ample evidence that the location of maximum SSTAs during El Niño events (and to a lesser degree, La Niña events) spans a wide range of longitudes rather than clustering around only two locations (Giese and Ray, 2011). Another type of event, referred to as "mixed" El Niño, is sometimes used to refer to events sharing characteristics with both EP and CP El Niños (Kug, Jin and An, 2009).

FIGURE 2.1
(a–h) Spatial pattern of SSTA (shaded) and rainfall anomaly (contours, positive solid, negative dashed, 2 mm·day-1 interval, zero contour omitted) averaged over the Nov–Dec–Jan season of selected ENSO events

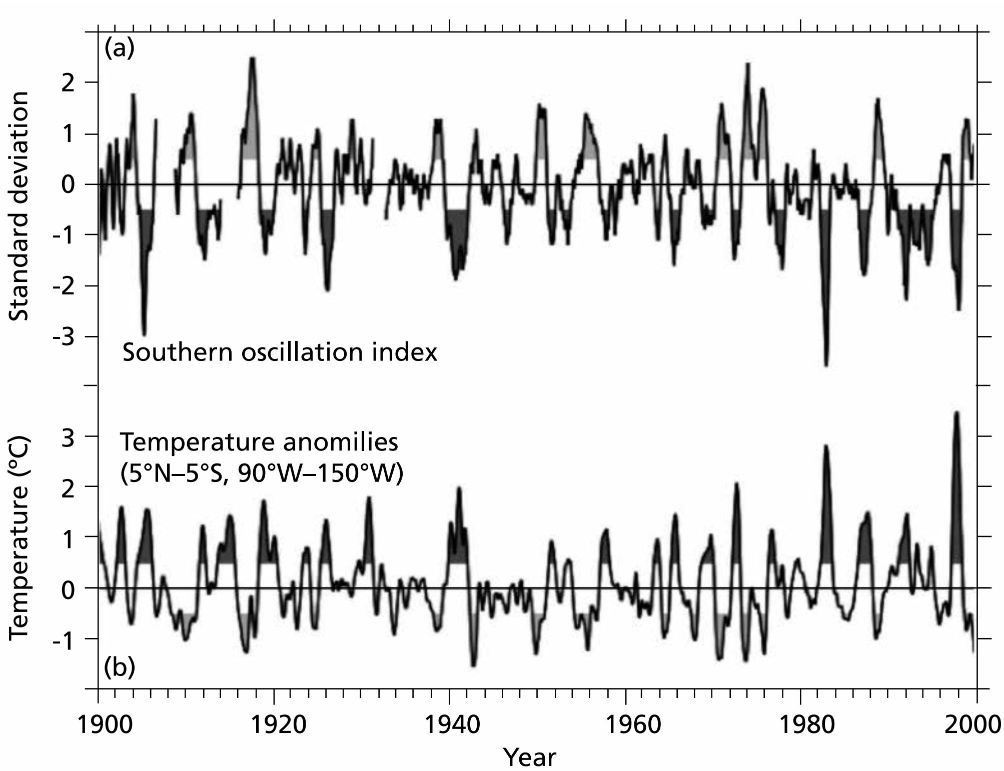


Note that strong warm events (1997/98, 2015/16) induce very strong eastward and equatorward shifts of rainfall.

Source: adapted from Timmermann *et al.* (2018).

A number of measures have been introduced to define the different event types, with an emphasis on the warm (El Niño) ENSO phase. These definitions can vary between countries and depend on the impacts of interest. Indices informing classifications can be based on atmospheric variables such as the differences in air pressure between two locations (e.g. the Southern Oscillation Index [SOI], which measures changes in air pressure between Tahiti and Darwin, Australia) or the outgoing longwave radiation anomaly, a proxy for deep atmospheric convection. Other indices rely on oceanic variables such as the SST, subsurface ocean temperature or sea surface salinity. See for instance the correlation between SOI and SSTA in Figure 2.2.

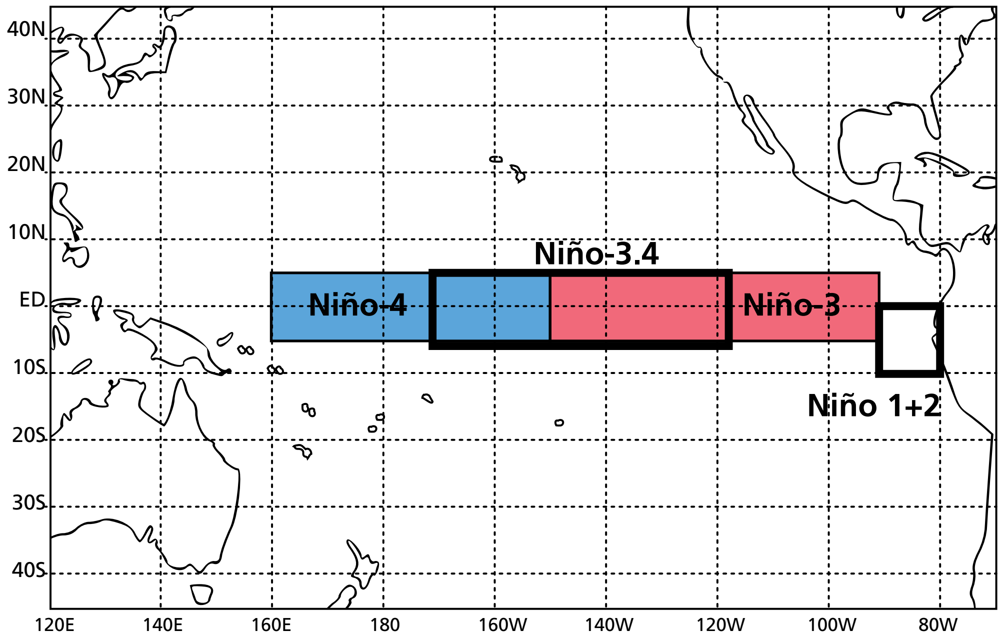
FIGURE 2.2
(a) SOI after typical seasonal variations have been subtracted out: periods of SOI greater in magnitude than 0.5 are shaded to emphasize the relationship with ENSO episodes. Low SOI is associated with warm sea temperatures (El Niño), and high SOI with cold sea temperatures (La Niña). (b) SSTAs: positive anomalies greater than about 0.5 °C indicate El Niño events. Negative anomalies less than about –0.5 °C indicate La Niña events



Source: McPhaden, 2002.

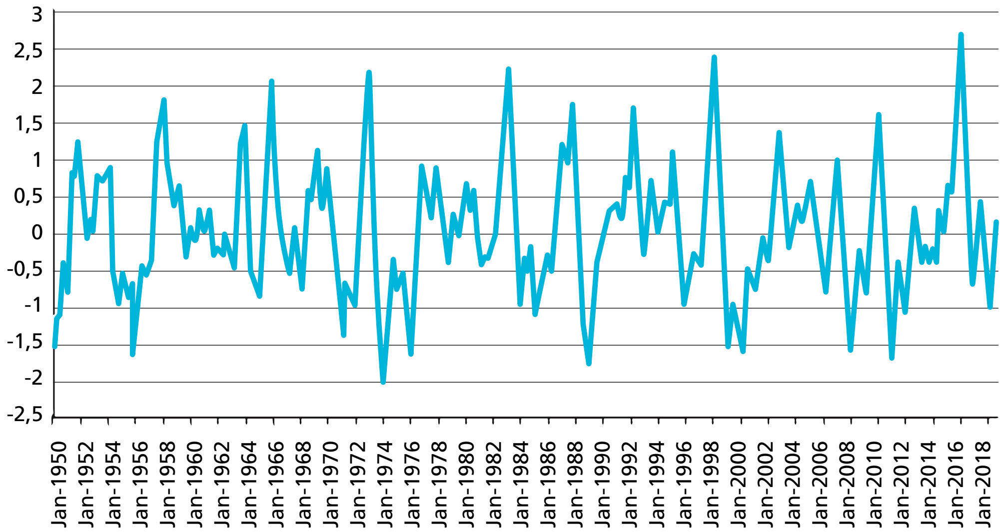
In this document, we will use the most commonly accepted index to define ENSO events: the Oceanic Niño Index (ONI) proposed by the National Oceanic and Atmospheric Administration of the United States (NOAA), which identifies an El Niño event when five consecutive three-month running mean of SSTAs in the Niño-3.4 region (5°S–5° N, 170°–120° W) exceed 0.5 °C (see Figure 2.3 for ENSO regions and Figure 2.4 for ONI time series). To differentiate between CP and EP El Niño events, we used the simple definition proposed by Kug, Jin and An (2009) and Yeh *et al.* (2009): an El Niño event is classified as a CP type when the SSTA averaged over the Niño-4 region (5 °S–5 °N, 160 °E–150 °W) exceeds the SSTA averaged over the Niño-3 region (5°S–5°N, 90°–150°W). EP El Niño events are characterized by Niño-3 SSTA exceeding the Niño-4 SSTA. However, it must be kept in mind that different definitions and their implementation details can result in slightly different classifications, but that the most proposed definitions generally result in similar average patterns for CP and EP El Niño events.

FIGURE 2.3
Regions used for defining ENSO events based on SST



Source: https://www.ncdc.noaa.gov/teleconnections/enso/indicators/sst.php

FIGURE 2.4
ONI values from 1950 to 2018



Source: http://www.cpc.ncep.noaa.gov/data/indices/oni.ascii.txt

A useful means of defining extreme El Niño events is the occurrence of rainfall over the equatorial eastern Pacific, as the warm SST anomalies tend to induce atmospheric convection and thus heavy precipitation over this climatologically cold and dry region (Cai *et al.*, 2015; Takahashi and Dewitte, 2016). Rainfall anomalies at the height of the 1982/83, 1997/98 – and to a lesser extent the 2015/16 El Niño events – expanded into the Niño-3 region. Such intrusions are completely absent in moderate CP and EP El Niño events (Figure 2.1). We will thus define extreme El Niño events as those exhibiting positive rainfall anomalies exceeding 4 mm·day^{-1} in the Niño-3 region, when averaged from December to February.

Finally, La Niña events are usually defined using the ONI index when five consecutive three-month running mean of SSTAs in the Niño-3.4 region are colder than −0.5 °C. However, weak La Niña events generally do not impact aquaculture and capture fisheries because they correspond to a weak intensification of the mean seasonal cycle. We will focus here only on strong La Niña events and, although their signature is more focused on the Niño-4 region (Cai *et al.*, 2015), for practical considerations we define them when five consecutive three-month running mean of SSTAs in the Niño-3.4 region are colder than −1 °C.

To summarize, the following criteria are used to define the different type of ENSO events discussed in this document:

- Moderate CP El Niño events: ONI index >0.5 °C for five consecutive months and Niño-4 > Niño-3 when averaged from September to February during El Niño peak.
- Moderate EP El Niño events: ONI index >0.5 °C for five consecutive months, Niño-4 > Niño-3 when averaged from September to February during El Niño peak and December to February Niño-3 rainfall anomaly <4 mm·day^{-1}.
- Extreme EP El Niño events: ONI index >0.5 °C for five consecutive months, Niño-4 > Niño-3 when averaged from September to February during El Niño peak and December to February Niño-3 rainfall anomaly >4 mm·day^{-1}.
- Strong La Niña events: ONI index < −1 °C for five consecutive months. As mentioned above, there is no discernible impact of weak La Niña events on aquaculture and capture fisheries so weak La Niña events will not be considered in this document.

In addition to these well-known categories, we will also occasionally discuss a specific type of El Niño event, referred to as **"coastal" El Niño** (Peng *et al.*, 2019; Takahashi and Martínez, 2019). This type of El Niño is characterized by warm conditions in the far eastern Pacific, but normal or cool conditions elsewhere in the central Pacific. These events are associated with meridional dynamics in the far eastern Pacific related to an abrupt enhancement of the intertropical convergence zone (ITCZ) and strong northerly winds. Such events have been rarely observed but notable examples of such events occurred in 1891, 1925 and more recently in 2017, when the northern coast of Peru suffered torrential rains, leading to enormous losses of life and property (Ramírez and Briones, 2017; Takahashi, Karamperidou and Dewitte, 2019).

The resulting classification, per year, is presented in Table 2.1.

TABLE 2.1
Classification of the different type of ENSO events that occurred from 1950 to date based on the following categories: extreme El Niño, Eastern Pacific El Niño, Central Pacific El Niño, Coastal El Niño and Strong La Niña. The criteria used to define these different type of events are provided in the text above.

Year	Central Pacific El Niño		Eastern Pacific El Niño		Extreme El Niño		Coastal El Niño		Strong La Niña	
	Start	End	Start	End	Start	End	Start	End	Start	End
1951			Jun-51	Jan-52						
1953	Feb-53	Feb-54								
1955									Sep-55	Jan-56
1957			Apr-57	Jul-58						
1958	Nov-58	Mar-59								
1963	Jun-63	Feb-64								
1965			May-65	Apr-66						
1968	Oct-68	May-69								
1969			Aug-69	Jan-70						
1970									Dec-70	Mar-71
1972					May-72	Mar-73				
1973									Jul-73	Mar-74
1975									Jun-75	Feb-76
1976			Sep-76	Feb-77						
1977	Sep-77	Jan-78								
1982					Apr-82	Jun-83				
1986			Sep-86	Apr-87						
1987	Apr-87	Feb-88								
1988									Jun-88	Feb-89
1991			May-91	Jun-92						
1994	Sep-94	Mar-95								
1997					May-97	May-98				
1998									Aug-98	Mar-00
2002			Jun-02	Feb-03						
2004	Jul-04	Feb-05								
2006			Sep-06	Jan-07						
2007									Sep-07	Mar-08
2009	Jul-09	Mar-10								
2010									Jul-10	Feb-11
2014	Nov-14	Mar-15								
2015					Apr-15	May-16				
2017							Jan-17	Apr-17		
2018	Oct-18	Ongoing as of Aug-19								

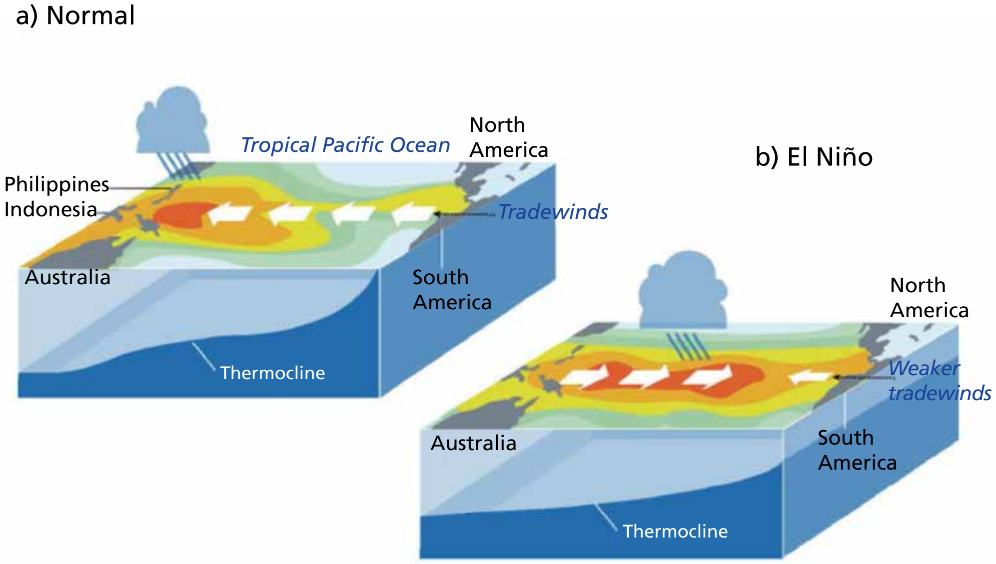
3 ENSO forecasting

KEY MESSAGES

- Accurate ENSO predictions are currently available up to nine months ahead of the ENSO peak.
- The extent to which ENSO forecasts can be improved with a longer time lead is still intensely debated.
- Current operational forecasts are not able to accurately predict which type of El Niño will occur, even at short lead-times.
- Differences in the predictability between El Niño and La Niña are unknown.

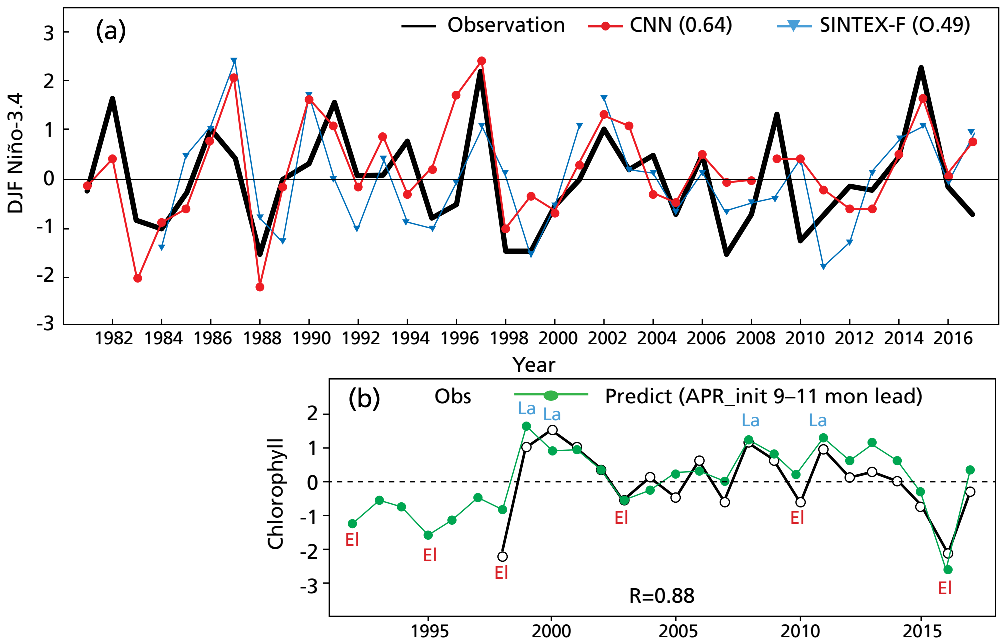
ENSO dynamics have been extensively studied over recent decades (Timmermann *et al.*, 2018). It is now commonly accepted that the development of an event in boreal summer and fall stems from the Bjerknes positive feedback (Bjerknes, 1966). As illustrated in Figure 3.1, a positive feedback loop consisting of a warm SSTA in the central Pacific promoting enhanced deep atmospheric convection and an associated westerly wind anomaly (Gill, 1980) drives an anomalous eastward flow that pushes the warm pool eastward in the central Pacific and deepens the thermocline in the eastern Pacific, hence reinforcing the initial warming. The demise of ENSO events during the following winter is explained by several negative feedbacks that offset the positive Bjerknes feedback, including instantaneous atmospheric feedbacks and delayed oceanic feedbacks. Because these positive and negative feedbacks are largely deterministic, ENSO growth and decay phases are rather well predicted, with reasonably accurate forecasts of ENSO up to three seasons before its peak (e.g. Kirtman *et al.*, 2014).

FIGURE 3.1
Schematic showing (a) normal (ENSO neutral) and (b) El Niño conditions in the equatorial Pacific Ocean



Source: adapted from McPhaden, 2002.

FIGURE 3.2
(Top) Time series of winter Niño-3.4 index for observations (black) and for an 18-month lead forecast using the deep learning statistical model (red) and state-of-the-art dynamical forecast system (blue). (Bottom) Time series of winter normalized chlorophyll anomalies in the tropical Pacific (170 °E–100 °W, 10 °S–10 °N) for observations (black) and for a 10-month lead forecast using an earth system model (green) winter normalized chlorophyll anomalies



Source: adapted from Ham, Kim and Luo, 2019; Park *et al*., 2019.

One major limitation on prediction is that seasonal predictions made during or before the boreal spring have much lower accuracy than those made after spring. In numerical prediction models, it appears as a sudden decrease of the prediction skill when these models are initialized in spring or before (Barnston *et al*., 2012). Consequently, current ENSO forecasting systems generally provide accurate predictions two to three seasons before the ENSO peaks. However, the ocean is a source of long-lasting memory for the climate system, providing some hope regarding the potential to improve ENSO forecasts at longer lead-times. There is evidence that El Niño (La Niña) events exhibit the tendency to be preceded by positive (negative) heat content anomalies from six months to up to two years before the event (Meinen and McPhaden, 2000). The presence of such an early oceanic precursor is, however, insufficient for ENSO events to develop and the added value of better accounting for these oceanic precursors in current forecasting systems is still unknown. These oceanic precursors allow for the provision of some ENSO skill beyond one year in state-of-the-art forecast system models (Figure 3.2a). Several studies argue that the chaotic nature of the ocean–atmosphere system inherently limits ENSO predictability and that the scope for further improving ENSO skill beyond six months lead-time is very limited (Newman and Sardeshmukh, 2017), while others argue that ENSO could be predicted at lead-times exceeding one year by improving the present operational forecasting systems (Ham, Kim and Luo, 2019; Petrova *et al*., 2017). A recent attempt to improve ENSO prediction using deep learning for instance, suggests that the prediction skill is much higher for those using this type of non-linear statistical model than those with current state-of-the-art dynamical forecast systems (Figure 3.2a).

Current forecasting systems also have difficulty in predicting the different types of El Niño events, even at short lead-time (Ren *et al*., 2019), and it is currently unknown if distinct precursor patterns exist for different ENSO types. However, it has been suggested that CP El Niño events may be more difficult to predict due to their smaller amplitude and smaller signal to noise ratio (Imada *et al*., 2015). Despite an improved understanding of ENSO dynamics, ENSO prediction skill has not demonstrated a steady improvement over the past few decades and ENSO prediction skill even decreased at the turn of the twenty-first century (McPhaden, 2012). This decrease may be related to the reduced ENSO amplitude and the more frequent occurrence of CP El Niño events during that period because their evolution and climate impacts may be less predictable than those of EP and extreme El Niño events.

The difference in the predictability between El Niño and La Niña is unknown and the mechanisms leading to multi-year La Niña events are not well understood. Using ensemble forecasting techniques, a recent study identified potential predictors for the likelihood of multi-year La Niña events, suggesting the possibility of longer-term forecasts for La Niña as well (DiNezio *et al*., 2017).

Another recent study (Park *et al*., 2019) suggests that new earth system models that include a biogeochemical component can skilfully predict seasonal to multi-annual chlorophyll fluctuations in many regions of the world, as a result of a simulation of the chlorophyll response to ENSO. In the tropical Pacific, prediction skill is limited to less than one year, with reduced skill for boreal spring predictions in line with the so-called "predictability barrier". Prediction of increased (decreased) chlorophyll in the equatorial central/eastern Pacific is usually related to an upcoming El Niño (La Niña event). This allows the prediction (to some extent) of variation in fish captures in the coming year in the Humboldt Current system (Figure 3.2b). This relationship also holds for the tropical Indian Ocean, which is subject to a lagged ENSO signal carried into the Indian Ocean through atmospheric teleconnections (see Section 5). This prediction skill can be extended up to two years in extra-tropical regions such as the north Atlantic and south Pacific, as a consequence of the re-emergence of subsurface nutrient anomalies from one winter to the next.

The majority of analyses of ENSO predictability are dependent on hindcast datasets. Since the climate model tuning process in some cases considers the adequate representation of ENSO variability (Hourdin *et al*., 2017; Schmidt *et al*., 2017), such studies could overestimate the actual forecast skill, particularly associated with events with previously unobserved characteristics. For instance, although the 2015/16 event is considered a strong EP El Niño, comparable to the 1982/83 and 1997/98 events, it showed weaker warming in the eastern Pacific and greater warming in the central Pacific, which dramatically suppressed the heavy rainfall observed in western South America in the previous two cases, but the operational models in North America failed to predict this (L'Heureux *et al*., 2017). Furthermore, even when focusing on the Niño-3.4 region, statistical and dynamical models underpredicted the El Niño strength, except at a short lead-time. In this sense, structural uncertainty associated with incomplete knowledge of ENSO should be considered in addition to estimation uncertainty, which should be assessed considering the past real-time performance of operational systems, not only of models but also of human forecasters (e.g. L'Heureux *et al*., 2019).

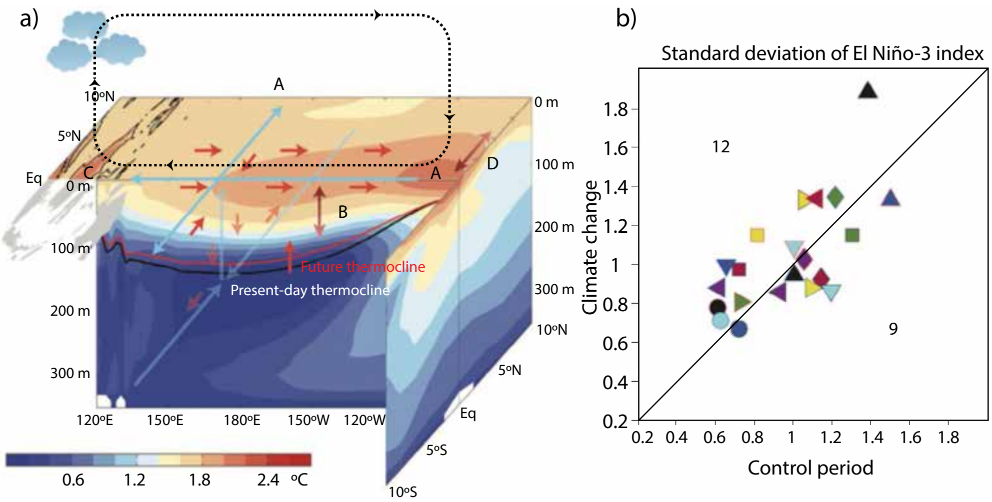
4 ENSO in the context of climate change

KEY MESSAGES

- Climate change is very likely to influence the mean climate of the Pacific region.
- The inability of climate models to realistically simulate the present-day climate and ENSO properties hampers the reliability of climate projections.
- As a consequence, it is not yet possible to confidently assess if and how ENSO activity (amplitude, frequency, pattern) will change in the future.
- Despite the absence of consensus, recent studies suggest a potential doubling of the frequency of extreme El Niño and La Niña events.

The increased frequency of CP El Niño events at the turn of the twenty-first century (Lee and McPhaden, 2010) could potentially be a response to anthropogenic forcing. In particular, the warming observed in the western Pacific in 2014/15 may be partly attributable to global warming. However, the limited number of observational records available prevent the drawing of any definitive conclusions on this matter. Indeed, climate change influence on the tropical Pacific climate is currently uncertain because of difficulties involved in detecting climate change signals due to the strong aliasing by natural decadal/multi-decadal variability. Current research thus relies heavily on the ability of coupled models to assess the tropical Pacific's response to climate change. These models indicate that climate change is likely to influence the mean climate of the Pacific region (Figure 4.1a), with a weakening of the tropical easterly trade winds, a shoaling of the equatorial thermocline and increased vertical temperature gradient, and a faster SST warming near the equator compared to off-equatorial regions (Cai *et al*., 2015). This will result in a decline in net primary production in the equatorial upwelling region, potentially associated with a local decrease in species and maximum potential catch by 50 percent for Pacific island countries and territories (PICTs) (Asch, Cheung and Reygondeau, 2018). However, because the physical pattern and the mechanisms involved are different, an El Niño event cannot be considered as an analogue of the long-term warming pattern in the tropical Pacific in the future.

FIGURE 4.1
Greenhouse-induced future changes projected by CMIP5[3] models in the tropical Pacific



(a) Schematic of greenhouse-induced changes (red arrows) to the mean Walker circulation (dashed black arrows) and mean ocean currents (cyan arrows) for CMIP5 ensemble mean. (b) Scatterplot in ENSO amplitude (El Niño-3 standard deviation) for the “control” period and “climate change” period for each CMIP5 models.

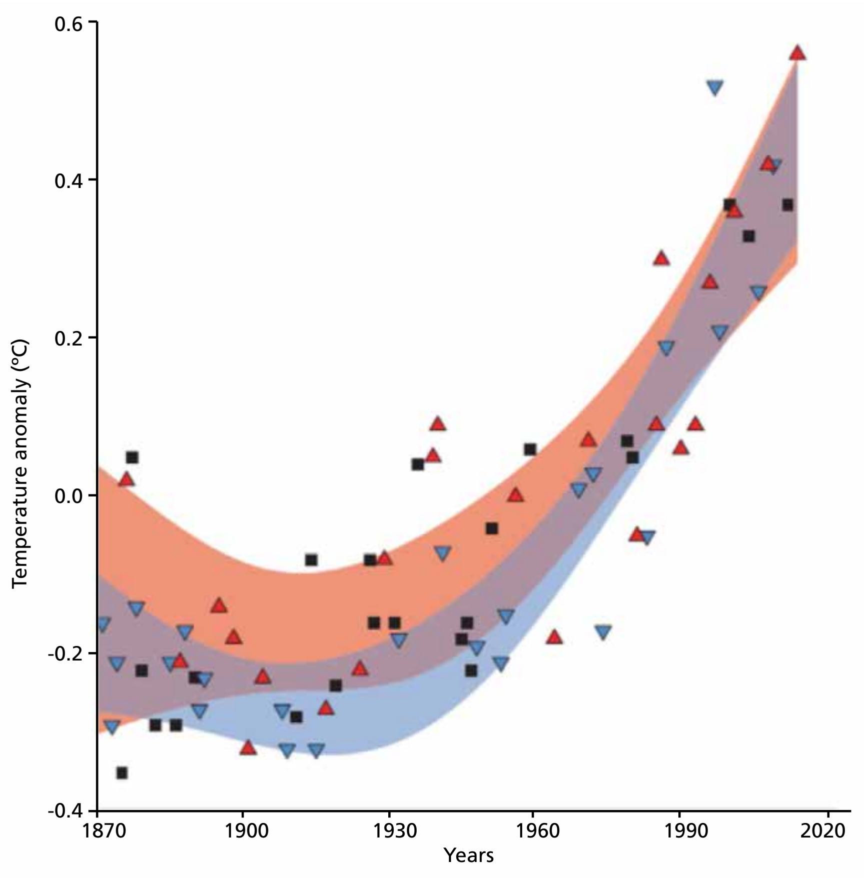
Source: adapted from Cai *et al*., 2015.

Despite these rather consistent changes in the mean state, it is not yet possible to say whether ENSO activity will be reinforced or damped (Figure 4.1b), or if the frequency of events will change because ENSO amplitude change varies considerably from one model to another (Cai *et al*., 2015). These inconsistencies in the projection of future ENSO variability are likely to be related to the delicate balance of amplifying and damping feedbacks controlling ENSO, rendering projections uncertain. The reliability of these projections may also be hampered by long-standing model biases (Bellenger *et al*., 2014), including an excessive equatorial cold tongue and a coastal upwelling not well resolved. Even without any future change in ENSO characteristics, the unabated warming observed and projected in the tropical Pacific has, and will continue to have, tremendous consequences for the frequency of coral bleaching events in this region. Before anthropogenic climate warming such events – often related to the occurrence of an El Niño event – were relatively rare, allowing for the recovery of reefs between events. The occurrence of an El Niño event now develops on a warmer mean state. This considerably increases the level of thermal stress for a given El Niño amplitude in the present-day and for the future climate as compared to the past. As climate change unfolds, tropical SSTs at coral reef locations are now warmer during current La Niña conditions than they were during El Niño events three decades ago (Figure 4.2; Hughes *et al*., 2018).

Consequently, tropical reef systems are transitioning to a new era in which the interval between recurrent bouts of coral bleaching is too short for a full recovery of mature assemblages. Estimates of future levels of thermal stress suggest that even the optimistic 1.5 °C Paris Agreement target is insufficient to prevent more frequent mass bleaching events for the world’s reefs (Lough, Anderson and Hughes, 2018).

[3] Climate Model Intercomparison Project version 5

FIGURE 4.2
Climate change throughout ENSO cycles



Sea surface temperature anomalies from 1871 to 2016, relative to a 1961–1990 baseline, averaged across 1° latitude by 1° longitude boxes containing coral reefs between the latitudes of 31 °N and 31 °S. Data points differentiate El Niño (red triangles), La Niña (blue triangles) and ENSO neutral periods (black squares). Ninety-five percent confidence intervals are shown for nonlinear regression fits for years with El Niño and La Niña conditions (red and blue shading, respectively; overlap is shown in purple).

Source: Hughes *et al*., 2018.

Despite a lack of consensus on how ENSO amplitude will evolve in the future, recent studies suggest that the potential consequences of the mean state changes include a near doubling of the frequency of extreme El Niño events (Cai *et al*., 2015). This projected increase in the frequency of extreme El Niño events creates favourable conditions for the occurrence of extreme La Niña events, the frequency of which is also expected to nearly double. The response of the tropical eastern Pacific rainfall anomalies to El Niño SST anomalies under greenhouse-induced warming is likely to strengthen, and the centre of maximum response to shift eastward. It has nonetheless been suggested that, under a continuous warming context, SSTA alone cannot be used as an indicator of changes in the intensity of upwelling or biomass in upwelling systems (Demarcq, 2009). This increased frequency of ENSO extremes is consistent with an increase in ENSO-related hydro-climate variability in the tropical Pacific region. Little research has been conducted on the impact of climate change on coastal El Niño but recent results suggests that climate change might have contributed to the impacts of the 2017 event (Christidis, Betts and Stott, 2019) and that the frequency of these events might increase in the future (Peng *et al*., 2019).

While ENSO-related catastrophic weather events may occur more frequently with unabated greenhouse gas emissions, the Intergovernmental Panel on Climate Change (Collins *et al*., 2019) states medium confidence on the projected doubling in the frequency of extreme El Niño in the twenty-first century under a 1.5 °C global warming and on the maintenance of enhanced risk in the twenty-first century even if greenhouse gas emissions were substantially reduced. The projected increased frequency of extreme El Niño and extreme La Niña events is indeed contingent upon the faster warming in the eastern equatorial Pacific (Cai *et al*., 2015), which has been challenged by the observed strengthening over recent decades. The ability of climate models to realistically simulate the present-day mean state climate and ENSO properties is another source of uncertainty. For instance, little is known about how other important characteristics of ENSO will respond to greenhouse-induced warming, such as ENSO phase locking, the termination and onset of El Niño events, ENSO precursors and amplifying or damping mechanisms, along with the interactions with the other basins. Model biases and recently observed strengthening of the Walker circulation (i.e. the atmospheric circulation over the equator) thus highlight the need for further testing as new models, observations and insights become available.

5 Global overview of ENSO impacts

KEY MESSAGES

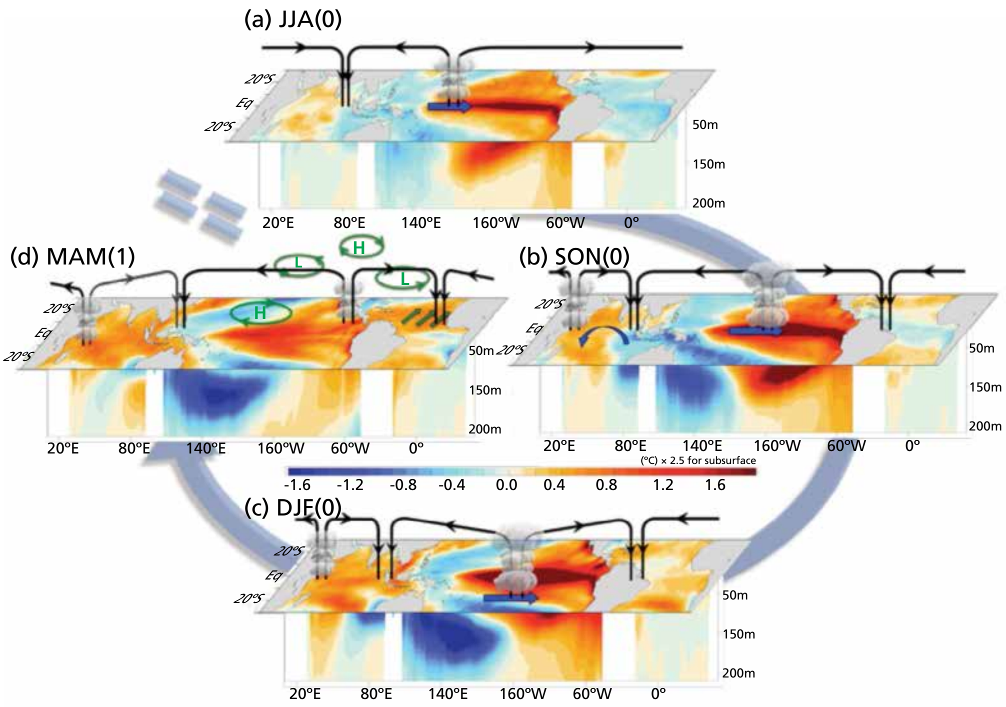
- ENSO alters climate, weather patterns and TCs as well as oceanic conditions and productivity across the globe through atmospheric and oceanic teleconnections.
- These ENSO impacts are sensitive to ENSO flavour (i.e. extreme El Niño, moderate EP El Niño, moderate CP El Niño, coastal El Niño and strong La Niña events).
- ENSO impact on marine landings varies between ENSO flavours. On average, global marine landings are reduced during extreme El Niño (−3.2 million tonnes) and EP El Niño (−0.7 million tonnes) but increase during CP El Niño (+0.8 million tonnes) and La Niña (+0.7 million tonnes).
- ENSO impacts also vary geographically, with more marked negative (extreme and CP El Niño) and positive (La Niña) impacts in the eastern Pacific than in any other marine region.
- ENSO events impact habitats, migration patterns and trophic webs, thus their effects may experience time lags before being felt via, for instance, changes in fishing rates.

5.1 GLOBAL IMPACTS ON OCEAN CONDITIONS, STORMS AND CLIMATE

ENSO dramatically alters oceanic conditions, climate and weather patterns across the globe (McPhaden, Zebiak and Glantz, 2006). In the tropical Pacific, weaker trade winds during El Niño conditions reduce upwelling intensity off South America and along the equator, leading to a deeper thermocline and warmer-than-normal SSTs in the eastern and tropical central Pacific. Rain patterns also shift further east than normal, leading to dryer conditions over the western tropical Pacific and wetter conditions in the east (Figure 5.1). Conversely, stronger trade winds during La Niña lead to an increase in upwelling intensity and hence lower than normal SSTs. The centre of the prevailing rain pattern also shifts further west than normal during La Niña.

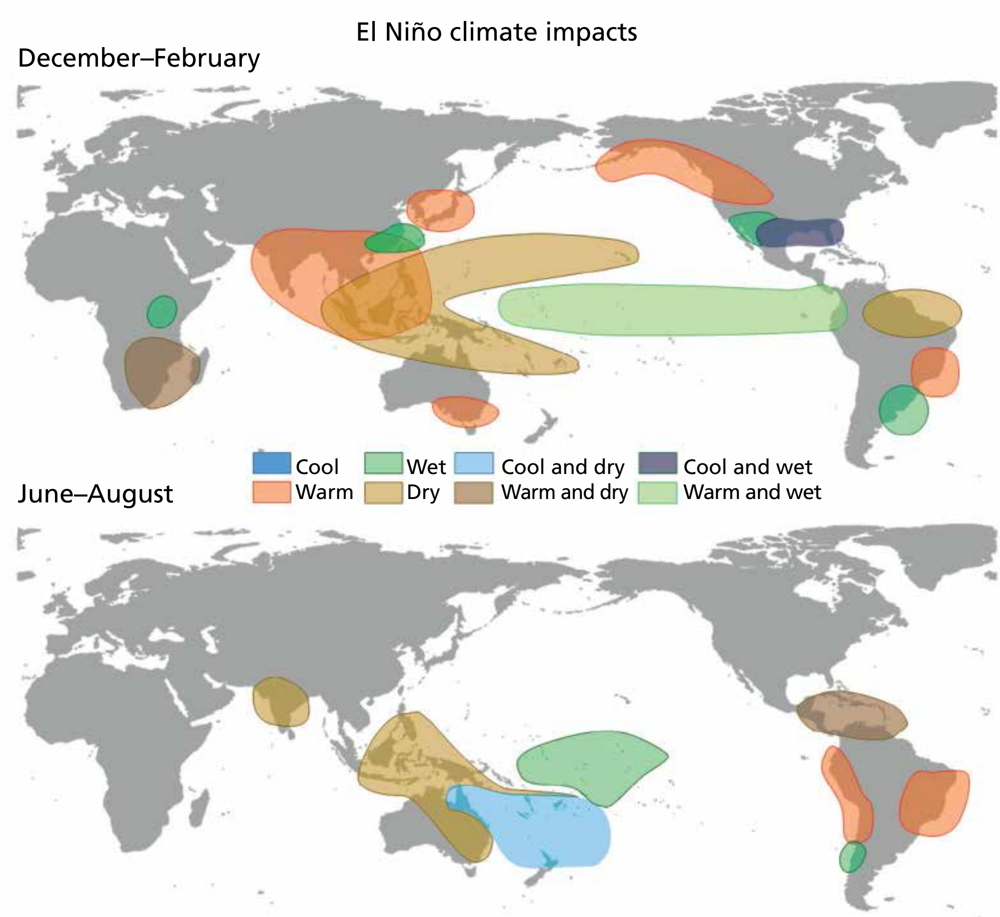
Consequently, El Niño events dramatically alter the Walker circulation (Figure 5.1). The eastward shift of convective activity from the western towards the central/eastern Pacific during El Niño events induces subsidence over the eastern Indian Ocean, the Maritime Continent and the Atlantic (Figure 5.1). These shifts in the Walker circulation induce a warming in remote ocean basins such as the Indian Ocean and the tropical north Atlantic (Figure 5.1c), with a time lag of one to two seasons (Cai *et al.*, 2019). ENSO can also affect regions outside the tropics, via large-scale atmospheric Rossby waves that propagate from the tropical Pacific forcing region into the extra-tropics. These tropical and extra-tropical atmospheric teleconnections of ENSO influence the intensity and occurrence of extreme events such as storms, heatwaves, droughts and floods (Yeh *et al.*, 2018). Aside from atmospheric teleconnections, ENSO also impacts regions outside the tropical Pacific through oceanic teleconnections. For instance, ENSO oceanic teleconnections include heat extremes off the west coast of Australia via the Indonesian Throughflow bridging the Pacific and the Indian Ocean (Feng *et al.*, 2011). Equatorial wind anomalies associated with ENSO also generate oceanic Kelvin waves along the west coast of the Americas (Clarke and van Gorder, 1994), affecting coastal marine ecosystems and fisheries there (Bertrand *et al.*, 2008).

FIGURE 5.1
Evolution of the tropical oceans during a typical extreme or EP El Niño event



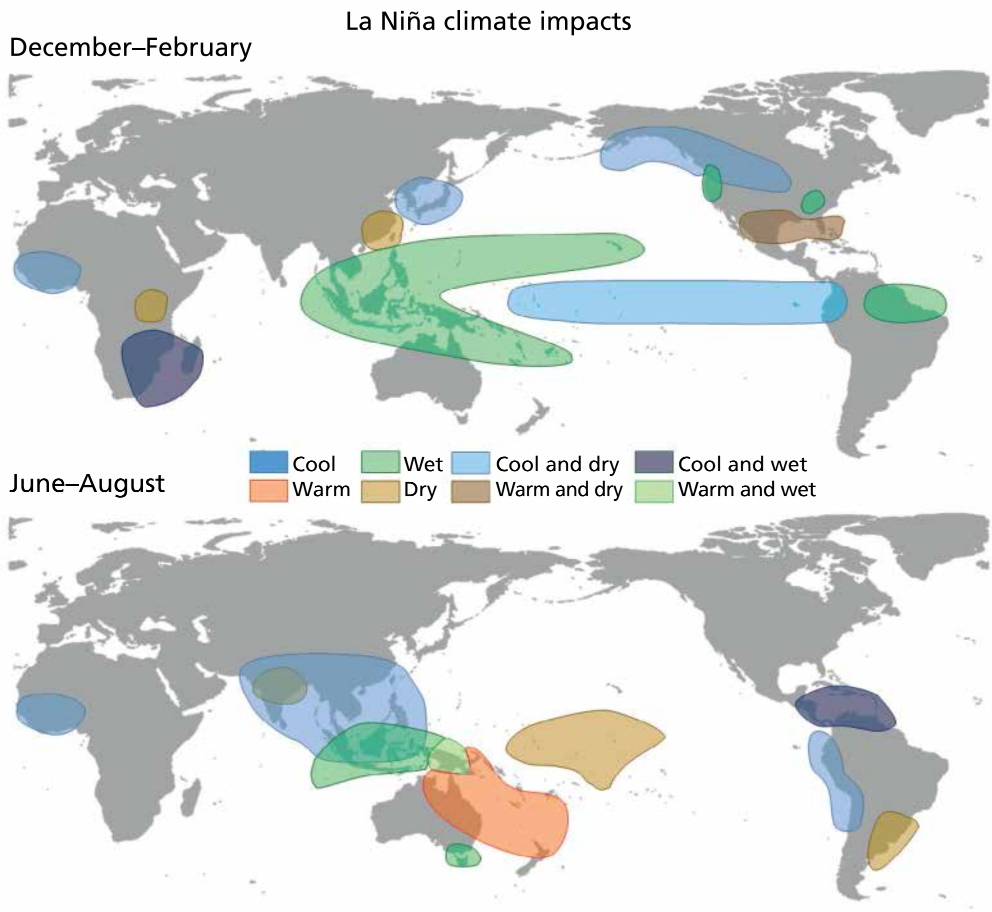
(a to d) Seasonally stratified SST anomaly lead or lag regression with normalized December–January–February (DJF) El Niño-3.4 (in °C, as indicated by colour shading) together with schematic surface wind and Walker circulation changes (arrows) for (a) preceding summer (June–August) and (b) autumn (September–November), (c) simultaneous winter (December–February) and following (d) spring (March–May). As El Niño grows, Walker circulation changes lead to the development of an Atlantic La Niña, (a) a positive Indian Ocean Dipole (a, b), an Indian Ocean basin-wide warming (c, d) and North Tropical Atlantic warming (c, d). As noted in parentheses after the season abbreviation, year 0 indicates an El Niño developing year, whereas year 1 indicates the subsequent decaying year. H: regions of anomalously high surface pressure; L: regions of anomalously low surface pressure.

FIGURE 5.2
Schematic of the climate impacts for a typical EP and/or extreme El Niño in boreal winter and summer



Source: modified from NOAA (http://bit.ly/2hI8XLm)

FIGURE 5.3
Schematic of the climate impacts for a typical La Niña in boreal winter and summer



Source: modified from NOAA (http://bit.ly/2hI8XLm)

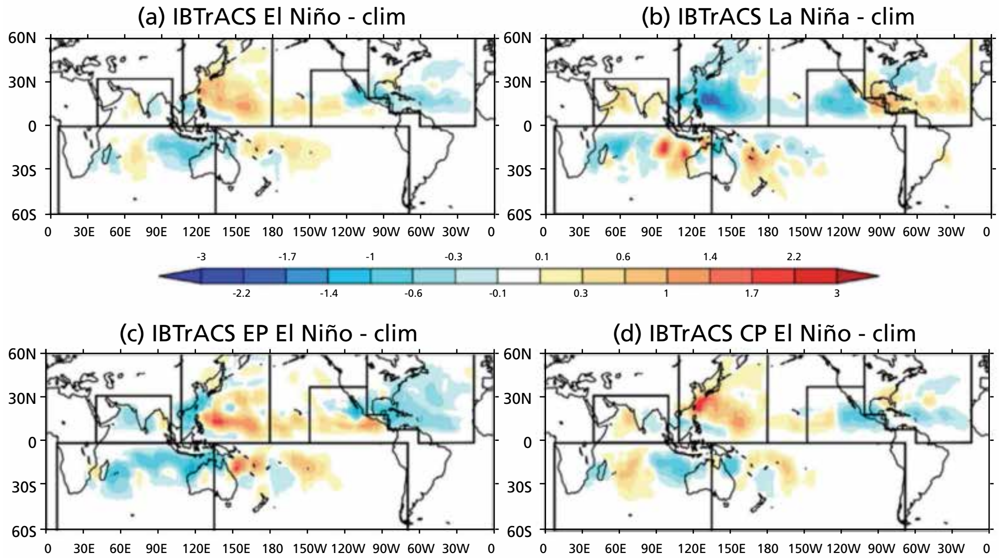
The maps in Figure 5.2 and Figure 5.3 summarize the main impacts on seasonal precipitation and near-surface temperature over land areas for El Niño and La Niña events (NB further detailed impacts on terrestrial regions are discussed in Chapters 8 and 9). The eastward rainfall shift during all El Niño events induces a drier climate over the Maritime Continent, the western Pacific and northern Australia in boreal winter. Consequently, numerous Pacific island countries experience drier than normal conditions during an El Niño, which can lead to severe droughts and forest fires. Other impacts include a decrease in the sea level and the possibility of coral bleaching in the numerous coral reefs in this region. During extreme El Niño events, the usually dry and cold coast of northern Peru and Ecuador becomes warm and very wet in winter because of the eastward shift of convective rainfall into the eastern Pacific, causing major flooding there. Extreme and El Niño also reduce the upwelling of cold, nutrient-rich water that sustains large fish populations, leading to fish kills off the coast of Peru and Chile. Southern Brazil and northern Argentina also experience wetter than normal conditions during the spring and early summer, while northern Brazil becomes hotter and drier. Over North America, the Gulf Coast between Texas and Florida experiences wetter-than-average conditions, while the majority of Canada generally exhibits a milder winter and spring. South-central Africa experiences drier conditions during winter. Impacts of La Niña events generally mirror those of El Niño.

ENSO teleconnections and impacts are, however, sensitive to the longitude where atmospheric deep convection is shifted and hence differ between extreme, EP and CP El Niño (Yeh *et al*., 2018). The centre of action for ENSO teleconnections during extreme and EP El Niño events is generally shifted eastward over the Eurasian continent, North America and the north Atlantic, while a westward shift is observed during CP El Niño events in the north Pacific. ENSO impacts are hence sensitive to ENSO flavour. For instance, the reduction of the Indian summer monsoon and rainfall reduction over Australia during El Niño is greater during CP than EP El Niños. Rainfall decreases across Australia during austral spring are generally larger during CP than during EP El Niños. While this reduction generally occurs over the northeastern and southeastern part of the continent during EP El Niños, it is greater over northwestern and northern Australia during CP El Niños. It must, however, be noted that the short observational record has so far prevented a clear identification of which changes are robust and which are not. The impacts of CP and EP EL Niño are discussed more fully for regions supporting aquaculture and inland fisheries in Chapters 8 and 9.

5.2 GLOBAL IMPACTS ON TROPICAL CYCLONES

TCs and severe storms can have significant effects on fish stocks, their supporting habitats, fishing fleets and fisheries yields, aquaculture facilities and, consequently, on protein intake and sources of livelihood for dependent communities. TCs directly impact coral reefs, mangroves, seagrasses and intertidal areas through physical damage, resuspension of sediments, pulses of nutrient enrichment and freshwater inundation, altering their extent, structural complexity and benefit as fish habitats, with subsequent effects on local fisheries (Dunstan *et al*., 2018). In addition, TCs as well as floods can damage or destroy fishing and aquaculture facilities, vessels, gear and livelihoods (Poulain and Wabbes, 2018; Sainsbury *et al*., 2018). As shown in Figure 5.4, ENSO considerably modulates the large-scale atmospheric and oceanic environment and consequently strongly affects TC activity at a global scale. Over the western north Pacific, TCs tend to track away from the Asian coast and form closer to the International Dateline during El Niño years (Figure 5.4a). Over the central and eastern Pacific, El Niño shifts TCs away from the Mexican coast and towards the International Dateline. TC activity in the north Atlantic is generally suppressed during El Niño, inducing a reduction of landfall along the coastline of the United States of America. In the south Pacific region, TC activity is enhanced east of 170 °E during El Niño, but reduced over the Coral Sea and Australia. The opposite effects are generally observed during La Niña events (Figure 5.4b). The various ENSO flavours result in substantial differences in their influence on Atlantic activity in most of the basins (Figure 5.4c, d). A more detailed description of the TC activity response to ENSO and its flavour will be provided in the following chapters for each basin. Specific comments on the impacts of TCs on ocean and fisheries conditions are provided, contextually, in the following sub-sections.

FIGURE 5.4
TC track density anomaly maps during May–November in the Northern Hemisphere and October–May in the Southern Hemisphere over the 1979–2010 period for (a) El Niño years, (b) La Niña years, (c) EP El Niño years and (d) CP El Niño years



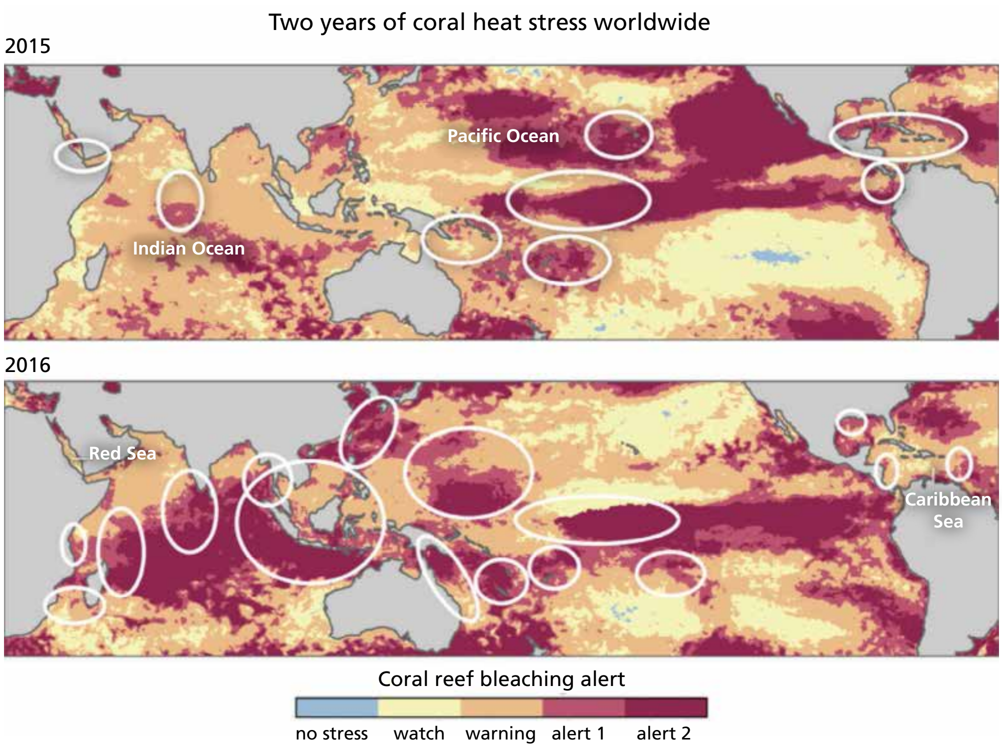
Source: from Lin *et al.*, 2020.

5.3 GLOBAL IMPACTS ON MARINE HEATWAVES

Across the tropics, coral reefs gather a huge diversity of plants and animals into relatively small areas, providing food for up to a billion people around the world, habitat for economically valuable fish species and protection from storms and waves. Corals depends on their partnership with symbiotic algae to thrive (see Chapter 7). When stressed by high temperatures, corals often expel these symbiotic algae and turn white. Prolonged and severe bleaching can lead to disease, starvation and death.

Impacts of global climate change on coral reefs are strengthened by pulse heat stress events associated with El Niño events. Historically, global-scale coral bleaching has been associated with El Niño events (Figure 5.5), which generally raise global temperatures. The first mass coral bleaching was observed during the strong El Niño in 1982/83, and the first global event coincided with the strong El Niño of 1997/98. The world's tropical reefs were stressed again during the much milder 2010 CP El Niño. Because of unabated global warming, the extreme 2015/16 El Niño event instigated unprecedented global coral heat stress across the world's oceans (Lough, Anderson and Hughes, 2018), coinciding with the most severe, widespread, and longest-lasting global-scale coral bleaching event (see Chapter 7) ever recorded (Figure 5.5). Unabated warming of the tropical oceans combined with projected more frequent and severe El Niño events (Cai *et al.*, 2014) will continue to exacerbate the levels of thermal stress experienced by coral reefs. Each strong El Niño event will likely result in a higher level of stress than previous ones and the emergence of significant bleaching in non-El Niño years. MHW impacts also extend to change in abundance, mortality, growth and phenology of fish species (Poulain and Wabbes, 2018; Hobday *et al.*, 2016; Mills *et al.*, 2013). For example, a warm event in 1999 contributed to a massive die-off of lobsters in Long Island Sound, northwest Atlantic, and to the spread of lobster shell disease which has decimated populations south of Cape Cod. On the other hand, the record landings of lobsters as a result of the 2012 heatwave in the Gulf of Maine, outstripped the processing capacity and market demand for the product which contributed to a price collapse (Mills *et al.*, 2013).

FIGURE 5.5
Coral bleaching events observed in (top) 2015 and (bottom) 2016



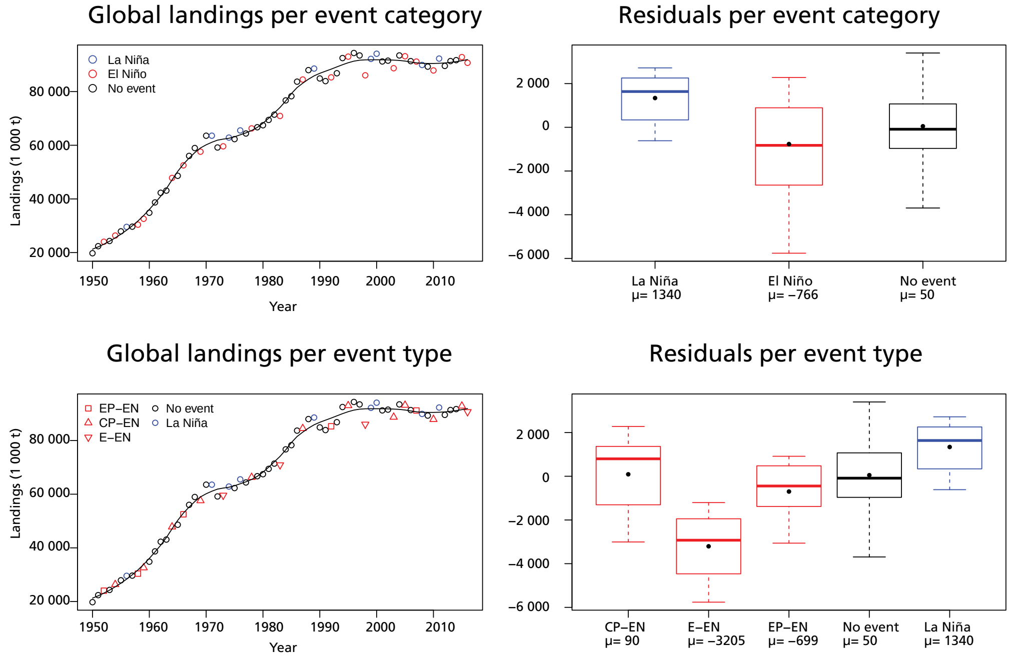
The likelihood of coral bleaching depends on how much surface temperatures exceed their climatological values and how long the unusual heat persists. Scientists track these conditions using satellite-based estimates of Degree Heating Weeks. Alert 1 means coral bleaching is likely. Alert 2 means widespread bleaching and significant mortality of corals are likely. Severe coral bleaching was reported in areas circled in white.

Source: NOAA.

5.4 GLOBAL IMPACTS ON MARINE CAPTURE FISHERIES

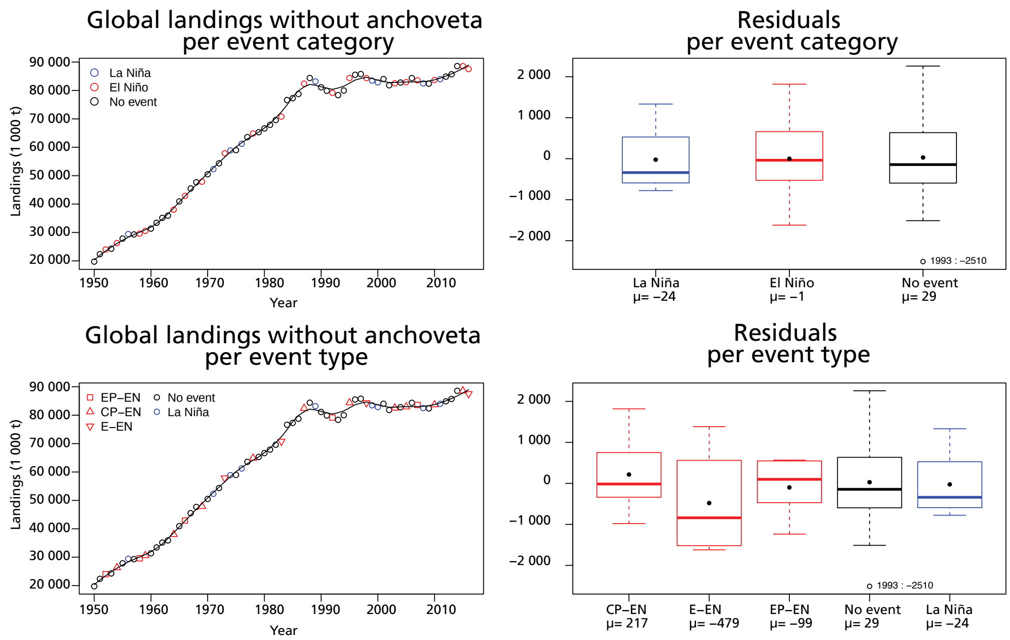
Although El Niño events are considered to be dramatic for marine fisheries in some parts of the world, on average ENSO results in changes of global marine catches of only about one percent relative to neutral years. Marine landings were indeed approximately 0.7 million tonnes lower during El Niño and 1.3 million tonnes higher during La Niña years when compared with the mean landings in the absence of an ENSO event (Figure 5.6). However, the variety of El Niño types illustrates the diversity of responses, with a stronger negative effect for extreme El Niño (–3.2 million tonnes) and EP El Niño (–0.6 million tonnes) and no significant effect during CP El Niño. ENSO impacts are much lower when the Peruvian anchovy is not considered (Figure 5.7), with no significant difference per event category. However, when considering the ENSO types, extreme El Niño years were characterized by a mean deficit of approximately 480 000 tonnes.

FIGURE 5.6
Left panels: global yearly landings (in 1 000 t) per event category (upper panel) and type (lower panel). The black solid line depicts the locally weighted scatterplot smoothing (LOESS) smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel)



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

FIGURE 5.7
Left panels: global yearly landings (in 1 000 tonnes), without the Peruvian anchovy, per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel)



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

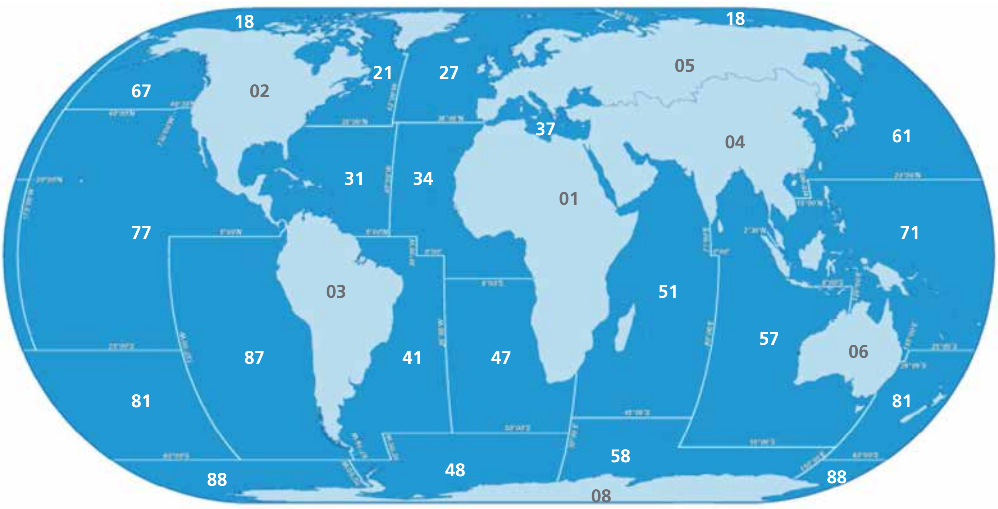
ENSO effects on marine fisheries may also experience a time lag due to the alteration of habitats that affect recruitment and ultimately stock sizes and geographical patterns being felt months or years after an event. For instance, in the eastern Pacific extreme or EP El Niños have been demonstrated to have major effects on nutrient structure (via alteration of upwelling), primary production, and higher trophic levels, leading to changes in fishing rates (e.g. Chavez *et al*., 2002). The specific impacts of ENSO on regional fisheries are detailed in Chapter 6 subsections.

TCs, which are influenced by El Niño, typically have a negative effect on fisheries and aquaculture, for instance by altering the migration of demersal species (Bacheler *et al*., 2019) and by damaging infrastructure (boats, engines, gears, fish aggregating devices [FADs] and coastal facilities) and altering patterns of fishing and post-harvest handling (Radway, Manley and Mangubhai, 2016). Details of the effects of ENSO on TCs in individual oceanic regions are detailed in Chapter 6.

6 Assessment of regional ENSO impacts on marine capture fisheries

Regional assessments were produced for oceans and FAO Major Fishing Areas (Figure 6.1) likely affected by ENSO events. FishStatJ v3.5 (FAO-FishStatJ., 2019a) data was used to inform the assessments.

FIGURE 6.1
FAO Major Fishing Areas



(18) Arctic Sea, (21) Northwest Atlantic, (27) Northeast Atlantic, (31) Western Central Atlantic, (34) Eastern Central Atlantic, (37) Mediterranean and Black Sea, (41) Southwest Atlantic, (47) Southeast Atlantic, (48) Antarctic Atlantic, (51) Western Indian Ocean, (57) Eastern Indian Ocean, (58) Antarctic and Southern Indian Ocean, (61) Northwest Pacific, (67) Northeast Pacific, (71) Western Central Pacific, (77) Eastern Central Pacific, (81) Southwest Pacific, (87) Southeast Pacific, (88) Pacific Antarctic.

Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

6.1 PACIFIC OCEAN

KEY MESSAGES

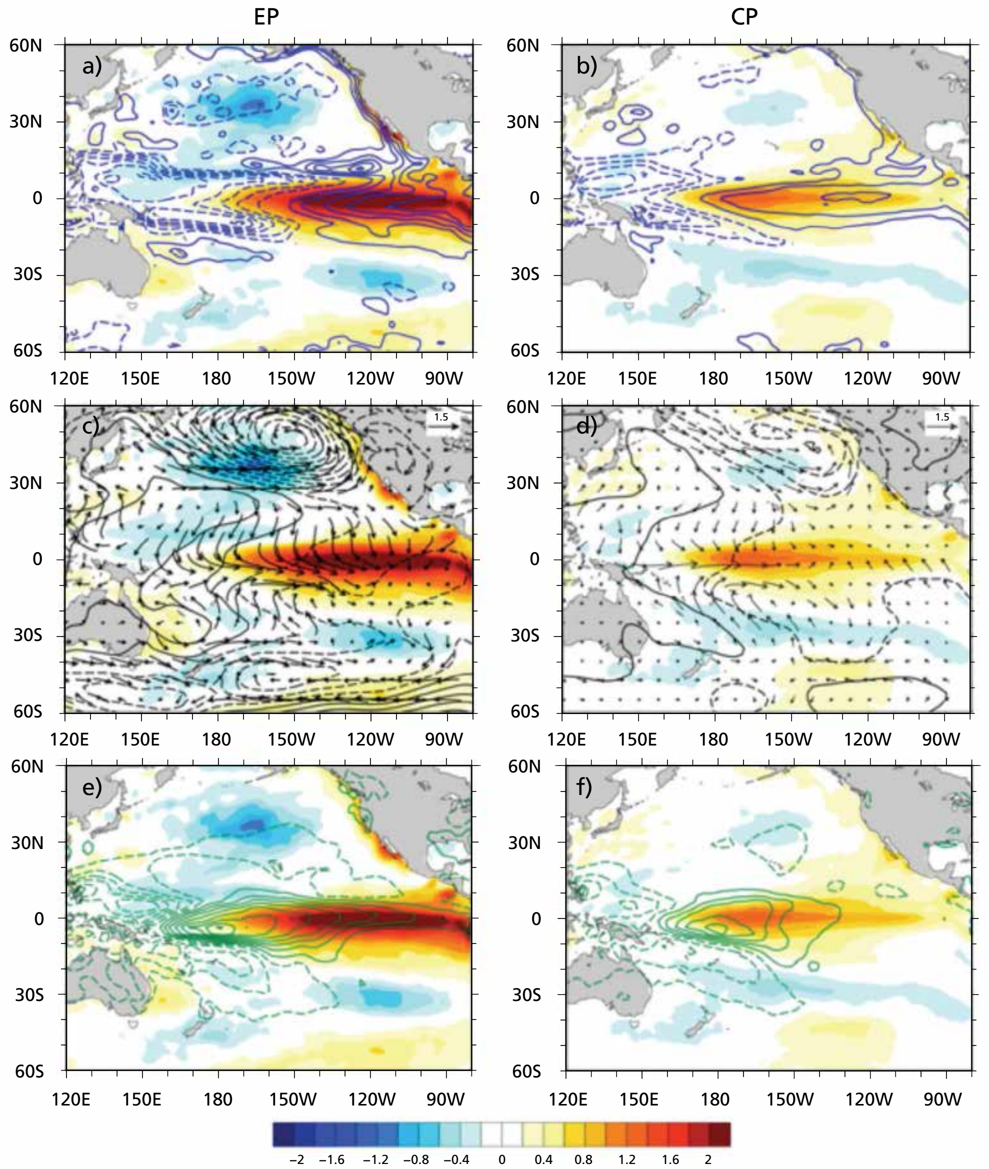
- ENSO is the main driver of interannual variations in SST, sea level, precipitation and TC activity in the tropical Pacific.
- ENSO impacts on fisheries are strong in the Pacific Ocean as a whole, with approximately 1 million tonne anomalies associated with El Niño (negative) and La Niña (positive).
- The consequences of ENSO on fisheries strongly vary between regions of the Pacific Ocean.
- MHWs associated with ENSO have a devastating effect on coral reefs.
- The possible increase in the frequency of extreme El Niño and La Niña events in the future may expose the populated regions on opposite sides of the Pacific Ocean to extreme coastal erosion and flooding.

6.1.1 Impacts on ocean conditions, climate and extreme events

Impact on ocean conditions and climate

During all El Niño events (Figure 6.2a, b), weaker equatorial trade winds induce a warming east of the Dateline, an eastward shift of the western Pacific warm pool, modest cooling (<0.5 °C) over the far western Pacific (west of 160 °E). They exhibit a zonal seesaw in sea level anomalies, indicative of a deeper (shallower) thermocline in the eastern (western) equatorial Pacific (Figure 6.2a, b). The tropical Pacific also experiences a zonal seesaw in sea level pressure anomalies (Figure 6.2c, d), with increased pressure in the western Pacific and decreased pressure in the eastern part of the basin. These pressure anomalies are associated with westerly wind anomalies along the equator, which are part of the positive Bjerknes feedback that allows El Niño to grow. In the extra-tropical North Pacific, El Niño events are associated with a deepened and eastward-extended Aleutian Low, and with a deeper thermocline and warmer conditions along the west coast of North America. This canonical El Niño pattern, however, significantly varies depending on ENSO flavour. While systematically larger for extreme El Niño events, both extreme and EP El Niño display a maximum surface warming in the eastern equatorial Pacific and a strong zonal dipole in sea level anomalies (Figure 6.2a). In contrast, maximum warming for CP El Niño events is located further west with weak SST signals in the eastern Pacific (Figure 6.2b). During these events, positive thermocline depth anomalies in the central/eastern Pacific are weaker and extend further west as compared to EP El Niño events while negative thermocline depth anomalies remain confined to the far western Pacific (Figure 6.2a, b). CP El Niño events also exhibit weaker sea level pressure seesaw located further west, and weaker equatorial westerly wind anomalies more confined to extreme and EP El Niño events (Figure 6.2c, d). Similarly, precipitation anomalies (Figure 6.2e, f) extend all the way to the eastern Pacific in the case of extreme events, while they are limited to the western part of the basin during CP El Niño events. The deepening of the Aleutian low and the deeper thermocline along the western coast of North America, which are critical for marine ecosystem dynamics along the United States of America west coast, appear to be more pronounced during EP El Niño events (Figure 6.2a–d).

FIGURE 6.2
Composites of anomalous SST (shaded, same in each row), sea surface height (SSH, top, contours), sea level pressure (SLP) or winds (middle, contours/vectors), and precipitation (bottom, contours) for EP+extreme (left), and CP (right) El Niño events during boreal winter (December, January, February)



Source: from Capotondi *et al*., 2020.

Impacts on tropical cyclones

The tropical Pacific hosts three main regions of TC formation. The northwestern Pacific is the largest and the most active (for both frequency and intensity) TC basin in the world. On average, this region has 30 named storms, 19 TCs and five major TCs (Category 3 and larger), which severely impact the densely populated Asian countries (e.g. the Philippines, Taiwan, Japan, China, Democratic People's Republic of Korea, Republic of Korea and Viet Nam). After the northwest Pacific, the northeastern Pacific is the second most active region prone to TCs globally, with an annual average of 19 named storms, nine TCs and five major TCs. These TCs can have important economic consequences for the southwestern coast of the United States of America, Mexico, the Hawaiian Islands, as well as military and commercial maritime routes between these areas. Finally, the southwest Pacific is less active, with 13 named storms and only four TCs occurring, on average, per year. As this region includes part of the Maritime Continent, eastern Australia and many small island nations and territories, TCs are a primary cause of natural disasters in the region.

It is now well established that ENSO is a major contributor of the year-to-year variability in TCs in each of these three regions (Lin *et al*., 2020). The northwestern Pacific is known to experience an increase in TC frequency during El Niño years, mainly related to an increase in TC activity in the southeast part of this TC-prone region (Figure 5.4a). In the northeastern Pacific, El Niño acts to shift the TC-prone region westwards and increase their lifespan. In the south Pacific, El Niño tends to shift TC activity northeastwards. La Niña events tend to generate opposite patterns, although they do not systematically mirror those of El Niño (Figure 5.4b). CP and EP El Niño events also have different impacts on Pacific TC activity (Figure 5.4c, d). These specific impacts will be detailed in the following sections for each subregion considered.

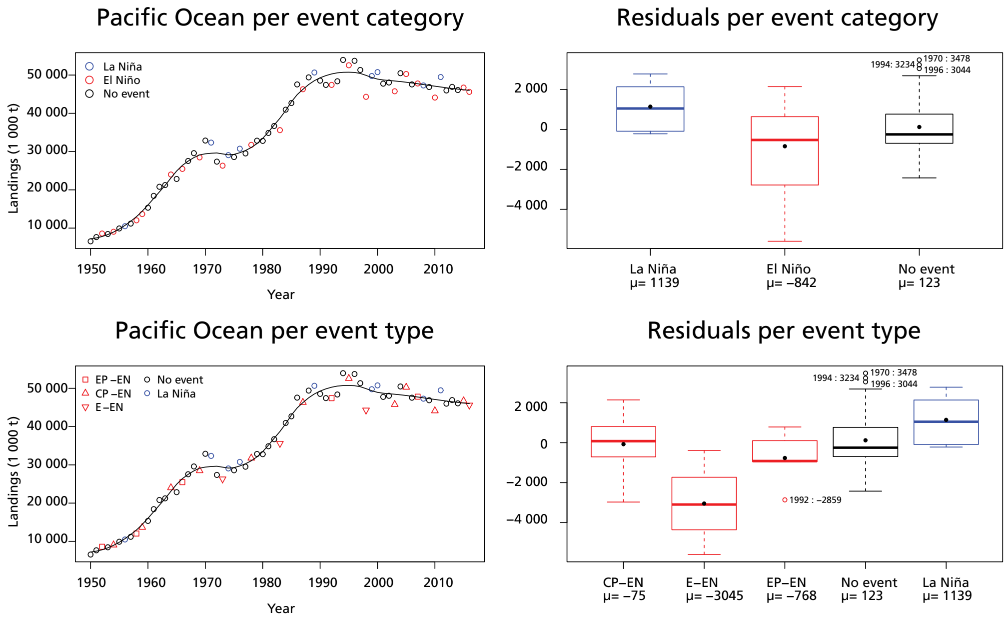
Coastal vulnerability in the entire Pacific is dominated by ENSO (Barnard *et al*., 2015). Elevated wave energy flux, water levels and coastal erosion characterize boreal winter El Niño conditions along the North American west coast. Owing to increased TC activity, the northeastern coast of Australia becomes more vulnerable during La Niña. Although more variable seasonally and/or subregionally, Japan and New Zealand also exhibit significant relationships with ENSO forcing and coastal response. The possible increase in the frequency of extreme El Niño and La Niña events in the future may expose the populated regions on opposite sides of the Pacific Ocean to extreme coastal erosion and flooding, independent of sea level rise.

6.1.2 Impacts on capture fisheries, ocean conditions, storms and climate

ENSO impacts on fisheries are strong in the Pacific Ocean (FAO Major Fishing Areas 61, 67, 71, 77, 81, 87 and 88) where, on average, landings were approximately 0.8 million tonnes lower during El Niño and 1.1 million tonnes higher during La Niña years since 1950 (Figure 6.3). Considering the variety of El Niño types illustrates the diversity of response, with a stronger negative effect for extreme El Niño (−3 million tonnes) and EP El Niño (−0.8 million tonnes), no significant impact of CP El Niño and a positive effect of La Niña (+1.1 million tonnes). As described further, the consequences of ENSO on fisheries vary strongly between regions of the Pacific Ocean.

FIGURE 6.3

Left panels: yearly landings (in 1 000 t) for the Pacific Ocean per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel)



Data source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

6.1.3 Southeast Pacific (FAO Major Fishing Area 87)

KEY MESSAGES

- The Humboldt Current System (HCS) is the oceanic region most impacted by ENSO variation. ENSO impact on fisheries is much more severe in the northern than the southern HCS.
- El Niño impacts on the southeast Pacific considerably differ between El Niño types.
- While CP El Niño events do not significantly impact the HCS and related fisheries, strong and coastal El Niño events lead to warm ocean temperatures, heavy rain, floods and heavy river discharges in northern Peru that can impact small-scale fisheries (SSF) infrastructure.
- The "tropicalization" of the HCS during strong El Niño events has differential impacts on coastal species, which results in winners (e.g. lobsters, octopus, tuna) and losers (e.g. crabs, Peruvian anchoveta).
- While extreme El Niños have the greatest impact, the response strongly differs from one event to the other, with the extreme El Niño of 1982/83 producing a much larger impact than that of 2015/16.
- While ENSO events can dramatically affect pelagic fish populations, they do not seem to play a major role in their long-term dynamics.
- Management responses have to adapt to the type of El Niño to avoid over- or under-reactions.
- It has been shown that adaptive fisheries management, as performed by Peru for commercial fisheries, is well suited to confront ENSO impacts.
- Institutionalizing participatory governance systems, promoting dedicated scientific studies and improving monitoring would increase the adaptive capacity of SSF to cope with ENSO.

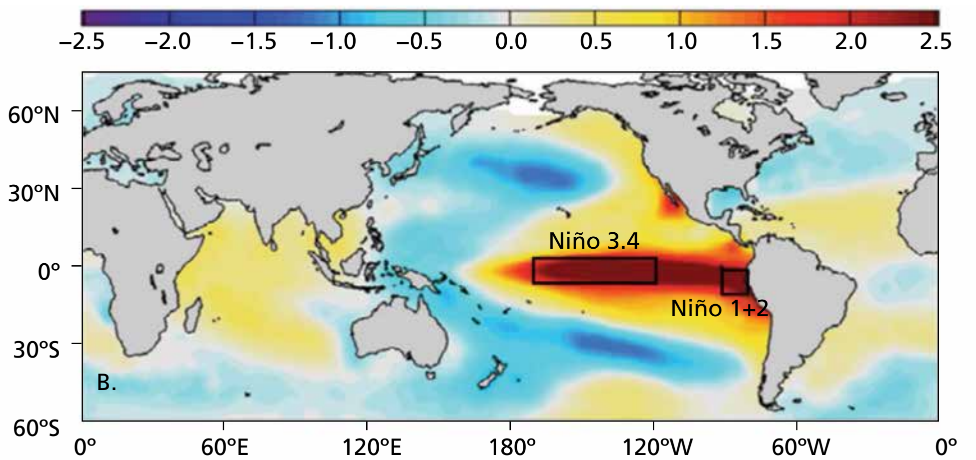
6.1.3.1 Impacts on ocean conditions, climate and extreme events

Impact on ocean conditions and climate

In the eastern Pacific, ENSO variability is most pronounced along the equator and the coasts of Ecuador and Peru (Wang and Fiedler, 2006) and to a lesser extend off Chile (e.g. Ulloa *et al*., 2001) (Figure 6.4). El Niño impacts on the southeast Pacific region differ considerably according to El Niño types. For EP and extreme El Niño events, the SST increases along the South American coast to Chile (e.g. Santoso, McPhaden and Cai, 2017). ENSO-related coastal warming is driven by downwelling Kelvin waves induced by mid-Pacific westerly wind anomalies that deepen the eastern Pacific thermocline, nutricline and oxycline. For instance, during extreme and EP El Niño events, the oxygen content increases in coastal waters due to the deepening of the oxygen minimum zone upper limit under the action of coastal trapped waves forced by intense downwelling equatorial Kelvin waves (Espinoza-Morriberón *et al*., 2019; Gutiérrez *et al*., 2008). Moreover, El Niño conditions allow warmer and more oxygenated waters from the equatorial region to reach the coast of Peru (Espinoza-Morriberón *et al*., 2019). These events result in a depressed thermocline and thus reduced rates of macronutrient supply and primary production off Peru (Pennington *et al*., 2006), which also contributes to an oxygen increase on the shelf (Gutiérrez *et al*., 2008). Conversely, coastal El Niño events are associated more with surface processes than with downwelling Kelvin waves, so the ocean warming is shallow (Takahashi, Karamperidou and Dewitte, 2019).

FIGURE 6.4

Spatial pattern of the first empirical orthogonal function of the SST time series was calculated after the trend and the seasonal cycle were removed. The southern Galapagos region and the northern HCS showed the highest variance relative to any coastal area of the world ocean



Source: Redrawn from Chavez *et al*., 2008.

When compared to EP El Niño events, both coastal and extreme El Niño events generally achieve considerably larger warm anomalies in the eastern Pacific and a strong reduction in primary production along the northern HCS off the coast of Peru. During these events, the strong warming in the eastern Pacific is related to a southward shift of the ITCZ, resulting in heavy and devastating rainfalls over large parts of Peru during the austral summer, with greater incidence of catastrophic floods for extreme (Cai *et al*., 2015) and coastal El Niño events (Takahashi and Martínez, 2019) compared to EP El Niño events. The reduction of the coastal ecosystem productivity and the intense rainfall and floods, which may damage coastal infrastructure, are the main threats of both coastal and EP El Niño events for fisheries.

The canonical behaviour described above does not extend to all extreme events. While the recent 2015/16 El Niño was extreme, marked by a record-breaking warm anomaly in the central Pacific, it was weaker in many measures than the two previous extreme El Niños (Santoso, McPhaden and Cai, 2017) – the coastal warming was weaker during this event, resulting in weaker anomalous rainfall in the eastern equatorial Pacific.

In contrast to EP, extreme and coastal El Niño events, near neutral or even cooler conditions prevail in the eastern Pacific during typical CP El Niños (Capotondi *et al*., 2015). Along the western coast of South America, the impact of CP El Niño events on upwelling is very different from other type of events, with a tendency for colder SSTs during CP El Niño events and dryness in Peru and Ecuador during the usual rainy season, with disruptions to local agriculture. In addition, CP El Niños cause a deepening of the thermocline and a reduction of primary production in the central Pacific rather than in the eastern Pacific (Radenac *et al*., 2012).

Impact on marine heatwaves

The sporadic occurrence of anomalously warm conditions associated with El Niño events can induce diverse, immediate and long-term effects on eastern equatorial Pacific reef-building corals and associated organisms, extending to the Galápagos Islands and Panama (see Chapter 7). Repeated El Niño events over the past decades have had significant, negative impacts on the growth and abundance of corals throughout the eastern Pacific (Glynn *et al*., 2017). Long-term ecological effects of extreme El Niño events can markedly reduce coral cover for months to years and cause local species disappearances. Since the last very strong 1997/98 El Niño coral reef bleaching event, live coral cover has increased significantly on many, but not all, equatorial eastern Pacific reefs (Glynn *et al*., 2017).

A synthesis of impacts of ENSO types on ocean conditions and weather in the southeast Pacific is presented in Table 6.1.

TABLE 6.1

Schematic impact of the different categories of ENSO on selected oceanic and atmospheric variables during the event in the southeast Pacific. NHCS: Northern Humboldt Current system (from northern Chile to northern Peru), SHCS: Southern Humboldt Current system (central to south Chile).

		ENSO Category				
Variable	**Area**	**Central Pacific El Niño**	**Eastern Pacific El Niño**	**Extreme El Niño**	**Coastal El Niño**	**Strong La Niña**
Ocean temperature	Galapagos	No clear impact	Moderate increase	Strong increase / Moderate increase	Moderate increase	Moderate decrease
Ocean temperature	NHCS	No clear impact	Moderate increase	Strong increase / Moderate increase	Strong increase	Moderate decrease
Ocean temperature	SHCS	No clear impact	Moderate increase	Strong increase / Moderate increase	Strong increase	Moderate decrease
Primary production	Galapagos	No clear impact	Moderate decrease	Strong decrease / Moderate decrease	No data	Moderate increase
Primary production	NHCS	No clear impact	Moderate decrease	Strong decrease / Moderate decrease	Moderate decrease	Moderate increase
Primary production	SHCS	No clear impact	Moderate decrease	Moderate decrease / Moderate decrease	No data	Moderate increase
Rainfall/flooding	NHCS	No clear impact	No clear impact	Strong increase / Moderate increase	Strong increase	No clear impact
Rainfall/flooding	SHCS	No clear impact	No clear impact	No clear impact	No data	No clear impact
At sea security	NHCS	No clear impact	No clear impact	Strong increase	Strong increase	No clear impact
Risk for terrestrial installation	NHCS	No clear impact	No clear impact	Strong increase	Strong increase	No clear impact

Colour scale:

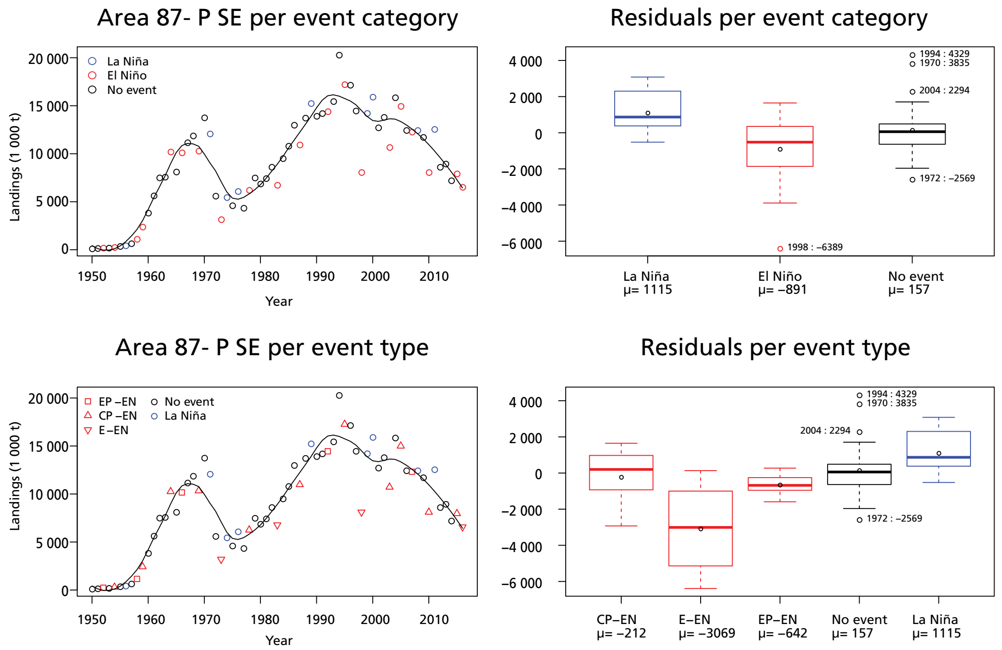
No data	No data
No clear impact	No clear impact
Moderate increase	Moderate decrease
Strong increase	Strong decrease

6.1.3.2 Impacts on capture fisheries

ENSO impacts on fishery landings of the southeast Pacific (FAO Major Fishing Area 87) are remarkable (Figure 6.5), with an averaged negative anomaly of approximately 0.9 million tonnes during El Niño and an averaged positive anomaly of approximately 1.1 million tonnes during La Niña years. Consistent with the physical response described above, the different types of El Niño impact very differently the fishery landings in the southeast Pacific: while CP El Niños have no significant effect on landings, EP and extreme El Niños result in reduced landings, with the reduction being far greater for extreme (–3 million tonnes) compared to moderate EP El Niño events (–0.6 million tonnes).

FIGURE 6.5

Left panels: yearly landings (in 1 000 tonnes) for the FAO Major Fishing Area 87 in the southeast Pacific Ocean per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 tonnes) per event category (upper panel) and type (lower panel)

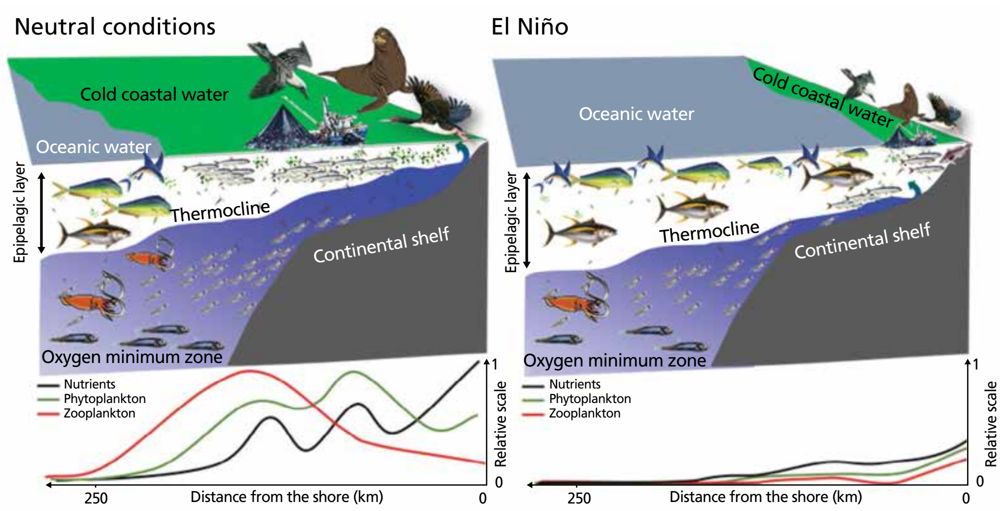


Data source: FishStatJ v3.5 (FAO-FishStatJ., 2019a)

Because the Galápagos Islands are located in the centre of ENSO action, they are strongly impacted by ENSO events (Defeo *et al*., 2013), particularly during extreme and EP El Niños. In this archipelago, the majority of the 45 marine species are recognized as vulnerable, endangered or critically endangered and were identified as directly threatened by the occurrence of El Niño events (Edgar *et al*., 2010). Along with the Galapagos Islands, the northern HCS, off Peru, is the other oceanic region mostly impacted by El Niño conditions (Chavez *et al*., 2008), with strong consequences for fisheries. In the HCS – the current most productive marine ecosystem in terms of fish caught globally – climate is considered to be the most important driving factor, but overfishing is likely to exacerbate the effects of climate stressors (Bertrand, Vögler and Defeo, 2018; Chavez *et al*., 2008). While CP El Niño events marginally affect coastal upwelling, extreme and EP El Niños generate downwelling Kelvin waves that propagate eastward, deepening the thermocline, making coastal upwelling "inefficient" in terms of nutrient enrichment, bringing to the surface oceanic warm and low nutrient water. While coastal ecosystems are only moderately impacted during EP El Niño events, the productive coastal area thus reduces dramatically during extreme events (Figure 6.6) and the oceanic ecosystem impinges on the shore (Bertrand *et al*., 2008; Chavez *et al*., 2002). The 1997/98 El Niño event, for instance, caused losses of more than USD 26 million in revenue (Badjeck *et al*., 2010).

FIGURE 6.6

Conceptual model of inshore–offshore pelagic ecosystem changes associated with El Niño



In non-El Niño years, the thermocline is shallow, so wind-driven upwelling is highly efficient in terms of nutrient supply, and the coastal ecosystem exhibits high biomass and primary productivity and extends far from shore. It is dominated by large phytoplankton, supports a food web with large zooplankton, small pelagic fish, seabirds, marine mammals and fishers. An oceanic low biomass and primary productivity ecosystem is found offshore of the coastal ecosystem when nutrients are depleted. It is dominated by picophytoplankton whose grazers are protists with similar growth rates creating an efficient recycling system. A complex food web evolves with a smaller proportion of the primary production reaching the upper trophic levels composed of oceanic species such as tuna or dolphin fish. During extreme El Niño years the productive coastal area is reduced dramatically and the oceanic ecosystem impinges close to the shore. This conceptual model also matches the case of the California Current system.

Source: inspired by Chavez *et al*., 2002; Guevara-Carrasco and Bertrand, 2017.

Impacts on demersal fish and invertebrates

Strong and coastal El Niño events are characterized by high temperatures, heavy rain, floods and heavy river discharges in northern Peru. Such conditions restrict SSF operations, and furthermore, when fishing can take place, income can be reduced because fisheries products cannot reach national markets due to flooding and impassable roads (Kluger *et al*., 2018). During extreme El Niño events, the tropicalization of the HCS diversely impacts benthic species, resulting in winners and losers (Arntz *et al*., 2006); a strong La Niña generally produces opposite effects (Table 6.2; Table 6.3).

Giant kelp (*Macrocystis pyrifera, Macrocystis integrifolia* and *Lessonia trabeculata*) can be heavily damaged in some areas during major El Niños. Macroalgae are very sensitive to the reduction of nutrients that accompanies sea temperature rise and suffer high mortality during El Niños (Arntz *et al*., 2006). For crustaceans, high temperatures during extreme and, to a lesser extent EP El Niño events, can lead to mass mortality e.g. of the brachurian crabs (*Romaleon setosus* and *Platyxanthus oribigny*) off Peru and a migration to deeper waters of *Cancer porteri*, impacting the artisanal crab fishery (Fischer and Thatje, 2016). Conversely, the distributional range of penaeid shrimps (e.g. *Xiphopenaeus riveti*; *Penaeus stylirostris*) and the spiny lobster (*Panuliris gracilis*) extends southwards. Peruvian fishers adjusted their fishing methods to catch greater quantities of shrimps after the 1982/83 El Niño (Arntz *et al*., 2006; Barber and Chávez, 1986; Thatje, Heilmayer and Laudien, 2008). However, such tropicalization effects were less pronounced during the two following extreme El Niño events in 1997/98 and 2015/16. In Galapagos, the most important artisanal shellfisheries are for the sea cucumber (*Isostichopus fuscus*) and the spiny lobsters (*Panuliris gracilis* and *Panuliris penicillatus*), and are favoured by El Niño events (Defeo *et al*., 2013). Nevertheless, the removal of large lobsters and fish predators by artisanal fishing probably magnified impacts of the 1982/83 El Niño through a cascade of indirect effects involving population expansion of grazing sea urchins (Edgar *et al*., 2010).

In northern Peru (e.g. the Bay of Sechura located at approximately 5.5 °S), extreme, EP and coastal El Niño conditions reduce or cause a complete die-off of scallop (*Agropecten purpulatus*) biomass. Conversely, increased SSTs in southern Peru resulted in drastic (1982/83), significant (1997/98) or moderate (1991/92) increases in scallop stock biomass. These increases had a positive net effect for Peruvian scallop fisheries, that can compensate for the economic loss in the north, except during the coastal El Niño of 2017. La Niña events impact scallops in the opposite way, but increases in northern Peru do not compensate for decreases in the south (Badjeck *et al*., 2009). This is discussed more fully in Chapter 8 in the context of coastal aquaculture for scallops.

Extreme and, to a lesser extent EP El Niño events, cause a reduction in the surf clam (*Mesodesma donacium*) biomass and landings in Peru and northern Chile, but lead to increases in southern Chile (Ortega *et al*., 2016). Finally, in Peru and northern Chile, increasing SSTs enhance the recruitment, growth and availability of octopus prey items during El Niño events, leading to a dramatic increase in *Octopus mimus* abundance (Arntz *et al*., 2006).

The Peruvian hake (*Merluccius gayi peruanus*) is the most abundant commercially exploited demersal fish species in the northern HCS. During extreme and EP El Niño events, its availability to fisheries (Table 6.3), and in particular that of juveniles, increases over the Peruvian coast due to higher oxygen content and possibly temperature effects (Guevara-Carrasco and Lleonart, 2008). However, since this increased range is associated with fish dispersion, direct El Niño effects on demersal fisheries can be detrimental (Arntz *et al*., 2006). In addition, this expansion is accompanied by a drastic energy exhaustion and a decrease in female hake fecundity with overall negative impacts on Peruvian hake populations during extreme and EP El Niños and positive effects during strong La Niña events (Ballón *et al*., 2008) (Table 6.2).

Nevertheless, El Niño impacts do not seem to drive hake long-term population dynamics that appear to be driven by multidecadal climatic conditions (Salvatteci *et al*., 2019) and, increasingly importantly during recent decades, by fishing pressure (Ballón *et al*., 2008; Guevara-Carrasco and Lleonart, 2008). In contrast, extreme and EP El Niño events have a positive effect on the recruitment of common *Merluccius gayi gayi* and southern *Merluccius australis* hake in central-southern Chile (Payá and Ehrhardt, 2005).

Impacts on pelagic species

For decades, Peru has supported the world's highest production of forage fish, mostly composed of anchoveta (*Engraulis ringens*). In the HCS, anchoveta has been the predominant small pelagic fish over the last 25 000 years (Salvatteci *et al*., 2019). However, its abundance reached a maximum during the current warm period, an era characterized by high productivity and intense oxygen minimum zone conditions. Thus, industrial fisheries developed during a period of exceptional productivity in relation to that of the last 25 000 years. Given that dramatic decreases in pelagic fish abundance have occurred in response to previous large-scale climate changes, future climate may result in substantial changes in ecosystem structure and fish productivity (Salvatteci *et al*., 2019).

It was long considered that El Niño's impact on fishery resources was straightforward in that they were considered to always have negative impacts on anchoveta but favour sardine (e.g. Bakun and Broad, 2003). This overly simplistic view has been questioned in view of the recognition that different categories of El Niño exist (Timmermann *et al*., 2018) and because various factors occurring at different spatiotemporal scales need to be considered to understand the impact of a given event (Bertrand *et al*., 2004). Extreme and to a lesser extent, EP El Niños, affect the distribution of small and medium-sized pelagic fish (anchoveta, sardine, mackerel and jack mackerel) that generally migrate closer to the coast, avoiding the warm waters in northern Peru and, in some cases, move into deeper waters (Alheit and Niquen, 2004; Barber and Chávez, 1986; Bertrand *et al*., 2004, 2008). El Niño events were also reported to produce massive die-offs of anchoveta in Peru and northern Chile while favouring other pelagic species such as sardine (*Sardinops sagax*) or Chilean jack mackerel (*Trachurus murphyi*) (Arntz *et al*., 2006; Arntz and Fahrbach, 1996; Bakun and Broad, 2003). The majority of extreme and EP El Niños indeed resulted in a reduction of anchoveta biomass and landings, but actual impacts on post-event recovery differ considerably between events (Alheit and Niquen, 2004; Bakun and Broad, 2003). Extreme and EP El Niño events in 1972/73, 1977/78 and 1982/83 were followed by a slow recovery, while recovery was rapid after the 1987 and 1997/98 El Niños. Finally, the EP El Niños of 1991/92 or 2002/03 had no perceptible impact on anchoveta biomass (Bertrand *et al*., 2004) as seen for CP El Niño (Table 6.2; Table 6.3).

In contrast to what was widely thought (e.g. Bakun & Broad, 2003), El Niño events do not actually favour sardine (Bertrand *et al*., 2004; Gutiérrez *et al*., 2012), but increase their susceptibility to capture. During extreme and most CP El Niños, sardine and jack mackerel move into coastal waters, increasing their availability to fisheries, so catches increase in the northern HCS (Alheit and Niquen, 2004). However, extreme and CP El Niños have a detrimental impact on sardine biology, leading to reduced condition factor and gonadosomatic index (Cárdenas, 2009), resulting in overall negative effects (Barber and Chávez, 1986; Bertrand *et al*., 2004; Cárdenas, 2009). Finally, oceanic predators such as the bonito (*Sarda chilensis*), dolphin fish (*Coryphaena hippurus*) and yellowfin tuna (*Thunnus albacores*) follow the warm front closer to the coast, increasing their availability to fishers (Barber and Chávez, 1986).

In central-southern Chile, El Niño impacts are less clear for most species. For instance, the relationship between the anchoveta fishery and ENSO in the region is not straightforward (Cubillos, Serra and Fréon, 2007). Having said that, El Niño seems to negatively impact the recruitment of the common sardine (*Strangomera bentincki*) (Cubillos and Arcos, 2002). Conversely, El Niño appears to favour jack mackerel populations with the generation of strong cohorts (Bertrand *et al*., 2004).

Since the early 2000s the jumbo flying squid (*Dosidicus gigas*) population in the region exploded and today, approximately 600 000 tonnes are landed annually in Peru (Guevara-Carrasco and Bertrand, 2017). Extreme La Niña and El Niño events seem to negatively impact jumbo flying squid presence and fisheries in the HCS (Guevara-Carrasco and Bertrand, 2017; Waluda, Yamashiro and Rodhouse, 2006). The influence of ENSO on the abundance of *Dosidicus gigas* depends on the intensity and characteristics of each El Niño or La Niña event (Waluda, Yamashiro and Rodhouse, 2006). It seems that SST does not directly impact this species but effects reflect reductions in prey availability that can be negatively affected by extreme events (Argüelles *et al*., 2008; Waluda, Yamashiro and Rodhouse, 2006).

To summarize, ENSO events can dramatically impact both pelagic fish populations and their associated fisheries, but the strength of the impact depends on the type of event. Extreme El Niños have by far the most effect, followed by the EP El Niños. The impact of strong La Niña events is usually opposite to those of extreme and EP El Niños, but with fewer consequences (Table 6.2; Table 6.3). However, ENSO does not seem to play a major role in the long-term population dynamics of pelagic fishes, which appear to be controlled by factors affecting ocean conditions over multidecadal to millennial timescales (Alheit and Niquen, 2004; Bertrand *et al.*, 2004; Gutierrez *et al.*, 2007; Salvatteci *et al.*, 2018, 2019).

6.1.3.3 Impacts on fish and fisheries: synthesis

Table 6.2 and Table 6.3 synthesize the effects of different ENSO types on the ecology and fisheries (when different from ecology) per key species.

TABLE 6.2.

Schematic impact of the different categories of ENSO on the ecology (biomass, population structure and biology) of fisheries resources in the southeast Pacific.
NHCS: Northern Humboldt Current system (from northern Chile to northern Peru–south Ecuador)
SHCS: Southern Humboldt Current system (centre to south Chile)

			ENSO category				
Taxonomic group	**Species**	**Area**	**Central Pacific El Niño**	**Eastern Pacific El Niño**	**Extreme El Niño**	**Coastal El Niño**	**Strong La Niña**
Benthonic	Kelp	HCS	No clear impact	Moderate negative impact	Strong negative impact / Moderate negative impact	No data	Moderate positive impact
	Crabs	NHCS	No clear impact	Moderate negative impact	Strong negative impact / Moderate negative impact	No data	Moderate positive impact
	Penaeid shrimps, spiny lobster	NHCS	No clear impact	Weak positive impact	Strong positive impact / Moderate positive impact	Moderate positive impact	Strong negative impact
	Spiny lobster	Galapagos	No clear impact	Weak positive impact	Strong positive impact / Moderate positive impact	No data	Strong negative impact
	Sea cucumber	Galapagos	No clear impact	Weak positive impact	Strong positive impact / Moderate positive impact	No data	Strong negative impact
	Scallops	NHCS	No clear impact	Weak positive impact	Strong positive impact / Moderate positive impact	Strong negative impact	Moderate negative impact
	Surf clam	NHCS	No clear impact	Weak positive impact	Strong negative impact / Moderate negative impact	No data	Moderate positive impact
	Surf clam	SHCS	No clear impact	Weak positive impact	Moderate positive impact	No data	Moderate negative impact
	Octopus	HCS	No clear impact	Weak positive impact	Strong positive impact / Moderate positive impact	No data	Moderate negative impact
Demersal	Peruvian hake	NHCS	No clear impact	Weak negative impact	Moderate negative impact	Weak negative impact	Moderate positive impact
	Common and southern hakes	SHCS	No clear impact	Weak positive impact	Moderate positive impact	No clear impact	Weak negative impact
Pelagic	Anchoveta	NHCS	No clear impact	Moderate negative impact / No clear impact	Strong negative impact / Moderate negative impact	No clear impact	Strong positive impact
	Anchoveta	SHCS	No clear impact	No clear impact / No clear impact	No clear impact / No clear impact	No clear impact	No clear impact
	Sardine	NHCS and Galapagos	No clear impact	Weak negative impact	Moderate negative impact / Weak negative impact	No clear impact	No clear impact
	Sardine	SHCS	No clear impact	No clear impact	No clear impact	No data	No clear impact
	Chilean jack mackerel	NHCS	No clear impact	No clear impact	Weak positive impact / No clear impact	No data	No clear impact
	Chilean jack mackerel	SHCS	No clear impact	No clear impact	Moderate positive impact / Weak positive impact	No data	No clear impact
	Araucanian herring	SHCS	No clear impact	No clear impact	Moderate negative impact / Weak negative impact	No clear impact	Weak positive impact
	Tunas, dolphin fish, etc.	HCS	No clear impact	Weak positive impact	Strong positive impact / Moderate positive impact	Moderate positive impact	Strong negative impact
	Flying jumbo squid	NHCS	No clear impact	No clear impact	Strong negative impact / Weak negative impact	No clear impact	Moderate negative impact

Colour scale:

No data	No data
No clear impact	No clear impact
Weak positive impact	Weak negative impact
Moderate positive impact	Moderate negative impact
Strong positive impact	Strong negative impact

TABLE 6.3.

Schematic impact of the different categories of ENSO on the fisheries success (catchability), independent of fisheries regulations, during the event in the southeast Pacific.
NHCS: Northern Humboldt Current system (from northern Chile to northern Peru)
SHCS: Southern Humboldt Current system (centre to south Chile). Note that the information is provided only for cases when the response of fisheries differs from the response of ecology

			ENSO category				
Taxonomic group	**Species**	**Area**	**Central Pacific El Niño**	**Eastern Pacific El Niño**	**Extreme El Niño**	**Coastal El Niño**	**Strong La Niña**
Benthonic	Spiny lobster Galapagos	Galapagos	No clear impact	Weak positive impact	Strong positive impact / Moderate positive impact	No data	Moderate negative impact
	Sea cucumber	Galapagos	No clear impact	Weak positive impact	Strong positive impact / Moderate positive impact	No data	Moderate negative impact
Demersal	Peruvian hake	NHCS	No clear impact	No clear impact	Weak positive impact / Weak negative impact	No data	Weak negative impact
Pelagic	Anchoveta	NHCS	No clear impact	Weak positive impact / No clear impact	Strong negative impact / Moderate negative impact	Weak positive impact	Moderate positive impact
	Sardine	NHCS	No clear impact	Weak positive impact	Moderate positive impact	No data	Moderate negative impact
	Sardine	SHCS	[dark grey]	[dark grey]	Moderate positive impact	No data	No clear impact
	Chilean jack mackerel	NHCS	No clear impact	Weak positive impact	Weak positive impact / No clear impact	No data	Moderate negative impact
	Chilean jack mackerel	SHCS	No clear impact	No clear impact	Weak negative impact	No data	No clear impact

Colour scale:

No data	No data
No clear impact	No clear impact
Weak positive impact	Weak negative impact
Moderate positive impact	Moderate negative impact
Strong positive impact	Strong negative impact

6.1.3.4 Coping strategies

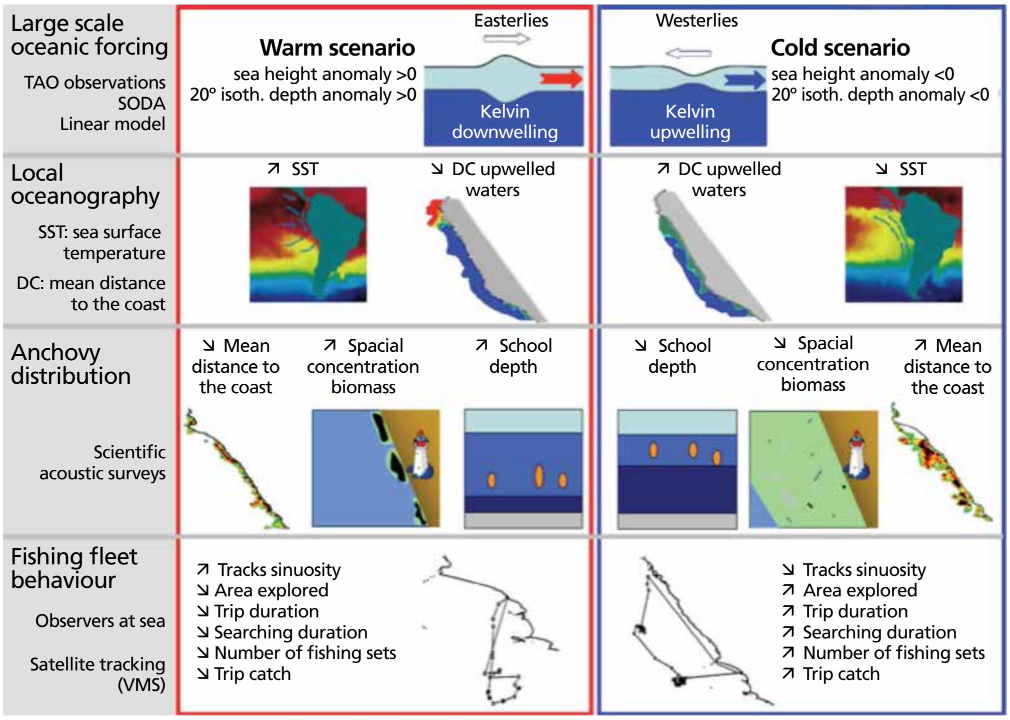
Fisheries represent a small percentage of the Galápagos economy (<4 percent). Therefore, positive or negative ENSO impacts on fisheries will have limited implications for the larger economy. However, fishers targeting sea cucumber, spiny lobster and coastal demersal fish can be affected. The fisheries sector has a moderately strong ability to adapt because fishers have the advantage of strong social and institutional support, some access to credit, and 90 percent of fishers have alternative livelihoods (Larrea and Di Carlo, 2011).

A series of steps have been recommended to support Galapagos fisheries in the face of climate change, ENSO included (Larrea and Di Carlo, 2011):

- Establish sustainable management measures for demersal fish. Improve conservation efforts for seamounts, mangroves and other key areas.
- Protect sea cucumber, spiny lobster and demersal species from overfishing, as these species are the most vulnerable to climate change.
- Establish sustainable management regulations for pelagic species that may not be heavily fished at present, but could become more important in the future.
- Enhance people's adaptive capacity by promoting the diversification of livelihood activities and by strengthening education.

With regard to Peru, Clark (1976) indicated that "to manage the anchoveta stock properly under all the environmental conditions that occur in Peru, particularly during El Niño events, the Peruvian authorities would need to be able to predict environmental changes and their effects on the stock. Variations in upwelling strength along the coast of Peru result from large scale changes across the Pacific Ocean, and may soon be predictable from leading indicators...". Thirty years later, Bertrand *et al.* (2008) showed that, when measured two to six months in advance in the central Pacific, the detection of downwelling (upwelling) Kelvin waves – as an indicator of El Niño (La Niña) conditions – can be used as an early signal of forthcoming conditions for anchoveta and fisheries (Figure 6.7). This information, used in the dashboard of the Peruvian fishery adaptive management, allows advanced access to information necessary to decide temporary management measures for reducing fishing pressure (fishery closure or other measures). Taking into account large-scale oceanic forcing signals provides a few precious months of preparation – months that are indispensable in the decision-making process designed to make the anchoveta fishery sustainable (Bertrand *et al*., 2008).

FIGURE 6.7
Synthesis of the ecosystem and fisheries characteristics under warm (El Niño) and cold (La Niña) ecological scenarios driven by oceanic Kelvin waves forcing observed in the coastal HCS



The qualitative response of the metrics describing the coastal ecosystem dynamics are presented for (i) Peruvian coastal oceanography: SST, mean distance to the coast of the upwelling waters; (ii) anchoveta distribution: mean distance to the coast, anchoveta spatial patchiness, mean depth of fish schools; (iii) fishing fleet behaviour: mean travel duration, mean searching duration, mean number of fishing sets, mean trip catch, synthetic index of fishing trip trajectories.

Source: Redrawn from Bertrand *et al*., 2008.

In Peru, three major governmental responses to El Niño-related collapse were used (Ros-Tonen and van Boxel, 1999):

- Strong regulation of fishery through closed seasons and imposing total allowable catches (TACs). Fishing restrictions are intensified when an El Niño occurs, in order to prevent overexploitation and to protect the sector from another collapse.
- The administration attempted to shift production away from anchoveta (used for fishmeal) in favour of food fish production and species whose numbers were positively affected by the El Niño events. This diversification of effort is often frustrated by the better profitability of fishmeal production compared with food fish processing, which sees entrepreneurs unwilling to invest in the food fish industry.
- Efforts to reduce excess fleet and fish processing plant capacity.

Coping strategies adopted by the Peruvian anchoveta fishery to deal with climate variability and its impacts have been reviewed by Arias Schreiber, Ñiquen and Bouchon (2011) and are summarized in Table 6.4.

TABLE 6.4
Strategies developed by the Peruvian anchoveta fishery to deal with environmental variability and extreme climatic events.

Impact	Coping strategy	Implementation
Changes in the distribution of anchoveta shoals	• Geographical distribution of fishmeal plants along the coast • Simultaneous ownership of fishing vessels and processing factories • Low-cost uploading facilities	Fisheries companies
Invasion of non-native species into anchoveta fishing grounds	• Fishmeal production based on non-native fish	Fisheries companies
Management regulations rapidly become out-of-date	• Monitoring of stocks through EUREKA program • Rapid and flexible management	Management authorities
Uncertain changes in fishmeal prices	• Fishmeal production based on market demand • Reducing price dependence from soybean production	Fisheries companies

Source: Arias Schreiber, Ñiquen and Bouchon, 2011.

For artisanal fisheries, scallop fisheries and mariculture, Kluger *et al.* (2018) recommended to:

- Establish a reliable early warning system for potential environmental disturbances and to develop emergency response, especially in terms of protecting human livelihoods that depend on marine resources.
- Support local small-scale producers in establishing long-term financial plans that enable them to better cope with the consequences of losses caused by mortalities of their target resource (i.e. making savings during non-El Niño years).
- Develop strategies that provide structured support to resource users for the post-disturbance phase, e.g. through financial support and/or affordable credits, or rapid and effective assistance with reconstruction of damaged infrastructure.
- Spread the risk of a localized environmental disturbance.

More generally, Peru applies an adaptive management approach to industrial fisheries with at least two stock assessments per year and two seasonal catch limits in the form of TAC, as well as the regulatory capacity to halt fishing at any time, depending on the population and biological conditions of the stocks (e.g. when the proportion of juveniles in the catch is too high) and environmental conditions (IMARPE, 2016). Such adaptive management is well-suited to the highly variable HCS, and especially to ENSO-associated impacts (Bertrand, Vögler and Defeo, 2018). Conversely, Peruvian artisanal medium-scale and SSF that showed marked increases in landings (1.2 million tonnes) by 2012 are mainly uncontrolled (i.e. open access) and informal (Bertrand, Vögler and Defeo, 2018; Guevara-Carrasco and Bertrand, 2017). For millennia, SSF in the region have become adapted to a wide range of climate variability and uncertainty. They have therefore developed a variety of strategies including intensification, substitution, diversification, pluralism, migration and exit. However, several factors jeopardise Peruvian SSFs, including: i) a lack of scientific knowledge regarding the ecology and population dynamics of most exploited species; ii) open access regimes (NB, at the same time it has been argued that open access facilitates fishers' mobility (Badjeck, 2008); iii) lack of regulations for most exploited species (e.g. quota, fishing closure, effort control, minimum size); and iv) a lack of monitoring, control, surveillance and enforcement of management actions. Specialized and localized fisheries are likely to be more vulnerable to climatic hazard, and to ENSO in particular (Bertrand, Vögler and Defeo, 2018).

In Chile, the "management plans" policy is a move towards polycentric governance of fisheries, i.e. a system with multiple governing authorities at different levels rather than a monocentric unit. Faced with ENSO variation, polycentric systems can have significant advantages given their mechanisms for mutual monitoring, learning and adaptation over time (Bertrand, Vögler and Defeo, 2018). Most institutional and scientific efforts have been dedicated to industrial fisheries that are well managed overall, and the main difficulties (poverty, food, sustainability) relate to SSF. Promoting biological and ecological studies, improving spatial monitoring and institutionalizing participatory governance systems would foster the sustainability of SSF and their adaptive capacity to cope with ENSO and climate change. Implementation of flexible, integrated SSF management structures that can adjust rapidly to new circumstances would mitigate the expected effects of climate variability and change.

6.1.4 Eastern central (northeast tropical) Pacific (FAO Major Fishing Area 77)

KEY MESSAGES

- Physical and ecological impacts of ENSO are milder in the eastern central (also referred to as northeast tropical) Pacific than they are in the southeast Pacific.
- While the most southern portion of the California Current System (CCS) is remotely forced by ENSO, its northern portion is more controlled by local climate fluctuations acting on the north Pacific.
- Extreme El Niño events generally have the most widespread consequences on the physical properties and ecosystem throughout the CCS, including reduced upwelling, sea level increase and anomalously warm temperature.
- In contrast to moderate CP and EP El Niños, only extreme El Niño appears to increase the probability of wetter than average conditions along the western coast of the United States of America.
- Overall, ENSO impacts on global fishery landings of the eastern central Pacific are moderate with a maximal effect during extreme El Niño – with an average reduction in landings of 136 000 tonnes.
- During extreme and to a lesser extent EP El Niños, a variety of (sub)tropical species enter the upwelling zone.
- The impact of ENSO on anchovy and sardine populations is not clearly established and likely not pervasive.
- Extreme and EP El Niños classically cause a decrease in salmon abundance in the southern part of their range (California, Oregon) and null or positive effects in the north.

6.1.4.1 Impacts on ocean conditions, climate and extreme events

Impacts on ocean conditions and climate

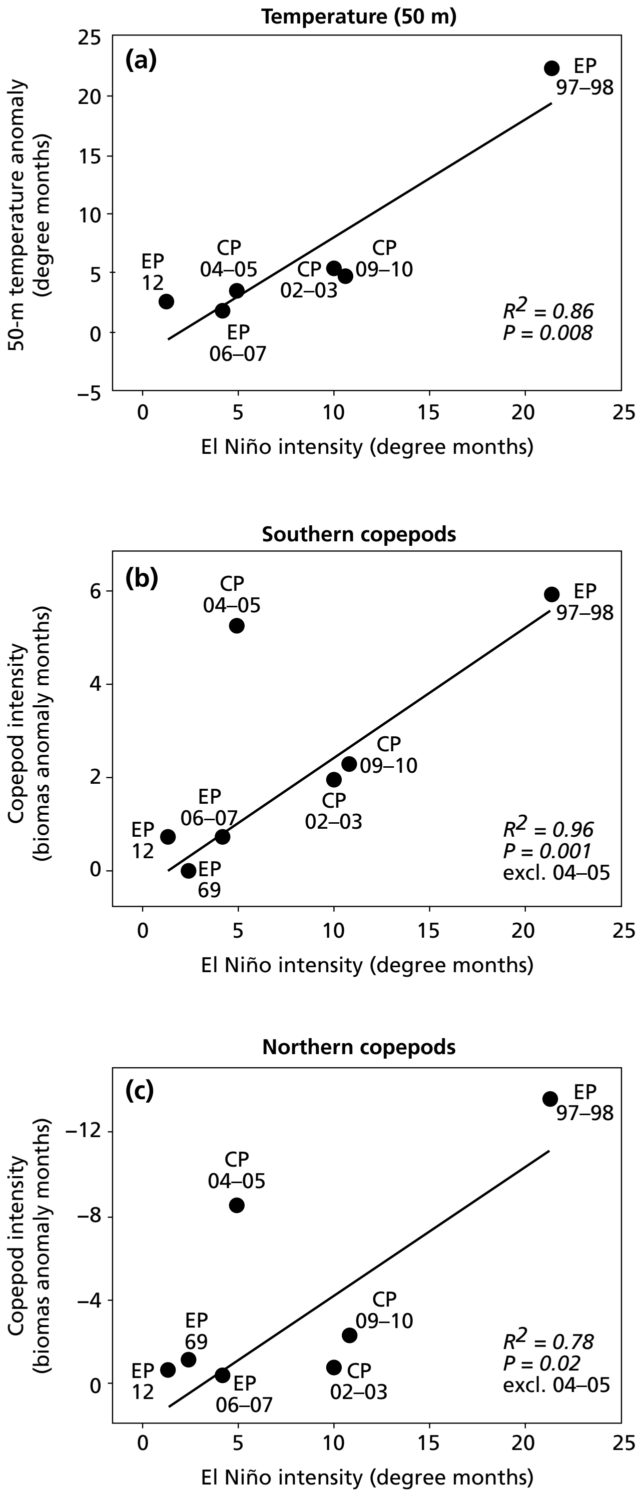
The CCS ranges between the southern-most point of the California peninsula and Oregon. It is a moderately productive upwelling current system and supports several important fisheries. As in the HCS (Figure 6.3), ENSO is an important driver of the interannual variability of the CCS because it alters the SST, the upwelling source and intensity, the thermocline depth, and large-scale circulation, and hence biological productivity (Checkley and Barth, 2009). Three main mechanisms drive CCS changes during El Niño: i) thermocline depth anomalies in the tropical Pacific propagating eastward and subsequently poleward in the equatorial and coastal wave guides; ii) equatorward (poleward) winds decrease (increase) due to expansion of the Aleutian Low; and iii) anomalous advection of warm subtropical water from the south. They tend to inhibit the upwelling of nutrients into the euphotic zone during El Niño events, and are therefore consistent with reduced primary productivity and negative impacts on higher trophic levels. However, ENSO is not the only driver of the CCS and local atmospheric forcing drives a large amount of the interannual variability in CCS SST variations. Indeed, regional forcing in the north Pacific related to modulations of the

Aleutian Low and the North Pacific High dominates SST variation throughout most of the CCS, while remote tropical forcing is more important in its far southern portion. In addition, cold events in the CCS appear to be more closely related to tropical La Niña than are warm events in the CCS to El Niño (Fiedler and Mantua, 2017).

Primary production generally decreases and contracts nearshore during El Niño events (Chavez *et al*., 2002). Total mesozooplankton biomass decreases during most El Niño events in the northern CCS (Fisher, Peterson and Rykaczewski, 2015) but is only moderately affected in its southern portion (Lilly and Ohman, 2018). However, the southern CCS experiences warm-water intrusions during El Niño, resulting in the appearance of non-resident offshore and southerly euphausiid species, as detailed in the following subsection. The timing, magnitude, and duration of the biological response varies considerably, depending on the type and magnitude of the event (Figure 6.8; Fisher, Peterson and Rykaczewski, 2015; Lilly and Ohman, 2018). Extreme El Niño events generally have the most widespread consequences on physical properties and ecosystems throughout the CCS. During extreme events, the North Californian Current experiences a decline in upwelling favourable winds, reduced alongshore flow, anomalously warm temperature, higher salinity and deeper mixed layer depth (Chavez *et al*., 2002; Jacox *et al*., 2015) as well as a decrease in nutrients, chlorophyll and zooplankton composition (Corwith and Wheeler, 2002). As seen in the southeast Pacific, the amplitude of physical and biogeochemical responses to extreme El Niños varies from one event to another. While these impacts were exceptionally large during the 1982/83 and 1997/98 events, they were not as strong – although noticeable – during the 2015/16 event (McClatchie, 2016) and almost absent during the 1972/73 event (Wells *et al*., 2013). Weaker EP and CP El Niño events are less studied but it has been suggested that weak, or even short duration, events can alter the pelagic food web in the North CCS (Fisher, Peterson and Rykaczewski, 2015). Anomalously warm water occurred rapidly following the initiation of EP El Niño events, but was delayed following CP El Niño events, resulting in physical and biological peaks occurring in winter during EP El Niño events and in the spring during CP El Niño events. CCS zooplankton assemblages also showed a tendency toward greater changes in species composition during EP than CP El Niños, while La Niña events generally result in opposite but weaker responses than that of El Niño (Lilly and Ohman, 2018).

FIGURE 6.8

Relationship of El Nino intensity measured by the average of the SST anomalies in the Niño-3.4 region multiplied by the number of months that those anomalies were >0.5 °C (degree months) vs. the (a) 50 m temperature anomaly (b) southern and (c) northern copepod intensity measured as the average temperature or biomass anomalies multiplied by the number of months when positive temperature anomalies (>0.25 °C) or positive (negative) biomass anomalies of warm (cold) greater than (less than) 0.1 mg C m-3 were observed for two consecutive months at NH 5 (44.6 °N). SST, sea-surface temperature



Source: Fisher, Peterson and Rykaczewski, 2015.

ENSO also modulates the meridional position of the ITCZ in the eastern central Pacific. The ITCZ variation driven by ENSO is characterized by an equatorward (poleward) shift in the Pacific during El Niño (La Niña) episodes. This ITCZ movement in the eastern central Pacific depends on ENSO type (Xie and Yang, 2014): while the shift is absent or more local during CP El Niño events, this southward shift is more prominent during EP El Niño events, especially during extreme El Niño events when it extends to the equatorial region (Lengaigne and Vecchi, 2010). As a consequence, El Niño induces increased rainfall in the northwestern and northeastern regions of Mexico, as well as in the Yucatán Peninsula during boreal winter, but results in a relative decrease in some parts of the southern states of Mexico (Pavia, Graef and Reyes, 2006). La Niña winters generally exhibit opposite rainfall patterns. Along the western coast of the United States of America, only extreme El Niño appears to increase the probability of wetter than average conditions over the principal water supply regions of northern California and the Sierras, in contrast to weaker El Niño (Hoell *et al.*, 2016).

Impacts on tropical cyclones

TCs in the northeastern Pacific are often overlooked because they originate off the coast of Central America and generally travel westward, far from coastlines. However, some systems can make strong landfalls and impact the northwest United States of American as well as the Hawaiian Islands coast. The main impact of TCs in Mexico is high rainfall that occurs when TCs interact with Mexican mountains (Romero-Vadillo, Zaytsev and Morales-Pérez, 2007). Northeast Pacific TCs are indeed an important source of precipitation in southwestern North America (Englehart and Douglas, 2001). They are also related to gulf surge events, which influence precipitation in Mexico and the southwestern states of the United States of America, such as Arizona and New Mexico (Higgins and Shi, 2005).

El Niño events induce a westward shift of the mean genesis location away from the Mexican coast and towards the International Dateline (Figure 5.4a) as well as extending TC lifespans (Chu, 2004). Consequently, the likelihood of TCs reaching the Hawaiian Islands is higher during El Niño events than during La Niña. TCs in the northeastern Pacific have also been suggested to exhibit a nonlinear response to the strength of ENSO (Krishnamurthy *et al.*, 2016): while a stronger El Niño results in disproportionate inhibition of TCs in the northeastern Pacific, the increase in TCs during La Niña events is insensitive to event intensity. EP and CP El Niño events also appear to have slightly different impacts on TC activity (Figure 5.4c, d). While TC activity exhibits a clear westward shift during CP El Niño events, there is a southward shift during EP El Niño events, with increased TC genesis south of the main TC-prone region. The combined effects of elevated wave energy, water levels and directional shifts common during El Niño events have historically resulted in severe coastal erosion along the Californian coast in boreal winter, while the coast of British Columbia experienced more severe erosion during La Niña events (Barnard *et al.*, 2015).

Impacts on marine heatwaves

In the central equatorial Pacific, MHWs have occurred in conjunction with all types of El Niño events, resulting in massive coral bleaching events around the islands of this region for several decades (Barkley *et al.*, 2018). These events occurred when steadily rising SSTs caused by global warming superimposed with El Niño SST anomalies, crossed tolerance thresholds and caused coral to bleach. Coral reef communities at islands located in the central Pacific are thus exposed to extended periods of thermal stress during El Niño events (Brainard *et al.*, 2018). For instance, eight severe (>30 percent bleaching) and two moderate (<30 percent bleaching) events occurred at Jarvis island since 1960, each coinciding with extreme, CP or EP El Niño

(Barkley *et al*., 2018). The coral bleaching observed at this island during the extreme 2015/16 El Niño was unprecedented in magnitude, related to a massive ocean heatwave (Brainard *et al*., 2018).

A synthesis of impacts of ENSO types on ocean conditions and weather in the eastern central Pacific is presented in Table 6.5.

TABLE 6.5
Schematic impact of the different types of ENSO on the oceanic and atmospheric ocean properties in the eastern central Pacific.
CCS: California Current System

		ENSO category				
Variable	**Area**	**Central Pacific El Niño**	**Eastern Pacific El Niño**	**Extreme El Niño**	**Coastal El Niño**	**Strong La Niña**
Temperature	CCS					
Sea level/ thermocline	CSS					
Primary production biomass	Northern CCS					
Primary production biomass	Southern CCS					
Rainfall	Northern California					
Rainfall	Southern California					
TCs	Northeast Tropical Pacific					
MHWs	Central Pacific					

Colour scale:

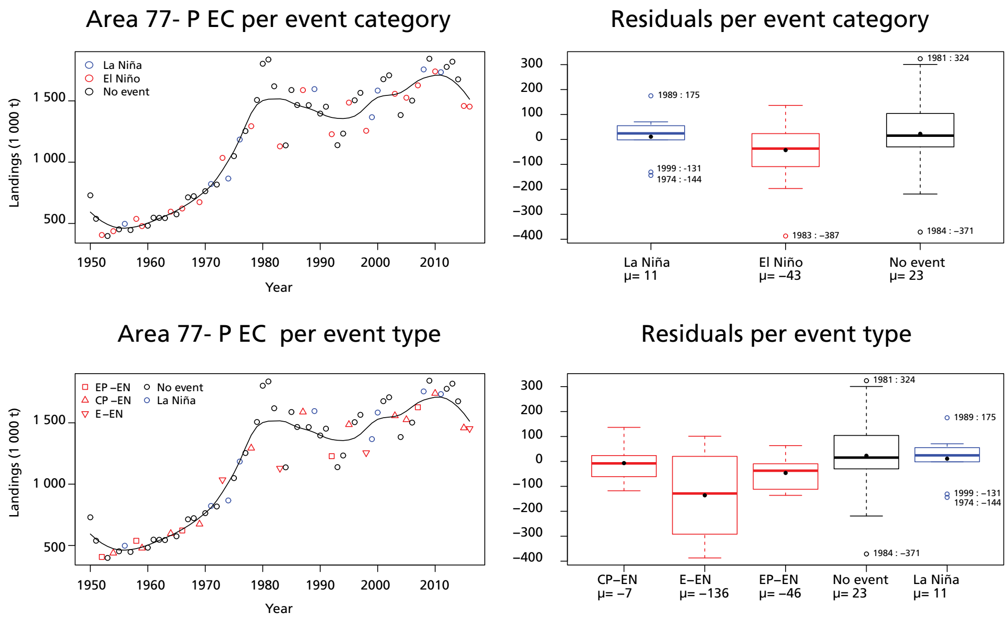
No data	No data
No clear impact	No clear impact
Moderate increase	Moderate decrease
Strong increase	Strong decrease

6.1.4.2 *Impacts on capture fisheries*

ENSO impact on global fishery landings of the eastern central Pacific (FAO Area 77) are weak with on average, a negative anomaly of approximately 43 000 tonnes during El Niño (Figure 6.9). Considering the variety of El Niño types illustrates the diversity of response, with a stronger negative effect for extreme El Niño (–136 000 tonnes) and to a lesser extent EP El Niño (–46 000 tonnes).

FIGURE 6.9

Left panels: yearly landings (in 1 000 t) for the FAO Major Fishing Area 77 in the eastern central Pacific Ocean per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel)



Data source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

Historically, CCS fisheries were dominated by small pelagic species (anchovies and sardines) that exhibit pronounced fluctuations in biomass over decadal periods. In the 1990s, Pacific hake and market squid fisheries developed and became dominant following the collapse of the sardine stock (McClatchie, 2014). As described above, El Niño results in changes in many physical, chemical and biological properties and processes in the CCS (Chavez *et al*., 2002; McClatchie, 2014). The intensity and timing of these changes varies between ENSO events and in some cases, the impacts on physical properties or biological communities may be difficult to separate from "normal" interannual variability. Compared with the HCS, ENSO impacts in the CCS appear moderate. Strong or moderate ENSO events in the equatorial Pacific do not systematically produce effects at mid-latitudes. The most spectacular change was observed following the extreme El Niño of 1997/98, with a shift toward subtropical communities off southern California due to advective processes (Chavez *et al*., 2002; McClatchie, 2014). Shifts in the northern ranges of 29 families of eastern Pacific tropical fishes were reported in southern Californian waters (Lehodey *et al*., 2020). These changes led to a decrease by 30 percent of fishery landings from the Mexican Pacific in 1998. In the same year, California fisheries landed 47 percent less fish and invertebrates from California than in 1997; market squid (*Loligo opalescens*), red sea urchin (*Strongylocentrotus franciscanus*), chinook salmon (*Oncorhynchus tshawytscha*) and numerous groundfish species declined, but spot prawn (*Pandalus platyceros*) and ridgeback prawn (*Sicyonia ingentis*) and some demersal fish increased (Arntz *et al*., 2006).

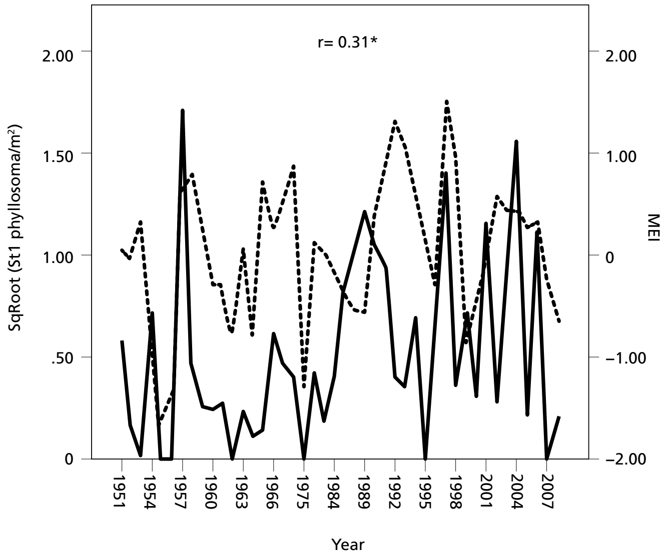
Impacts on coastal and demersal species

During extreme and, to a lesser extent EP El Niños, warm-water masses from oceanic and equatorial regions enter the upwelling zones, bringing a variety of (sub)tropical immigrant taxa. The autochthonous benthic fauna emigrates to deeper water or northward, or suffers mortality. The intruding equatorial water masses with lower oxygen than ambient waters may cause oxygen deficiency at upper slope depths. However, some local macrofauna with high temperature tolerance undergo important population expansion due to reduced competition or access to alternative food resources. Both these negative and positive effects (Table 6.6) influence local fisheries and the livelihood of coastal populations (Arntz *et al*., 2006). Along the Pacific coast of Mexico, extreme and EP El Niño events result in increased sea level, which drowns mangroves fringing the shoreline, but results in a net increase through mangroves being driven inland.

Kelp beds contribute substantially to biomass and benthic habitat structure. Giant kelp (*Macrocystis pyrifera*) communities on the California coast decline during El Niño, chiefly due to ENSO-generated storm swells causing physical damage, but also as a result of high temperature and low nutrient levels that interfere with growth and reproduction (Arntz *et al*., 2006; Glynn, 1988). Kelp mortality also deprives key invertebrate stocks (abalone, rock lobster, sea urchins and holothurians) of protection and food. The extreme 1982/83 and 1997/98 El Niños resulted in greater losses of giant kelp than the moderate EP El Niño events of 1986/87 and 1991/92 (Edwards, 2019). However, the impact of the two extreme El Niños was located in different regions. The 1982/83 event was more destructive in central California, while the 1997/98 event was more destructive to the giant kelp in southern California. Finally, both events appeared similarly destructive to the populations in Baja California, Mexico. Kelp recovery after El Niño varies between events due to variation in ocean conditions following each ENSO, with faster recovery when El Niño events are followed by La Niña (Edwards, 2019). Furthermore, giant kelp growth can be extraordinary during strong La Niña (e.g. during 1988/89).

Fish and intertidal assemblages experience major changes associated with ENSO. During extreme and EP El Niños, these include reduced recruitment and mortality of species with cold water affinities and enhancement of those with subtropical affinities; altered population growth rates; and shifts in genetic structure (Arntz *et al*., 2006). For example, red sea urchin (*Strongylocentrotus franciscanus*) catches strongly decreased off Baja California during the 1997/98 El Niño. Conversely, spiny lobsters (*Panulirus interruptus*) early-stage phyllosoma generally increase during El Niño events (Figure 6.10). During extreme and EP El Niños, spiny lobsters produced large amounts of larvae and juveniles, but this resulted in small reproductive females due to the accelerated development of the juveniles (Arntz *et al*., 2006). Ten decapod species, including the shrimp *Farfantepenaeus californiensis*, showed northern range extensions into the Southern California Bight during and after the 1991/92 and 1997/98 El Niños, which brought relief for those fishers who were suffering from the disappearance of their normal invertebrate target species. In general, warmer waters and increased rainfall during El Niño favour the reproduction and recruitment of shrimp populations and fisheries. El Niño-related northern range extensions of (sub)tropical fish included for example, two species of triggerfish, the yellowtail (*Seriola lalandi*) and the California barracuda (*Sphyraena argentea*) (Arntz *et al*., 2006). In central California, El Niño events correspond with both very low young-of-the-year rockfish abundance and low productivity throughout the ecosystem more generally (Santora *et al*., 2017).

FIGURE 6.10
The time series of stage 1 of spiny lobsters *Panulirus interruptus* phyllosoma abundance (solid line) plotted with the Multivariate ENSO Index (MEI) (dashed line)



Source: Koslow, Rogers-Bennett and Neilson (2012).

In the Gulf of California, demersal fish recruitment appeared to be modulated by ENSO. For instance, strong La Niña years, characterized by high nutrient concentrations, enhance algal growth with a consequent increase in leopard grouper (*Mycteroperca rosacea*) recruitment. During extreme El Niño years, rainfall dramatically increases, increasing nutrient concentrations inside mangrove estuarine habitats and hence yellow snapper (*Lutjanus argentiventris*) recruitment. In the North Pacific, Pacific halibut (*Hippoglossus stenolepis*) larval abundance in nursery areas and year-class strength are higher during extreme and EP El Niño events because the increased speed of coastal currents acts to entrain more offshore waters, and larvae, onto the shelf (Lehodey *et al*., 2020). Monitoring of fish recruitment could thus be used to adapt fisheries management ahead of time, allowing regulation of effort or setting of quotas based on the variability of climate indices (Aburto-Oropeza *et al*., 2010).

Impacts on pelagic species

There is currently no evidence for a relationship between El Niño and recruitment of northern anchovy (*Engraulis mordax*). However, extreme El Niño events have pervasive negative effects on northern anchovy, affecting the growth, mortality, size-at-age, fecundity, spawning distribution and movements of juveniles and adults. In contrast, Pacific sardine (*Sardinops sagax*) recruit successfully in some El Niño years, but not all. For instance the spawning habitat of the Pacific sardine was narrowly restricted to the coastal boundary during El Niño 1998, but one year later during La Niña 1999, the spawning habitat extended for a few hundred kilometres farther offshore (Ohman *et al*., 2017). In addition, the potential positive effect of El Niño on sardine is not persuasive in space and time and El Niño may not have a detectable effect on the sardine until a population threshold is exceeded (McClatchie, 2016, 2014).

During extreme and, to a lesser extent EP El Niños, California market squid (*Loligo opalescens*) experienced reduced growth rates and smaller body sizes. This was paralleled with a catastrophic drop in squid biomass due to unfavourable environmental conditions (e.g. reduced krill density). Squid that hatched and grew through these El Niño events were notably smaller and had slower growth rates compared to squid that grew during strong La Niña events, due to shifts in upwelling intensity and associated productivity (Jackson and Domeier, 2003; McClatchie, 2016). However, the species has a short lifespan, an advantage that allows for quick recovery after El Niño-related collapses, especially in southern California. The rate of recovery may differ from one ENSO event to another, but the mechanisms are complex and not fully understood (Lehodey *et al*., 2020).

Conversely, coastal areas of the United States of America as far north as Oregon experienced unusually high abundance of the jumbo flying squid (*Dosidocus gigas*) during the 1997/98 El Niño event (Pearcy, 2002). Large numbers of jumbo flying squid were also caught off the coast of Costa Rica during 1997 (Ichii *et al*., 2002). This suggests that the fleet may shift northward when catches are low in Peruvian waters, indicating that unusual environmental conditions in the eastern Pacific Ocean could either reduce the presence of squid in Peruvian waters or that intermediate conditions may favour the accumulation of squid in this region.

Finally, extreme and EP El Niños classically cause a decrease in salmon (*Oncorhynchus kisutch* and *Oncorhynchus tshawytscha*) abundance in the southern part of their range (California, Oregon) and null or positive effects in the north (Canada and Alaska) (Johnson, 1988; Pearcy and Schoener, 1987). Catches of salmon were close to average off northern California during the 2015/16 extreme El Niño. In California, decreases in salmon abundance during El Niño are accompanied by a deterioration of the condition factor, with dressed weight reaching 69 percent of mean weights from other years. This negative impact is stronger during extreme El Niño than other types. These El Niño salmon are known as "snakes" due to their substantially reduced body mass relative to length. This weight reduction during El Niño is likely due to a disruption in their normal feeding cycle. Indeed, the prey assemblages that normally sustain these fish do not form and there is little to feed on. Juvenile rockfish, euphausiids and herring largely disappear, while anchovies are more dispersed and do not form their usual large aggregations. Juvenile rockfish and anchovies are probably the most important prey because of their high caloric values. The disruption of these prey complexes results in the low Chinook weight, and this leads to reduced condition and fecundity (Adams, Ainley and Nelson, 2017).

6.1.4.3 Impacts on fish and fisheries: synthesis

Table 6.6 synthesizes the effects of different ENSO types on the ecology of fisheries resources in the eastern central Pacific.

TABLE 6.6
Schematic impact of the different categories of ENSO on the ecology (biomass, population structure and biology) of fisheries resources in the eastern central Pacific.

			ENSO category				
Taxonomic group	**Species**	**Area**	**Central Pacific El Niño**	**Eastern Pacific El Niño**	**Extreme El Niño**	**Coastal El Niño**	**Strong La Niña**
Benthonic	Kelp *Macrocystis pyrifera*	California Current	No clear impact	Moderate negative impact / Weak negative impact	Strong negative impact / Moderate negative impact	No data	Strong positive impact / Moderate positive impact
	Red sea urchin (*Strongylocentrotus franciscanus*)	Southern California Current	No data	Moderate negative impact / Weak negative impact	Strong negative impact / Moderate negative impact	No data	Strong positive impact / Moderate positive impact
	California spiny lobster (*Panulirus interruptus*)	California Current	No clear impact	Weak positive impact	Moderate positive impact	No data	Moderate negative impact
	Shrimp (*Farfantepenaeus californiensis*)	Southern California Current	No clear impact	Moderate positive impact / Weak positive impact	Strong positive impact / Moderate positive impact	No data	Strong negative impact
	Shrimp (general)	Tropical Eastern Central Pacific	No clear impact	Moderate positive impact / Weak positive impact	Strong positive impact / Moderate positive impact	No data	Strong negative impact
Demersal	Pacific halibut	Northeast tropical Pacific	No data	Weak positive impact	Weak positive impact	No data	Moderate negative impact
	Salmon (*Oncorhynchus kisutch* and *O. tshawytscha*)	California, Oregon	No data	Weak negative impact / No clear impact	Moderate negative impact / Weak negative impact	No data	Weak positive impact
Pelagic	Anchovy *Engraulis mordax*	California Current	No clear impact	No clear impact	Moderate negative impact / Weak negative impact	No data	No clear impact
	Sardine (*Sardinops sagax*)	California Current	No clear impact	No clear impact	Weak positive impact / Weak negative impact	No data	No clear impact
	California market squid *Loligo opalescens*	California Current	No clear impact	Moderate negative impact	Strong negative impact / Moderate negative impact	No data	Strong positive impact / Moderate positive impact

Colour scale:

No data	No data
No clear impact	No clear impact
Weak positive impact	Weak negative impact
Moderate positive impact	Moderate negative impact
Strong positive impact	Strong negative impact

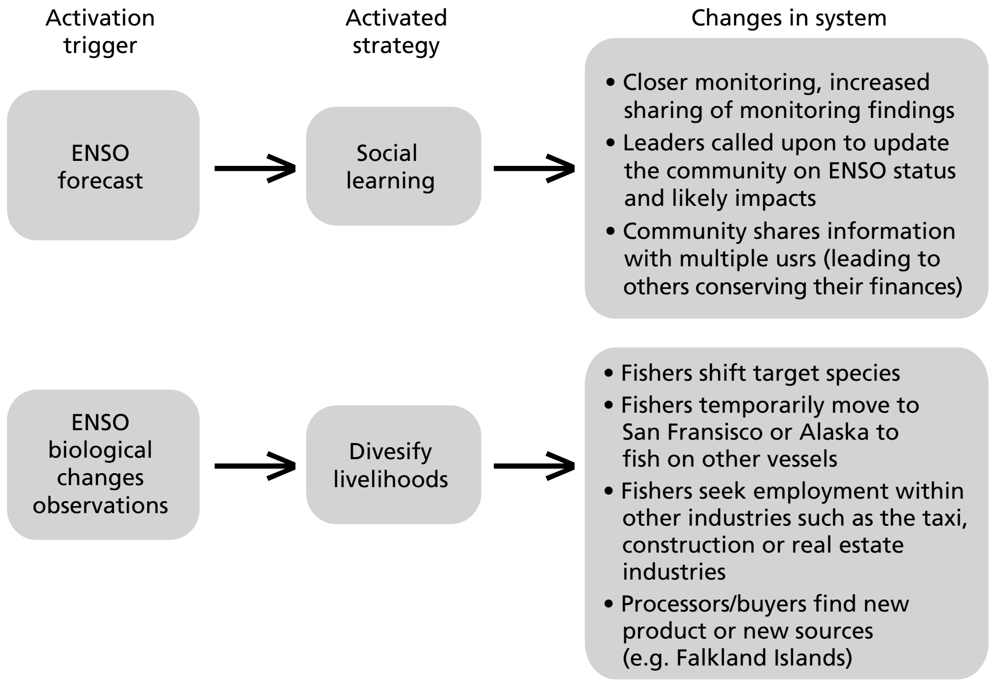
6.1.4.4 Coping strategies

Managing resources in a variable environment requires a balance between the trade-offs and benefits of multiple, competing objectives that demand flexible governance and management. Aguilera, Broad and Pomeroy (2018) synthesized the adaptive strategy of the Monterey Bay fisheries communities targeting anchovy, sardine and squid. The five strategies that most substantively contribute to the adaptive capacity of the case in relation to ENSO are:

- increase access to early warning systems
- encourage social learning
- match formal and informal rules to system dynamics
- diversify livelihoods
- build economic safety nets.

They proposed a two-step activation strategy for California that could be recommended elsewhere, first with a forecast and second with observations (Figure 6.11). This two-step activation is consistent with ENSO characteristics, because initial ENSO event declarations are based on conditions in the equatorial Pacific rather than its influence on other regions. The local system does not fully rely on adaptive capacity until ENSO is determined to have reached the California region (Aguilera, Broad and Pomeroy, 2018).

FIGURE 6.11
Two-step activation for adaptive capacity-building strategies in relation to ENSO



Source: Aguilera, Broad and Pomeroy, 2018.

6.1.5 Western central Pacific (FAO Major Fishing Area 71) and southwest Pacific (FAO Major Fishing Area 81)

KEY MESSAGES

- Dry/cold (wet/warm) conditions prevail across much of the north and equatorial western Pacific for all El Niño (La Niña) types of events.
- Both extreme and EP El Niño events exhibit a similar shoaling pattern in the western Pacific, localized west of the Dateline, while this shoaling is weaker and shifted westward for CP El Niño events.
- La Niña favours TC landfall in northwest Pacific (the Philippines, China Sea) and along the east coast of Australia. Extreme and CP El Niños increase TC activity on the populated islands and atolls of the Federated States of Micronesia, while only extreme El Niño increases TC activity near French Polynesia.
- Coral bleaching events are commonly reported during extreme El Niño events. This negatively impacts the landings of giant clams and reef fishes.
- In the western Pacific, skipjack tuna landings increase (decrease) during El Niño (La Niña) events. The opposite occurs in the central Pacific. Albacore landings present an opposite trend.

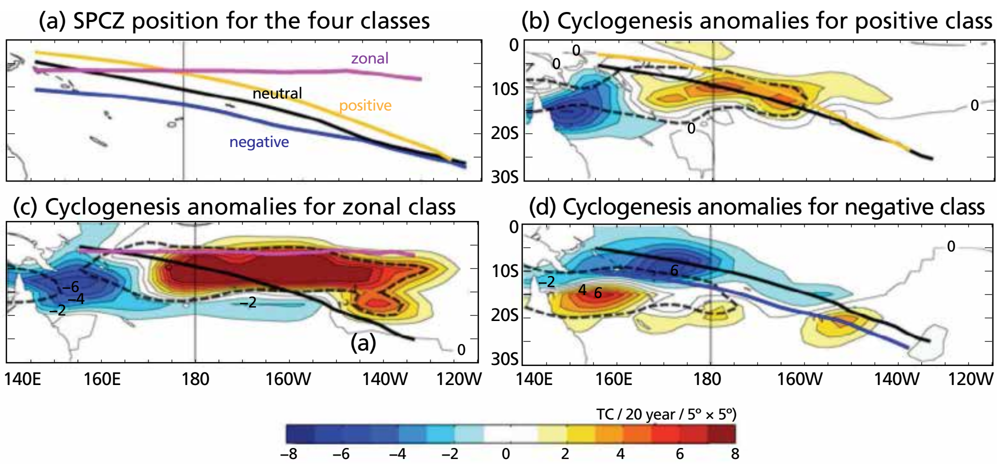
6.1.5.1 Impacts on ocean conditions, climate and extreme events

Impacts on ocean conditions and climate

During typical El Niño events, weaker equatorial trade winds induce an eastward shift of the western Pacific warm pool and modest cooling (<0.5 °C) over the far western Pacific (west of 160 °E). Conversely, stronger trade winds during La Niña episodes confine the warm pool to the extreme west of the equatorial Pacific, where surface waters warm slightly. Equatorial trade winds forcing also induces a clear seesaw pattern in sea level during ENSO events, with a thermocline shoaling (deepening) during El Niño (La Niña) over the western Pacific. While systematically larger for extreme El Niño events, both extreme and EP El Niño events exhibit a similar shoaling pattern in the western Pacific, localised west of the Dateline between 15 °N and 10 °S (Figure 6.1a). In contrast, this shoaling is weaker and shifted westward for CP El Niño events (Figure 6.1b), being confined west of 160 °E and north of the equator (Chang *et al.*, 2013).

Dry (wet) conditions prevail across much of the north and equatorial western Pacific during El Niño (La Niña) events, regardless of their flavour. In the south Pacific, the location of the South Pacific Convergence Zone (SPCZ), which largely controls rainfall, ocean circulation and tropical cyclogenesis patterns in the south Pacific, is displaced during ENSO, causing heavy rainfall or dry conditions depending on the strength of the particular event and the island location. While moderate CP and EP El Niño events induce a northeastward (resp. southwestward) displacement of the SPCZ (Figure 6.12), this picture does not hold during extreme El Niño events, when the SPCZ undergoes an equatorward swing of up to ten degrees of latitude and collapses to a more zonally oriented structure (Vincent *et al.*, 2011).

FIGURE 6.12
(a) Positions of the SPCZ for each class. Purple "zonal", orange "positive", black "neutral" and blue "negative" years. (b) positive, (c) zonal and (d) negative composites of TC genesis density anomaly with respect to the neutral cases (in number of genesis per 20 years and per 5 ° x 5 ° boxes). The thick dashed contour is the isoline for TC/20 years/(5 ° x 5 °) of TC genesis density. Climatological SPCZ and composite SPCZ are reported on each map



Source: adapted from Vincent *et al.*, 2011.

Impacts on tropical cyclones

The frequency and intensity of TCs in the tropical western Pacific are affected by ENSO. During El Niño years, the TC season is generally characterized by longer-lived and larger TCs. El Niño also favours a southeastward shift of TCs genesis in the northwestern Pacific (Figure 5.4a). During El Niño events, TCs generate southeast of their climatological position, moving towards the northwest, and then re-curving close to the direction of Japan (Wu, Chang and Leung, 2004). This generally leads to fewer TCs tracking towards the southern countries, i.e. the Philippines and the South China Sea. On the other hand, La Niña years favour a reduction of TC activity because of reduced TC lifespans (Figure 5.4b) but TC generation is shifted towards the west

(Figure 5.4b), inducing more TCs to track westward. These TCs can enter the South China Sea, increasing the chance of making landfall in China (Wu, Chang and Leung, 2004). As a consequence, ENSO strongly influences the Pacific wave climate, the eastward shift of TC activity during El Niño years, leading to increases in wave heights over the equatorial Pacific (Hemer, Church and Hunter, 2009).

TCs in the northwestern Pacific are also sensitive to ENSO type (Figure 5.4c, d; Wu *et al*., 2018). TC activity related to ENSO shows a stronger sensitivity to the intensity of CP El Niño events as compared to EP El Niño events (Patricola and Wehner, 2018). During CP El Niño events, the westward shift of the heating position from CP El Niño induces anomalous westerly winds and a northwestward extension of the monsoon trough, which favour TC genesis. During extreme El Niño, TC genesis position shifts southeastward and TCs have longer lifetimes and increased frequency of occurrences in most of the basin. During CP El Niño, TC genesis and activity displaces similar changes, but maximum centres extend westward to east of the Philippines compared to extreme events (Figure 5.4c, d). Unlike extreme and CP El Niño, TC genesis during EP El Niño does not show such a dramatic southeastward shift, with only modest positive anomalies east of the Philippines. Extreme and CP El Niños can therefore have severe impacts on the populated islands and atolls of the Federated States of Micronesia. During the initial, developing phase of El Niño, the region experiences heavy rainfall, increased TC activity, a drop in SST and sea level. During the mature and decaying phase, easterlies return, drought conditions develop, and SST and sea level increase. The more frequent TCs, with heavy rain and strong storm surge, damage infrastructure and increase coastal erosion and saltwater intrusion. During the decaying phase, drought conditions may result in water shortages, impacting human communities and agriculture. During the 2015/16 El Niño, drought conditions resulted in declarations of states of emergencies in Palau, Marshall Islands, Guam, and the Northern Mariana Islands (Rupic *et al*., 2018). More generally, some reported El Niño impacts in the region of the Pacific islands was synthesized by Kelman (2017) (Table 6.7).

TC genesis in the south Pacific generally occurs within ten degrees south of the SPCZ location (Figure 6.12a), as this region combines all the large-scale atmospheric conditions favourable for cyclogenesis (Vincent *et al*., 2011). As a consequence, it has long been known that northeastward displacements of the SPCZ associated with El Niño are associated with a similar displacement of the TC genesis region (Figure 6.12b), with increased cyclogenesis in the southwestern Pacific (e.g. Basher and Zheng, 1995), and decreased cyclogenesis near Australia (Figure 5.4a). The opposite occurs during southwestward displacements of the SPCZ associated with La Niña (Figure 6.12b). However, recent research also indicates that the different ENSO flavours have distinct impacts on SPCZ position and its related cyclogenesis (Vincent *et al*., 2011). For instance, cyclogenesis in the central Pacific only occurs during strong and extreme EP El Niño events (Figure 6.12c), while this observation was previously attributed to El Niño years in general. These events lead to a higher extreme wave climate in the eastern part of the southwest Pacific, despite the relatively low cyclone observation rate there (Stephens and Ramsay, 2014). In addition, Chand *et al*. (2013) identified two more ENSO regimes that resembled CP El Niño events. The positive–neutral regime showed an influence similar to that of El Niño, increasing TC activity in the eastern and central south Pacific, while the negative–neutral regime showed a La Niña-type influence with enhanced activity in the Coral Sea and eastern Australian regions. Chand *et al*. (2013) also suggest TCs around a group of small island nations including Fiji, Vanuatu, Marshall Islands and the Hawaiian Islands may become more frequent during future-climate El Niño events, compared with present-climate El Niño events, and less frequent during future-climate La Niña events.

TABLE 6.7
Some reported El Niño impacts in Pacific islands.

Country	Rainfall	Cyclones	Sea level
American Samoa		More frequent	
Cook Islands	More in north	More frequent	Higher
	Less in south	More intense	
Federated States of Micronesia	Less	More frequent	Lower
Fiji, Samoa, Solomon Islands	Less	More frequent/intense	Lower
French Polynesia		More frequent/intense	Lower
Kiribati	More	No change	Higher
Marshall Islands	Less	More intense	Lower
Nauru	More		Higher
New Caledonia		No change	
Niue	Less	More frequent	
Northern Mariana Islands	Less		
Palau	Less	No change	
Tokelau, Wallis and Futuna Islands		More frequent/intense	
Tonga	Less	No change	Lower
Tuvalu	More in north	No change	No change
	Less in south		
Vanuatu	Less	More frequent/intense	No change

Source: Kelman, 2017.

Impacts on marine heatwaves

Coral bleaching events are a common feature of MHWs in the tropical and subtropical Pacific (see Chapter 7) and are typically associated with strong El Nino phases (Selig, Casey and Bruno, 2010). The southwestern Pacific witnessed severe bleaching during the 2015/16 El Niño, including near the Cook Islands, Samoa, Tuvalu, Fiji, Vanuatu and New Caledonia (Dunstan *et al*., 2018). Similarly, devastating mass coral bleaching along the Great Barrier Reef in Australia has occurred during the demise of all types of El Niño events through changes in weather patterns rather than large-scale SST warming (McGowan and Theobald, 2017). These bleaching events significantly impact the extent and quality of coral reef habitats and are particularly devastating for coral reef-dependent fisheries when coral recovery does not occur, and regime shifts from coral-dominated systems to less desirable benthic assemblages occur. MHWs can also lead to direct or indirect fish mortality in both coastal and nearshore waters (Dunstan *et al*., 2018). The prospects for even greater mass bleaching events increase during future ENSO events as the climate continues to warm, with direct consequences for the overall health and sustainability of coral reef ecosystems.

A synthesis of impacts of ENSO types on ocean conditions and weather in the northeast tropical Pacific is presented in Table 6.8.

TABLE 6.8
Schematic impact of the different types of ENSO on the oceanic and atmospheric ocean properties in the northeast tropical Pacific.
MHW: marine heatwave

		ENSO Category				
Variable	**Area**	**Central Pacific El Niño**	**Eastern Pacific El Niño**	**Extreme El Niño**	**Coastal El Niño**	**Strong La Niña**
Temperature	Western Pacific	No clear impact	Moderate decrease	Moderate decrease	No clear impact	Moderate increase
Temperature/warm pool extent	Central Equatorial Pacific	Moderate increase	Moderate increase	Strong increase	No clear impact	Moderate decrease
Sea level/Thermocline	Western Pacific	Moderate decrease	Moderate decrease	Strong decrease	No clear impact	Moderate increase
Rainfall	Western Pacific	Moderate decrease	Moderate decrease	Strong decrease	No clear impact	Moderate increase
TCs	Western Pacific	Moderate increase	No clear impact	Strong increase	No clear impact	Moderate decrease
MHWs/bleaching	Australia	Moderate increase	Moderate increase	Moderate increase	No clear impact	No clear impact
MHWs/bleaching	Western Equatorial Pacific	No clear impact	No clear impact	No clear impact	No clear impact	Moderate increase
MHWs/bleaching	South Pacific	No clear impact	Moderate increase	Strong increase	No clear impact	No clear impact

Colour scale:

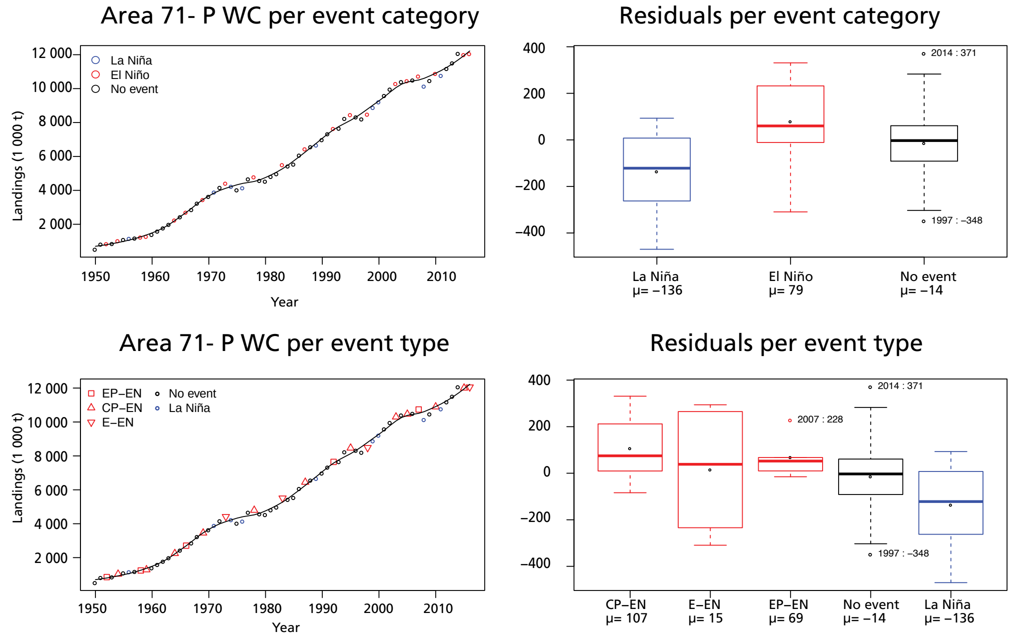
No data	No data
No clear impact	No clear impact
Moderate increase	Moderate decrease
Strong increase	Strong decrease

6.1.5.2 Impacts on capture fisheries

In the western central Pacific Ocean (FAO Major Fishing Area 71) ENSO impacts on fishery landings of the region are weak on average (Figure 6.13) with a positive anomaly of approximately 79 000 tonnes during El Niño and a negative anomaly of approximately 136 000 tonnes during La Niña. Considering the variety of El Niño, the positive effect was stronger for CP El Niño (+100 000 tonnes).

FIGURE 6.13

Left panels: yearly landings (in 1 000 t) for the FAO Major Fishing Area 71 in the western central Pacific Ocean per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel)



Data source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

Consumption rates of fresh fish among Pacific coastal communities are among the highest in the world. Coastal fisheries also provide many livelihoods, with an average of 50 percent of coastal households receiving their first or second income from activities related to fishing. The well-being of these PICTs is therefore tightly linked to oceans and climate. El Niño and La Niña events cause: i) variation in the distribution, and hence regional catch, of tuna; ii) extensive coral bleaching events that reduce local fish abundance; and iii) influence the distribution of TCs, which can result in severe impacts on fish habitats and fishing infrastructure (Dunstan *et al.*, 2018). These changes pose significant risks to the people and PICTs who depend on fisheries for their income and food security.

Impacts on invertebrates and coastal demersal and pelagic fish

See also Chapter 7. Elevated water temperatures associated with the 1997/98 El Niño and, more markedly, the 2015/16 El Niño triggered mass-bleaching events (zooxanthellae expulsion) and led to an 18 to 50 percent mortality rate of giant clam (*Tridacna maxima*) populations in atolls of French Polynesia where artisanal extraction and small-scale clam mariculture activities take place. Bleached or partially bleached clams have no value on the market. These events therefore immediately paralysed exports, threatening these livelihoods and highlighting the vulnerability of the activity (Andréfouët *et al.*, 2018). El Niño-related MHWs can lead to direct or indirect fish mortality in both coastal and nearshore waters. Coral bleaching affects coral-associated fishes, resulting in a loss of shelter and food, and mortality.

The 2016 bleaching event was for example accompanied by a major fish kill on the Coral Coast of Fiji. Some functional groups of fish (e.g. herbivores) can increase in abundance immediately after coral bleaching events but over longer periods, most reef-associated fish are expected to be less abundant in habitats with low coral cover, due to declines in the structural complexity of reefs (Dunstan *et al.*, 2018). Conversely, mobile fish species including nearshore pelagic fish, can avoid water bodies with elevated SSTs (Dunstan *et al*., 2018). Fish catch decline is not solely attributed to the warming of the oceans, but also to intense fishing pressure and other anthropogenic stresses as observed in the Philippines (Capili, Ibay and Villarin, 2005). ENSO-related heat stroke also favours toxic micro-organism blooms, impacting food security by causing dietary constraints and even poisoning due to contaminated food (Capili, Ibay and Villarin, 2005). In the Philippines, upwelling intensity seems to be modulated by ENSO, but no significant relationship was observed between ENSO and catches of Indian oil sardine (*Sardinella longiceps*) (Villanoy *et al*., 2011).

There is little evidence for direct ENSO impacts on benthic or demersal species in the southwest Pacific (FAO Major Fishing Area 81). An exception is along Australia's north coast, where enhanced catches of banana prawns (*Panaeus merguiensis*) in the Gulf of Carpentaria occur during high rainfall/river flow in La Niña years. La Niña events have also been found to enhance the transport of western rock lobster (*Panulirus cygnus*) larvae, while El Niño events enhance scallop (*Pecten fumatus*) recruitment. Finally, in South Australia, Victoria and the mid-latitudes of New Zealand, settlement of southern rock lobster (*Jasus edwardsii*) is higher during El Niño years. La Niña years were associated with higher settlement in Tasmania and southern New Zealand. In both cases, the relationships were relatively weak (Lehodey *et al*., 2020).

Impacts on tuna fisheries

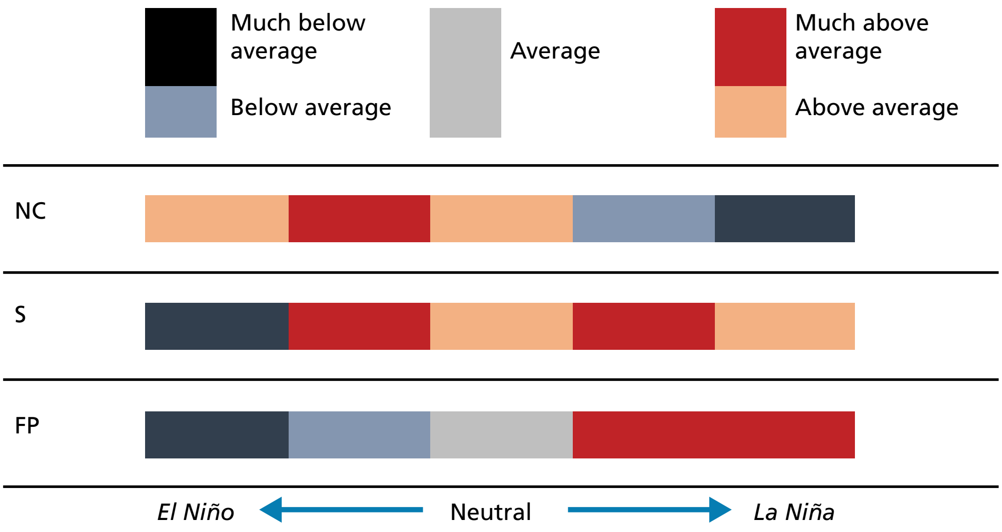
The equatorial and tropical Pacific is home to the world's largest tuna fisheries, dominated by four species of tuna: skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*), bigeye (*Thunnus obesus*) and albacore (*Thunnus alalunga*). ENSO is a main driver of tuna location and related catches in the Pacific (Lehodey *et al*., 1997). El Niño or La Niña events directly affect the horizontal movement and vertical distribution of these species. Changes in tuna distribution during El Niño (La Niña) phases are driven by the eastward extension (westward contraction) of their habitat that combines changes in prey density and their availability according to temperature and dissolved oxygen concentration. ENSO also strongly influences tuna recruitment, with an increase in favourable conditions for larvae survival during El Niño events in the eastern Pacific and a decrease in the central region (Lehodey *et al*., 2020). The thermocline is a physical barrier for skipjack and juvenile yellowfin and bigeye tuna, while adult yellowfin and bigeye tuna can dive below the thermocline to chase mesopelagic prey. Therefore, changes in the vertical thermal structure of the ocean associated with ENSO can potentially impact the catchability of tuna species according to the fishing gear (Lehodey *et al*., 2020). Typically, the thermocline in the western equatorial Pacific is shallower (deeper) during El Niño (La Niña) than in neutral conditions (Figure 3.1). Purse seiners targeting surface tuna use the top of the thermocline as a lower barrier to trap tuna schools. However, note that modern purse-seine nets can reach depths greater than 200 m, limiting the impact of these changes in thermocline depth (Lehodey *et al*., 2020).

Under strong El Niño conditions, skipjack fisheries are generally displaced further eastward along the equator and at higher latitudes – catches decline in western PICTs, such as Papua New Guinea, Federated States of Micronesia and Solomon Islands, but increase in Kiribati (Dunstan *et al*., 2018).

Catchability may be the main factor to explain ENSO impact on the albacore fishery. During El Niño, the vertical habitat compression of albacore due to shallowing of the vertical thermal structure increases catchability for the surface fishery in the western Pacific (e.g. in New Caledonia). In contrast, regions such as French Polynesia experience a deepening of that habitat during El Niño events, reducing albacore catchability (Lehodey *et al*., 2020). The opposite occurs during La Niña (Figure 6.14).

FIGURE 6.14

Results of the general linear models (GLMs) fitting albacore tuna catch per unit effort (CPUE) in New Caledonia (NC), Samoa (S) and French Polynesia (FP) versus SOI stratified into five classes. SOI values were stratified into five classes representative of strongest El Niño (<–15), moderate El Niño (>–15 and < –5) neutral (–5 to 5) and weak La Niña (>5 and <15) and strongest La Niña (>15). Three GLMs were fitted for exclusive economic zones (EEZs). The CPUE response was also stratified into five classes



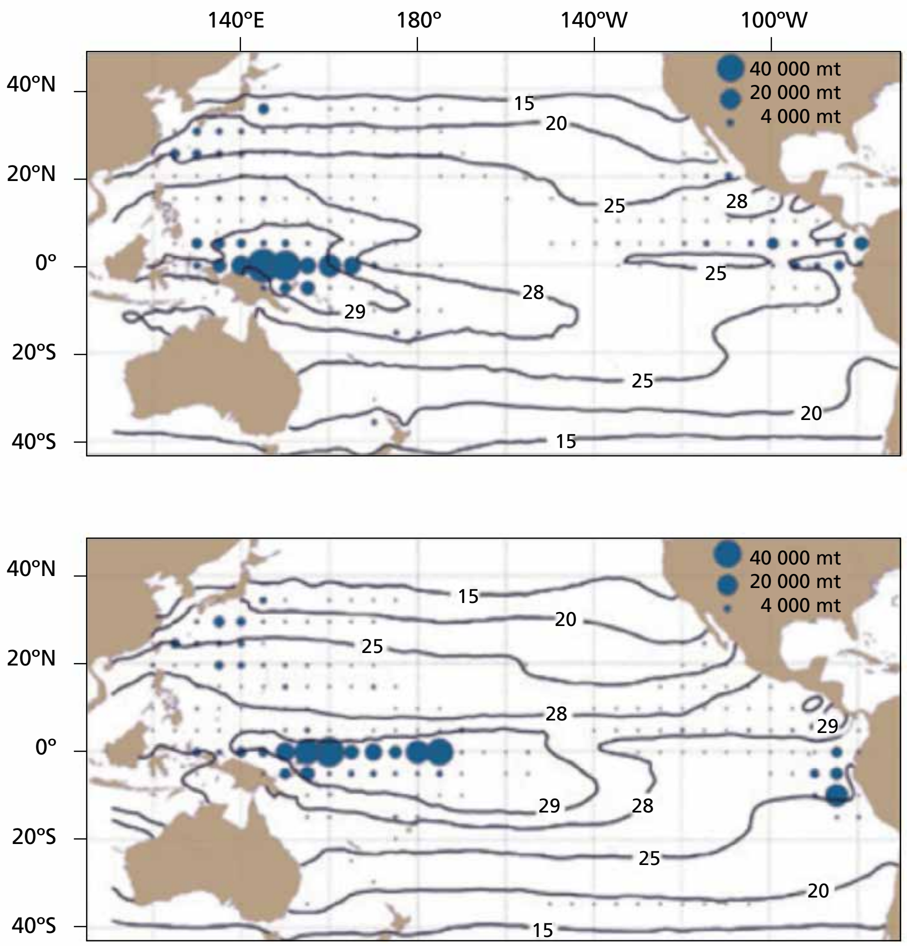
Source: Lehodey *et al*., 2020.

During El Niños, higher purse-seine catches are achieved in PICTs in the central Pacific, such as Kiribati (Figure 6.15). In the western Pacific (e.g. Solomon Islands and Papua New Guinea), catch rates increase several months after the completion of an El Niño in response to the increased productivity, higher recruitment and contraction of skipjack habitat. This is especially the case if an El Niño is followed by a La Niña episode (Lehodey *et al*., 2011). In the western Pacific warm pool, the shallowing of the thermocline and oxycline during El Niños reduces the depth at which yellowfin tuna have access to abundant food. This increases catch rates of this species by the surface fishery, potentially resulting in overfishing in years when vertical habitat space is compressed (Leung *et al*., 2019). The opposite happens during La Niñas, reducing the concentration of these species in shallower water and their vulnerability to surface fishing gear. The effect of ENSO phase on the thermocline and oxycline is the opposite in the eastern equatorial Pacific. Catches of skipjack tuna are less affected by the depth of the thermocline because this species lives in the surface layer and is vulnerable to being caught by purse seine and pole-and-line vessels at all times (Lehodey *et al*., 2011). There is a lag in these recruitment, biomass and distribution responses to ENSO phases. For example, the change in skipjack average abundance occurs about eight months after an ENSO phase (Figure 6.16), and in subsequent years for adult albacore.

Model results are consistent with the observed changes in purse seine fishing grounds and tagging data (Figure 6.15). They suggest that the eastward extension (westward contraction) of the species and fisheries distributions during El Niño (La Niña) phases are driven by changes in temperature, prey and dissolved oxygen concentration. As discussed previously, not all ENSO events are equal. For example, the 2015/16 El Niño did not strongly impact primary production in the eastern Pacific, as did other (EP) El Niño events (Lehodey *et al*., 2020).

FIGURE 6.15

Impact of ENSO on skipjack catch distribution and movement in the western central Pacific Ocean

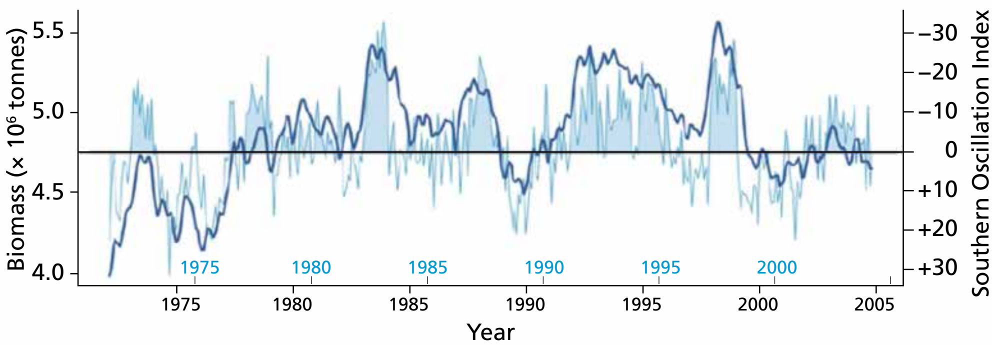


Skipjack tuna catch (t) and mean sea surface temperature (°C) in the tropical Pacific during the first half of 1989 (La Niña period) (top panel), and in the first half of 1992 (El Niño period) (bottom panel), showing effects of ENSO on the location of the warm pool (28–29 °C) and distribution of skipjack catch.

Source: Lehodey *et al*., 2011.

FIGURE 6.16

Estimated biomass (t) of young skipjack tuna (heavy blue line) in the western central Pacific Ocean, and the SOI lagged by eight months (shaded blue line)



Note that the SOI has been multiplied by 10 to highlight the variation.

Source: Lehodey *et al*., 2011.

Off northeastern Australia, there is evidence of a greater abundance of black marlin (*Makaira indica*) during El Niño years. Further south in the East Australian Current, there is little evidence of ENSO phases influencing the distribution or abundance of pelagic species. In Australia's largest pelagic fishery, the east coast longline fishery, studies seeking ENSO links to distribution and abundance of the target tuna and billfish have not revealed strong signals. This is due in part to weak temperature anomalies in the region in either ENSO phase (Lehodey *et al.*, 2020).

6.1.5.3 Impacts on fish and fisheries: synthesis

Table 6.9 synthesizes the effects of different ENSO types on the ecology of fisheries resources in the western central Pacific.

TABLE 6.9

Schematic impact of the different categories of ENSO on the ecology (biomass, population structure and biology) of fisheries resources in the western central Pacific.

			ENSO category				
Taxonomic group	**Species**	**Area**	**Central Pacific El Niño**	**Eastern Pacific El Niño**	**Extreme El Niño**	**Coastal El Niño**	**Strong La Niña**
Benthonic	Giant clam *Tridacna maxima*	French Polynesia	No data	No data	Strong negative impact / Moderate negative impact	No data	No data
	Banana prawns (*Panaeus merguiensis*), western rock lobster (*Panulirus cygnus*)	Australia's north coast	No clear impact	No clear impact	No clear impact	No data	Weak positive impact
	Scallop (*Pecten fumatus*)	Australia's north coast	No clear impact	No clear impact	Moderate negative impact	No data	No clear impact
Demersal	Reef fishes	Western Pacific	No clear impact	No clear impact	Strong negative impact / Moderate negative impact	No data	No clear impact
Pelagic	Indian oil sardine (*Sardinella longiceps*)		No clear impact	No clear impact	No clear impact	No data	No clear impact
Skipjack tuna		Western Pacific (western PICTs, e.g. Papua New Guinea, Federated States of Micronesia and Solomon Islands)	Moderate negative impact	No clear impact	Moderate negative impact	No data	Strong positive impact
Skipjack tuna		Central Pacific	Weak positive impact	No clear impact	Strong positive impact	No data	Moderate negative impact
Albacore tuna		Western Pacific (e.g. New Caledonia)	Weak positive impact	No clear impact	Weak positive impact	No data	Moderate negative impact
Albacore tuna		Central Pacific (e.g. French Polynesia, Samoa)	Moderate negative impact	No clear impact	Moderate negative impact	No data	Weak positive impact

Colour scale:

No data	No data
No clear impact	No clear impact
Weak positive impact	Weak negative impact
Moderate positive impact	Moderate negative impact
Strong positive impact	Strong negative impact

6.1.5.4 Coping strategies

Fisheries management in the western central Pacific is heterogeneous. Many countries have established segregated zoning for small-scale and industrial fishing, yet enforcement remains a challenge and gear restrictions are uncommon (FAO, 2011).

PICTs fisheries policy can learn from Vanuatu's experiences by incorporating conservative, but not permanent, regulations that can be lifted under a flexible open/closed management approach to increase access to fish for food and incomes during emergencies (Eriksson *et al*., 2017). Spatial closures can then be re-established once the crisis has passed. Protected areas are often implemented across a range of environments under rigid "no-access" or "no-take" rules to meet conservation goals. During times of crisis, this restriction of access to natural resources can exacerbate poverty. As experienced in Vanuatu, a more flexible management approach allowed protected areas to be utilized as reservoirs of food and income when temporarily opened to assist recovery. This approach may also generate a greater level of legitimacy and societal support for protected areas. However, improving capacity to meeting immediate needs for recovery, while not resulting in longer-term unsustainable fishing patterns is a challenge. For example, after the tsunami ravaged fishing fleets in Aceh in Indonesia, boat stocks were augmented without consideration of the former structure of the fleet, which increased the risk of unsustainable practices (Eriksson *et al*., 2017). In this context, anchored FADs are identified as a means to provide access to an alternative source of fish (open ocean pelagic fish such as tuna) while giving time for reef fisheries to recover (see Table 6.10).

From a disaster risk reduction (DRR) perspective, the challenges with El Niño for Pacific island communities are more related to inadequate vulnerability reduction than to ENSO-induced hazard influences (Kelman, 2017). Instead of focusing on one hazard-influencing phenomenon, opportunities should be created for the Pacific region to tackle wider DRR and development concerns. Dunstan *et al*. (2018) summarized potential management and policy adaptation options for coastal fisheries in Pacific small island developing states (SIDS) under various climate prediction scenarios. In Table 6.10, we report those related to ENSO events.

TABLE 6.10
Summary of potential management and policy adaptation options for coastal fisheries in SIDS under various climate prediction scenarios.

Event	Impacts	Adaptation options	Supporting policies
Increasing El Niño-like conditions	Movement of tuna eastward along the equator and at higher latitudes, with declines in catches in western PICTs.	Installation/maintenance of FADs, especially to help aggregate available tuna closer to coastal populations in western PICTs, including fisheries agency budget planning to ensure funds are available for maintenance and repair of FADs. Flexible arrangements to allocate more of the tuna resources to local food security. Increased allocation of area of the EEZ available to small-scale fishers. Improved post-harvest methods and food storage systems to stockpile tuna and small pelagics when good catches are made. Implementation of alternative livelihood programs for small-scale coastal communities. Creation of social safety nets, e.g. insurance programmes for SSF, community insurance banks, for communities.	Include nearshore FADs as part of the national infrastructure for food security. Transfer some access rights and allocations from industrial tuna fisheries to SSF. Apply targeted subsidy and training programmes to support key adaptations. Collaborative monitoring and decision-making processes to ensure that proposed interventions are appropriate and effective.

Event	Impacts	Adaptation options	Supporting policies
Short- to medium-term MHWs	Fish kills under persistently warmer conditions (e.g. due to low dissolved oxygen levels). Coral bleaching and subsequent overgrowth by macroalgae and increase in ciguatoxic microalgae. Changes in fish community composition and species' abundance. Declines in extent and quality of habitats and loss/contraction of fishing grounds. Depressed catch rates and declines in overall catches of key target species.	Awareness raising to avoid health implications of eating dead and decaying fish, and fish with ciguatera poisoning. Awareness raising of event, likely impacts, and importance of herbivorous fish in facilitating reef resilience and recovery. Flexible management practices to allow establishment of temporary "no-take" areas or gear restrictions (e.g. bans on night spearfishing with torches). Installation/maintenance of FADs to aggregate tuna and other small pelagic fish near coastal communities. Fuel and gear subsidies to encourage fishers to fish on FADs to transfer fishing effort away from reefs. Flexible arrangements to allocate more of the tuna resources to local food security. Improved post-harvest methods and food storage systems to stockpile tuna and small pelagic fish when good catches are made.	Strengthen fisheries legislation to apply community-based management. Promote access to nearshore pelagic fish such as tuna and fish expected to increase in abundance; include nearshore FADs as part of the national infrastructure for food security. Apply targeted subsidy and training programmes to support key adaptations. Collaborative monitoring and decision-making processes to ensure that proposed interventions are appropriate and effective.
Increased severity of cyclones and storms	Declines in extent and quality of habitats and loss/contraction of fishing grounds. Overgrowth of dead coral by macroalgae and increase in ciguatoxic microalgae. Changes in fish community composition and species' abundance. Depressed catch rates and declines in overall catches of key target species. Damage to fishing fleet.	Awareness raising to avoid health implications of eating fish with ciguatera poisoning. Awareness raising of event, likely impacts, and importance of maintaining stocks of herbivorous fish in facilitating reef resilience and recovery. Flexible management practices to allow establishment of temporary "no-take"areas or gear restrictions (e.g. bans on night spearfishing with torches). Installation/maintenance of FADs to aggregate tuna and other small pelagic fish near coastal communities. Fuel and gear subsidies to encourage fishers to fish on FADs, to transfer fishing effort away from reefs. Flexible arrangements to allocate more of the tuna resources to local food security. Improved post-harvest methods and food storage systems to stockpile tuna and small pelagic fish when good catches are made. Flexible licensing provisions (where relevant) and gear subsidies to allow fishers to target other species/ areas. Emergency preparedness training programmes in coastal communities and early warning systems to ensure preparedness (e.g. move fleet, secure gear).	Strengthen fisheries legislation to apply community-based management. Promote access to nearshore pelagic fish such as tuna and fish expected to increase in abundance; include nearshore FADs as part of the national infrastructure for food security. Apply targeted subsidy and training programmes to support emergency preparedness and key adaptations. Collaborative monitoring and decision-making processes to ensure that proposed interventions are appropriate and effective.

Source: Dunstan *et al.*, 2018.

6.1.6 North Pacific (FAO Major Fishing Areas 61 and 67) and Pacific Arctic (FAO Major Fishing Area 18)

KEY MESSAGES

- ENSO teleconnections alter the oceanic conditions and climate in the North Pacific.
- La Niña events positively impact fisheries. El Niño impacts vary according to the type of event, with a reduction of the landings (−96 000 tonnes) during extreme El Niño and an increase (+90 000 tonnes) during EP El Niño.
- ENSO impacts fish recruitment in the Pacific Arctic and influences the migration pattern of albacore in the northwest Pacific.
- Halibut and salmon landings increase during EP and extreme El Niño in Alaska while Japanese glass eel, neon flying squid and Asian mackerel purse seine fisheries are negatively affected.

6.1.6.1 Impacts on ocean conditions, climate and extreme events

Impacts on ocean conditions and climate

ENSO-related diabatic heating drives an atmospheric planetary wave response, which is channelled toward higher latitudes by the zonal mean circulation, acting to deepen the extra-tropical low pressure systems and strengthen the westerlies over the north and south Pacific (see Figure 2.1a; Alexander *et al.*, 2002). This leads to a clear heat flux and SST signature of El Niño in these extra-tropical regions, resulting in negative SST anomalies there. This pacemaker role of ENSO on global SST is also evident at decadal timescales, with the global surface warming slowdown during the last decades partly attributed to natural climate variability associated with decadal ENSO variations (e.g. England *et al.*, 2014). On the oceanic side, the equatorial thermocline variability associated with ENSO excites coastal Kelvin waves, which propagate poleward along the eastern northeast Pacific boundary, generating substantial sea level variability.

According to recent studies, EP or CP El Niños have distinct influences on north Pacific decadal oceanic and ecosystem variability by eliciting different teleconnections (Kilduff *et al.*, 2015). Both the Pacific Decadal Oscillation (PDO) and the North Pacific Gyre Oscillation (NPGO) – two indices of low frequency oceanic variability in the north Pacific – are influenced by El Niño (Newman *et al.*, 2016). EP El Niño events, via atmospheric teleconnections, force variability in the Aleutian Low pressure system and hence affect the PDO (Newman *et al.*, 2016). By contrast, CP El Niño events affect the North Pacific Oscillation (NPO) and the NPGO. Moreover, a recent study demonstrated that ENSO events frequency is linked with the PDO phases (Lin, Zheng and Dong, 2018). Rainfall anomalies in the northwest Pacific are induced by extreme El Niños, following both similar and different mechanisms than mean precipitation (Chou *et al.*, 2009).

Impacts on tropical cyclones

As discussed in the previous section, CP and extreme El Niño favour a southeastward shift of TCs genesis in the northwestern Pacific (Chia and Ropelewski, 2002), resulting in TCs having an increased probability of hitting Japan, Democratic People's Republic of Korea, Republic of Korea and northern China during La Niña years compared to El Niño years (Kim *et al.*, 2011). Beyond shifts in TC activity, the northeast Pacific also experiences an equatorward shift in storm track activity during El Niño, resulting in enhanced storm track activity along the east coast of North America (Eichler and Higgins, 2006). This also results in enhanced precipitation east of the Appalachians during El Niño and precipitation shifts to the Ohio Valley during La Niña.

Impacts on marine heatwaves

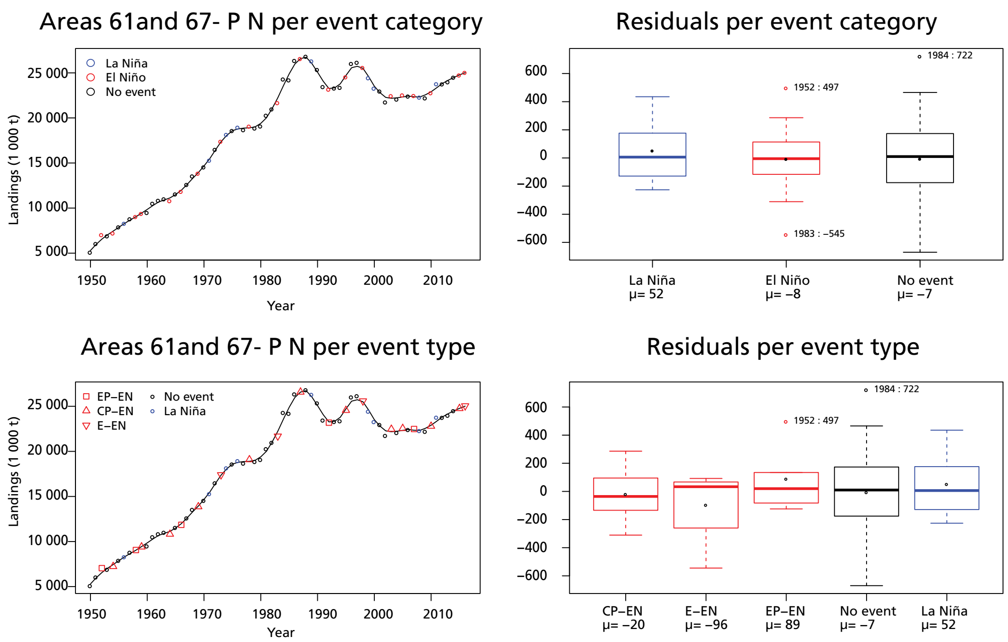
MHWs were recently observed in the northeast Pacific Ocean from October 2013 to June 2016 (Di Lorenzo and Mantua, 2016), culminating in record-breaking heat content anomalies in 2016 for the Gulf of Alaska (Walsh *et al*., 2018). This MWH, with wide-reaching ecological and socio-economic impacts, has been partly attributed to the combined effect of unabated global warming and the 2014 to 2016 El Niño sequence occurring in the central equatorial Pacific.

6.1.6.2 Impacts on capture fisheries

In the north Pacific (FAO Major Fishing Areas 61 and 67) ENSO impact on global fishery landings is weak (Figure 6.17) with on average a positive anomaly of approximately 50 000 tonnes during La Niña and no noticeable impact during El Niño. However, when considering the variety of El Niño, extreme El Niños led to a negative impact of approximately 96 000 tonnes, while EP El Niño led to a positive impact of approximately 90 000 tonnes.

FIGURE 6.17

Left panels: yearly landings (in 1 000 t) for FAO Major Fishing Areas 61 and 67 in the north Pacific per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel)



Data source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

The Pacific Arctic (FAO Major Fishing Area 18) is a biologically productive region, adjacent to the north Pacific, supporting subsistence and tribal fisheries, as well as lucrative commercial and recreational fisheries. One of the most striking consequences of the strengthening of poleward transport and increased ocean temperatures observed during El Niño events is the dramatic change in distribution and range expansions of a variety of fish and invertebrate species. During the 1982/83 extreme El Niño, triggerfish (*Melichthys niger*) were observed in Alaska, 2 800 km north of their previous northern record. During this period, market squid (*Loligo opalescens*) increased in Alaska, but disappeared from their usual fishing grounds in southern California (Pearcy and Schoener, 1987). These pronounced changes in fish availability force some fishers to move away from their usual fishing grounds.

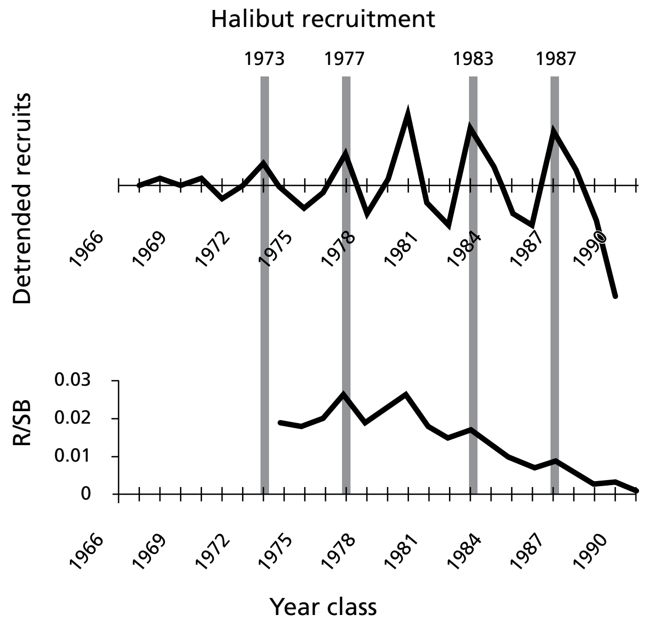
The northwest Pacific is one of the most productive fishing areas in the Pacific Ocean. This region, which encompasses the biologically rich Kuroshio Current, supports many commercial fisheries including small pelagic species such as Japanese sardine (*Sardinops melanostictus*), Japanese anchovy (*Engraulis japonicus*), Pacific saury (*Cololabis saira*), chub mackerel (*Scomber japonicus*) and Japanese common squids (*Todarades pacificus*), and also highly migratory species, including albacore tuna, skipjack tuna, Pacific bluefin tuna (*Thunnus orientalis*), and the neon flying squid (*Ommastrephes bartramii*) (Lehodey *et al*., 2020).

Impacts on demersal and pelagic species

ENSO impacts fish recruitment in the Pacific Arctic. In particular, the abundance of larvae of the Pacific halibut (*Hippoglossus stenolepis*) and of the arrow-tooth flounder (*Atheresthes stomias*) is higher in the Gulf of Alaska in El Niño years compared with non-El Niño years (Bailey and Picquelle, 2002). Enhanced transport of larvae onshore and towards the coast may contribute to the tendency for relatively strong year classes of Pacific halibut in the Gulf of Alaska during extreme and EP El Niño years (Figure 6.18). Still, strong halibut year classes may occur in non-El Niño years, as observed for the strong 1980 year class that cannot be attributed to an El Niño effect. For the arrow-tooth flounder, higher larval recruitment does not seem to impact the fishery recruitment because the juveniles prefer colder water. Thus, the benefit of enhanced onshore transport may be offset by less desirable temperatures in El Niño conditions (Bailey and Picquelle, 2002).

FIGURE 6.18

Comparison of *Hippoglossus stenolepis* recruitment anomalies (top panel), calculated as the deviation from the five-year running mean, and R/SB (recruits per spawning biomass, bottom panel) to El Niño events, indicated by labelled vertical lines. (Pacific halibut recruitment and spawning biomass data provided by the International Pacific Halibut Commission.)

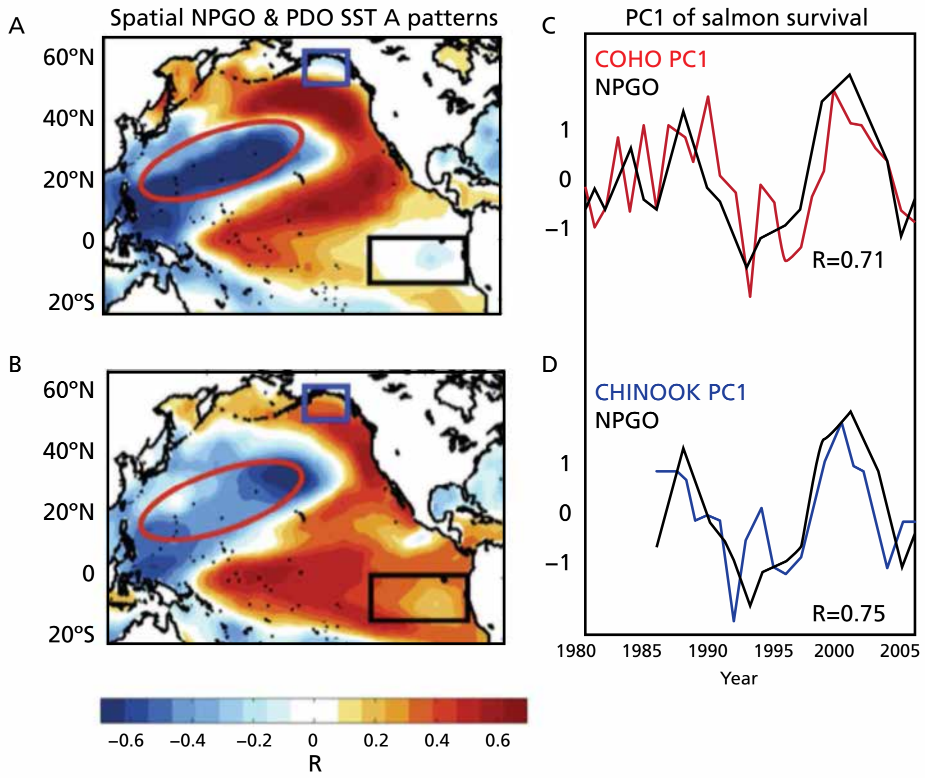


Source: Bailey and Picquelle, 2002.

Variability in the PDO partly forced by EP El Niño events is related to fluctuations in salmon catch, with the PDO index being positively correlated with Alaska stocks and negatively correlated with California, Oregon, and Washington stocks. The contrasting response of salmon survival rates to increased ocean temperature is a result of differential responses of food web productivity to increased ocean warming in the two systems (Kilduff *et al.*, 2015). By contrast, CP El Niños remotely influence NPGO low frequency variability. Unlike the PDO, the NPGO is associated with anomalously cold coastal waters in the Gulf of Alaska (Kilduff *et al.*, 2015). With the increase of CP El Niño events since the 1980s, the NPGO has intensified, and now appears to be a better index of salmon survival than the PDO (Kilduff *et al.*, 2015; Figure 6.18). This intensification of the NPGO is also associated with increased coherence of survival rates among different salmon stocks (Kilduff *et al.*, 2015; Lehodey *et al.*, 2020).

FIGURE 6.19

Spatial correlation maps of the (A) annual NPGO and (B) annual PDO with wintertime (January–March) SSTA. Coloured rectangles and ovals highlight differences between the NPGO and PDO spatial signals. Correlation of dominant mode of variability (first principal component) of (A) Coho salmon (red line) and (B) Chinook salmon (blue line) survival rates with the NPGO (black)



Source: Lehodey *et al.*, 2020, adapted from Kilduff *et al.*, 2015.

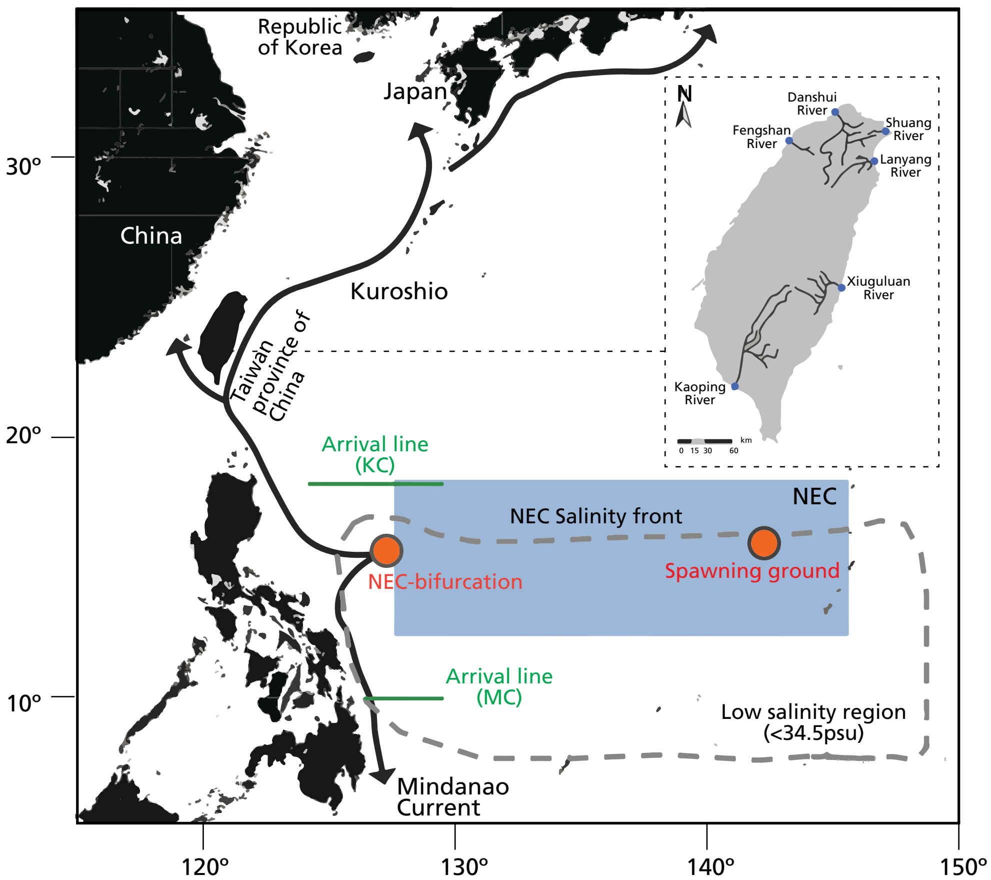
Amongst the large highly migratory species inhabiting the Northwest Pacific, Japanese longline fisheries data indicate that ENSO influences the migration pattern of albacore, as they are more widely spread during El Niño years. Given that all tuna species spawn in warm waters, it is likely that their spawning habitats are all impacted by ENSO variability, as demonstrated for skipjack tuna (Lehodey *et al.*, 2020).

Landings of the southeast Asian mackerel purse-seine fishery in Taiwan Province of China targeting chub mackerel, spotted mackerel (*Scomber australasicus*), round scad (*Decapterus lajang*) and blue mackerel scad (*Decapterus maruadsi*) suffered severe declines of about 48 percent following the 1997/98 extreme El Niño. These losses resulted in an estimated decline in revenues of about USD 6.2 million in 1998. In parallel, fishing costs increase during El Niño, presumably because of an increased number of days spent searching for the disappearing fish. If the year 1998 was a normal year, without the extreme El Niño effect, the fishery could have saved almost 40 percent in total effort-related costs (Sun *et al.*, 2006). The neon flying squid (*Ommastrephes bartramii*) supports another major fishery in the northwest Pacific. ENSO results in substantial reduction/enhancement of available neon flying squid habitats in the summers following CP El Niño/La Niña, where the latter led to an expansion of favourable spawning and nursery grounds (Alabia *et al.*, 2016).

In the same way, Japanese glass eel (*Anguilla japonica*) catches in Japan decline during El Niño events. This change is related to intensified North Equatorial Current water flows into the Mindanao Current when the North Equatorial Current bifurcation moves northward during an El Niño event, thus causing a decrease in the probability of eel larvae being transported into the Kuroshio Current (Figure 6.20); the opposite current pattern occurs during La Niña years (Hsiung *et al.*, 2018). During El Niño years, (i) the southward movement of the salinity front might cause the larvae to experience slower currents, and (ii) the northward movement of the North Equatorial Current bifurcation might broaden the separation between their spawning ground and North Equatorial Current bifurcation. This prolongs the time needed for the larvae to enter the Kuroshio Current from their spawning ground. In addition, this might cause more water to flow into the Mindanao Current, leading to a decline in the rate at which larvae are entrained into the Kuroshio Current (Hsiung *et al.*, 2018).

FIGURE 6.20

Schematic view of salinity structure, oceanic circulation and the North Equatorial Current bifurcation in the northwest Pacific Ocean related to the presumed spawning location of *Anguilla japonica*. Blue spots in the inserted map show the catch sites of glass eel in Taiwan Province of China



Source: modified from Hsiung *et al.*, 2018. Map conforms to United Nations World map, February 2020.

6.1.6.3 Impacts on fish and fisheries: synthesis

Table 6.11 synthesizes the effects of different ENSO types on the ecology of fisheries resources in the north Pacific and Pacific Artic.

TABLE 6.11

Schematic impact of the different categories of ENSO on the ecology (biomass, population structure and biology) of fisheries resources in the north Pacific and Pacific Arctic marine fisheries.

			ENSO category				
Taxonomic group	**Species**	**Area**	**Central Pacific El Niño**	**Eastern Pacific El Niño**	**Extreme El Niño**	**Coastal El Niño**	**Strong La Niña**
Demersal fish	Pacific halibut *Hippoglossus stenolepis*	Gulf of Alaska	No clear impact	Strong positive impact / Moderate positive impact	Strong positive impact / Moderate positive impact	No data	Moderate negative impact / No clear impact
	Arrow-tooth flounder *Atheresthes stomias*	Gulf of Alaska	No clear impact	No clear impact	No clear impact	No data	No clear impact
	Salmon	Alaska	Moderate positive impact	Weak positive impact	Strong positive impact / Moderate positive impact	No data	Moderate negative impact / Weak negative impact
Pelagic fish	Asian mackerel purse-seine fishery in Taiwan Province of China: chub mackerel (*Scomber japonicus*), spotted mackerel (*Scomber australasicus*), round scad (*Decapterus lajang*) and blue mackerel scad (*Decapterus maruadsi*)	Northwest Pacific	Weak negative impact / No clear impact	Moderate negative impact / No clear impact	Strong negative impact / Moderate negative impact	No data	No clear impact
	Japanese glass eel (*Anguilla japonica*)	Northwest Pacific	Weak negative impact / No clear impact	Moderate negative impact / No clear impact	Strong negative impact / Weak negative impact	No data	Strong positive impact / Weak positive impact
	Neon flying squid (*Ommastrephes bartramii*)	Northwest Pacific	Moderate negative impact / No clear impact	Weak negative impact / No clear impact	Moderate negative impact / Weak negative impact	No data	Moderate positive impact

Colour scale:

No data	No data
No clear impact	No clear impact
Weak positive impact	Weak negative impact
Moderate positive impact	Moderate negative impact
Strong positive impact	Strong negative impact

6.1.6.4 Coping strategies

The countries forming the Western and Central Pacific Fisheries Commission present annual and multi-annual work programmes to manage fisheries under their administration. The Northern Committee of this commission includes the north Pacific tuna fisheries, exploited by Japan, United States of America, Canada and Taiwan Province of China (Fache and Pauwels, 2016). The recent Commission for the Conservation and Management of Highly Migratory Fish Stocks in the Western and Central Pacific Ocean – Northern Committee 2019–2021 work programme, includes provisions on harvest strategies, scientific support, compliance monitoring, etc., for north Pacific fisheries (https://www.wcpfc.int/meetings/14th-regular-session-northern-committee).

6.2 ATLANTIC OCEAN

KEY MESSAGES

- El Niño events act to warm the tropical north Atlantic in boreal spring following its peak but also impact the equatorial Atlantic.
- ENSO categories and types have no significant impact on fisheries landings over the Atlantic Ocean as a whole.
- The responses of the eastern tropical and southeast Atlantic differ.

6.2.1 Impacts on ocean conditions, climate and extreme events

Impact on ocean conditions and climate

In the Atlantic Ocean, one of the most robust remote ENSO impacts is the teleconnection to tropical north Atlantic SST in boreal spring following the ENSO peak: a broad region of positive (negative) SST anomalies to the north of the equatorial Atlantic lags the mature phase of El Niño (La Niña) in boreal winter, peaking in boreal spring (Figure 5.1). This results in a northward (southward) shift of the Atlantic ITCZ during El Niño, resulting in a drier- (wetter-) than-normal climate in the northeast of Brazil in boreal spring. As illustrated in Figure 5.1c, ENSO has been proposed to influence this region either through a tropical pathway (a weakening of the Walker circulation that generates anomalous descending motion over the tropical Atlantic; see Wang *et al*., 2009) or an extra-tropical pathway (i.e. through the Pacific–North American pattern; García-Serrano *et al*., 2017). The respective role of these tropical and extra-tropical processes is uncertain as the weakened northeasterly trades can be caused by the anomalous Walker and local Hadley cells or a Gill-type response to Amazonian heating (Garcia-Serrano *et al*., 2017).

In the equatorial Atlantic, the Atlantic Niño dominates the interannual variability: ENSO's influence on the Atlantic Niño is not robust, with only a weak concurrent correlation between ENSO and the equatorial Atlantic SST (Cai *et al*., 2019). During El Niño, a weakening Walker circulation and the associated easterly wind anomalies along the equator in the Atlantic tend to generate cold anomalies through the Bjerknes positive feedback. However, this cooling may be offset by either tropospheric warming in response to El Niño and/or by oceanic downwelling Kelvin waves induced by a meridional SST gradient due to warming in the tropical north Atlantic, propagating into the region (Cai *et al*., 2019). Near the coast, ENSO also appears to have a rather insignificant effect on the Canary Current upwelling system and related primary productivity (Cropper, Hanna and Bigg, 2014).

Tropical cyclones

TCs are the primary source of hazardous weather in the tropical north Atlantic (Emanuel, 2003), with a period of greatest activity extending from August to October. These TCs can cause devastation in the Caribbean, Central America and the United States of America. During the development of El Niño (La Niña) events, fewer (more) TCs generally occur over the North Atlantic in response to stronger (weaker) wind shears (Patricola, Chang and Saravanan, 2016). This impact of ENSO occurs regardless of ENSO flavours but while ENSO impact on Atlantic TCs is linearly related to ENSO amplitude, CP El Niño events appear to have a stronger impact on Atlantic TC activity than EP El Niño for El Niño events of similar intensity (Kim, Webster, and Curry, 2009; Patricola, Chang and Saravanan, 2016). Among the large-scale climatic phenomena, the Atlantic multidecadal oscillation (AMO) and ENSO are both known to strongly affect TC activity by modulating the SSTs and wind shear over this region (Krishnamurthy *et al*., 2016).

Impact on marine heatwaves

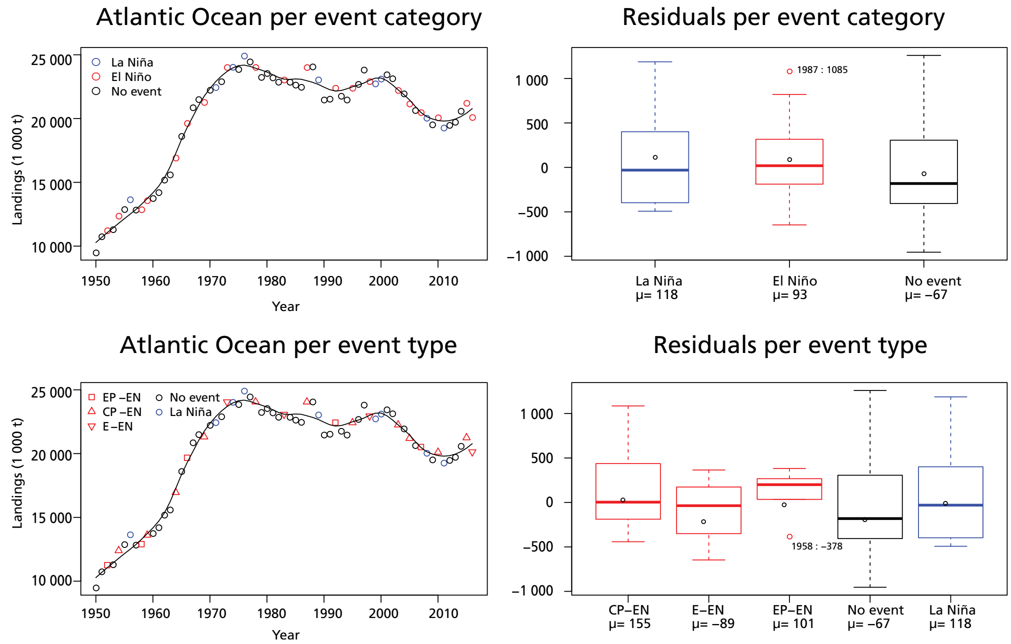
Coral bleaching events have been regularly reported over the Caribbean reefs and along the southeastern coast of South America. The relationship of the events, MHWs and ENSO will be detailed in the next subsections and in Chapter 7.

6.2.2 Impact on capture fisheries

ENSO categories and types have no significant impact on fisheries landings when considering the Atlantic Ocean (FAO Major Fishing Areas 21, 27, 31, 34, 41 and 47) globally (Figure 6.21). Indeed, both types of ENSO events slightly increase the volume of landings in comparison with no event. Considering the diversity of ENSO types, ENSO impact is not clear, with the strongest effect (+155 000 tonnes) during CP El Niño and La Niña events (+118 000 tonnes).

FIGURE 6.21

Left panels: yearly landings (in 1 000 t) for the Atlantic Ocean per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel)



Data source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

6.2.3 Southwest Atlantic (FAO Major Fishing Area 41)

KEY MESSAGES

- El Niño events induce strong weather and marine anomalies (upwelling, winds, precipitation and floods) in the southern part of South America.
- Although negative impacts on fish landings are observed only after extreme El Niño, all El Niño types have some negative impact on coastal species.

6.2.3.1 Impacts on ocean conditions and climate

Impact on ocean conditions and climate

ENSO influence is generally less robust in the south Atlantic than in the north Atlantic. For some El Niño events, oceanic processes in the Atlantic compete with the tropospheric temperature warming mechanism, resulting in either warming or neutral conditions in the south Atlantic (Chang *et al.*, 2006). During La Niña, the upper ocean temperature changes are roughly the reverse of those evident during El Niño.

El Niño events generally favour above normal rainfall over southern Brazil, northern Argentina and Uruguay during the austral spring and summer through an intensified subtropical jet stream over southeastern South America (e.g. Grimm, Ferraz and Gomes, 1998). This signal is larger during EP and extreme El Niño events when compared to CP El Niño events because of a stronger atmospheric teleconnection pattern (Tedeschi, Cavalcanti and Grimm, 2013). The southeastern coast of South America generally experiences increased freshwater discharges, northerly wind anomalies and intensified upwelling during El Niño periods. These features result in an increase in primary productivity along the continental shelf north of 45 °S during El Niño events (Machado, Barreiro and Calliari, 2013). In addition to massive occasional precipitation and high river flow associated with El Niño events, an increase in frequency and strength of storm surges was observed in coastal areas of the Río de la Plata (the border area between Argentina and Uruguay). These were accompanied by an increase in speed and frequency of onshore southerly winds augmenting coastal erosion rates. These factors could have severe consequences for the marine ecosystem and the economy, including flood risks, destruction of coastal infrastructure, mass mortality of marine species, and introduction of invasive species (Bertrand, Vögler and Defeo, 2018). These regions are included in a climatic hotspot, i.e. a region where SST has changed most rapidly over the past 50 years and is projected to rise by more than 3 °C by 2099 (Popova *et al.*, 2016). Drier conditions are projected along the semi-arid coast of northeastern Brazil, but precipitation and river runoff are increasing in southeastern South America (25 °S to 40 °S). This last region exhibited one of the greatest increases in precipitation worldwide during the last century, which led to high river runoff. The trend is expected to continue, with an increase in precipitation of 5 percent to 20 percent by 2050 (Nagy *et al.*, 2008).

Impact on marine heatwaves

The largest and most diverse coral formations in the South Atlantic Ocean are found on the continental shelf in the southern portion of the state of Bahia in Brazil. Coral bleaching in this area has been related to regional phenomena but also to the remote influence of El Niño, with a lag of six months (Lisboa, Kikuchi and Leão, 2018). A synthesis of impacts of ENSO types on ocean conditions and weather in the southwest Atlantic is presented in Table 6.12.

TABLE 6.12

Schematic impact of the different types of ENSO on the oceanic and atmospheric ocean properties in the southwest Atlantic.

		ENSO category				
Variable	**Area**	**CP El Niño**	**EP El Niño**	**Extreme El Niño**	**Coastal El Niño**	**Strong La Niña**
Temperature	South Pacific	Moderate increase	Moderate increase	Moderate increase	No clear impact	Moderate decrease
Rainfall	East Brazil	Moderate decrease	No clear impact	No clear impact	No clear impact	Moderate increase
Rainfall	Southern Brazil	No clear impact	Moderate decrease	Strong decrease	No clear impact	Moderate increase
Rainfall	Southeast South America	No clear impact	Moderate increase	Strong increase	No clear impact	Moderate decrease
Upwelling/PP	Southeastern coast	Moderate increase	Moderate increase	Strong increase	No clear impact	Moderate decrease
Risk for terrestrial installations	Southeastern coast	Moderate increase	Moderate increase	Moderate increase	No clear impact	No clear impact
Marine heatwave	Southeastern coast	Moderate increase	Moderate increase	Moderate increase	No clear impact	No clear impact

Colour scale:

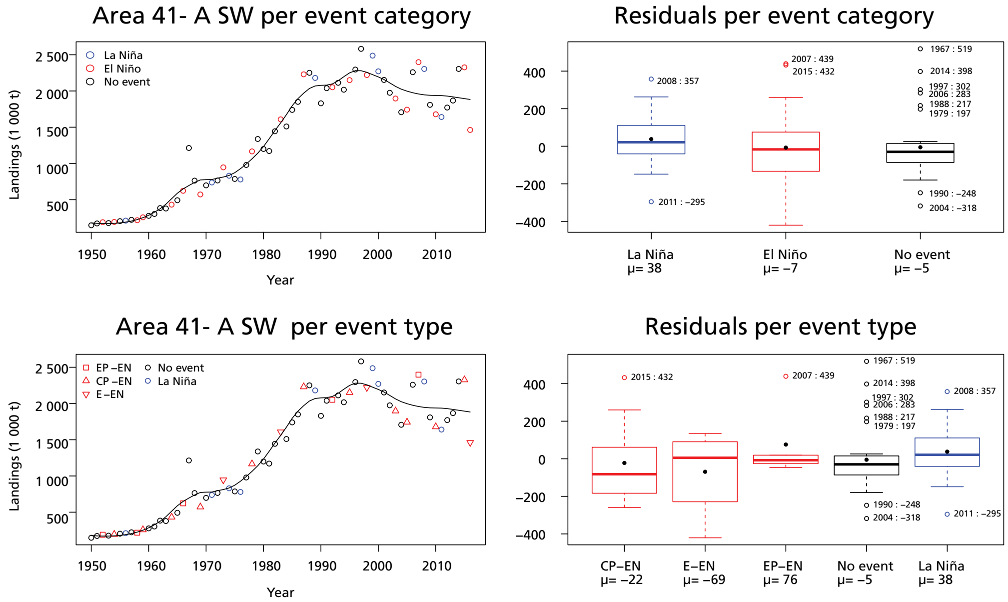
No data	No data
No clear impact	No clear impact
Moderate increase	Moderate decrease
Strong increase	Strong decrease

6.2.3.2 Impacts on capture fisheries

In the southwest Atlantic Ocean (FAO Major Fishing Area 41), ENSO categories and types have no strong impact on fisheries landings (Figure 6.22). However, extreme El Niño induces a negative anomaly of approximately 70 000 tonnes, while EP El Niño induces a positive anomaly of 76 000 tonnes.

FIGURE 6.21

Left panels: yearly landings (in 1 000 t) for FAO Major Fishing Area 41 in the southwest Atlantic Ocean per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel)



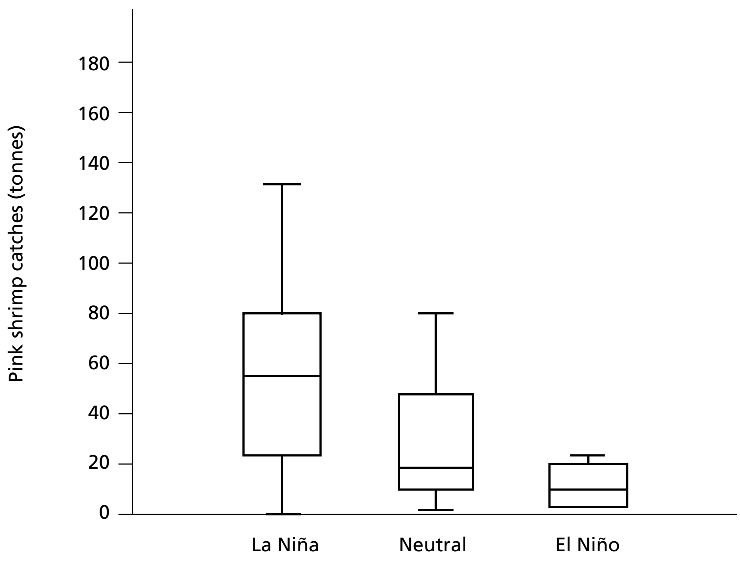
Data source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

The southern Brazil/northern Argentina region encompasses the estuarine complexes of the Patos Lagoon (Rio Grande do Sul State, Brazil) and the Rio de la Plata estuary (Argentina–Uruguay). In general, studies evidence a strong impact of ENSO in the most commercially important marine species within these estuaries, resulting in a negative relationship between freshwater discharge and fish production, with implication for fisheries value chains. Between 1997 and 2015, trophic guilds of less dominant estuarine fish (herbivore–phytoplankton, macroalgae herbivore, insectivore and piscivore) increased their relative abundance in estuaries during heavy rainfall and lower salinity conditions associated with moderate and very strong El Niño events. The opposite was observed for dominant (more than 90 percent of the total abundance) trophic fish guilds (omnivore and, to a lesser extent, detritivore and zooplanktivore), which were associated with higher values of salinity and water transparency which occur mostly during non-El Niño conditions. However, moderate and very strong El Niño events have not substantially disrupted the dominance patterns among trophic fish guilds in the estuary. Instead, they have increased trophic estuarine diversity by flushing freshwater fishes with distinct feeding habits into the estuary (Possamai *et al.*, 2018).

In this area, low (high) shrimp catches are related (with a one year-lag) to El Niño (flood) and La Niña (drought) events (Figure 6.23). For example, total shrimp estimated catch in two coastal lagoons of Uruguay for the period 1988 to 2013 ranged between 0.7 tonnes and 162 tonnes. Very high captures occurred in some years consistent with

La Niña or neutral conditions (1990, 1997, 2009 and 2012). The opposite occurred during periods of El Niño in subsequent years (1992, 1998, 2003 and 2004) (Gasalla, Abdallah and Lemos, 2017; Santana, Silveira and Fabiano, 2015). In the Patos Lagoon, El Niño-related low catches of pink shrimp were estimated to amount to an average economic loss per year of around USD 7.4 million. This loss is particularly relevant considering that in a stable year the pink shrimp fishery revenue is around USD 9 million (Gasalla, Abdallah and Lemos, 2017). Moreover, an increase in the abundance of marine species occurs under La Niña conditions when low precipitation and freshwater outflow occur. On the opposite end of the spectrum, high precipitation and river discharge related to El Niño were associated with low abundance of marine and dominant euryhaline fishes, such as *Mugil platanus* and *Atherinella brasiliensis* in estuaries (Garcia, Vieira and Winemiller, 2001). Mullet fisheries provide a good example because both juvenile and adult mullets decline in abundance during El Niño episodes of high rainfall and near-zero salinity (de Abreu-Mota, Medeiros and Noernberg, 2018). Therefore, climate variability creates enormous stress for the fishers of the Patos Lagoon and markedly affects fishing communities because the income level of fishers is low even in good seasons, and can drop below the poverty line in bad seasons. About 160 fishing villages depend upon the mullet fishery along the coasts of Rio Grande do Sul, Santa Catarina and Paraná in southern Brazil (de Abreu-Mota, Medeiros and Noernberg, 2018). Given the deteriorating status of resources and the unfavourable climatic conditions that prevailed in the past decades (several times caused by ENSO events), it can be concluded that artisanal fishers' livelihoods are currently in a vulnerable socio-economic situation (Gasalla, Abdallah and Lemos, 2017). Effective resilient fisheries should rely on three factors. First, there should be a flexible fish allocation system based on ecosystem variability. Secondly, fish allocation should prioritize food security and poverty alleviation. Thirdly, a monitoring system should be implemented that takes into consideration ecosystem, fisheries and human dimensions to support a flexible and adaptive fisheries management, with resilient fisheries as the ultimate goal (de Abreu-Mota, Medeiros and Noernberg, 2018).

FIGURE 6.23
Boxplot of estimated catch (tonnes) of the pink shrimp in Uruguayan coastal lagoons categorized by the occurrence of ENSO events



Source: redrawn from Santana, Silveira and Fabiano, 2015.

In the Southern Brazilian Bight (SSB) during the 1997/98 ENSO, species usually found in deeper and lower temperature habitats showed increased relative abundances. Some piscivorous species such as hake (*Merluccius hubsii*), flatfish (*Paralichthys patagonicus*) and Brazilian flathead (*Percophis brasiliensis*) were also more abundant during this period (Paes and Moraes, 2007). Two mechanisms have been proposed (Paes and Moraes, 2007) for linking oceanographic conditions in the SBB and the occurrence of intense ENSO events, and can be further detailed in two non-exclusive sub-hypotheses:

- After an extreme El Niño, primary productivity and pelagic fishery production should increase, relative to non-ENSO periods.
- After a CP or EP El Niño or an intense La Niña, pelagic production will be reduced. Nevertheless, some catadromous species of commercial interest (e.g. mullets, croaker and shrimps) may benefit from the prevailing conditions, since a considerable number of moderately pristine estuaries are still available on the southern Brazilian coast.

Ecosystem degradation in the Río de la Plata ecosystem, expressed as increased system entropy and diminished system biomass, is strongly forced by extreme and EP El Niño events, and weakly forced by strong La Niña events. Meridional sea surface temperature anomalies were used as indicators of ENSO-induced forcing by Vögler *et al.* (2015).

6.2.3.3 Impacts on fish and fisheries: synthesis

Table 6.13 synthesizes the effects of different ENSO types on the ecology of fisheries resources in the southwest Atlantic.

TABLE 6.13.
Schematic impact of the different categories of ENSO on the ecology (biomass, population structure and biology) of fisheries resources in the southwest Atlantic Ocean.

			ENSO category				
Taxonomic group	**Species**	**Area**	**Central Pacific El Niño**	**Eastern Pacific El Niño**	**Extreme El Niño**	**Coastal El Niño**	**Strong La Niña**
Coastal	Shrimps (e.g. *Farfantepenaeus paulensis*)	South Brazil–north Argentina	Moderate negative impact / No clear impact	Strong negative impact / Moderate negative impact	Strong negative impact / Moderate negative impact	No data	Strong positive impact / Moderate positive impact
	Mullet (*Mugil platanus*) and Brazilian silverside (*Atherinella brasiliensis*)	South Brazil–north Argentina	No data	Moderate negative impact / Weak negative impact	Strong negative impact / Moderate negative impact	No data	Strong positive impact
Demersal	Icthtyophagous species: hake *Merluccius hubsii*, flatfish *Paralichthys patagonicus*, and the Brazilian flathead *Percophis brasiliensis*	SBB	No data	No data / No data	Moderate positive impact	No data	Weak negative impact

Colour scale:

No data	No data
No clear impact	No clear impact
Weak positive impact	Weak negative impact
Moderate positive impact	Moderate negative impact
Strong positive impact	Strong negative impact

6.2.3.4 Coping strategies

Most of the fish stocks are considered to be either fully exploited (e.g. squids) or overexploited (e.g. hakes), while a few such as the Patagonian grenadier (*Macruronus magellanicus*) are considered moderately exploited (FAO, 2011). Fisheries management success is varied (FAO, 2011; Johnson *et al.*, 2019). For instance, institutional and economic barriers hinder adaptation strategies in the La Plata River basin (enacted through the Joint Technical Commission for the River Plate Maritime Front, CTMFM). Adaptation strategies and measures for Brazilian fishing communities are being developed, as well as several technical groups on fisheries management. Most fisheries (except for coastal SSF) are regulated under management strategies, but enforcement is lacking.

6.2.4 Western Central Atlantic (FAO Major Fishing Area 31)

KEY MESSAGES

- The tropical north Atlantic tends to warm in boreal spring following EP and extreme El Niño peak.
- El Niño (La Niña) suppresses (enhances) Atlantic TCs. TC are therefore more likely to reach the coast of the United States of America during La Niña.
- El Niño favours MHWs in the Caribbean.
- ENSO event are linked to shifts in the spatial population distribution of large pelagic fish in the western central tropical Atlantic.
- Only extreme El Niño induces a negative landings anomaly, but all El Niños have a negative impact on small pelagic fish.

6.2.4.1 Impacts on ocean conditions, climate and extreme events

Impacts on ocean conditions and climate

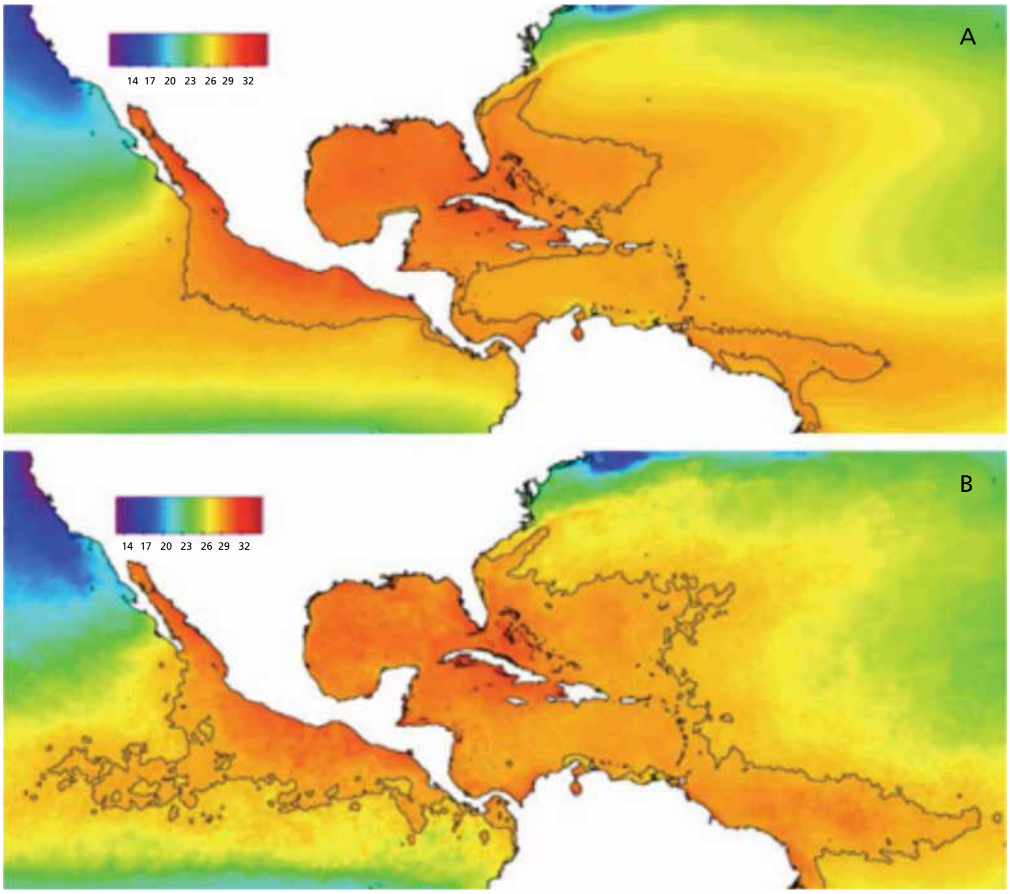
As mentioned above, the tropical north Atlantic tends to warm in boreal spring following the ENSO peak (Figure 5.1c). As the Atlantic warm pool is adjacent to the tropical north Atlantic (Figure 6.24), the ENSO remote forcing acts on the Atlantic warm pool in a similar way to the tropical north Atlantic. Consequently, El Niño (La Niña) events tend to be followed by a larger (smaller) than usual Atlantic warm pool (Figure 6.24; Enfield, Lee and Wang, 2006). The interannual variability of plankton biomass in the northern Gulf of Mexico during winter and spring is also largely controlled by ENSO, which could impact the reproductive success and biological condition of upper trophic levels, including commercially important species (Gomez *et al*., 2019). This response is also asymmetric, with much larger and broader impact (biomass increase) during El Niño compared to La Niña events.

During boreal spring, as the tropical north Atlantic warms up, the Atlantic ITCZ exhibits an anomalous northward shift, with a dipole in the precipitation anomaly field (Xie and Carton, 2004). In that season, rainfall over the Caribbean Sea increases following El Niño. This precipitation dipole is not limited to the oceanic sector but extends into the South American continent as well, with a large decrease in rainfall over Brazil's Nordeste region and a modest increase over the continent north of the equator.

These impacts, however, vary as a function of ENSO flavour. While EP El Niños are usually followed by a significant warming of the tropical north Atlantic basin during boreal spring, the tropical Atlantic does not show a robust response to CP El Niño (Amaya and Foltz, 2014; Taschetto *et al*., 2016). South America is also greatly affected by the occurrence of different types of ENSO (e.g. Tedeschi, Cavalcanti and Grimm, 2013). For example, eastern Brazil experiences negative precipitation anomalies for CP El Niño during austral summer but not during EP or extreme El Niño. In contrast, southern Brazil experiences positive precipitation anomalies during EP and extreme El Niño that do not exist during CP El Niño.

FIGURE 6.24

Composite images (July–September) derived from the AVHRR Pathfinder v5.0 showing areas with SST warmer than 28.5 °C (black contours). Panel A corresponds to the climatological SST (1985–2006) and panel B shows the large warm pool event of 1998.



Source: Manzano-Sarabia *et al*., 2008.

Impacts on tropical cyclones

While ENSO is known to modulate TCs in the Atlantic Ocean, climate signals are stronger in the Caribbean than for the remainder of the tropical Atlantic (Klotzbach, 2011a). As a consequence, much more activity occurs in the Caribbean during La Niña conditions (Figure 5.4b) compared with El Niño conditions (Figure 5.4a; Klotzbach, 2011b). In addition, the probability of TCs making landfall over the United States of America is significantly higher during La Niña than El Niño and the spatial distribution of TC-related flooding was shown to depend on the phase of ENSO (Villarini *et al*., 2014). The reduction in landfall frequency is greater along the Florida peninsula and East Coast than it is along the Gulf Coast, especially for major TCs (Klotzbach, 2011a). While the probability of most states being impacted by a TC is greater in La Niña than in El Niño, the state with the most dramatic increase in the likelihood of a TC making landfall in a La Niña year is the state of North Carolina. As expected, damage from continental United States of America TCs is significantly reduced during El Niño seasons and increased during La Niña seasons (Klotzbach *et al*., 2018).

While EP and extreme El Niño are known to reduce Atlantic TC activity (Figure 5.4c), the influence of CP El Niño events is more controversial (Figure 5.4d) due to a short data record and the ENSO-independent Atlantic SST variability (Kim, Webster and Curry, 2009; Larson *et al*., 2012).

Impacts on marine heatwaves

Three out of four major heat stress events in the Caribbean (1998, 2010 to 2011 and 2014 to 2017) can be related to the occurrence of an El Niño event (Muñiz-Castillo *et al.*, 2019). There is a six to 12-month period between El Niño and heat stress events, consistent with the lagged response of the Atlantic SSTs to ENSO remote forcing. Although some major Caribbean heat stress events have been associated with El Niño, rising temperatures have caused heat stress during all ENSO phases. Since the 1997/98 El Niño, all the following El Niño events (weak or strong) have been associated with high exposure to heat stress. For instance, the most widespread heat stress event in the Caribbean in 2005 occurred during a relatively weak El Niño event. This increased sensitivity may be linked to other low frequency modes of variability, such as the recent AMO warming and anthropogenic warming.

A synthesis of impacts of ENSO types on ocean conditions and weather in the western tropical Atlantic is presented in Table 6.14.

TABLE 6.14

Schematic impact of the different types of ENSO on the oceanic and atmospheric ocean properties in the western tropical Atlantic.

		ENSO category				
Variable	**Area**	**CP El Niño**	**EP El Niño**	**Extreme El Niño**	**Coastal El Niño**	**Strong La Niña**
Temperature/warm pool extent	Western Atlantic	No clear impact	Moderate increase	Strong increase	No clear impact	Moderate decrease
Temperature/warm pool extent	Central equatorial Pacific	No clear impact	Moderate increase	Strong increase	No clear impact	Moderate decrease
Primary productivity	Northern Gulf of Mexico	No clear impact	Moderate increase	Strong increase	No clear impact	Moderate decrease
Rainfall	East Brazil	Moderate decrease	No clear impact	No clear impact	No clear impact	No data
Rainfall	Southern Brazil	No clear impact	Moderate increase	Moderate increase	No clear impact	Moderate decrease
TCs	Caribbean	No clear impact	Moderate decrease	Strong decrease	No clear impact	Strong increase
Risk for terrestrial installation	North Carolina/Florida	No clear impact	Strong decrease	Strong decrease	No clear impact	Strong increase
Marine heatwave	Caribbean	Moderate increase	Moderate increase	Strong increase	No clear impact	No clear impact

Colour scale:

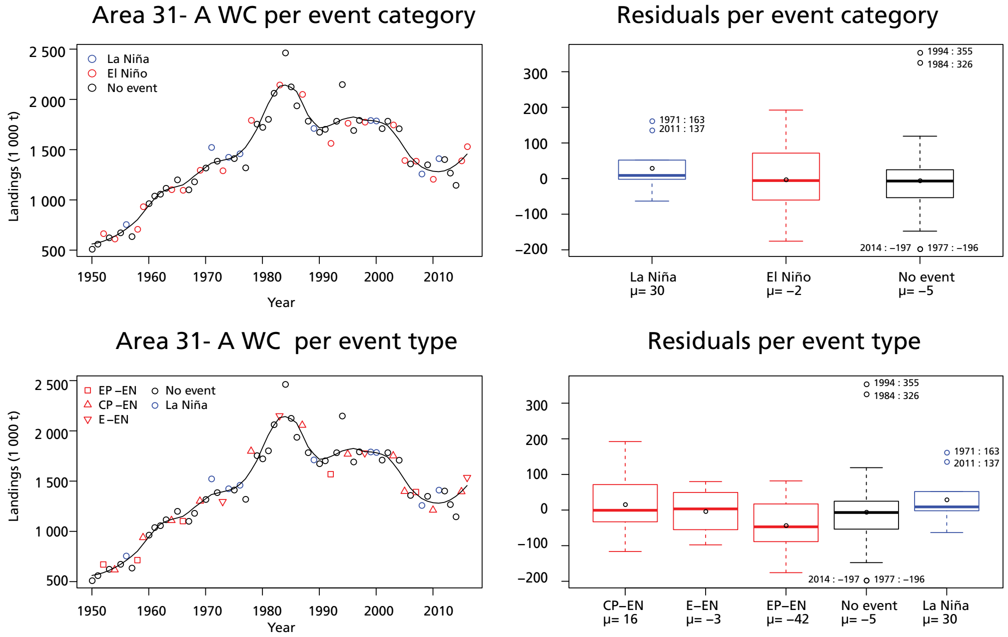
No data	No data
No clear impact	No clear impact
Moderate increase	Moderate decrease
Strong increase	Strong decrease

6.2.4.2 *Impacts on capture fisheries*

In the western central Atlantic Ocean (FAO Major Fishing Area 31), ENSO categories and types have no significant impact on fisheries landings (Figure 6.25). Only EP El Niño induces a negative anomaly of approximately 40 000 tonnes.

FIGURE 6.25

Left panels: yearly landings (in 1 000 t) for FAO Major Fishing Area 31 in the western central Atlantic Ocean per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel)



Data source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

Commercial fisheries in the western central Atlantic are affected by climate change in general – through changes in fish physiology and behaviour, as well as impacts on habitats (Oxenford and Monnereau, 2018) – but specific ENSO-driven impacts are more difficult to pinpoint. It has been noticed that small pelagic fish in general are very sensitive to interannual alterations of SST and most species are considered to be at the limit of their thermal tolerance. Moreover, coral bleaching, increased sea level and nutrient load (which increases toxic algal blooms, ciguatera fish poisoning and prevalence of shellfish diseases) and *Sargassum* influxes, combine to disrupt fisheries and coastal communities' livelihoods (Oxenford and Monnereau, 2018).

Gulf menhaden (*Brevoortia patronus*) is a species of commercial and ecological importance in the northern Gulf of Mexico, provisioning the second largest fishery by weight in the United States of America. The oil content of this species is positively correlated to spring Mississippi river discharge and El Niño. Indeed, El Niño-driven increases in freshwater discharge determine the size of the resulting freshwater and nutrient-laden plume aggregating prey (Leaf, 2017). However, such improved conditions seem to be accompanied by low recruitment of Gulf Menhaden due to a modification of the circulation and high river discharge influencing dispersal (Gomez *et al*., 2019). El Niño-related low salinity conditions also negatively impact red snapper recruitment (Gomez *et al*., 2019).

In the Pajarales lagoon complex of the Caribbean coast of Colombia, the exotic tilapia (*Oreochromis niloticus*) benefits from enhanced river streamflow under La Niña conditions (Blanco, Narváez Barandica and Viloria, 2007). Conversely, tilapia retreat to the river or die in lower flow conditions when salinity increases (salinity >10). In French Guiana, shrimp (*Farfantepenaeus subtilis* and *Farfantepenaeus brasiliensis*) fisheries are positively and negatively affected by El Niño (not segregated by category or type) and La Niña, respectively, through ENSO-driven alterations of air and water temperature, rainfall, salinity and flow of rivers, etc. (Sanz *et al*., 2017). Shifts in the spatial population distribution of large pelagic fish (e.g. *Katsuwonus pelamis*, *Makaira* *nigrican*, *Xiphias gladius*) in the western central and eastern tropical Atlantic are linked with ENSO events, with a stronger effect in the former and a more subtle one in the latter (Chang *et al*., 2013).

6.2.4.3 Impacts on fish and fisheries: synthesis

Table 6.15 synthesizes the effects of different ENSO types on the ecology of fisheries resources in the western central Atlantic.

TABLE 6.15
Schematic impact of the different categories of ENSO on the ecology (biomass, population structure and biology) of fisheries resources in the western central Atlantic.

			ENSO category				
Taxonomic group	**Species**	**Area**	**Central Pacific El Niño**	**Eastern Pacific El Niño**	**Extreme El Niño**	**Coastal El Niño**	**Strong La Niña**
Benthic	Shrimp (*Farfantepenaeus subtilis* and *Farfantepenaeus brasiliensis*)	French Guiana	Moderate negative impact	Moderate negative impact	Moderate negative impact	No data	Moderate positive impact
Demersal	Tilapia (*Oreochromis niloticus*)	Caribbean coast of Colombia	Moderate negative impact	Moderate negative impact	No data	No data	Strong positive impact
	Gulf Menhaden (*Brevoortia patronus*)	Gulf of Mexico	No clear impact	Moderate positive impact / No clear impact	Strong positive impact / Moderate positive impact	No data	Moderate negative impact / Weak positive impact

Colour scale:

No data	No data
No clear impact	No clear impact
Weak positive impact	Weak negative impact
Moderate positive impact	Moderate negative impact
Strong positive impact	Strong negative impact

6.2.4.4 Coping strategies

Numerous institutional arrangements facilitate sustainable fisheries management in the western central Atlantic. Yet, despite the large number of institutions involved, fisheries management data is neither centralized nor complete. Most stocks are considered to be fully exploited. The region includes 10 percent of the world's coral reefs, which have been declining since the 1980s (FAO, 2011).

Adaptation measures have been adopted throughout the region. These include the development of mobile applications for tracking and early warning; investment in improved infrastructure; and the mainstreaming of climate change into fishery policy and planning (Oxenford and Monnereau, 2018). For instance, coastal wetland areas in the Gulf of Mexico are the target of adaptation projects because they constitute important fish habitats: coastal restoration and rehabilitation in the context of a wetland conservation management strategy (Shelton, 2014).

6.2.5 Eastern central (tropical) Atlantic (FAO Major Fishing Area 34)

KEY MESSAGES

- Extreme and EP El Niño induces a delayed warming in the northeastern tropical Atlantic. On the contrary, CP El Niño induces a delayed cooling in the same region.
- ENSO's influence on the Atlantic Niño is not robust, with only a weak concurrent correlation between ENSO and the equatorial Atlantic SST.

- Only extreme El Niño induces a positive landings anomaly, and EP El Niño a negative one.
- There is currently no robust evidence of any impact of ENSO on fish and fisheries of the eastern central Atlantic.

6.2.5.1 Impacts on ocean conditions and climate

As mentioned at the beginning of the section, the combination of mid-latitude and equatorial teleconnections tends to weaken the northeasterly trade winds in the tropical north Atlantic, reducing evaporative cooling, warming SST, and peaking in spring, i.e. one season after El Niño (Enfield and Mayer, 1997). However, this response differs with ENSO flavour due to different atmospheric teleconnection from the Pacific to the Atlantic (Amaya and Foltz, 2014; Taschetto *et al*., 2016). While this response is found during extreme and EP El Niño, CP El Niño induces a cooling in the northeastern tropical Atlantic and near-neutral conditions elsewhere.

El Niño causes a weakening Walker circulation, which should induce easterly wind anomalies and cold anomalies along the equator in the Atlantic that can intensify through the positive Bjerknes feedback. This cooling is, however, likely to be offset either by tropospheric warming in response to El Niño (Chang *et al*., 2006) and/or by oceanic downwelling Kelvin waves induced by a meridional SST gradient due to the tropical north Atlantic warming (Lübbecke and McPhaden, 2012). These competing effects may explain the weak influence of ENSO on equatorial Atlantic SST and the weak concurrent relationship between ENSO and the Atlantic Niño (Keenlyside and Latif, 2007). This influence is, however, modulated by ENSO flavours (Rodrigues *et al*., 2011; Tokinaga, Richter and Kosaka, 2019): strong and long-lasting El Niño tends to lead to equatorial Atlantic easterlies and an Atlantic Niña, while CP El Niño events favour westerlies and a concurrent Atlantic Niño. Because of the positive meridional SST gradient, a warmer tropical north Atlantic Ocean can also lead to wetter conditions over the Sahel and a deficit of rain over the Guinea Coast region via a northward displacement of the ITCZ (Nicholson, 2009).

A synthesis of impacts of ENSO types on ocean conditions and weather in the eastern tropical Atlantic is presented in Table 6.16.

TABLE 6.16
Schematic impact of the different types of ENSO on the oceanic and atmospheric ocean properties in the eastern tropical Atlantic.

		ENSO category				
Variable	**Area**	**CP El Niño**	**EP El Niño**	**Extreme El Niño**	**Coastal El Niño**	**Strong La Niña**
Temperature	Tropical North Atlantic					
Temperature	Equatorial Atlantic					

Colour scale:

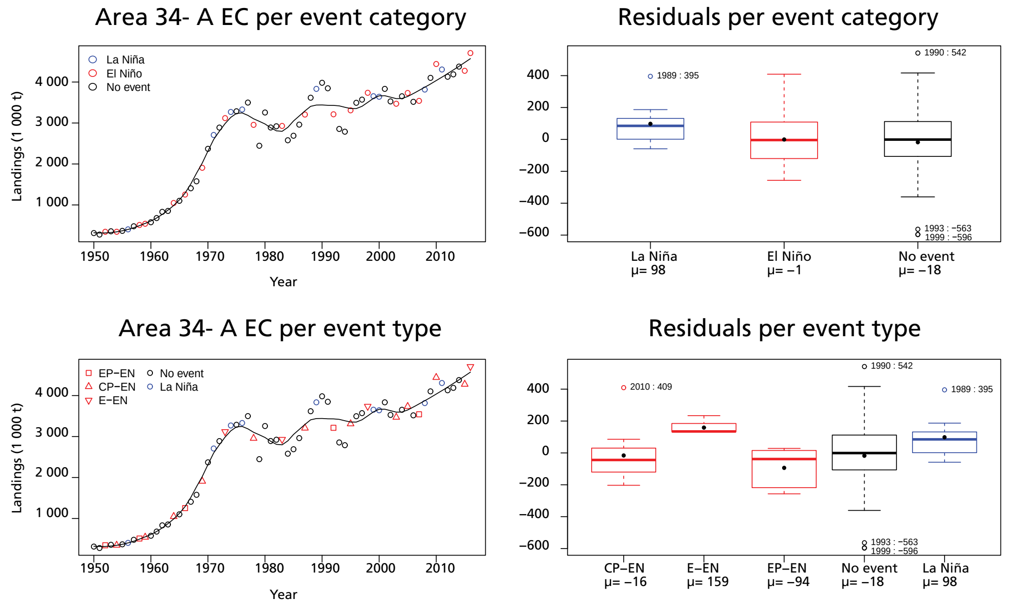
No data	No data
No clear impact	No clear impact
Moderate increase	Moderate decrease
Strong increase	Strong decrease

6.2.5.2 Impacts on capture fisheries

In the eastern central Atlantic Ocean (FAO Major Fishing Area 34), ENSO categories and types have no significant impact on fisheries landings (Figure 6.26). Only extreme El Niño induces a positive anomaly of approximately 160 000 tonnes, and EP El Niño a negative one of approximately 94 000 tonnes.

FIGURE 6.26

Left panels: yearly landings (in 1 000 t) for FAO Major Fishing Area 34 in the eastern central Atlantic Ocean per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel)



Data source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

ENSO effects on the tropical Atlantic may be delayed by several months with respect to those on the Pacific, as the teleconnection between the Pacific and Atlantic affects SST with a delay (Roy and Reason, 2001). Some studies reported an impact of ENSO on fisheries. For instance, the effects on sardine catch of the 1997/98 extreme El Niño and 1998/99 strong La Niña were felt on the West African coast with a delay of several months. In the tropical Atlantic (and Pacific), fisheries and fish stocks are affected by species habitat compression, which in turn is impacted by phenomena such as ENSO that disturb temperatures, oxygen levels, prey distribution, primary production, and other variables (Prince and Goodyear, 2006). The 1987/88 CP El Niño likely had repercussions or a teleconnected phenomenon in the eastern Atlantic, specifically in the form of a north equatorial counter current (aka "Guinea Niño") driving round sardinella (*Sardinella aurita*) offshore and thus making them more difficult to catch, yet improving the catchability of various brackish species such as croakers, soles, catfish, sharks and spiny lobsters (Binet, 2001). In the late 1980s, Gambian coastal waters experienced an apparent abundance shift from bonga shad (*Ethmalosa fimbriata*) to sardinellas (*Sardinella aurita* and *Sardinella maderensis*), which may be a natural interdecadal shift or an ENSO-induced phenomenon (Binet, 2001). However, considering the weak correlation between ENSO and oceanic conditions in the equatorial Atlantic and scarcity of studies relating to ENSO and fish and fisheries, we conclude that there is currently no robust evidence of any impact of ENSO on fish and fisheries of the eastern central Atlantic.

6.2.5.3 Coping strategies

In the absence of any clear impacts of ENSO on fish and fisheries of the eastern central Atlantic, coping strategies are more related to climate change and other extreme events (see Barange *et al*., 2018). The FAO Fishery Committee for the Eastern Central Atlantic carries out stock assessment in the eastern central Atlantic. Most of the commercially important stocks in the region are classified as being fully exploited or overexploited, especially demersal species, with few stocks considered non-fully exploited (FAO, 2011).

Only a few countries implement management plans and regular scientific monitoring of the main fisheries resources. West African fishing countries implement adaptation programmes in the context of their national strategy for fisheries, aquaculture and climate change and these are supported by various national and international projects (Shelton, 2014). Management and adaptation measures in the concerned countries include TACs, fishing licences, closed seasons, minimum mesh and harvest sizes, no-trawl zones, restrictions on foreign fleets, etc.

Key priorities for adaptation, as identified by FAO, include (Kifani *et al*., 2018) improved management planning for fisheries and ecosystem governance to mitigate and prevent further marine ecosystem quality degradation; build or further develop institutional research and management capacities; protect assets and fishing communities against climate change effects (e.g. extreme climate events).

6.2.6 Southeast Atlantic (FAO Major Fishing Area 47)

KEY MESSAGES

- The influence of ENSO on the Benguela upwelling system is not clear. If any influence, strong and long-lasting EP El Niño may intensify the upwelling while CP El Niño may reduce it.
- Fishery landings increase slightly (+100 000 tonnes) during El Niño.
- In the Benguela upwelling ecosystem, El Niño events would increase anchovy catchability, and La Niñas sardine catchability.
- However, there is currently no robust evidence of any impact of ENSO on fish and fisheries of the southeast Atlantic Ocean.

6.2.6.1 Impacts on ocean conditions and climate

The Angola-Benguela front can be defined in terms of thermal gradients and shows seasonal and interannual changes in its location. The Benguela upwelling system has been suggested to be very sensitive to ENSO flavour (Rodrigues *et al*., 2011; Tokinaga, Richter and Kosaka, 2019). While strong and long-lasting EP El Niños lead to equatorial Atlantic easterlies and a cooling of the Benguela upwelling, CP El Niño events induce westerlies and a concurrent warming in this region. The impacts of ENSO events on the southeast Atlantic take place through its impact on the pattern of northeast–southwest SST anomalies known as south Atlantic subtropical dipole mode (Rodrigues, Campos and Haarsma, 2015). ENSO and rainfall patterns in southern Africa have been related, with El Niño corresponding to lower rainfall and drought conditions and La Niña to higher rainfall (Augustyn *et al*., 2018).

A synthesis of impacts of ENSO types on ocean conditions and weather in the southeast Atlantic is presented in Table 6.17.

TABLE 6.17
Schematic impact of the different types of ENSO on the oceanic and atmospheric ocean properties in the southeast Atlantic.

		ENSO category				
Variable	**Area**	**CP El Niño**	**EP El Niño**	**Extreme El Niño**	**Coastal El Niño**	**Strong La Niña**
Temperature/sea level	Benguela upwelling system	Moderate increase	No clear impact	Moderate decrease	No clear impact	No clear impact
Rainfall	Guinea coast	No clear impact	Moderate increase	Moderate increase	No clear impact	Moderate decrease

Colour scale:

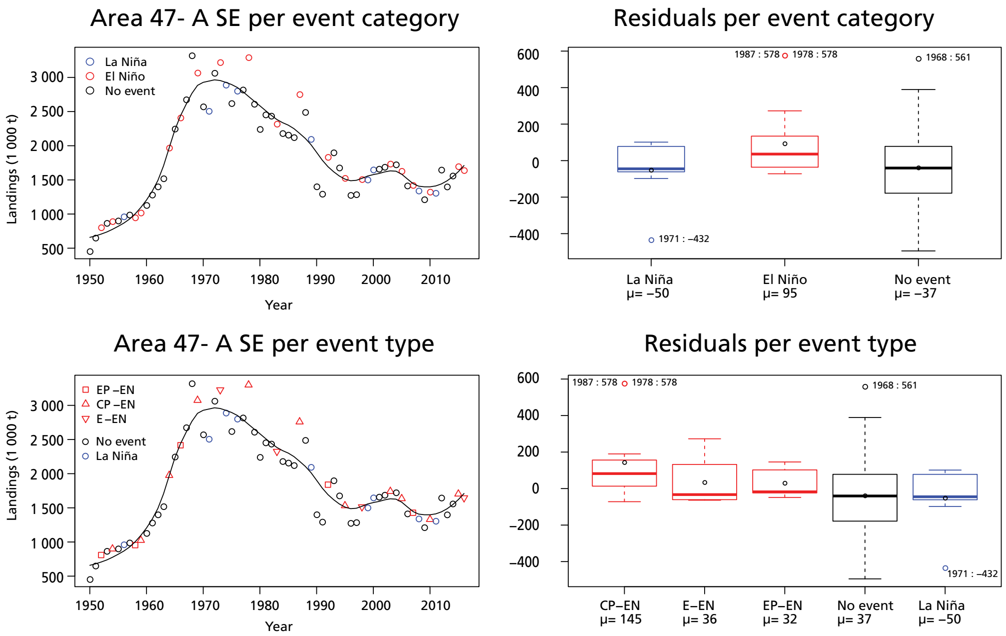
No data	No data
No clear impact	No clear impact
Moderate increase	Moderate decrease
Strong increase	Strong decrease

6.2.6.2 *Impacts on capture fisheries*

In the southeast Atlantic Ocean (FAO Major Fishing Area 47), we observe an average positive anomaly of approximately 100 000 tonnes on fisheries landings during El Niño events. Among ENSO categories the higher positive anomaly occurred during CP El Niños (approximately 145 000 tonnes) while La Niñas correspond to a negative anomaly of approximately 50 000 tonnes (Figure 6.27).

FIGURE 6.27

Left panels: yearly landings (in 1 000 t) for FAO Major Fishing Area 47 in the southeast Atlantic Ocean per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel)



Data source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

In the Benguela upwelling ecosystem (Jury, 2006), anchovy (*Engraulis encrasicolus)* catches tend to increase after El Niño events, while sardine (*Sardinops sagax*) catches improve after La Niña events, with both responses having a delay of several months. However, considering the weak correlation between ENSO and oceanic conditions in the equatorial Atlantic and the scarcity of studies relating to ENSO and fish and fisheries, we conclude that there is currently no robust evidence of any impact of ENSO on fish and fisheries of the southeast Atlantic Ocean.

6.2.6.3 *Coping strategies*

In the absence of a clear impact of ENSO on fish and fisheries of the southeast Atlantic Ocean, coping strategies are more related to climate change and other extreme events (see Barange *et al*., 2018). The Benguela Current Commission, representing Angola, Namibia and South Africa, implemented a five-year (2015–2020) FAO and Global Environment Facility-supported project to enhance climate change resilience by influencing fisheries policies and planning (http://www.fao.org/gef/projects/detail/en/c/1056798/). Proposed (and sometimes adopted) adaptation measures include encouraging diversification, introducing insurance schemes, strengthening harbour defences and using alternative fishing gear to target alternative species (e.g. when sardine abundance is low, the sardine fisheries could target more abundant anchovies by midwater trawling (van der Lingen and Hampton, 2018).

6.3 INDIAN OCEAN

KEY MESSAGES

- El Niño-induced changes in the Walker circulation often lead to a cooling (warming) of the eastern (western) Indian Ocean in autumn preceding its peak (i.e. the Indian Ocean Dipole [IOD]) and a basin-wide warming in spring following its peak (i.e. the Indian Ocean Basin-wide warming).
- Over the Indian Ocean as a whole, fisheries landings are not affected by ENSO whatever the category or type.

6.3.1 Impacts on ocean conditions, climate and extreme events

Ocean conditions and climate

The Pacific Ocean and the Indian Ocean are connected through the atmosphere, via the Walker circulation, and through the ocean via the passages of the Indonesian Archipelago. On the oceanic side, the positive thermocline anomalies in western Pacific during La Niña eventually propagate southward to the north Australian and west Australian coasts, promoting there an anomalous cooling peaking in austral summer, a regional mode often referred to Ningaloo Niño (Feng *et al*., 2013). On the atmospheric side, ENSO-induced changes in the Walker circulation often lead to an SST dipole pattern called the IOD (Saji *et al*., 1999) but the IOD can occur independently of ENSO (Fischer *et al*., 2005). An event usually develops in boreal summer (Figure 5.1a), peaks in autumn (Figure 5.1b) and decays rapidly in the beginning of winter (Figure 5.1c). A positive IOD is characterized by anomalous easterlies at the equator, inducing SST cooling/thermocline shoaling over the southeast equatorial Indian Ocean along the Java and Sumatra coast and an anomalous warming/thermocline deepening in the western Indian Ocean (WIO) (Figure 5.1). This IOD pattern in autumn is then followed by a basin-scale warming named the Indian Ocean Basin (IOB) mode peaking in boreal spring, (Figure 5.1d) about one season after the mature phase of ENSO. IOB-related anomalous easterlies also cause shallow thermocline anomalies off Sumatra, while concurrent deepening of the thermocline develops in the southern Indian Ocean in response to Ekman pumping (Figure 5.1). These ENSO-related IOB signals are, however, delayed by at least a season compared to those of IOD and are less prominent.

Tropical cyclones

Although rarely studied, the relationship between ENSO and TC activity in the southwestern Indian Ocean is important as this region includes vulnerable populated areas and encompasses substantial fishing activity. As summarized in Lin *et al.* (2020), TC activity during El Niño is enhanced in the southwestern Indian Ocean, extending as far west as the East African coast, and decreased in the southwestern part of the basin (Figure 5.4a). An opposite pattern occurs during La Niña events (Figure 5.4b). Above (below) TC activity occurs during La Niña (El Niño) years. This relationship, however, weakened considerably after the late 1990s, because of an increasing influence of local Indian Ocean SST on TC activity (Ramsay, Richman and Leslie, 2017).

Marine heatwaves

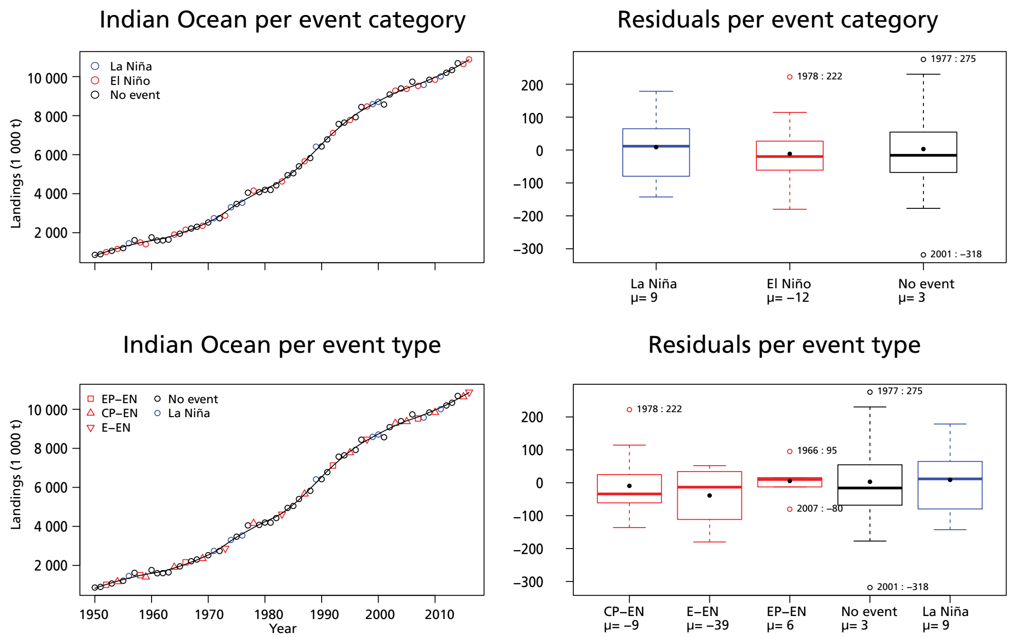
ENSO also modulates the occurrence and frequency of MHWs in the Indian Ocean. While El Niño events favour their occurrence off the tropical northwestern Australian coast (some likely alleviated by co-occurring positive IOD events), La Niña events promote the occurrence of MHWs at the subtropical reefs in the southeast Pacific in association with co-occurring Ningaloo Niño events at this location (Zhang *et al*., 2017). These ENSO-related MHWs have also been observed more frequently in recent decades as a combined result of natural decadal variability and/or global warming (e.g. Zhang *et al.*, 2017). Because of unabated global warming, these extreme events and related coral bleaching events are likely to become more frequent in the near future (Lough, Anderson and Hughes, 2018).

6.3.2 Impacts on capture fisheries

ENSO categories and types have no significant impact on fisheries landings when considering the Indian Ocean (FAO Major Fishing Areas 51, 57 and 58) globally (Figure 6.30).

FIGURE 6.28

Left panels: yearly landings (in 1 000 t) for the Indian Ocean per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel)



Data source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

6.3.3 Western Indian Ocean (FAO Major Fishing Area 51)

KEY MESSAGES

- Positive IODs (partly triggered by El Niño events) induce a thermocline deepening in the WIO.
- TC activity in this region is reduced during both La Niña years and extreme El Niño events, while it increases during neutral years and moderate El Niño events.
- El Niños, especially extreme events, foster the occurrence of MHWs.
- ENSO impact on fishery landings in the region is weak, with on average a reduction of approximately 16 000 tonnes during El Niño. The reduction is higher for extreme (–53 000 tonnes) and CP (–21 000 tonnes) El Niño, but landings increase during EP El Niño (+25 000 tonnes).
- El Niño events in 2016, combined with increased human pressure and local threats, prevented the recovery of coral reefs to their pre-1998 state.

- ENSO events are known to affect tuna fisheries in the Indian Ocean: CPUE of tuna was observed to be negatively correlated to the IOD.

6.3.3.1 Impacts on ocean conditions, climate and extreme events

Impacts on ocean conditions and climate

As discussed above, positive IOD events (partly triggered by El Niño events) induce a thermocline deepening in the WIO, which propagates westwards as symmetrical Rossby wave signals on either side of the equator, from fall until the following spring. This thermocline deepening is generally larger and more persistent in the Southern Hemisphere, where it interacts with the normally shallow Indian Ocean thermocline ridge (Rao and Behera, 2005). This generally results in a reduction of the depth-integrated chlorophyll in this region with negligible surface signals (Currie *et al*., 2013). IOB-related thermocline deepening in the southern Indian Ocean is also weaker and centred further south than the corresponding IOD (Rao and Behera, 2005).

Impacts on tropical cyclones

As mentioned above and seen in Figure 5.4a and b, TC activity in the southwestern Indian Ocean is generally enhanced (reduced) during El Niño (La Niña). A recent study suggests that this relationship is non-linear (Astier, Plu and Claud, 2015): TC activity in this region seems to be reduced during both La Niña years and extreme El Niño events, while it increases during neutral years and moderate El Niño events.

Impact on marine heatwaves

The WIO contains 16 percent of the world's coral reefs. Major coral bleaching events have been observed in several regions of the WIO, especially during the three global coral bleaching events reported in 1998, 2010 and 2016. These regions include the Maldives archipelago, the southwestern Indian Ocean and the Mozambique channel, and the Red Sea. The bleaching events followed El Niño events, during which the Indian Ocean experiences a delayed IOB warming, increasing the MHW-related thermal stress experienced by tropical reefs. These heatwaves are particularly devastating during extreme El Niño events. The El Niño 1997/1998 coupled with global warming, caused a high temperature increase in this region, resulting in intense thermal stress that devastated coral reefs. Many locations suffered coral mortality rates of 50 percent to 90 percent from this event, and the impacts were worse in this region than anywhere in the world. Coral reefs of the WIO crossed a threshold in 1998. The repeated El Niño events in 2016, combined with increased human pressure and local threats, have prevented the recovery of coral reefs to their pre-1998 state. On average, coral cover declined by 25 percent, from 40 percent before 1998 to 30 percent after 1998. Algal cover increased 2.5 times after 1998, from 15 percent before to about 35 percent. Fish community structure is now dominated (about 80 percent of biomass) by small bodied herbivores and detritivores (Obura *et al*., 2017). The third global bleaching event in 2016 impacted the WIO, with 30 percent of reefs showing evidence of high or severe bleaching, but only 10 percent showing high or severe mortality. Seychelles was the worst hit country, followed by Madagascar. Parts of Mauritius, Kenya and the United Republic of Tanzania were also badly impacted, while Comoros showed only slight impact. The threat from all major drivers of coral reef decline has increased and is projected to continue to increase in the coming decades – ocean warming and acidification, fishing pressure, human population growth and development in the coastal zone and expanding global trade (Obura *et al*., 2017).

A synthesis of impacts of ENSO types on ocean conditions and weather in the WIO is presented in Table 6.18.

TABLE 6.18
Schematic impact of the different types of ENSO on the oceanic and atmospheric ocean properties in the WIO.

		ENSO category				
Variable	**Area**	**CP El Niño**	**EP El Niño**	**Extreme El Niño**	**Coastal El Niño**	**Strong La Niña**
Temperature/sea level	WIO					
TCs	WIO					
Marine heatwave						

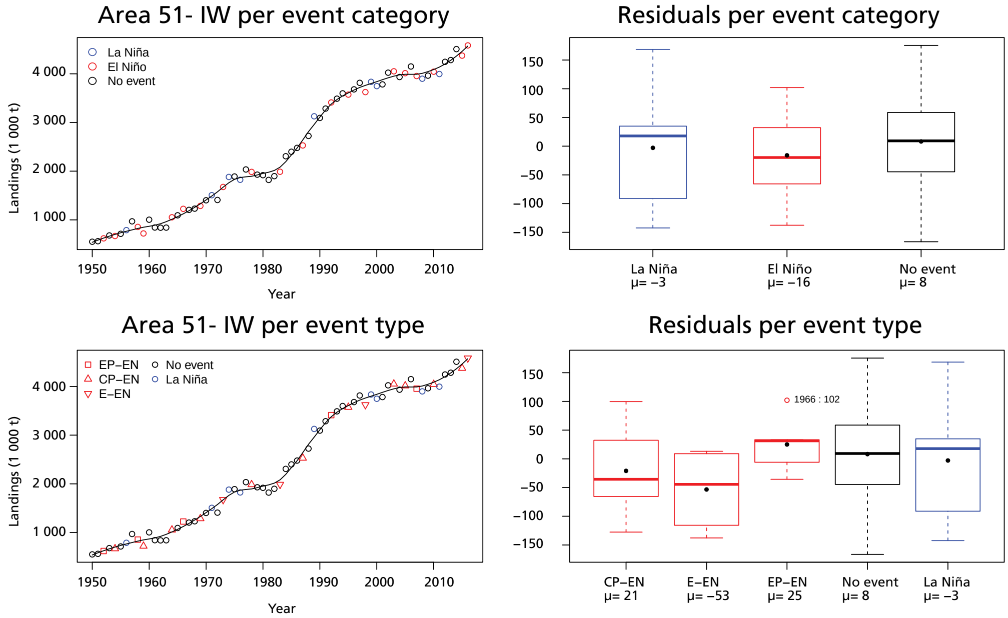
Colour scale:

No data	No data
No clear impact	No clear impact
Moderate increase	Moderate decrease
Strong increase	Strong decrease

6.3.3.2 Impacts on capture fisheries

In the WIO (FAO Major Fishing Area 51) ENSO impacts on fishery landings are weak (Figure 6.29) with on average a negative anomaly of approximately 16 000 tonnes during El Niño. Considering the variety of El Niño the negative effect was stronger for extreme El Niño (–53 000 tonnes) and CP El Niño (–21 000 tonnes) but is positive for EP El Niño (+25 000 tonnes).

FIGURE 6.29
Left panels: yearly landings (in 1 000 t) for FAO Major Fishing Area 51 in the western Indian Ocean per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel)



Data source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

A large number of people live in coastal areas in the WIO and many of them rely on marine resources for food and employment. Indian Ocean SIDS depend heavily on seafood (e.g. industrial tuna fisheries and small-scale coastal fisheries; Moustahfid, Marsac and Gangopadhyay, 2018) which can account for up to 90 percent of their populations' animal protein intake (FAO, 2016). Even in a continental country such as Mozambique, where there are 90 000 fishers, it is estimated that 50 percent of the population's protein intake comes from fish (FAO, 2016). The fisheries sector generates nine percent of the gross marine product in this region (Obura *et al*., 2017). Of this total, 87 percent is from large-scale commercial and industrial or semi-industrial fisheries, of which tuna is the most important source of national revenue (Marsac, 2018). In this region, warming, oxygen depletion, acidification and overfishing have already impacted the resources, and any additional stress can have severe repercussions. This was the case in 1997/98 when warming, coinciding with the extreme El Niño, had a dramatic impact on reef ecosystems, tunas and their associated small-scale and industrial fisheries (Moustahfid, Marsac and Gangopadhyay, 2018).

Impacts on coastal demersal fish and invertebrates

See also Chapter 7. Coral reefs and their surrounding ecosystems, including mangroves and seagrass beds that provide important fish habitat and support coastal fisheries in the WIO region, are already facing unprecedented stress from warming and rising seas, acidification and storms. The high temperature anomalies observed in 1998 had a severe impact on coastal fish: 62 percent of fish species declined in abundance within three years (Moustahfid, Marsac and Gangopadhyay, 2018). Coral mortality is accompanied by declines in coral cover and rugosity that have been causing major changes in the relative abundance of both individual coral genera and parrotfish (Scaridae). Corallivore fish displayed a strong trend towards decreased abundance with the loss of coral, while carnivores showed a range of responses, both positive and negative. Overall, more species showed a reduced abundance than an increased abundance (Pratchett *et al*., 2011). Coral reefs in the WIO seem to have shifted from a pre-1998 state to a post-1998 state, with 25 percent lower coral cover and 2.5 times more algae abundance. For almost two decades, coral and algal covers have been equivalent, which may be an early indication that at the regional scale reefs are approaching a threshold, beyond which they may become dominated by algae, or by other non-hard coral invertebrates. This could be exacerbated by the fish communities also shifting from more complex to simpler trophic webs in which herbivore and detritivore foraging by small fish are dominant processes (Moustahfid, Marsac and Gangopadhyay, 2018; Obura *et al*., 2017). Twenty years after it occurred, coral reefs of the WIO are still recovering from the major El Niño climate event of 1997/98. The repeated El Niño events in 2016 combined with increased human pressure and local threats prevent the recovery of coral reefs to their pre-1998 state. Similar impacts, although apparently less severe, have occurred in mangroves and seagrass beds (Moustahfid, Marsac and Gangopadhyay, 2018; Obura *et al*., 2017). Human populations in WIO states continue to grow, with a concurrent increase in their dependence on food extracted from the ocean. It is difficult to see how the spectre of "too many fishers, too few fish" can be avoided without successful interventions to reduce fishing pressure and mitigate the impacts of coastal development on marine resources (Groeneveld, 2016).

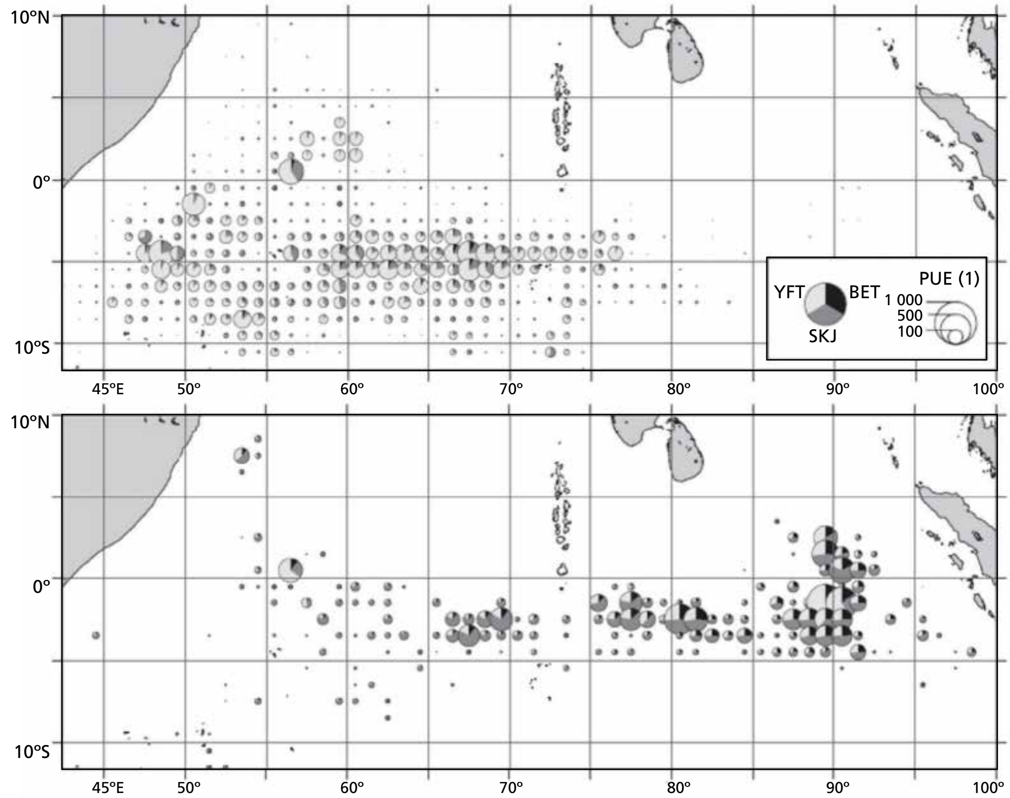
Impacts on tuna fisheries

Variability in the distribution and catch rates of tuna species has been observed in association with the IOD, a basin-scale pattern of surface and subsurface temperature affecting the Indian Ocean climate, and with El Niño events. IOD events may occur in the same years as ENSO – such as occurred in 1998 – or in its absence (Moustahfid, Marsac and Gangopadhyay, 2018). ENSO events are indeed known to affect tuna fisheries in the Indian Ocean. For instance, in the period 1980 to 2010, maximum landings took place during an EP El Niño year (2006), while the lowest occurred during CP El Niño and strong La Niña years (2009 and 1988, respectively) (Kumar, Pillai and Manjusha, 2014).

CPUE of tuna was observed to be negatively correlated to the IOD. During warm positive IOD events, CPUE decreased and catch distributions were restricted to the northern and western margins of the WIO. During cold negative IOD events, tuna CPUE increased, particularly in the Arabian Sea and seas surrounding Madagascar, and catches expanded into central regions of the WIO (Moustahfid, Marsac and Gangopadhyay, 2018). The anomalously high SST during the 1997/98 extreme El Niño, in phase with a positive IOD event, led to a deepening of the mixed layer in the west and a shoaling in the east, coincided with anomalously low primary production in the WIO and a major shift in tuna stocks. Fishing grounds in the WIO were deserted and purse-seine tuna fishing fleets underwent a massive shift toward the eastern basin (Figure 6.30, Figure 6.31), which was unprecedented for the tuna fishery (Moustahfid, Marsac and Gangopadhyay, 2018; Robinson *et al*., 2010). As a result, many countries throughout the Indian Ocean lost significant tuna-related revenue. For example, direct, indirect and induced economic effects of the tuna industry expenditure benefiting the Seychelles' economy declined in 1998 by 58 percent, 26 percent and 35 percent, respectively. This impact was of a comparable scale to the extreme El Niño impacts seen in the Chilean and Peruvian fishmeal fisheries (Robinson *et al*., 2010). A strong surface warming and deepening of the mixed layer also reduced tuna fishing revenue in 2007. However, this period corresponding to positive dipole anomaly cannot be associated to ENSO.

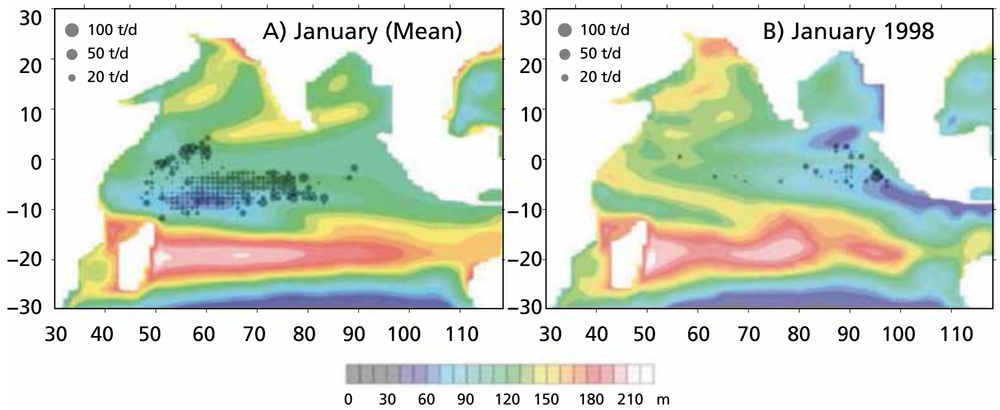
FIGURE 6.30

Average first quarter CPUE of yellowfin tuna (YFT), bigeye tuna (BET) and skipjack tuna (SKJ) for the period 1992 to 2007 (upper panel) and 1998 only (lower panel)



Source: Robinson *et al*., 2010.

FIGURE 6.31
Purse seine CPUE (t/day) associated with free tuna swimming schools in January (circles) and 20 °C isothermal depth (m, colour shaded)



Data sources: purse seine catch and effort data are available freely on the IOTC website (http://www.iotc.org/data/datasets); the 20 °C isothermal depth is calculated by interpolation between consecutive depth levels from the Global Ocean Data Assimilation System (GODAS) model outputs of the National Centers for Environmental Prediction (NCEP) (http://www.cpc.noaa.gov/products/GODAS/). A) Climatological 20 °C isothermal depth in January (1980 to 2005) and average CPUE for 1991 to 2002. Fishing days: 970. CPUE: 8.5 t/day; B) 20 °C isothermal depth and CPUE in January 1998. Fishing days: 1 260. CPUE: 2.0 t/day; C) 20 °C isothermal depth and CPUE in January 2007. Fishing days: 1 367. CPUE: 2.8 t/day.

6.3.3.3 Impacts on fish and fisheries: synthesis

Table 6.19 synthesizes the effects of different ENSO types on the ecology of fisheries resources in the WIO.

TABLE 6.19
Schematic impact of the different categories of ENSO on the ecology (biomass, population structure and biology) of fisheries resources in the WIO.

			ENSO Category				
Taxonomic group	**Species**	**Area**	**Central Pacific El Niño**	**Eastern Pacific El Niño**	**Extreme El Niño**	**Coastal El Niño**	**Strong La Niña**
Demersal	Corallivore reef fishes	WIO					
Pelagic	Tunas	WIO					

Colour scale:

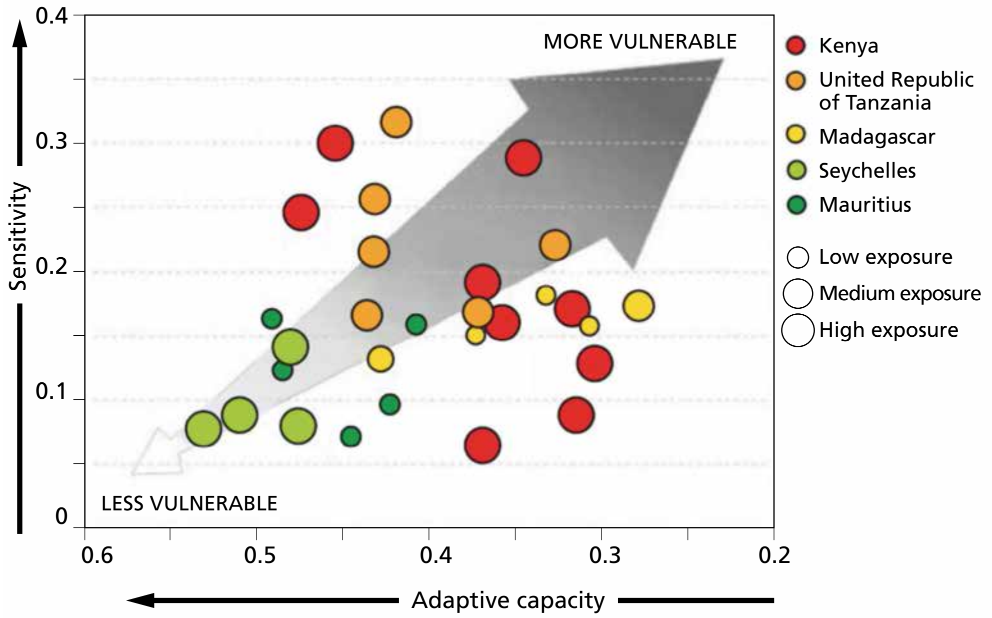
No data	No data
No clear impact	No clear impact
Weak positive impact	Weak negative impact
Moderate positive impact	Moderate negative impact
Strong positive impact	Strong negative impact

6.3.3.4 Coping strategies

For SSF see also Chapter 7. By applying the framework of exposure, sensitivity and adaptive capacity, Cinner *et al.* (2012) classified the vulnerability of 29 WIO coastal communities to the impact of coral bleaching on the coral reef fisheries that supply livelihoods for millions of people (Figure 6.32). Kenya had the highest overall vulnerability, followed by the United Republic of Tanzania, Madagascar, Seychelles and Mauritius. On this basis, they proposed a series of key policy actions at a variety of spatial and temporal scales (Table 6.20).

FIGURE 6.32

Plot of the vulnerability of coastal communities to the impacts of coral bleaching on fisheries



Adaptive capacity (x-axis; note values reversed so high adaptive capacity is on the left) is plotted against sensitivity (y-axis,) such that more vulnerable communities are in the top right of the graph and less vulnerable communities in the bottom left. These two dimensions of vulnerability can be modified by policy and development. The third dimension of vulnerability, exposure, is represented as the size of the bubble (larger = more exposure). To aid in visualization, exposure values were represented as the lowest, middle and highest third rather than scaled to actual site values. Colours represent a gradient of vulnerability based on the country's mean vulnerability score from least vulnerable (green) to most vulnerable (red): dark green = Mauritius; light green = Seychelles; yellow = Madagascar; Orange = United Republic of Tanzania, Red = Kenya.

Source: adapted from Cinner *et al*., 2012.

TABLE 6.20
Examples of key policy actions to reduce aspects of vulnerability at different spatial and temporal scales.

Scale	Short-term	Medium-term	Long-term
International	• Mobilization of relief funds (c)	• Mobilization of funding to invest in infrastructure (a) • Regional conservation planning (a,b,c) • Adaptation investments	• Climate change mitigation (c) • Mobilization of funding to invest in governance (a)
National	• Relief planning & coordination (c) • Social safety nets (a,c) • Flexible regulations that allow for rapid transitions during extreme events (a,b)	• Management measures to make reef ecosystems more resilient (b) • Investment in coastal infrastructure (a) • Investments in information networks and early warning systems (a) • Planned migration (a,c) • Adaptation planning (a,b,c)	• Investment in alternative energy (c) • Carbon trading policies (c) • Developing new industries (b) • Investments in education & literacy (a) • Improving governance (a)
Local	• Evacuations from most vulnerable sites (c) • Diversification within the fishery (b) • Improved information & market terms (a) • Adaptive management approaches (e.g. temporarily imposing or removing fisheries closures) (a,b)	• Supplemental livelihood activities (increase linkages to other economic sectors) (b) • Strengthen community groups, social networks & vertical linkages (a) • Improvements in coastal infrastructure (a) • Migration to non-coastal areas (b,c)	• Alternative livelihoods (transition out of fishing) (b) • Enhance capacities and health status of fishing communities (a) • Poverty reduction (a) • Developing forums to maintain & support ecological knowledge (a) • Investments in strong local governance institutions (a)

(a) Interventions to enhance adaptive capacity; (b) interventions to ameliorate sensitivity; (c) interventions to lower exposure.

Source: Cinner *et al*., 2012.

The WIO island states are also highly exposed to adverse natural events. Risk analysis by the World Bank (2017) in south WIO island states (Comoros, Madagascar, Mauritius, Seychelles and Zanzibar) revealed that TCs and extreme non-TC rainfall are the main drivers of disaster risk. This analysis also shows an increasing trend in the frequency and intensity of extreme weather-related events across the entire south WIO region, and the exacerbating effects of climate variability and change pose additional challenges to the financial and fiscal sustainability of the region's governments. Development of a regional framework for natural disaster risk financing, as well as comprehensive national disaster risk financing and insurance strategies could help protect the countries' development and social gains.

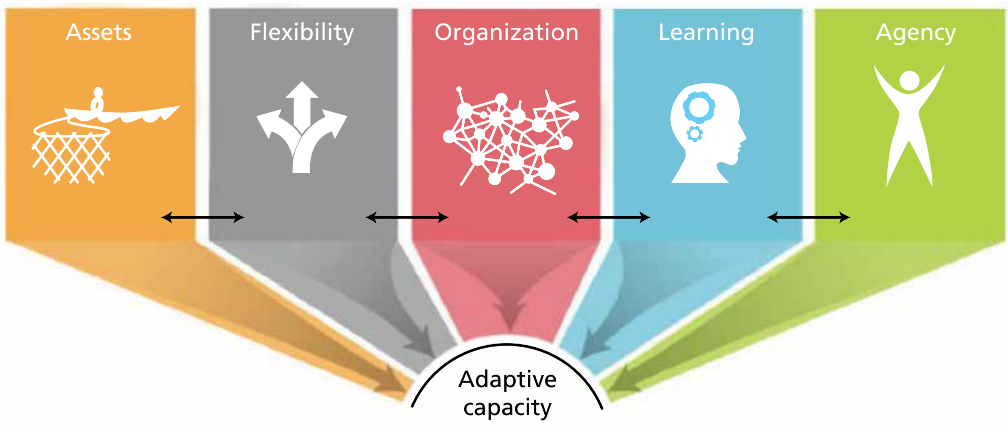
For large pelagic fish, another major spatial shift of the tuna fishing fleets, similar to the one that was observed during the 1997/98 El Niño event in the WIO, would have a devastating impact on SIDS that have developed economies that are strongly dependent on tuna fisheries (Moustahfid, Marsac and Gangopadhyay, 2018). In warm conditions, large pelagic fish change their movement patterns and may dwell in deeper layers, thus making surface gears less efficient. Such ecological changes force the pelagic fleets to redeploy to other areas and to adapt their fishing techniques, which is manageable for the wealthy fishing companies. By contrast, locally-operated artisanal or semi-industrial fishing fleets could be severely affected unless they can innovate and adapt their gears to the changing habitat conditions (e.g. by fishing deeper). However, opportunities could be created to mitigate such negative economic impacts in a warmer climate. For instance, the strategy could be to target deep-dwelling tunas (large yellowfin, bigeye and albacore) in the Seychelles EEZ and beyond, with the locally-operated semi-industrial longline fleet (Moustahfid, Marsac and Gangopadhyay, 2018).

Overall Cinner *et al*., (2018) highlighted five key measures to build adaptive capacity to climate change and thus to extreme events in tropical coastal communities. These include (Figure 6.33):

- Ensuring that people have the assets to draw upon in times of need.
- Providing the flexibility to change. Having some flexibility can enable people to minimize losses or even take advantage of climate-related change. For example, fishers might need to change fishing grounds or target new species.
- Learning about climate change and adaptation options. People need to learn about new techniques and strategies that can help them cope with changing circumstances.
- Investing in social relationships. The formal and informal relationships that people have with each other and their communities can help them deal with change by providing social support and access to both knowledge and resources.
- Empowering people to have a say in what happens to them, ensuring the ability to determine what is right for them.

FIGURE 6.33

Five domains of adaptive capacity to climate change: assets, flexibility, social organization, learning and agency. The five domains are interlinked; feedbacks and interactions can occur between any of the domains, not just the neighbouring ones graphically represented by connecting arrows



Source: adapted from Cinner *et al*., 2018.

6.3.4 Eastern Indian Ocean (FAO Major Fishing Area 57)

KEY MESSAGES

- An equatorial easterly anomaly induced by IOD (partly triggered by ENSO) induces an equatorial Kelvin wave and generates upwelling and SST cooling in the equatorial eastern Indian Ocean.
- La Niña promotes an anomalous warming and thermocline deepening along the north and west coast of Australia, known as Ningaloo Niño.

- La Niña events generally promote increased TC activity along the west coast of Australia.
- While La Niña favours MHWs along the subtropical coast of west Australia, El Niño favours them along the northwest coast.
- Only a weak positive landings anomaly takes place during extreme El Niño years.
- In western Australia the recruitment of targeted tropical fish species depends on ENSO, with La Niña conditions associated with higher recruitment.

6.3.4.1 Impacts on ocean conditions and climate

As discussed before, positive and negative IOD events usually co-occurred with El Niño and La Niña events, respectively. This relationship has been suggested to be modulated by El Niño flavour (Zhang *et al.*, 2017). The magnitude of EP El Niño is strongly related to the co-occurring IOD magnitude while the occurrence of IOD events during CP El Niño strongly depends on the location of the El Niño maximum warming. Indeed, a warming located too far west prevents the development of an IOD.

In the eastern Indian Ocean, equatorial easterly anomaly induced by IOD events (partly triggered by ENSO) induce an equatorial Kelvin wave and generate upwelling and SST cooling. A westward-propagating upwelling Rossby wave is reflected offshore on either side of the equator, as illustrated by the two negative thermocline lobes (Figure 5.1). In addition to these near equatorial signals, the IOD-related thermocline shoaling in the equatorial eastern Indian Ocean propagates counter-clockwise as a coastal trapped Kelvin wave around the rim of the Bay of Bengal (BoB). The IOD-induced thermocline variations are further responsible for a chlorophyll increase in the equatorial eastern Indian Ocean in fall and southern BoB in winter and a chlorophyll decrease around the southern tip of India in fall (Currie *et al.*, 2013).

The oceanic connection existing between the Pacific and the Indian Ocean between the Indonesian straights allows thermocline anomalies observed in the western Pacific during ENSO events to propagate southward to the north Australian and west Australian coasts, promoting there an anomalous warming peaking in austral summer during La Niña – a regional mode often referred to as Ningaloo Niño (Feng *et al.*, 2013).

Impact on tropical cyclones

La Niña events are generally associated with increased TC activity along the west coast of Australia, and TC activity decreases during El Niño events. However, this relationship has weakened considerably since the late 1990s, because of an increasing influence of local Indian Ocean SST on TC activity (Ramsay, Richman and Leslie, 2017).

Although the northern Indian Ocean does not experience as many TCs as the other basins, the four TCs that occur each year in this basin can be devastating for southern Asian countries, including India, Bangladesh, Pakistan, Myanmar and Oman. For instance, in 2008 TC Nargis claimed over 130 000 lives in Myanmar (McPhaden *et al.*, 2009). TC formation in this region displays a double peak, peaking before (May–June) and after (October–December) the monsoon. Most TCs form in the BoB. ENSO affects TCs in the northern Indian Ocean mainly during the post-monsoon season. During an El Niño year, fewer intense TCs are observed in the BoB (Ng and Chan, 2012).

Impact on marine heatwaves

The occurrence of Ningaloo Niño in conjunction with La Niña events has resulted in major MHWs along the subtropical coast of west Australia over past decades, as in 2010 to 2011 which resulted in a massive coral bleaching event and the mortality of economically-important fish species (Wernberg *et al.*, 2013). The negative phase of the Interdecadal Pacific Oscillation since the late 1990s has also contributed towards the increased frequency of MHWs in this region (Feng *et al.*, 2015).

Such heatwaves have also occurred further north, including the equatorial eastern Indian Ocean, over the Maritime Continent, as well as along the tropical coast of northwest Australia, leading to massive coral beaching (Zhang *et al*., 2017), such as seen in early 2016. These events generally occur during or after the peak of strong El Niño events in response to reduced cloud coverage and Australian monsoon weakening (Benthuysen *et al*., 2018).

A synthesis of impacts of ENSO types on ocean conditions and weather in the eastern Indian Ocean is presented in Table 6.21.

TABLE 6.21

Schematic impact of the different types of ENSO on the oceanic and atmospheric ocean properties in the eastern Indian Ocean.

		ENSO category				
Variable	**Area**	**CP El Niño**	**EP El Niño**	**Extreme El Niño**	**Coastal El Niño**	**Strong La Niña**
Temperature/ sea level	Sumatra/Java coast	Moderate decrease	Moderate decrease	Strong decrease	No clear impact	Moderate increase
TCs	West Australia	Moderate decrease	Moderate decrease	Moderate decrease	No clear impact	Moderate increase
Marine heatwave	Southwest Australia	No clear impact	No clear impact	No clear impact	No clear impact	Strong increase
Marine heatwave	Northwest Australia	No clear impact	No clear impact	Strong increase	No clear impact	No clear impact
TCs	BoB	Moderate decrease	Moderate decrease	Moderate decrease	No clear impact	Moderate increase

Colour scale:

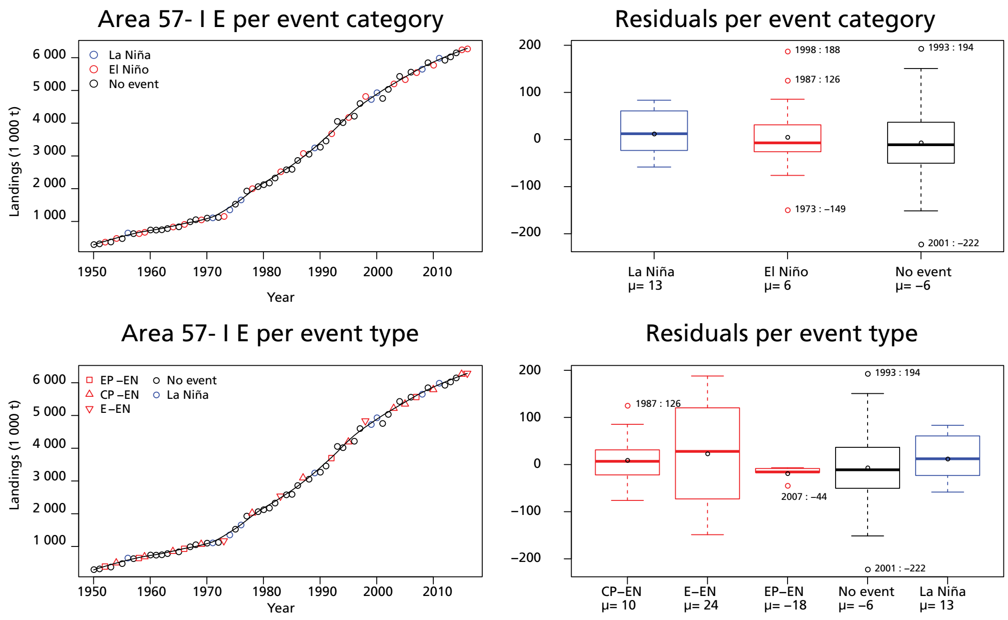
No data	No data
No clear impact	No clear impact
Moderate increase	Moderate decrease
Strong increase	Strong decrease

6.3.4.2 Impacts on capture fisheries

ENSO categories and types have no significant impact on fisheries landings when considering the eastern Indian Ocean (FAO Major Fishing Area 57) (Figure 6.34). Only a weak positive anomaly of approximately 24 000 tonnes takes place during extreme El Niño years.

FIGURE 6.34

Left panels: yearly landings (in 1 000 t) for FAO Major Fishing Area 57 in the eastern Indian Ocean per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel)



Data source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

In western Australia the recruitment of tropical fish species (emperor, *Lethrinus spp*.) targeted by fishers depends on ENSO, with La Niña conditions associated with higher recruitment. The mechanism behind high recruitment during La Niña years is unclear. A stronger southerly flow of the Leeuwin Current in La Niña years could increase the supply of larval fish from the northern reefs of western Australia. Furthermore, warmer waters during La Niña years may increase reproductive output of adult fish and/or survival of larvae in the plankton, which could also increase supply of recruits. Conversely, primary production in the offshore waters is lower during La Niña years, suggesting there is less food available for pelagic fish larvae and that high recruitment in these years is not related to oceanic productivity.

However, local rates of recruitment were generally poor predictors of older juvenile abundance. Instead, local juvenile abundance was more closely related to structural characteristics of macroalgae nursery habitat quality (density, canopy height, canopy cover) and/or predator biomass. The relationship between macroalgal structure and ENSO along the west coast of Australia is unclear and further examination of the causes of increased recruitment is required (Wilson *et al*., 2017).

Given the dynamic nature of fish recruitment supply to the SOI, coupled with the effects of climatic and oceanic processes on the structure of macroalgal patches, protection of macroalgal nursery habitats that maintain high canopy density, height and cover is critical to supporting the conservation of fish populations (Wilson *et al*., 2017).

6.3.4.3 Coping strategies

The Southern Indian Ocean Fisheries Agreement (SIOFA), which includes several countries in or fishing in the eastern Indian Ocean (Australia, European Union, Japan, Democratic People's Republic of Korea, Republic of Korea, Thailand, Madagascar, etc.), promotes an ecosystem approach to fisheries management in the fishing area (http://www.agriculture.gov.au/fisheries/international/siofa).

The Indian Ocean Tuna Commission (IOTC), the regional organization responsible for the management of tuna and other large pelagic fisheries in the Indian Ocean, encompasses 32 members, including Indian Ocean coastal states and distant fishing nations (European Union, Japan, Republic of Korea and China). The IOTC has the difficult task of establishing fishing quotas for member states, largely because of bipartisan disagreements between coastal states and distant fishing nations. No harvest controls are enforced, except for skipjack tuna, and thus the IOTC management measures have been deemed to be weak (Lecompte *et al*., 2017).

7 Coral bleaching and damage to reefs and related fisheries

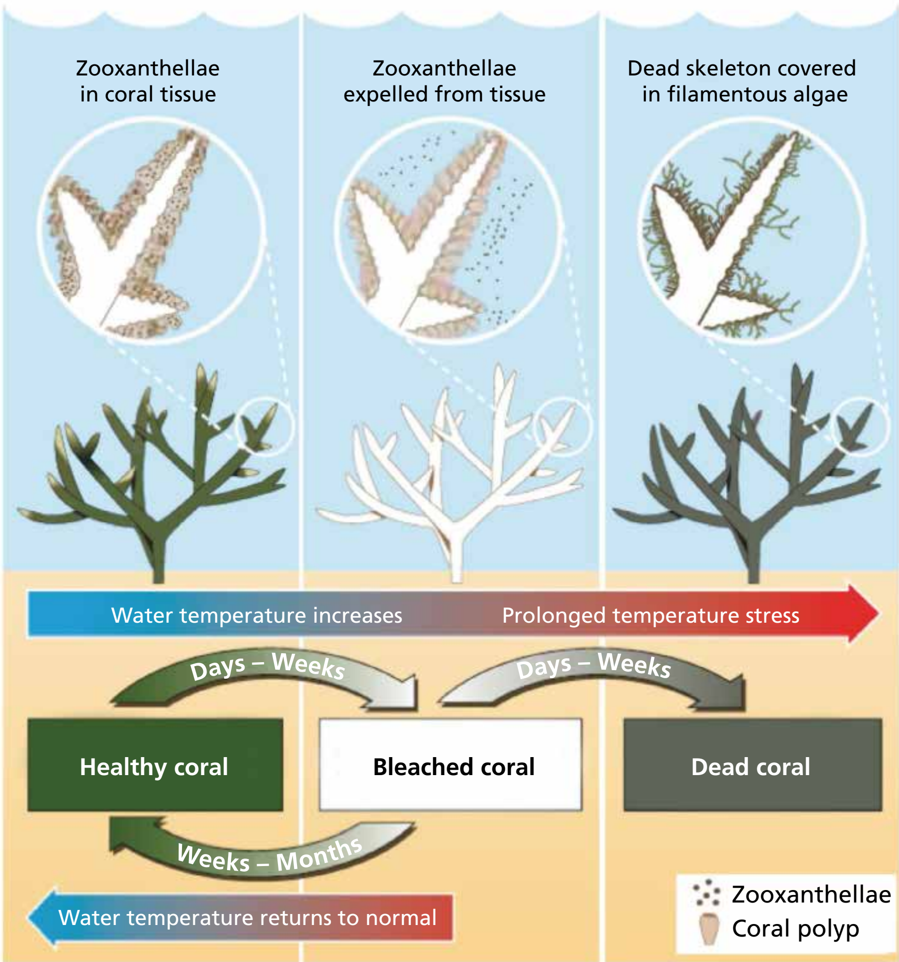
KEY MESSAGES

- Elevated sea temperatures associated with El Niño events cause bleaching, which reduces coral growth or increases coral mortality: in recent years ENSO activity has devastated many tropical reefs.
- The third global bleaching event in 2016 impacted the WIO, with 30 percent of reefs showing evidence of high or severe bleaching, but only 10 percent showing high or severe mortality.
- In addition to direct or indirect effects of ENSO on reef fishes, positive correlations have been observed between the annual incidence of ciguatera fish poisoning and local increases in SST in PICTs that experience warming during El Niño conditions.
- The repetition of strong El Niño events in a warmer ocean and the resultant loss of productive habitat will likely result in diminished fish catches for coastal communities and reduced protection from storms and rising seas, putting coastal communities in peril.

7.1 IMPACT ON CORAL REEFS

Millions of people depend on coral reefs for their income and livelihoods. Coral reefs are particularly important for fisheries, tourism and coastal protection (Cinner *et al.*, 2012). High sea temperatures associated with El Niño events cause bleaching, which reduces coral growth or kills corals outright (Figure 7.1).

FIGURE 7.1
Stages in mass coral bleaching

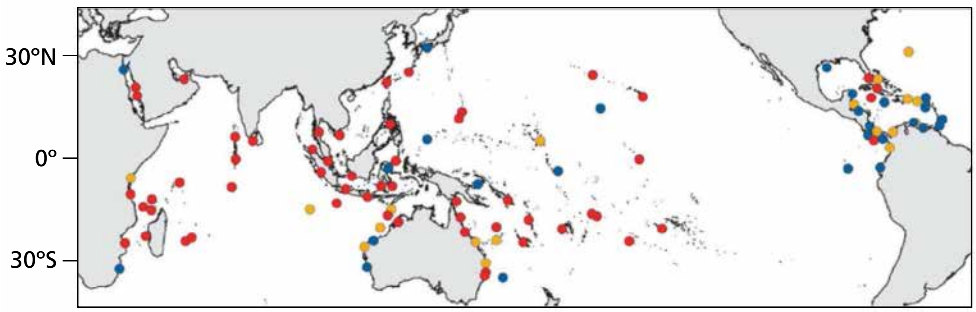


During mass coral bleaching, water temperature increases above a critical threshold, typically over a large area. Under these stressful conditions, corals begin to lose their zooxanthellae, eventually appearing "bleached". At this stage, the bleached corals are still living and, if stressful conditions subside soon enough, they can regain their zooxanthellae. In this case, corals can survive, but are likely to suffer sub-lethal impacts, such as reduced rates of growth and reproduction and increased susceptibility to diseases. However, should temperature stress continue, corals are likely to die. Where mass coral bleaching causes high levels of coral mortality, these ecosystems typically take years to decades to recover.

Source: Marshall, Schuttenberg and West, 2006.

Coral cores show that reef ecosystems in the tropical eastern Pacific collapsed for 2 500 years during a period that began 4 000 years ago (Toth *et al.*, 2012). This collapse was associated with increased ENSO variability and its coupling with the ITCZ. In recent years, ENSO activity has again devastated many tropical reefs. Enhanced ENSO-like conditions in a warming world could once again put Pacific reefs at risk of collapse (Toth *et al.*, 2012). The 1997/98 extreme El Niño caused bleaching worldwide, resulting in 16 percent of corals being destroyed globally. The 2015/16 bleaching event affected 75 percent of 100 globally distributed study sites (Figure 7.2). Due to global warming, SSTs are higher, and in some reef areas outside of the equatorial Pacific, this has resulted in warmer temperatures during present-day La Niña conditions than during El Niño events in previous decades (Hughes *et al.*, 2018). Consequently, coral bleaching is occurring more frequently in all ENSO phases, increasing the likelihood of annual bleaching in the coming decades. Climate change will continue to increase the number of extreme heating events on coral reefs and further drive down the return times between them (Hughes *et al*., 2018).

FIGURE 7.2
The global extent of mass bleaching of corals in 2015 and 2016

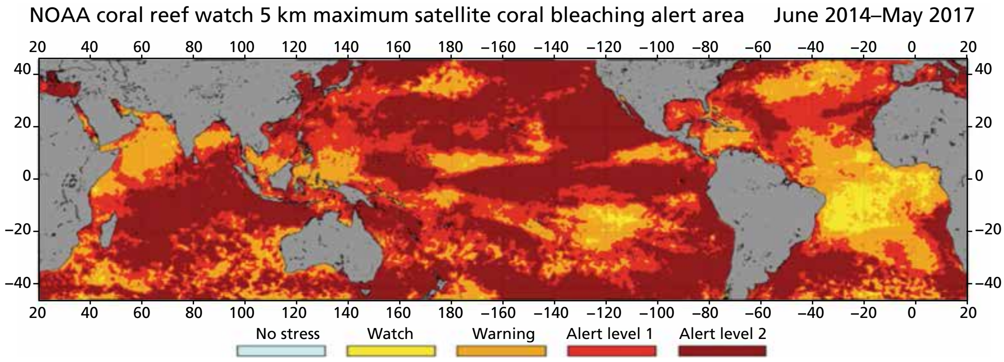


Symbols show 100 reef locations that were assessed: red circles, severe bleaching affecting >30 percent of corals; orange circles, moderate bleaching affecting <30 percent of corals; and blue circles, no substantial bleaching recorded.

Source: Hughes *et al*., 2018.

Regions from the NOAA Coral Reef Watch's satellite Coral Bleaching Alert Area that experienced high heat stress that can cause coral bleaching between 1 June 2014 and 31 May 2017 are shown in Figure 7.3. Alert Level 2 heat stress indicates widespread coral bleaching and significant mortality. Alert Level 1 heat stress indicates significant coral bleaching. Lower levels of stress may have caused some bleaching as well. More than 70 percent of coral reefs around the world experienced a heat stress that can cause bleaching and/or mortality during the three-year long global event. The combination of global warming signals and the intense 2015/16 El Niño probably resulted in a prolonged exposure of reef building corals to warm waters. In October 2015, El Niño affected SSTs and prolonged the mass coral bleaching event (Figure 7.3). The increase in the degree of heating weeks poses a huge problem and leads to a decline in coral reef health. One stressor potentially inhibiting coral recovery from the 2015/16 El Niño is climate change raising the baseline of SST – after an El Niño it is more difficult for corals to recover in the warmer ocean (Kelman, 2017).

FIGURE 7.3
Regions that experienced high heat stress that can cause coral bleaching, from 1 June 2014 to 31 May 2017



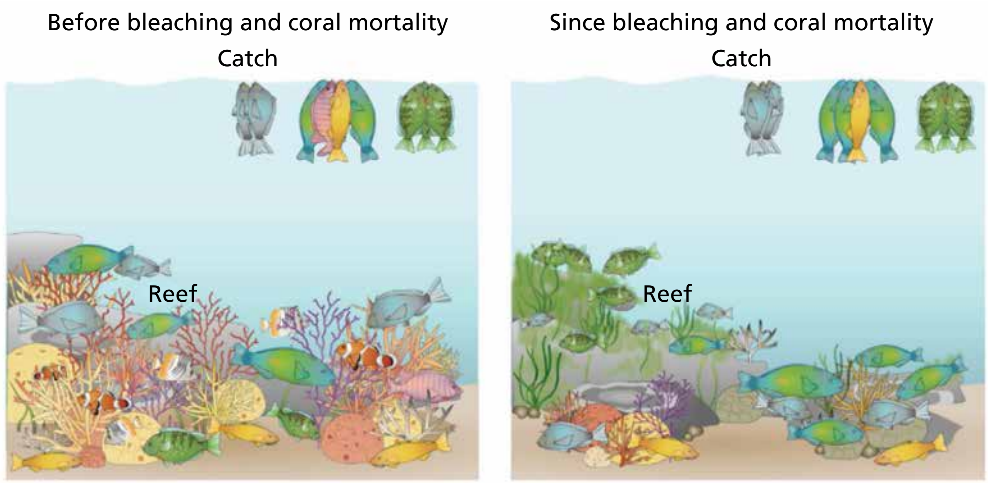
Source: NOAA coral reef watch's satellite coral bleaching alert area.

7.2 IMPACT ON REEF FISH AND FISHERIES

Most research indicates that a loss of coral cover, and subsequent decline in the architectural complexity of coral reefs, negatively impacts many reef organisms and the functions that reefs provide. Degraded coral reefs support less biodiversity, less fish biomass, shorter food chains and lower overall fisheries productivity (Rogers, 2019). Local abundance of herbivorous fish can increase immediately after extensive coral bleaching, possibly due to the greater abundance of algae caused by coral loss. However, over longer time frames, reef-associated fish are expected to be less abundant in habitats with low coral cover due to declines in the structural complexity of reefs (Dunstan *et al*., 2018; Pratchett *et al*., 2011). Temperature-associated coral mortality events such as El Niño are pulse disturbances. However, associated impacts on reef fisheries and the livelihoods of communities that depend on them, can take years to decades. This is due to two processes. First, a reduction in small size classes of reef fishery species typically occurs when the reef structural complexity of dead corals erodes, which arises several years after coral mortality. Second, the loss of smaller cohorts of target reef species takes time to lead to a collapse of associated adult stocks (Cinner *et al*., 2012; Pratchett *et al*., 2011).

Despite widespread mortality of coral reefs in the Seychelles following thermal stress in 1998, trap fisheries in this region have maintained or even increased their catches over the past 20 years. This is because many reefs have shifted into an alternative state dominated by macroalgae rather than living corals (Figure 7.4). Some climate change winners, such as rabbitfish of the siganid family or herbivorous parrotfish of the scarid family, consume reef macroalgae or surface-dead coral, and have increased in numbers on phase-shifted reefs to exploit the newly abundant food source. Both rabbitfish and parrotfish have relatively high turnover rates, and are valued food fish in the Seychelles trap fishery. However, catch instability has increased in recent years i.e. the variation and unpredictability in catches increased both in space and time, which puts subsistence fishers at risk. This increased variability is a consequence of a more heterogeneous reefscape. The reefscape now consists of patches of recovering, shifted and healthy reefs, and target fish are not uniformly associated with each reef type. One day of fishing on a shifted reef might yield a large catch of schooling rabbitfish, but another day might not target such a reef, or might miss the wandering school. More worryingly, once macroalgal cover exceeds a threshold of about 70 percent, even rabbitfish populations decline. Fisheries independent data show that all target groups decline under the extremes of reef degradation. Facing this bleak future, the continued productivity of the Seychelles fishery will largely depend on the continued availability of relatively healthy, recovering reef patches. Seascapes of the future, dominated by low complexity, macroalgal covered reefs, may mean that food security in the tropics will be increasingly dependent on specific species, such as the rabbitfish (Rogers, 2019).

FIGURE 7.4
Different reefscapes, similar catch



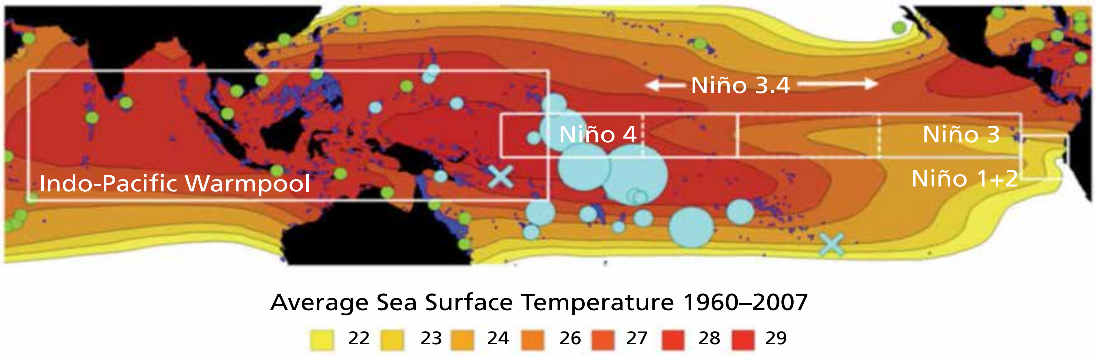
Healthy (left) and degraded (right) reefs may support similar levels of fisheries catch. In a healthy reefscape pre-bleaching, there is high biodiversity and target families of the fishery are all present, although perhaps sparsely and uniformly distributed. By contrast, in the fragmented reefscape of the present day, post-bleaching, some diversity has been lost but most fisheries targets persist. Their distribution, however, has changed, with some fish favouring recovering reefs, others favouring shifted reefs and some still dependent on persisting patches of healthy reefs.

Source: Rogers, 2019.

In addition to the direct or indirect effect of ENSO on reef fishes, positive correlations have been observed between the annual incidence of fish poisoning (ciguatera) and local increases in SST in PICTs that experience warming during El Niño conditions. Ciguatera fish poisoning (CFP) is the most common non-bacterial illness associated with fish consumption, affecting 50 000 to 200 000 people annually. It has been known for centuries in regions where people eat fish associated with coral reef environments. The ciguatera toxin is produced by benthic dinoflagellate plankton in the genus *Gambierdiscus*, which lives on dead coral surfaces and bottom dwelling algae. The toxin accumulates in tissues of fish that eat the algae and bio-accumulates up the food chain. Consequently, the toxins may be found at highest concentrations in large or old carnivorous fish. Humans eating contaminated fish are susceptible to the toxidrome, which includes gastrointestinal upset followed by neurologic symptoms including paresthesias and hot–cold reversal. CFP prevalence in tropical areas is affected by ENSO and warm SST conditions (Gingold, Strickland and Hess, 2014; Pratchett *et al*., 2011). Tropical storms and TCs have a significant effect on CFP with an 18 month delay (Gingold, Strickland and Hess, 2014). Since ENSO increases storm strength and frequency in many regions (see section 5.1), additionally to direct impact on SST, ENSO can increase CFP as a consequence of the storms.

The disturbances to reefs that can promote ciguatera include rises in SST (Figure 7.5). However, CFP does not occur throughout the tropical Pacific, for example, it has not been observed in much of Solomon Islands, or in Pitcairn (Pratchett *et al*., 2011). SST needs to exceed a given lower threshold for long enough to generate enough toxin in the ecosystem for ciguatera and to be widely observed in a human population. However, if SST exceeds an upper limit for long enough, occurrence of ciguatera decreases (Llewellyn, 2010). Thus, increases in SST may have both a positive and negative effect on CFP case rates and thus food security. The zone in which ciguatera is prevalent may therefore move poleward in association with climate change and El Niño events (Pratchett *et al*., 2011).

FIGURE 7.5
Distribution of ciguatera and ciguateric fish relative to average sea surface temperatures for the period 1960–2007 from the HadISST dataset



Light blue circles depict annual case rates of fish poisoning from the SPEHIS dataset (1988–1996) with circle size indicating the case rate as per the legend to the right. The two light blue crosses indicate the Solomon Islands and Pitcairn where zero cases of ciguatera were recorded in the SPEHIS dataset. Small green circles indicate reported locations of ciguatera or capture of ciguateric fish from the primary scientific literature, as well as quality testing reports for various major fish markets (e.g. Japan, China Hong Kong SAR). Blue dots locate coral reefs obtained from the Worldfish Center Reefbase (www.reefbase.org). The geographic extent for the El Niño and Indo-Pacific warm pool indices are also represented.

Source: Llewellyn, 2010.

7.3 COPING STRATEGIES

The increased occurrence of strong El Niño events in a warmer ocean and the resultant loss of productive habitat will likely result in diminished fish catches for coastal communities and reduced protection from storms and rising seas, putting coastal communities in peril. This will reduce the adaptive capacity and resilience of communities to cope with varied natural, social and economic challenges (Moustahfid, Marsac and Gangopadhyay, 2018). Collectively these impacts can lead to a socio-ecological trap, from which resource users may not be able to escape without significant assistance and better stewardship of their resources (Cinner, 2012). Strong leadership from local to national levels would help mitigate the impact of climate change and adapt to projected climate change (Moustahfid, Marsac and Gangopadhyay, 2018).

In their synthesis, Obura *et al.* (2017) recommended that actions and interventions should focus on building the resilience and recovery ability of coral reefs, as well as of management systems to protect coral reefs:

- Improve the management of protected areas, fishery grounds and other use areas to minimize and even eliminate impacts to critical habitats. Local, national and regional connectivity and integration of protected areas and management principles should be a priority.
- Improve the scope and coverage of area-based management tools, including monitoring, habitat maps, economic valuations, and others.
- Promote the full range of management models (regimes), including government-run, co-managed and privately-managed areas. Ensure staffing is at appropriate levels, with training programmes to build capacity and cope with staff turnover.
- Manage fisheries to maintain taxon and functional group diversity, and limit selective impacts to key trophic groups (secondary consumers/predators as well as herbivores). No-take areas are necessary to maintain fish community structure in key areas, but effective fisheries management may be sufficient in broader areas to maintain the ecological functions of fish.
- Manage and reduce bottom-up factors that promote algal growth, including sewage from coastal towns and tourism areas, river discharge of sediments and nutrients, and surface runoff. Land-use change and waste management on land are the primary mechanisms for effecting these changes, so reef management should be fully integrated with land-based management measures.

8 ENSO and aquaculture

KEY MESSAGES

- Aquaculture is currently the principal source of fish and seafood for human consumption, with global production first surpassing that of capture fisheries in 2014.
- Production occurs in marine, brackish and freshwater habitats worldwide.
- It is seen by many as a means of adding resilience to the human food supply system and potentially lowering impacts on wild fisheries.
- Due to its well-reported effects on climate and extreme events, on the aquatic and terrestrial systems that support aquaculture, and on the cultured species themselves, ENSO has considerable potential to affect aquaculture production.
- We examine potential effects of ENSO on aquaculture at a series of different levels including global, regional and national levels, as well as at the level of the most commonly cultured plants and animals.

After total aquaculture production overtook that of capture fisheries in 2014 (FAO-FishStatJ., 2019b), aquaculture is now the principal source of fish and seafood for human consumption. It is considered an important means by which resilience can be added to the global food supply system by introducing diversity and flexibility (but see Troell *et al.*, 2014 who indicates that such promise will not be realized if government policies fail to provide adequate incentives for resource efficiency, equity, and environmental protection). In the context of a rapidly growing, and often underfed human global population (FAO *et al.*, 2019), it is essential for food security reasons to understand how different factors potentially affect aquaculture production. This is required to minimize any potential shocks to the continued supply of aquaculture products (Cottrell *et al.*, 2019), especially relevant given the need for the sector to diversify and reduce its environmental and ecological impacts (Froehlich *et al.*, 2018) and to counter the challenges presented by climate change (Dabbadie *et al.*, 2018). Although aquaculture production is still largely dominated by freshwater production, aquaculture operations are now found across the world's continents (discounting Antarctica) in marine, brackish and freshwater habitats, as well as on land, and vary considerably in terms of the scale of production, associated infrastructure and how intensive management processes are. As such, they are exposed to a wide range of influences that could potentially affect production, including climatic variation.

The effects of climatic variation on aquaculture have been examined in detail in the context of climate change (Allison, Badjeck and Meinhold, 2011; Brander *et al.*, 2018; Dabbadie *et al.*, 2018), and are sometimes related to ENSO-associated climatic events as indicators of future conditions under continued anthropogenic-driven climate change. ENSO is the primary driver of variation in the tropical and global precipitation record (Trenberth *et al.*, 2014), and El Niño is characteristically associated with increased air temperatures, reduced precipitation and droughts in Southeast Asia, and parts of Africa and South America. New *et al.* (2001) estimated that ENSO explained 38 percent of the interannual variance in globally averaged land precipitation and about 8 percent of the space–time variability of precipitation at a global level. Su *et al.* (2018) estimated that discharge in >35 percent of rivers worldwide is sensitive to the influence of ENSO and its influence can be considerable, with 25 percent of the natural variability in the flow of the River Nile being associated with ENSO (Eltahir, 1996).

The availability of suitable volumes of unpolluted water is key to aquaculture production, but human activities affect the quality and quantity of water available to support the sector, as well as inland fisheries (Chapter 9). By the late 1990s (Postel, Daily and Ehrlich, 1996) it was estimated that human demand globally was such that more than 50 percent of all accessible freshwater was utilized, and that this would likely increase to 70 percent by 2025. Such effects have obvious potential to impact aquaculture and ENSO has marked effects on several fundamental abiotic factors that likely influence the success of individual aquaculture operations, including water availability, quality and temperature (Mariotti, 2007; Räsänen and Kummu, 2013; Scarsbrook *et al*., 2003; Tamaddun *et al*., 2019), seed availability (Kluger *et al*., 2019), disease (Kovats *et al*., 2003; Lafferty *et al*., 2015), as well as the availability of food for cultured taxa (Zeldis *et al*., 2008) and human populations (Ambikapathi *et al*., 2017; Cottrell *et al*., 2019; Iizumi *et al*., 2014). Beyond the realization that ENSO affects many characteristics of climate and ecosystem function across the world, it was recognized that effects associated with El Niño and La Niña events differed considerably, leading to them being considered to have opposite effects on regional temperature and precipitation (Kenyon and Hegerl, 2008). However, in recent years there has been a growing realization that ENSO effects are more complex than previously thought and that responses to El Niño and La Niña events may be asymmetrical (Lee, Ward and Block, 2018; Liang *et al*., 2016). Furthermore, it has become increasingly obvious that a diversity of flavours are included within different ENSO categories , e.g. that warm events in the tropical Pacific extend to a diversity of different El Niño types (Takahashi *et al*., 2011), with potentially contrasting effects on climate, ecosystems and the provision of goods and services to human populations. Recent evidence has confirmed previous suspicions that ENSO events have become increasingly more extreme in recent decades (Grothe *et al*., 2019).

As might be expected, there is a detailed literature describing the effects of ENSO on various factors affecting aquaculture, including water quality and temperature, growth, food availability, product quality, disease risk, damage to aquaculture facilities and site suitability (Cornejo-Grunauer, 2002; Hossain *et al*., 2002; Lafferty *et al*., 2015; McCoy *et al*., 2017; Pielke and Landsea, 2002; Yáñez *et al*., 2018; Zeldis *et al*., 2008). However, to our knowledge, there has been no broad examination of whether ENSO affects aquaculture production, or the impacts of the different El Niño events. Here, following the approach used in previous sections, we examine potential effects of different ENSO categories and El Niño event types on aquaculture across different production sectors (marine/brackish, freshwater habitats), geographical regions and for the ten countries that currently dominate global production. Finally, given their importance in terms of global food security, we examine evidence for similar ENSO effects for key aquaculture products.

8.1 ENSO AND GLOBAL AQUACULTURE PRODUCTION

KEY MESSAGES

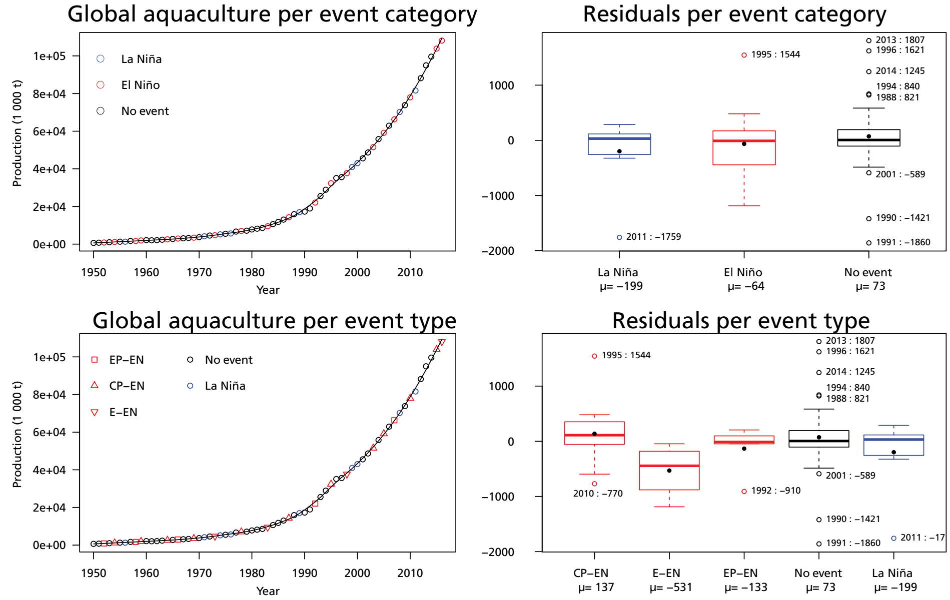
- Global aquaculture production increased from below 1 million tonnes in 1950 to more than 100 million tonnes in 2016.
- Annual mean production anomalies were statistically similar between different ENSO categories or El Niño event types.
- Annual production anomalies estimated as a percentage of long-term mean production were generally less than 1 percent, but were −2.1 percent during extreme El Niño for all aquaculture combined, and −3 percent during extreme El Niño for marine/brackish water production.
- Aquaculture production in land-locked developing countries was reduced on average by 3.6 percent in both CP and extreme El Niño years.

Annual global aquaculture production (Figure 8.1) increased dramatically (<1 million tonnes to >100 million tonnes) during the period 1950 to 2016. At a global level, a total of 438 different taxa or products were identified as being cultured in 2016, producing an estimated global aquaculture yield of 108.1 million tonnes – considerably more than the estimated 90.5 million tonnes from marine (79.2 million tonnes) and inland (11.3 million tonnes) capture fisheries in the same period (FAO-FishStatJ., 2019b). There was an extremely wide variation in the contribution of different products/species to aquaculture (Table 8.1), with the five largest single contributions made by marine macroalgae (Japanese kelp, 9.9 percent; *Eucheuma* seaweeds nei, 9.0 percent), freshwater fishes (grass carp, 5.0 percent; silver carp, 4.4 percent) and marine bivalves (cupped oysters nei, 4.3 percent). In 2016, marine (52.3 million tonnes, 48.4 percent) and freshwater (47.1 million tonnes; 43.5 percent) aquaculture dominated global aquaculture production, with brackish water aquaculture producing a relatively (8.1 percent) small contribution (8.7 million tonnes).

Comparison of residuals associated with each ENSO event category or El Niño type showed no statistically significant differences (ANOVA, p-value>0.05) for any comparison described here, but this may reflect limits in the data (e.g. small sample sizes for some comparisons). As such, we focus here (and in subsequent sections) on comparisons between mean anomalies calculated for each ENSO category and El Niño type, and what they relate to in terms of relative production in: a) 2016 and b) compared to the mean production reported for the entire time series. Given production in 2016 in most cases was close to the peak, a) will tend to underestimate past fluctuations, while b) may overestimate the likely impact of future ENSO-associated fluctuations in production, if annual yields continue to increase at the rate they have done over recent years.

FIGURE 8.1

Left panels: yearly global aquaculture production (in 1 000 t) per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

Global aquaculture production under neutral conditions (no event) was associated with a mean increase of +73 000 tonnes (+0.1 percent of 2016 production; +0.3 percent of mean production between 1950 to 2016). In the same period, production was reduced by a mean of −199 000 tonnes under La Niña conditions, the equivalent of −0.8 percent of mean production over the 1950 to 2016 period, or −0.2 percent of 2016 total global production, and by a mean of −64 000 tonnes under El Niño (−0.1 percent of 2016 total production, −0.3 percent mean 1950 to 2016). Comparison of global aquaculture yields during the different ENSO event types indicated that on average, yields were increased under CP El Niño by +137 000 tonnes (+0.1 percent of 2016 production; +0.5 percent mean 1950 to 2016) but were reduced under extreme El Niño by −531 000 tonnes, reflecting only −0.5 percent of 2016 production but −2.1 percent of mean production between 1950 and 2016. Production anomalies were also negative under EP El Niño, but to a lesser extent (−133 000 tonnes; −0.1 percent of 2016 production, −0.5 percent of mean production between 1950 and 2016).

Aquacultural production in marine/brackish water (Table 8.1) showed similar patterns, but mean annual production anomalies were generally smaller than for global aquaculture production, with the exception of La Niña which showed a greater mean reduction (−211 000 tonnes, representing −0.4 percent of 2016 production, or −1.4 percent of mean production between 1950 and 2016). Although anomalies were generally slightly lower than seen for total global aquaculture, in most cases the impact of these anomalies increased in terms of percentage yield as marine/brackish aquaculture only represents a proportion of global production. The most notable anomaly was under extreme El Niño (Table 8.1), where it (−449 000 tonnes) reflected a reduction of −3 percent from the mean production between 1950 and 2016.

Global aquaculture production in freshwater (Table 8.1) in 2016 differed from marine/brackish waters in that it was dominated (>96 percent) by fish (cf. >50 percent of marine/brackish production was of macroalgae). There was no evidence for any large-scale effect of ENSO on freshwater aquaculture production. Anomalies for different ENSO categories were associated with small positive (neutral and La Niña) or negative (El Niño) shifts in annual production, reflecting <0.1 percent of 2016 production and 0.1 percent to 0.2 percent of mean production between 1950 and 2016. When different El Niño types were considered, CP El Niño was associated with an increase (+42 000 tonnes) in mean annual production but this only reflected −0.1 percent of 2016 production, or −0.4 percent of mean production between 1950 and 2016. Production anomalies for global freshwater aquaculture were negative for both extreme El Niño (−82 000 tonnes) and EP El Niño (−111 000 tonnes) reflecting similar percentage reductions in mean annual production (Table 8.1) for both types of El Niño relative to 2016 (−0.2 percent) or the 1950 to 2016 mean (−0.7 percent to −1.0 percent).

Aquaculture production in low-income food-deficient countries (LIFDCs) represented 8.8 percent of total global aquaculture production in 2016 (8.7 percent between 1950 and 2016), and was dominated by the culture of freshwater fishes (Table 8.1). Production anomalies associated with different ENSO categories varied between −6 000 tonnes (El Niño) and +10 000 tonnes (La Niña) with no obvious large-scale effects on production in percentage terms relative to either 2016 values (<+0.1 percent to +0.1 percent) or the long-term (1950 to 2016) mean (+0.1 percent to +0.4 percent). Production anomalies were all negative (−1 000 tonnes to −12 000 tonnes) for all three El Niño types, but again impacts were minimal in terms of percentage reductions in production (2016: <−0.1 percent to −0.1 percent; 1950 to 2016: <−0.1 percent to −0.5 percent).

Land-locked developing countries accounted for a very small (Table 8.1; 2016: 0.38 percent) proportion of global aquaculture, with production being dominated by fish such as tilapia, catfish and cyprinid fishes. Although production anomalies were small (−2 000 tonnes to + 1 000 tonnes) for the different ENSO categories and El Niño conditions (−3 000 tonnes to +1 000 tonnes) these reflected fluctuations between −3.6 percent and 1.2 percent in terms of long-term (1963 to 2016) mean production. Production was reduced under La Niña and El Niño categories, as well as CP and extreme El Niños.

TABLE 8.1

Summary of total yield (t) in 2016 for different sectors of global aquaculture, and their relative contribution to global aquaculture production (2016). The relative contribution of the five species providing the largest contributions are provided for each sector. Also shown is the mean anomaly (1950 to 2016) in aquaculture production (1 000 t) associated with different ENSO event categories or types of El Niño in the different sectors of global aquaculture (red text reflects increases in yield, blue reductions in yield). The associated estimated change in yield is shown relative to (total aquaculture yield reported for that sector in 2016) and [the mean yield over the entire time series available], with values >±1% highlighted in bold.

			Mean anomaly x 1 000 tonnes (% 2016 yield) [% mean yield]					
Sector *Five principal species/categories*	**(2016 yield) [mean yield] t**	**% 2016**	**No event**	**Strong La Niña**	**El Niño**	**CP El Niño**	**E El Niño**	**EP El Niño**
Global *Japanese kelp (9.9%); Eucheuma seaweeds nei (9.0%); grass carp (5.0%); silver carp (4.4%); cupped oysters nei (4.3%)*	(108 129 956) [25 910 235]	100	+73 (+0.1) [+0.3]	−199 (−0.2) [−0.8]	−64 (−0.1) [−0.3]	+137 (+0.1) [+0.5]	−531 (−0.5) **[−2.1]**	−133 (−0.1) [−0.5]
Global Brackish/Marine *Japanese kelp (17.5%); Eucheuma seaweeds nei (16.0%); cupped oysters nei (7.7%); Gracilaria seaweeds (7.0%); Japanese carpet shell (6.8%)*	(61 052 397) [14 806 004]	56.5	+59 (+0.1) [+0.4]	−211 (−0.4) **[−1.4]**	−43 (−0.3) [−0.3]	+95 (+0.2) [+0.6]	−449 (−0.7) **[−3.0]**	−23 (−<0.1) [−0.2]
Global Freshwater *Grass carp (11.6%); silver carp (10.0%); c ommon carp (8.6%); bighead carp (6.7%); Nile tilapia (6.4%)*	(47 077 559) [11 104 231]	43.5	+13 (+<0.1) [+0.1]	+12 (+<0.1) [+0.1]	−21 (−<0.1) [−0.2]	+42 (+0.1) [+0.4]	−82 (−0.2) [−0.7]	−111 (−0.2) **[−1.0]**
Low-income food-deficient countries *Catla (25.6%); Roho labeo (12.8%); striped catfish (9.9%); freshwater fishes nei (8.7%); silver carp (6.2%)*	(9 515 200) [2 249 000]	8.8	−3 (−<0.1) [−0.1]	+10 (+0.1) [+0.4]	−6 (−0.1) [−0.3]	−1 (−<0.1) [−<0.1]	−12 (−0.1) [−0.5]	−10 (−0.1) [−0.4]
Land-locked developing countries (1963) *Nile tilapia (32.5%); North African catfish (11.1%); silver carp (9.6%); common carp (6.8%); mrigal carp (4.9%)*	(413 419) [82 652]	0.38	+1 (+0.2) **[+1.2]**	−1 (−0.2) **[−1.2]**	−2 (−0.5) **[−2.4]**	−3 (−0.7) **[−3.6]**	−3 (−0.7) **[−3.6]**	+1 (+0.2) [+1.2]

Global aquaculture production has been characterized by explosive growth from 0.64 million tonnes in 1950 to 108.13 million tonnes in 2016. The most marked apparent effect of ENSO on global aquaculture was a mean reduction of −531 000 tonnes during extreme El Niño events, reflecting −2.1 percent of mean production between 1950 and 2016 (−3 percent for marine/brackish water aquaculture). However, in terms of the data analysed here, there is little evidence that ENSO systematically affects global aquaculture production, either when all data are combined or divided between freshwater and marine/brackish water activities. This likely partly reflects how ENSO affects ecosystems at different geographical scales, e.g. El Niño may have positive effects in one region, while another region experiences negative effects over the same period. Furthermore, a large number (>430) of species are cultured globally, with contrasting habitat requirements and likely responses to changes in abiotic conditions associated with ENSO variation (water availability, temperature, etc.). An additional and important factor is the great success achieved in increasing aquaculture production during the period 1950 to 2016 due to economic investment, scientific advances, technical innovation and hard work by aquaculture operators. As such, it is possible that these factors work together to dampen any apparent signal of ENSO-derived effects on global aquaculture, and further analyses are required (e.g. at the level of geographical region, country, species or even individual aquaculture operator) to ensure that absence of evidence is not absence of an effect.

8.2 ENSO AND REGIONAL AQUACULTURE PRODUCTION AND ENSO

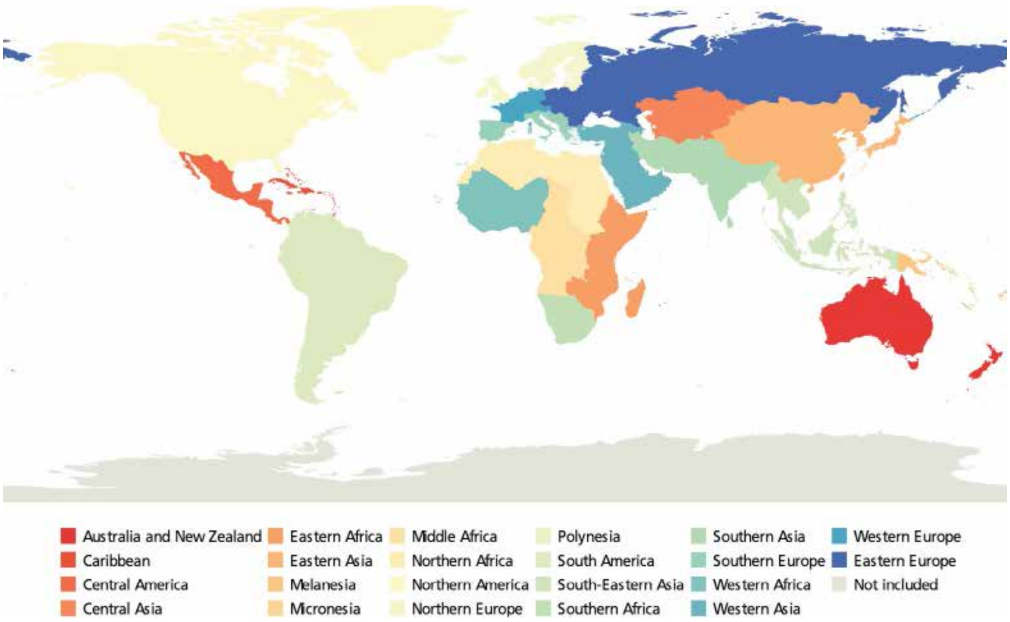
KEY MESSAGES

- We described known climatic effects of ENSO variation and estimated ENSO effects on aquaculture production across 22 broad geographical regions.
- Aquaculture production was largely (2016, 92 percent) derived from different regions in Asia.
- In each region there was no significant effect of ENSO event category or El Niño event type on aquaculture production.
- However, certain conditions (La Niña and extreme El Niño) were more often associated with larger variation in production anomalies, indicating that they have more scope to produce shocks in the aquaculture sector.

We next examined potential effects of ENSO variation on aquaculture production at a regional level (Figure 8.2). As before, we used FAO summary data on aquaculture production (marine, brackish water and freshwater combined) for countries classified into 22 different global regions, as defined by FAO-FishStatJ (2019b), across which ENSO variation has markedly different effects on climate. We then pooled estimated annual aquaculture production data for each country in the region for the period 1950 to 2016, and used LOESS to calculate production residuals to estimate production anomalies for each ENSO category (no event, La Niña and El Niño) and the three different El Niño event types (CP El Niño, extreme El Niño and EP El Niño). We then compared these values using ANOVA, but in every case, there were no significant differences (p-value >0.05). We concentrate on describing the mean regional production anomalies in terms of percentage differences from 2016 production in a given region, or the long-term annual mean production in that region (typically calculated for the period 1950 to 2016).

The great majority (92 percent) of global aquaculture production in 2016 (108 million tonnes; Table 8.2) originated in Asia (99.5 million tonnes). Of this, 61.2 percent was produced in Eastern Asia, followed by Southeast Asia (22.5 percent) and then Southern Asia (7.9 percent). Outside of Asia, annual aquaculture production in 2016 was >1 million tonnes in only three regions: South America (2.2 percent), Northern Europe (1.6 percent) and Northern Africa (1.3 percent). Production in other regions ranged from 0.6 percent of global production (Northern America, Southern Europe) down to 0.001 percent in Polynesia.

FIGURE 8.2
Geographical regions used to calculate aquaculture production 1950 to 2016



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a). Map conforms to United Nations World map, February 2020.

8.2.1 Eastern Asia

The Eastern Asia region (Figure 8.2, Table 8.2) includes China, China Hong Kong SAR, China Macao SAR, Japan, Democratic People's Republic of Korea, Republic of Korea, Mongolia and Taiwan Province of China, with a total surface area of >11 million km^2. The climate of the constituent countries is extremely diverse, ranging from tropical (southern China, southern Japan, Taiwan Province of China), through to temperate (northern Japan, Republic of Korea, Democratic People's Republic of Korea, desert (Mongolia) and subarctic (northern China).

Jiang *et al*. (2003) detailed the considerable evidence for effects of ENSO on the climate of Eastern Asia, including El Niño reducing the intensity of the east Asian winter monsoon, increasing precipitation during spring across the region, and late spring/early summer rainfall over China during and after the mature phase of ENSO. In their large-scale assessment of global climatic effects of ENSO, Davey *et al*. (2014) noted that El Niño results in a mixed response in terms of temperature anomalies in Japan, in that November and December are typically warmer while July to September are cooler. They did not report any associated effect on precipitation. La Niña is associated with a warm anomaly across Japan and the Korean peninsula, and with drier conditions in southeast China. No rivers in the eastern Asia region were identified by Ward *et al*. (2010) as having their discharge characteristics influenced by ENSO, but Lee, Ward and Block (2018) noted El Niño effects on both the Yangtze (positive anomaly) and Yellow River (negative anomaly) basins. They did not note any obvious impacts of La Niña in these systems, but suggested that rivers in northeast and northwest China and Mongolia would show reduced streamflow during La Niña periods. The region has displayed marked responses to ENSO variation in the past, including extreme rainfall events in the mid- and lower-reaches of the Yangtze River in China in the summer following a winter El Niño event, resulting in flooding, loss of life and economic impacts (Chen *et al*., 2012; Hardiman *et al*., 2018). This was particularly marked in

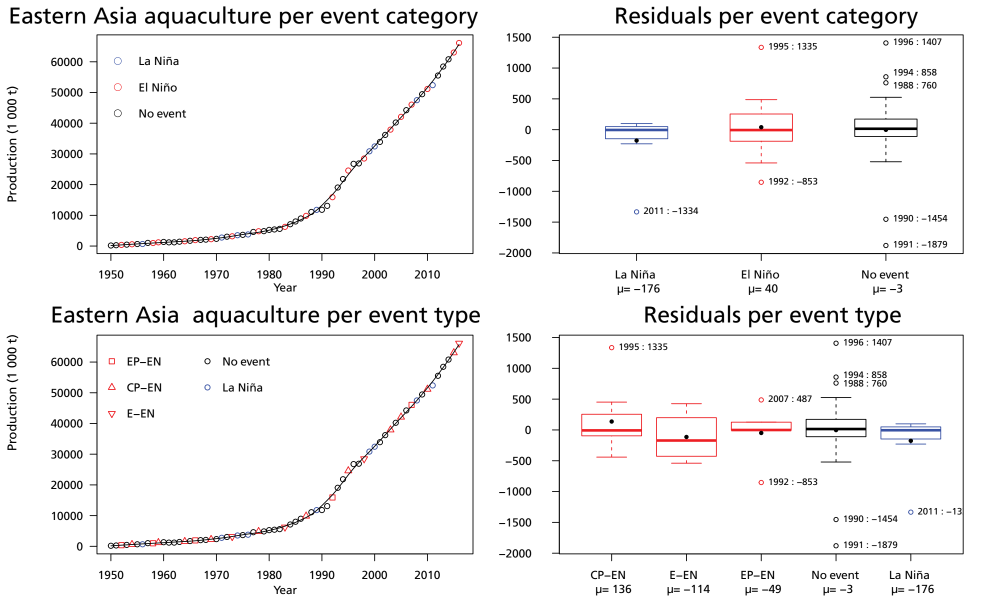
1998 and 2016: in the latter case accumulated precipitation over a 10 day period was 300 mm to 400 mm above average, and flooding caused damage worth approximately USD 10 billion (Yuan, Wang and Hu, 2018). Conversely, La Niña conditions are not associated with any precipitation anomalies in the basin (Hardiman *et al*., 2018). The diversity of El Niño events is well recognized in the region, although largely focused on China and Japan. In terms of temperature anomalies, EP El Niño results in surface air temperature increases over northern China between June and August. Conversely, CP El Niño is associated with a cold anomaly in surface air temperature in northeast China in June to August, and over northern China between March and May (Yang and Jiang, 2014). Cold anomalies are apparent across the Tibetan Plateau during EP El Niño, and warm anomalies during CP El Niño (Yang and Jiang, 2014). The effects of CP and EP El Niño differ markedly in terms of their effects on precipitation in the region: during EP El Niño, northern China tends to be drier, and southern China wetter (Feng and Li, 2011; Wang, Li and He, 2017; Yang and Jiang, 2014). CP El Niño however, results in marked reductions in precipitation in eastern China, especially in the mid- and lower-reaches of the Yangtze River valley, as well as in southwest China (Yang and Jiang, 2014; Zhang *et al*., 2011). CP El Niño is also associated with reduced precipitation in southern Japan compared to EP El Niño events (Graf and Zanchettin, 2012; Wang, Li and He, 2017). Liang *et al*. (2016) examined discharge characteristics in the Huaihe, Yangtze and Yellow rivers under both EP and CP El Niños and showed that they differed in both the Yellow (CP discharge > EP discharge) in the developing phase and Yangtze (EP discharge > CP discharge) in the decaying phase of the El Niño.

In 2016, the Eastern Asia region (Table 8.2) was ranked first in terms of aquaculture production, producing 61.2 percent of total global production. Annual aquaculture yield in the region increased from 178 078 tonnes to 66.1 million tonnes during the period 1950 to 2016 (Figure 8.3), with a mean annual production of 17.5 million tonnes. In 2016, records from 147 different species or products were provided in the region, ranging from a contribution of 2 tonnes (areolate grouper) through to 10.7 million tonnes (Japanese kelp), with a mean (±SD) annual production of 449 831 tonnes ± 1 235 560 tonnes. Seven species/categories (Japanese kelp: 16.1 percent; grass carp: 8.0 percent; cupped oysters nei: 7.1 percent; Japanese carpet shell: 6.3 percent; silver carp: 5.9 percent; bighead carp: 4.7 percent; common carp: 4.5 percent) accounted for more than 50 percent of total aquaculture production in the region.

Statistical comparisons revealed no measurable response to different ENSO conditions (ANOVA p-value >0.05) during the period 1950 to 2016. Production anomalies (Table 8.2) under neutral ENSO conditions were negligible (–3 000 tonnes), reflecting a percentage decrease of <–0.1 percent relative to both eastern Asian aquaculture production in 2016 and the mean estimate for the 1950 to 2016 period. La Niña conditions were associated with a reduction in annual aquaculture production of –176 000 tonnes, representing –0.3 percent of 2016 regional production and –1 percent of the long-term (1950 to 2016) mean. As a broad category, El Niño conditions were associated with a small positive production anomaly of 40 000 tonnes (2016: +0.1 percent; 1950 to 2016: +0.2 percent). With regard to the different El Niño types, mean aquaculture production in Eastern Asia increased slightly by +136 000 tonnes during CP El Niño events (2016: +0.2 percent; 1950 to 2016: +0.8 percent), but decreased slightly under both extreme El Niño (–114 000 tonnes; 2016: –0.2 percent; 1950 to 2016: –0.7 percent) and EP El Niño events (–49 000 tonnes; 2016: –0.1 percent; 1950 to 2016: –0.3 percent).

FIGURE 8.3

Left panels: regional annual global aquaculture production (in 1 000 t) per event category (upper panel) and type (lower panel) from Eastern Asia. The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

TABLE 8.2:

Summary of the total aquaculture yield (t) in 2016 for different geographical regions, and their relative contribution to global aquaculture production (% 2016). Also shown is the summary of the mean anomaly (1950–2016) in aquaculture production (1 000 t) in each region associated with different ENSO event categories or types of El Niño, and in parentheses, the change in yield relative to either: (the total aquaculture yield reported for that region in 2016) or [the mean yield over the entire time series available], with values >±1% highlighted in bold. Regions are ordered according to their relative contribution to global aquaculture production in 2016. Not shown is production in other regions with minor contributions (0.06% combined) to global aquaculture production in 2016 (Caribbean: 36 710 t, Melanesia: 18 665 t, Southern Africa: 9 575 t, Middle Africa, 6 652 t, Micronesia: 3 833 t and Polynesia: 1 407 t).

			Mean anomaly (1 000 t) (% 2016 yield) [% mean yield]					
Geographical region	**(2016 yield) [Mean yield] t**	**2016 %**	**No event**	**Strong La Niña**	**El Niño**	**CP El Niño**	**E El Niño**	**EP El Niño**
Eastern Asia *China, China Hong Kong SAR, China Macao SAR, Japan, Dem. People's Rep. of Korea, Republic of Korea, Mongolia, Taiwan Province of China*	(66 125 251) [17 549 582]	61.15	−3 (−<0.1) [−<0.1]	−176 (−0.3) **[−1.0]**	+40 (+0.1) [+0.2]	+136 (+0.2) [+0.8]	−114 (−0.2) [−0.7]	−49 (−0.1) [−0.3]
South–Eastern Asia *Brunei Darussalam, Cambodia, Indonesia, the Lao People's Dem. Rep., Malaysia, Myanmar, the Philippines, Singapore, Thailand, Timor–Leste, Viet Nam*	(24 372 139) [3 914 323]	22.54	+62 (+0.3) **[+1.6]**	−22 (−0.1) [−0.6]	−74 (−0.3) **[−1. 9]**	+41 (+0.2) **[+1.1]**	−428 **(−1.8)** **[−10.9]**	−42 (−0.2) **[−1.1]**
Southern Asia *Afghanistan, Bangladesh, Bhutan, India, Iran (Islamic Rep. of), Maldives, Nepal, Pakistan, Sri Lanka*	(8 546 467) [1 797 888]	7.90	+1 (+<0.1 [+0.1]	−7 (−0.1) [−0.4]	−7 (−0.1) [−0.4]	−15 (−0.2) [−0.8]	+34 (+0.4) **[+1.9]**	−21 (−0.3) **[−1.2]**
South America *Argentina, Bolivia (Plurinat. State of), Brazil, Chile, Colombia, Ecuador, the Falkland Is. (Malvinas), French Guiana, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela (Bolivarian Rep. of)*	(2 332 057) [477 192]	2.16	+14 (+0.6) [+2.9]	−16 (−0.7) **[−3.4]**	−18 (−0.8) **[−3.8]**	−24 **(−1.0)** **[−5.0]**	−22 (−0.9) **[−4.6]**	−4 (−0.2) [−0.8]
Northern Europe *Channel Islands, Denmark, Estonia, Faroe Islands, Finland, Iceland, Ireland, Isle of Man, Latvia, Lithuania, Norway, Svalbard and Jan Mayen Islands, Sweden, United Kingdom of Great Britain and Northern Ireland*	(1 733 426) [422 075]	1.60	+6 (+0.4) **[+1.4]**	+6 (+0.4) **[+1.4]**	−10 (−0.6) **[−2.4]**	−5 (−0.3) **[−1.2]**	−27 (−1.6) **[−6.4]**	−9 (−0.5) **[−2.1]**
Northern Africa *Algeria, Egypt, Libya, Morocco, the Sudan, Tunisia, Western Sahara*	(1 398 379) [217 113]	1.29	−3 (−0.2) **[−1.4]**	+12 (+0.9) **[+5.5]**	0 (–) [–]	+1 (+0.1) [+0.5]	+1 (+0.1) [+0.5]	−1 (−0.1) [−0.5]
Northern America *Bermuda, Canada, Greenland, St. Pierre and Miquelon, United States of America*	(645 447) [339 127]	0.60	−1 (−0.2) [−0.3]	−8 **(−1.2)** **[−2.4]**	+3 (+0.5) [+0.9]	+2 (+0.3) [+0.6]	+6 (+0.9) **[+1.8]**	+3 (+0.5) [+0.9]

Geographical region	(2016 yield) [Mean yield] t	2016 %	Mean anomaly (1 000 t) (% 2016 yield) [% mean yield] No event	Strong La Niña	El Niño	CP El Niño	E El Niño	EP El Niño
Southern Europe *Albania, Andorra, Bosnia and Herzegovina, Croatia, Gibraltar, Greece, Italy, Malta, Montenegro, North Macedonia, Portugal, San Marino, Serbia, Slovenia, Spain*	(616 153) [321 962]	0.57	−5 (−0.8) [−1.6]	+10 (+1.6) [+3.1]	+4 (+0.7) [+1.2]	+1 (+0.2) [+0.3]	+14 (+2.3) [+4.4]	+3 (+0.5) [+0.9]
Western Africa *Benin, Burkina Faso, Cabo Verde, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea–Bissau, Liberia, Mali, Mauritania, the Niger, Nigeria, Saint Helena, Senegal, Sierra Leone, Togo*	(375 716) [49 188]	0.35	+1 (+0.3) [+1.6]	+5 (+1.3) [+10.2]	−3 (−0.8) [−6.1]	−1 (−0.3) [−2.0]	−8 (−2.1) [−16.3]	−4 (−1.1) [−8.1]
Western Asia *Armenia, Azerbaijan, Bahrain, Cyprus, Georgia, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syrian Arab Republic, Turkey, the United Arab Emirates, Yemen*	(370 014) [74 888]	0.34	−1 (−0.3) [−1.3]	+2 (+0.5) [+2. 7]	0 (–) [–]	−1 (−0.3) [−1.3]	+5 (+1.4) [+6.7]	+1 (+0.3) [+1.3]
Central America (1955) *Belize, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama*	(357 799) [79 127]	0.33	−1 (−0.3) [−1.3]	−1 (−0.3) [−1.3]	0 (–) [–]	−2 (−0. 6) [−2.5]	+1 (+0.3) [+1.3]	+1 (+0.3) [+1.3]
Eastern Africa *British Indian Ocean Terr., Burundi, Comoros, Djibouti, Eritrea, Ethiopia, French Southern Terr., Kenya, Madagascar, Malawi, Mauritius, Mayotte, Mozambique, Rwanda, Réunion, Seychelles, Somalia, South Sudan, United Rep. of Tanzania, Uganda, Zambia, Zanzibar, Zimbabwe*	334 853 [150 567]	0.31	+1 (+0.3) [+0.7]	−3 (−0.9) [−2.0]	+1 (+0.3) [+0.7]	+6 (+1.8) [+4.0]	−12 (−3.6) [−8.0]	0 (–) [–]
Eastern Europe *Belarus, Bulgaria, Czechia, Hungary, Republic of Moldova, Poland, Romania, the Russian Federation, Slovakia, Ukraine*	324 621 [305 987]	0.30	+2 (+0.6) [+0.7]	+14 (+4.3) [+4.6]	−9 (−2.8) [−2.9]	−15 (−4.6) [−4.9]	+2 (+0.6) [+0.7]	−5 (−1.5) [−1.6]
Western Europe *Austria, Belgium, France, Germany, Liechtenstein, Luxembourg, Monaco, Netherlands, Switzerland*	275 161 [61 046]	0.25	+1 (+0.4) [+1.6]	−8 (−2.9) [−13.1]	+2 (+0.7) [+3.3]	+1 (+0.4) [+1.6]	+16 (+5.8) [+26.2]	−6 (−2.2) [−9.8]
Australia and New Zealand *Australia, New Zealand, Norfolk Island*	206 062 [60 065]	0.19	−1 (−0.5) [−1.7]	+2 (+1.0) [+3.3]	+1 (+0.5) [+1.7]	−1 (−0.5) [−1.7]	+7 (+3.4) [+11.7]	+2 (+1.0) [+3.3]
Central Asia (1998) *Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan*	42 352 [17 009]	0.04	0 (–) [–]	0 (–) [–]	0 (–) [–]	+1 (+2.4) [+5.9]	0 (–) []	−3 (−7.1) [−17.6]

8.2.2 South-Eastern Asia

The South-Eastern Asia region (Figure 8.2, Table 8.2) includes Brunei Darussalam, Cambodia, Indonesia, the Lao People's Democratic Republic, Malaysia, Myanmar, the Philippines, Singapore, Thailand, Timor-Leste and Viet Nam, with a total land area of 4.36 million km^2. The climate of the region is tropical, with hot and humid conditions. In most cases, the year is divided into dry and wet (monsoon) seasons, although the timing of the monsoon differs from country to country.

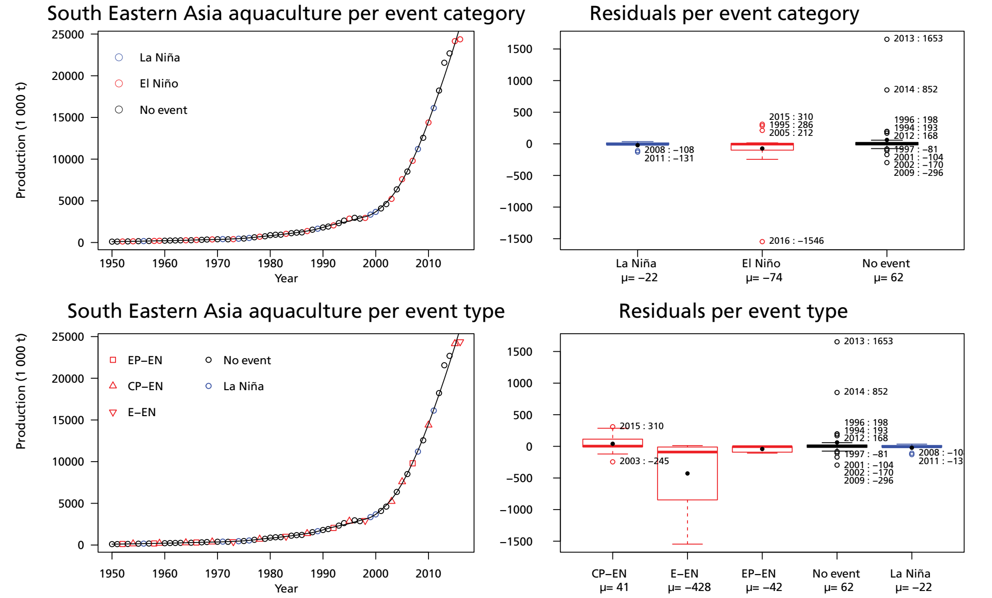
ENSO effects on regional climate include shifts in precipitation and air temperature, which in turn affect the availability and temperature of water. La Niña conditions typically result in positive precipitation anomalies across the region, with cooler conditions following periods with increased precipitation. El Niño years see the opposite for much of the region, with increased air temperature, reduced monsoonal rains, drought (Davey, Brookshaw and Ineson, 2014) and loss of crops (Iizumi *et al.*, 2014). The intensity of these impacts depends on the strength of the particular event, with extreme La Niña events resulting in widespread floods, rivers overflowing their banks and damaging housing and crops. The impact on the region's rainfall and temperature from ENSO events is more significantly felt during strong or moderate intensity events. Mekong River hydrology is influenced by ENSO (Räsänen and Kummu, 2013) e.g. discharge is reduced during El Niño events and higher during La Niña events (Ward *et al.*, 2010). Relationships between ENSO and some important indicators of water availability have changed following the construction of dams, e.g. runoff in the Mekong River Basin (Xue, Liu and Ge, 2011). EP El Niños are associated with an increase in surface air temperatures across Indochina and Sumatra, while CP El Niños also see positive temperature anomalies in Sumatra, but cold anomalies over the central Indochinese Peninsula and around the Philippines (Graf and Zanchettin, 2012; Yang and Jiang, 2014). Precipitation anomalies are positive in Malaysia during EP El Niño, and mildly negative during CP El Niño in northern Borneo (Graf and Zanchettin, 2012). Liang *et al.* (2016) reported no differences in the discharge of the Mekong River during CP and EP El Niños.

Aquaculture production in the region of South-Eastern Asia increased from 106 672 tonnes in 1950 to 24.4 million tonnes in 2016 (Figure 8.4), and the region was ranked second in terms of relative contribution (22.5 percent to global aquaculture (Table 8.2) in 2016. Aquaculture production in the region in 2016 included 105 different categories with yields ranging between 0.03 tonnes (humpback grouper) and 9.7 million tonnes (*Eucheuma* seaweeds nei) with a mean annual (±SD) yield of 232 116 tonnes ± 997 809 tonnes. Five different species/categories accounted for more than 64.7 percent of regional aquaculture production (*Eucheuma* seaweeds nei: 39.8 percent; pangas catfishes nei: 6.8 percent; Nile tilapia: 6.2 percent; Elkhorn sea moss: 6.2 percent; *Gracilaria* seaweeds: 5.6 percent).

There was no obvious effect of different ENSO conditions (ANOVA p-value >0.05) on aquaculture yield in the region during 1950 to 2016, but we report anomalies to provide an indication of the scale of effects (Table 8.2). Aquaculture production in South-Eastern Asia during neutral ENSO conditions for the period 1950 to 2016 was associated with a mean increase of +62 000 tonnes (2016: +0.3 percent; 1950 to 2016: +1.6 percent). Both La Niña (–22 000 tonnes; 2016: –0.1 percent; 1950 to 2016: –0.6 percent) and El Niño (–74 000 tonnes; 2016: –0.3 percent; 1950 to 2016: –1.9 percent) were associated with negative production anomalies. Production in CP El Niño events increased on average by 41 000 tonnes (2016: +0.2 percent; 1950 to 2016: +1.1 percent). Extreme El Niño events were associated with a notable reduction in annual production, with a mean anomaly of –428 000 tonnes, reflecting a reduction of –1.8 percent relative to production in 2016 or –10.9 percent relative to regional mean production between 1950 and 2016. EP El Niño events were also associated with a reduction in production, but by a smaller amount (–42 000 tonnes; 2016: –0.2 percent; 1950 to 2016: –1.1 percent).

FIGURE 8.4

Left panels: regional yearly global aquaculture production (in 1 000 t) per event category (upper panel) and type (lower panel) from South-Eastern Asia. The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

8.2.3 Southern Asia

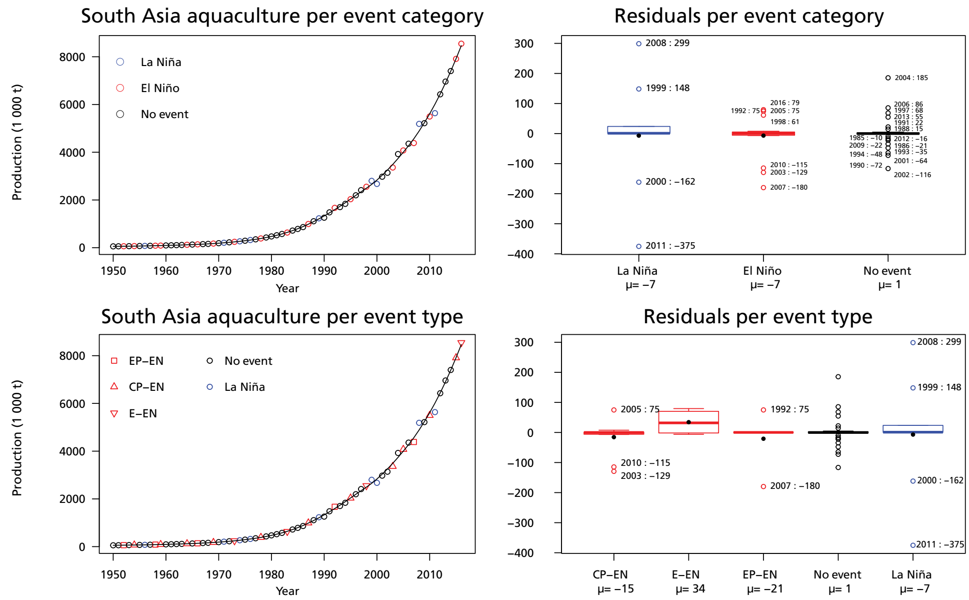
The Southern Asia region (Figure 8.2) includes Afghanistan, Bangladesh, Bhutan, India, Islamic Republic of Iran, Maldives, Nepal, Pakistan, and Sri Lanka, with a total land area of 6.42 million km². Climate in the region is very mixed and includes tropical areas with a marked monsoon period, subtropical, temperate, arid desert to arctic like conditions. It has long been recognized that the region sees characteristic climatic shifts with marked effects for human populations – it was this that inspired the original work of Walker (1933) in the late 1800s who tried to predict the occurrence of droughts in the Indian subcontinent, given their immense impacts on human well-being. El Niño conditions are associated with reduced summer monsoon precipitation and increased temperatures in India, Bangladesh and southeast Pakistan, while Sri Lanka and Islamic Republic of Iran see increased precipitation (Alizadeh-Choobari, Adibi and Irannejad, 2018; Davey, Brookshaw and Ineson, 2014). Severe droughts occur in India during El Niño events due to the failure of the monsoon (Kumar *et al.*, 2006) and cause subsequent crop failure (Iizumi *et al.*, 2014). La Niña conditions see a reverse, with much of the subcontinent experiencing cold and wet anomalies (Murari *et al.*, 2016). Graf and Zanchettin (2012) showed that the characteristic El Niño positive temperature anomaly was only present in the region during EP El Niño but not during CP El Niño conditions. Winter precipitation in north and central India is higher during EP El Niño conditions than CP El Niño (Yadav, Ramu and Dimri, 2013). CP El Niño is associated with dry conditions for central, eastern and southern areas of Islamic Republic of Iran, in contrast with EP El Niño, where the entire country is wetter than average (Alizadeh-Choobari, Adibi and Irannejad, 2018). Discharge anomalies differ under CP and EP El Niño conditions in the Brahmaputra, Ganges and Indus Rivers, with the sign of the difference varying with the phase of the El Niño (Liang *et al*., 2016).

Southern Asia was ranked third in terms of contribution (7.9 percent) to global aquaculture production in 2016 (Table 8.2). Production increased markedly (Figure 8.5) during the period between 1950 (56 325 tonnes) and 2016 (8.55 million tonnes). During 2016, 52 different aquaculture categories were reported to FAO from the region, with contributions varying between 2 tonnes (aquatic plants nei) and 2.4 million tonnes (catla), with a mean ±SD annual production of 164 355 tonnes ± 413 227 tonnes. Five species/categories were responsible for >71.4 percent of aquaculture production in Southern Asia in 2016 (catla: 28.5 percent; roho labeo: 14.2 percent; striped catfish: 11.1 percent; freshwater fishes nei: 9.6 percent; silver carp: 8.0 percent).

ENSO conditions or type of El Niño had no measurable (ANOVA p-value >0.05) influence on regional aquaculture yield in Southern Asia during this period, but we report anomalies to provide an indication of the scale of effects (Table 8.2). Mean production anomalies (Figure 8.5, Table 8.2) in aquaculture in Southern Asia were minor (2016: <0.1 percent to 0.1 percent; 1950 to 2016: 0.1 percent to 0.4 percent) during all three broad ENSO categories (neutral conditions +1 000 tonnes; La Niña and El Niño −7 000 tonnes). When the different types of El Niño were considered, the impacts were slightly larger, with mean decreases in annual regional production seen both under CP El Niño (−15 000 tonnes; 2016: −0.2 percent; 1950 to 2016: −0.8 percent) and during EP El Niño events (−21 000 tonnes; 2016: −0.3 percent; 1950 to 2016: −1.2 percent). Conversely, production during EP El Niño years showed a mean increase by +34 000 tonnes (2016: +0.4 percent; 1950 to 2016: +1.9 percent) under extreme El Nino.

FIGURE 8.5

Left panels: regional yearly global aquaculture production (in 1 000 t) per event category (upper panel) and type (lower panel) from Southern Asia. The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

8.2.4 South America

The South America region (Figure 8.2, Table 8.2) includes Argentina, Plurinational State of Bolivia, Brazil, Chile, Colombia, Ecuador, the Falkland Islands (Malvinas), French Guiana, Guyana, Paraguay, Peru, Suriname, Uruguay and Bolivarian Republic of Venezuela, with a total land area >17.5 million km². The region has an extremely diverse climate, including tropical, subtropical, temperate, arid desert, highland and cold sub-Antarctic areas (Penalba and Rivera, 2016).

ENSO has marked and variable effects on the climate of South America. Impacts on marine and coastal habitats are described in Section 6.1.3. Generally, El Niño events result in positive temperature anomalies for much of the region, although this does not extend to Patagonia (Davey, Brookshaw and Ineson, 2014). There are seasonal differences across the region: warming extends throughout the year in the northwest of South America, but is more restricted (July to March) in central South America and (June to August) in southern South America. Precipitation anomalies associated with El Niño are mixed, with wetter conditions in northern Peru/Ecuador (September to November), eastern Argentina, Uruguay and southeast Brazil (September to May). Drier conditions are seen in southern Peru (February to March) and across northern South America during El Niño events (Davey, Brookshaw and Ineson, 2014). Temperature anomalies are negative during La Niña across north, west and central South America (but not eastern Brazil) (Davey, Brookshaw and Ineson, 2014). During La Niña periods, wetter conditions are seen across the north of the continent in an arc from northern Peru, to central northeast Brazil. Conversely, there is a dry anomaly associated with La Niña in central southern Argentina and Chile (including the main aquaculture regions in the latter) (Davey, Brookshaw and Ineson, 2014).

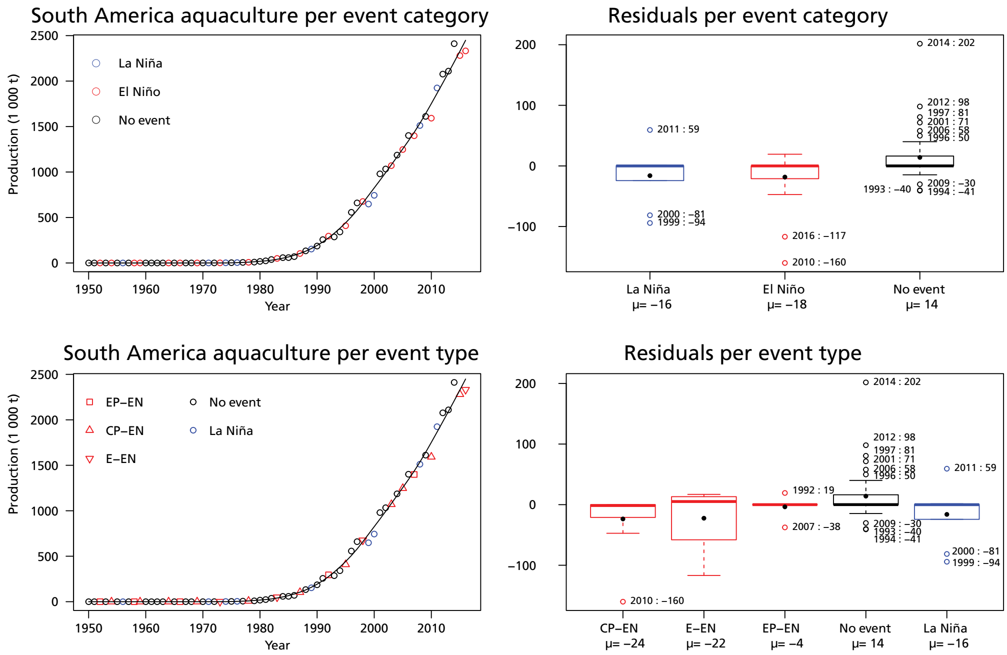
Such variation has very significant consequences in terms of social and economic impacts, including intense precipitation and flooding but also marked and extended droughts (Vicente-Serrano *et al*., 2011). In the Amazon region, drier conditions associated with El Niño result in reduced flood-levels and periods while high and prolonged flooding is associated with La Niña. El Niño is associated with increased streamflow in the Negro and Uruguay Rivers (Robertson and Mechoso, 1998), while discharge in the Amazon and Orinoco Rivers is reduced during El Niño years (Ward *et al*., 2010): approximately 10 percent of the variance in the discharge of the Amazon was explained by ENSO conditions (Amarasekera *et al*., 1997). Amarasekera *et al*. (op cit.) also showed that discharge in the Paraná was positively correlated with ENSO and that approximately 20 percent of variation could be explained by ENSO. Schöngart and Junk (2007) developed a forecast for the extent of flooding in the central Amazon based on ENSO.

There is a considerable literature examining the relative effects of different El Niño event types in the region (Tedeschi and Collins, 2016). Generally, CP El Niño sees less marked temperature anomalies than EP El Niño (Graf and Zanchettin, 2012). Differences in precipitation between the two types is less clear, but a negative anomaly occurs in northwest South America in both EP and CP El Niño (Graf and Zanchettin, 2012). CP El Niño is associated with reduced precipitation across wider northern South America, including Guyana, Suriname and northern Brazil. Under EP El Niño, positive precipitation anomalies are apparent in the Andes of southern Peru, northern Chile and Plurinational State of Bolivia (Graf and Zanchettin, 2012). CP and EP El Niños can have different effects at a national scale – in Ecuador CP El Niño affects drought variability in the Andes, while under EP El Niño variation in drought conditions is seen on the western plains (Vicente-Serrano *et al*., 2017). Liang *et al*. (2016) examined differences in discharge anomalies under EP and CP El Niño in several major rivers in South America under developing, mature and decaying phases of El Niño. During the developing phase, discharges were larger under EP El Niño in the Amazon, Orinoco, Magdalena and São Francisco rivers, similar in the Paraná and Parnaiba rivers and greater under CP El Niño in the Tocantins River. During the mature phase, all the rivers but the Tocantins River showed similar discharge anomalies during CP and EP El Niño events. During the decaying phase, only the most southern rivers (Paraná and São Francisco) showed differences, where in both cases discharge anomalies were greater during EP El Niños.

South America was ranked fourth (2.16 percent) in terms of contribution to global aquaculture production in 2016. Annual yield in the region increased from an estimated 40 tonnes in 1950 to 2.3 million tonnes in 2016, with large increases starting in the early 1990s (Figure 8.6). In 2016, production values for 69 different categories were reported in the region with contributions ranging from 0.9 tonnes (sterlet sturgeon) to 532 225 tonnes (Atlantic salmon), with a mean ±SD yield per category of 33 797 tonnes ± 102 797 tonnes. Five different species/categories accounted for more than 77 percent of aquaculture production including Atlantic salmon (22.8 percent), whiteleg shrimp (22.5 percent), Chilean mussel (12.9 percent), tilapias nei (12.5 percent) and rainbow trout (6.6 percent).

Comparison of production anomalies associated with different ENSO conditions or type of El Niño showed no evidence of differences in regional aquaculture yield in South America during the 1950 to 2016 period (ANOVA p-value >0.05). We report mean anomalies here to provide an indication of the scale of effects (Table 8.2). Neutral conditions were associated with an increase in mean yields of 14 000 tonnes (2016: +0.6 percent; 1950 to 2016: +2.9 percent) of 2016 aquaculture production in South America), while mean yields decreased under both La Niña (–16 000 tonnes; 2016: –0.7 percent; 1950 to 2016: –3.4 percent) and El Niño (–18 000 tonnes; 2016: –0.8 percent; 1950 to 2016: –3.8 percent). Mean aquaculture yields were lower by –24 000 tonnes (2016: –1.0 percent; 1950 to 2016: –5.0 percent) during CP El Niño, –22 000 tonnes (2016: –0.9 percent; 1950 to 2016: –4.6 percent) during extreme El Niño and –4 000 tonnes (2016: –0.2 percent; 1950 to 2106: –0.8 percent) during EP El Niño conditions.

FIGURE 8.6
Left panels: regional yearly global aquaculture production (in 1 000 t) per event category (upper panel) and type (lower panel) from South America. The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories or types



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

8.2.5 Northern Europe

The Northern Europe region (Figure 8.2) includes the Channel Islands, Denmark, Estonia, Faroe Islands, Finland, Iceland, Ireland, Isle of Man, Latvia, Lithuania, Norway, Svalbard and Jan Mayen Islands, Sweden and the United Kingdom of Great Britain and Northern Ireland, with a total land area of 1.64 million km². The climate is typically maritime temperate, with relatively cool, often damp summers, and winters that range between mild to cold subarctic conditions, in those countries in the north and east of the region.

There is a long and detailed literature examining interactions between ENSO and climate in Europe and it is typically considered that ENSO-related temperature and precipitation anomalies are difficult to detect across the wider region outside of extreme events (Brönnimann, 2007). In terms of Northern Europe, Brönnimann (2007) reviewed the literature available to that date and suggested that during a canonical El Niño event, the most marked effects were cold anomalies over Fennoscandia and the Baltic states and increased precipitation across the region during winter. La Niña events are considered to be symmetrical, i.e. warming over Fennoscandia and the Baltic states, and dry conditions across Northern Europe. A more recent summary (Davey, Brookshaw and Ineson, 2014) suggests that the El Niño-associated cooling over Fennoscandia and the Baltic states is less apparent during extreme El Niño events. Furthermore, they note no precipitation anomaly in the region during El Niño, and no effects in the region of La Niña on either precipitation or surface air temperatures. There was a small reduction in mean annual discharge in rivers in southern Norway under El Niño (increase under La Niña), but no signal in other rivers from across the region (Ward *et al.*, 2010). Causal links between river discharge and indicators of

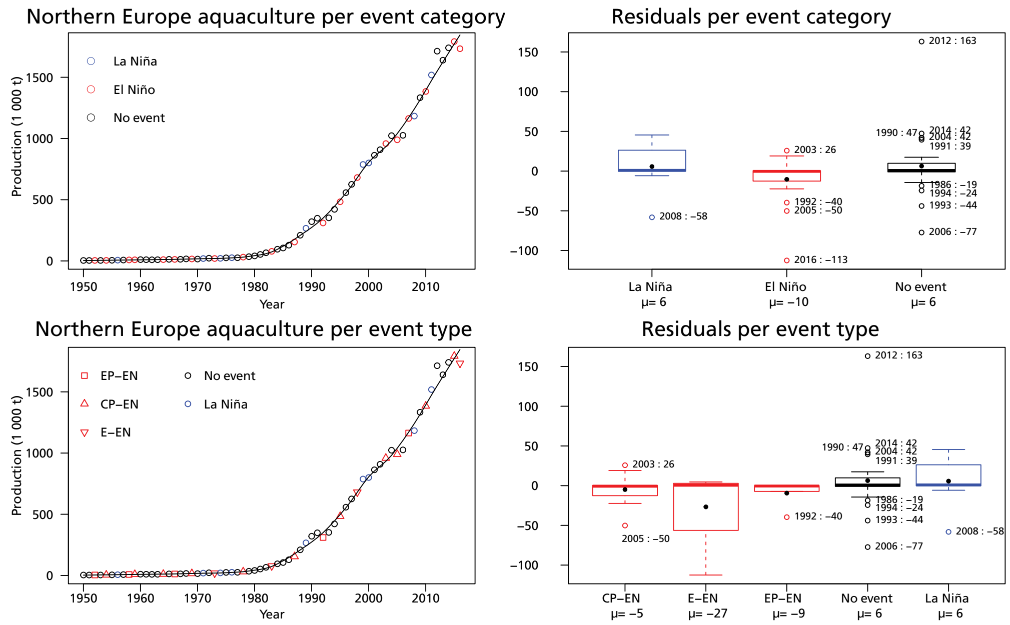
ENSO variability exist in the Northern Europe region (Su *et al.*, 2018) but these were generally less important than other ocean signals such as the North Atlantic Oscillation (NAO). In terms of the relative effects of CP and EP El Niño events in Northern Europe, Graf and Zanchettin (2012) note that cooling associated with El Niño in Fennoscandia and the Baltic states only occurs during CP El Niño winters.

Annual aquaculture production in Northern Europe increased from 3 776 tonnes in 1950 to 1.73 million tonnes in 2016, with large increases starting in the late 1980s (Figure 8.7). The region was ranked fifth in terms of its contribution to global aquaculture output in 2016 (Table 8.2: 1.6 percent). A total of 54 different categories were reported in 2016, with annual yields varying 0.1 tonnes (peeled shrimp) and 1.5 million tonnes (Atlantic salmon) with a mean ±SD annual yield of 32 706 tonnes ± 207 497 tonnes. In 2016, five different species accounted for more than 99 percent of production in the region (Atlantic salmon: 86.9 percent; rainbow trout: 9.3 percent; blue mussel: 1.8 percent; Pacific cupped oyster: 0.7 percent; Arctic char: 0.4 percent).

There were no statistical differences in mean production related to the different ENSO categories or types of El Niño between 1950 and 2016 (ANOVA p-value >0.05). Mean annual production (Table 8.2) increased by +6 000 tonnes (2016: +0.4 percent; 1950 to 2016: +1.4 percent) during both neutral and La Niña years, but decreased by –10 000 tonnes (2016: –0.6 percent; 1950 to 2016: –2.4 percent) on average under El Niño conditions. CP El Niño conditions were associated with a reduction of –5 000 tonnes (2016: –0.3 percent; 1950 to 2016: –1.2 percent) in annual aquaculture yield in the region. Decreases under extreme El Niño were more notable at –27 000 tonnes, representing –1. 6 percent of the yield in 2016, or –6.4 percent of the mean yield in the region between 1950 and 2016. EP El Niño years resulted in a decrease of –9 000 tonnes (2016: –0.5 percent; 1950 to 2016: –2.1 percent).

FIGURE 8.7

Left panels: regional yearly global aquaculture production (in 1 000 t) per event category (upper panel) and type (lower panel) from Northern Europe. The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

8.2.6 Northern Africa

The region of Northern Africa (Figure 8.2) includes the states of Algeria, Egypt, Libya, Morocco, Sudan, Tunisia and Western Sahara and extends across a surface land area of 8.1 million km^2. The climate in the region includes tropical, Mediterranean, temperate and desert areas, with large spatial variation in temperature and precipitation.

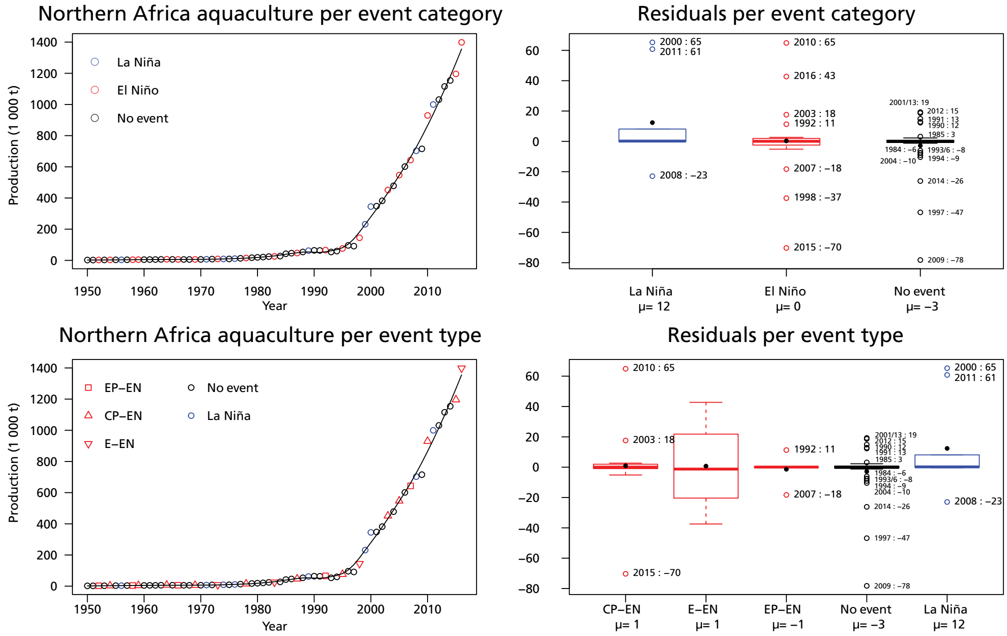
ENSO acts across the wider Mediterranean areas, with El Niño-associated with wetter conditions and La Niña with drought, but the effects vary considerably over space and time (Xoplaki *et al*., 2012). There is a positive correlation between the El Niño-3.4 index and precipitation anomalies along the Mediterranean coast of Northern Africa (north coast of Morocco, southeast coast of Tunisia and northwest coast of Libya), and with temperature in southeastern Tunisia and western Libya (Hao *et al*., 2018). There is also a negative correlation between winter El Niño-3 index and spring (March to May) precipitation across the north of Northern Africa (Knippertz *et al*., 2003). El Niño is associated with mixed effects in Morocco and Western Sahara – resulting in warming between January and March and cooling between July and September, while La Niña is associated with a cold anomaly across Morocco and Western Sahara (Davey, Brookshaw and Ineson, 2014). There is no apparent precipitation anomaly in the region, but ENSO effects explain 20 to 25 percent of the variance in natural discharge in the River Nile (Amarasekera *et al*., 1997; Eltahir, 1996), which is negatively correlated with ENSO, reflecting controls on precipitation in the Ethiopian highlands to the south of the region. Discharge in the Nile is below normal during all months with El Niño, and above normal under La Niña in September to November (Lee, Ward and Block, 2018). In terms of differences between CP and EP El Niño, the strong positive surface air temperature anomalies apparent in the western part of Northern Africa during CP El Niño are not present during EP El Niño periods (Graf and Zanchettin, 2012).

Northern Africa (Table 8.2; Figure 8.8) was ranked sixth in terms of regional aquaculture in 2016, producing 1.29 percent of global aquaculture output. Annual reported aquaculture production increased from 2 000 tonnes in 1950 to 1.4 million tonnes in 2016, with a large increase in annual yields starting in the late 1990s. In 2016, 29 different categories of aquaculture production were reported, with a mean ±SD annual yield of 48 220 tonnes ± 176 938 tonnes, and with contributions ranging from 3 tonnes (river eels nei) through to 0.94 million tonnes (Nile tilapia). Five species accounted for more than 95 percent of aquaculture production in the region in 2016 (Nile tilapia: 67.5 percent; mullets nei: 11.0 percent; cyprinids nei: 10.8 percent; common carp: 3.6 percent; gilthead seabream: 2.8 percent).

There were no obvious statistical differences (ANOVA p-value >0.05) in aquaculture production under the various ENSO categories or El Niño states (Table 8.2; Figure 8.8). Neutral conditions were associated with a small (−3 000 tonnes; 2016: −0.2 percent; 1950 to 2016: −1.4 percent) decrease in mean aquaculture production, and there was no apparent anomaly during El Niño conditions. There was a mean increase in production +12 000 tonnes under La Niña, equivalent to +0.9 percent of the 2016 yield and +5.5 percent of mean annual production between 1950 and 2016. Yield anomalies under each El Niño type were identical, and minor (+1 000 tonnes; 2016: +0.1 percent; 1950 to 2016: +0.5 percent).

FIGURE 8.8

Left panels: regional yearly global aquaculture production (in 1 000 t) per event category (upper panel) and type (lower panel) from Northern Africa. The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories or types



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

8.2.7 Northern America

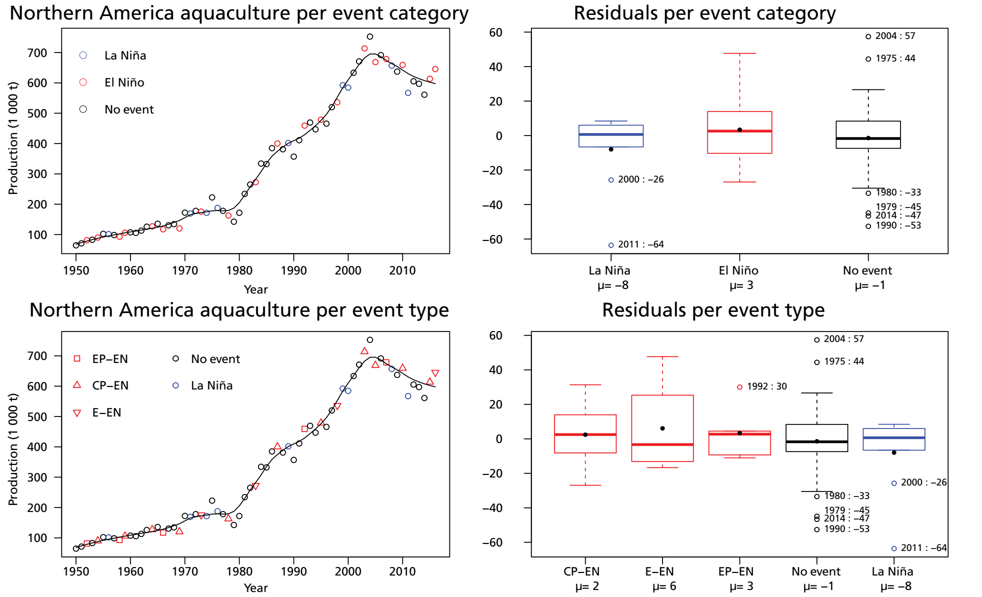
Northern America (Figure 8.2) includes Canada, Greenland and the United States of America, with a total land area of 18.7 million km^2. The region's climate is markedly diverse, ranging from tropical, temperate, semi-arid, arid to Arctic. ENSO has a strong effect on local climate: El Niño is associated with warm anomalies in Alaska, and western Canada between January and May (Davey, Brookshaw and Ineson, 2014). El Niño-associated warm anomalies extend from northeast Canada down to the Great Lakes between December and March, but El Niño conditions lead to cooler temperatures across the northeastern United States of America and northeast Canada between June and September (Davey, Brookshaw and Ineson, 2014; Hao *et al*., 2018). El Niño conditions result in cool anomalies in the southeast of the United States of America between December and April. El Niño precipitation anomalies are negative in the northeastern United States and Canada between December and May, and positive across the southern states of the United States of America between September and February (Davey, Brookshaw and Ineson, 2014). La Niña conditions are associated with cold anomalies between February and November in the Pacific northwest and southwest Alaska and warm anomalies across the southern states of the United States of America between October and April, and across the northeast of the region (including the Great Lakes) during July and October. La Niña conditions are associated with drier conditions across the southern states of the United States of America (Davey, Brookshaw and Ineson, 2014). River systems in the northwest of the region, and a smaller group of rivers in the southeast of the United States of America show a positive discharge anomaly with El Niño, while discharge anomalies in rivers across the southern states of the United States of America are negative under the same conditions (Ward *et al*., 2010).

CP and EP El Niño events have quite distinct impacts on climate in Northern America (Infanti and Kirtman, 2016). CP El Niño events result in relative drying of winters in the Pacific Northwest, central, northeast and southeast United States of America and part of central Canada (Liang *et al*., 2016), with potential impacts on the risk of subsequent droughts (Yu and Zou, 2013). CP El Niños result in cooling in the southeast of the region, warming in the northwest (Alaska), northern Canada and in the east of Arctic Canada (Graf and Zanchettin, 2012). EP El Niño events are associated with increased precipitation in the west of the region and in the southeast of the United States of America, and cooling across the southern United States of America, and warming across the north of the region (Infanti and Kirtman, 2016). Discharge in rivers across northern America is increased under EP compared to CP El Niño (Liang *et al*., 2016).

The region of Northern America (Table 8.2) was ranked seventh in terms of its contribution (0.60 percent) to global aquaculture production in 2016. Annual reported production increased from 64 583 tonnes in 1950 to 645 447 tonnes in 2016 (Figure 8.9), with a marked increase in annual yield from 1981, and a more recent slow-down in growth in the mid-2000s. Production for 33 different aquaculture products was reported from the region in 2016, with a mean ±SD annual yield of 19 559 tonnes ± 39 700 tonnes, and individual yields ranging between 3 tonnes (sea mussels nei) and 145 230 tonnes (channel catfish). Five different species/categories accounted for almost 80 percent of aquaculture production in Northern America in 2016 (channel catfish: 22.5 percent; Atlantic salmon: 21.6 percent; American cupped oyster: 18.3 percent; red swamp crawfish: 10.5 percent; Pacific cupped oyster: 5.3 percent).

There were no statistical differences in mean aquaculture production in the region between the different ENSO categories or types of El Niño between 1950 and 2016 (ANOVA p-value >0.05). Neutral conditions were associated with a small reduction in annual yield of −1 000 tonnes (2016: −0.2 percent; 1950 to 2016: −0.3 percent). Mean annual aquaculture production in Northern America was lower by −8 000 tonnes during La Niña, reflecting a reduction of −1.2 percent relative to 2016 and −2.4 percent relative to the 1950 to 2016 mean. Production showed a small increase in El Niño years (+3 000 tonnes; 2016: +0.5 percent; 1950 to 2016: +0.9 percent). Small increases were associated with both CP El Niño (+2 000 tonnes; 2016: +0.3 percent; 1950 to 2016 +0.6 percent) and EP El Niño (+3 000 tonnes; 2016: +0.5 percent; 1950 to 2016: +0.9 percent), while mean production increased by +6 000 tonnes under extreme El Niño (2016: +0.9 percent; 1950 to 2016: +1.8 percent).

FIGURE 8.9
Left panels: regional yearly global aquaculture production (in 1 000 t) per event category (upper panel) and type (lower panel) from Northern America. The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories or types



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

8.2.8 Southern Europe

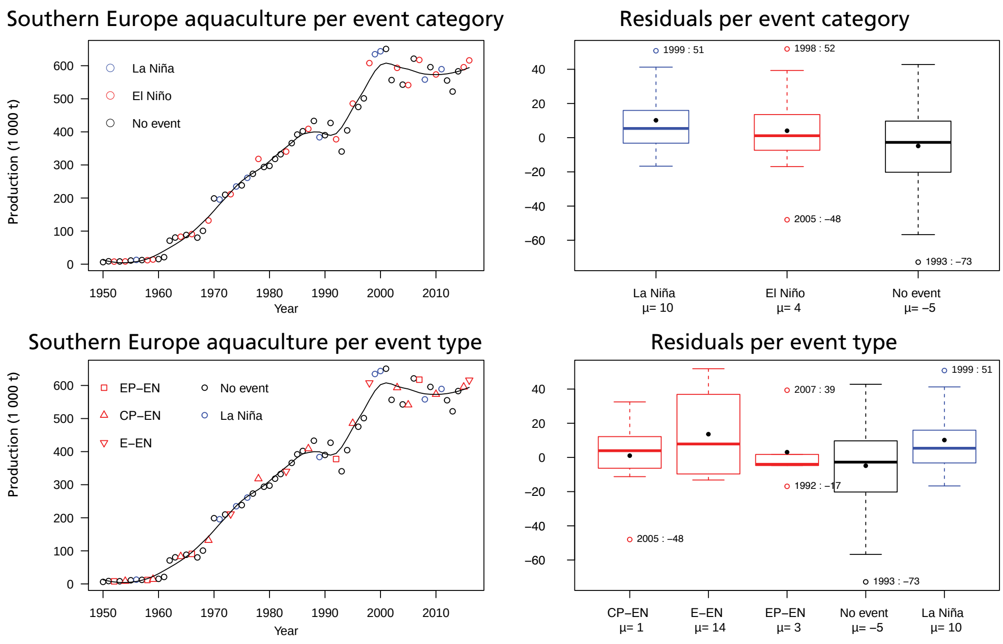
Data on aquaculture production from the region of Southern Europe (Figure 8.2) included information from Albania, Andorra, Bosnia and Herzegovina, Croatia, Gibraltar, Greece, Italy, Malta, Montenegro, North Macedonia, Portugal, San Marino, Serbia, Slovenia and Spain. The region has a total land area of 0.43 million km^2. Climates in the region range from semi-arid, Mediterranean, through to temperate maritime and temperate continental, and alpine.

El Niño events are associated with warm temperature anomalies across Spain, Italy, the Balkans and western Greece between October and November and positive precipitation anomalies across the Iberian Peninsula between August and November (Davey, Brookshaw and Ineson, 2014). Conversely, no temperature anomalies are apparent during La Niña events, but negative precipitation anomalies are apparent in the Iberian Peninsula, and positive ones more to the east of the region (Brönnimann, 2007; Davey, Brookshaw and Ineson, 2014). La Niña conditions are also associated with observed and modelled negative anomalies in streamflow in the west of the region (Lee, Ward and Block, 2018), and reduced discharge under La Niña conditions (Ward *et al.*, 2010). CP El Niño conditions are associated with negative surface air temperature anomalies in northern Italy, while EP El Niño is associated with negative temperature anomalies in southern Italy (Graf and Zanchettin, 2012).

Ranked eighth in terms of contribution (0.57 percent) to global aquaculture production in 2016 (Table 8.2), Southern Europe saw an increase in annual production from 6 065 tonnes in 1950 to 616 153 tonnes in 2016 (Figure 8.10). A total of 82 different aquaculture species/products were reported in 2016, with annual yields varying between <0.1 tonnes (*Gracilaria* seaweeds) through to 216 229 tonnes (sea mussels nei) with a mean ±SD annual production of 7514 tonnes ± 28 972 tonnes. Five species contributed more than 85 percent of total aquaculture production in Southern Europe in 2016 (Sea mussels nei: 35.1 percent; Mediterranean mussels: 14.6 percent; gilthead seabream: 12.8 percent; European seabass: 12.8 percent; rainbow trout: 9.9 percent).

There were no obvious statistical differences (ANOVA p-value >0.05) in aquaculture production under the various ENSO categories or El Niño states (Table 8.2; Figure 8.10). Neutral ENSO conditions were associated with minor mean reductions in annual aquaculture production of –5 000 tonnes (2016: –0.8 percent; 1950 to 2016: –1.6 percent). Aquaculture production in La Niña years in Southern Europe increased on average by 10 000 tonnes, equivalent to +1.6 percent of regional annual production in 2016 and to +3.1 percent of long-term (1950 to 2016) average annual production. On average, annual production increased by +4 000 tonnes (2016: +0.7 percent; 1950 to 2016: +1.2 percent) during El Niño years. Mean yields showed negligible increases under both CP El Niño conditions (+1 000 tonnes; 2016: +0.2 percent; 1950 to 2016: +0.3 percent) and EP El Niño (+3 000 tonnes; 2016: +0.5 percent; 1950 to 2016: +0.9 percent). Conversely, aquaculture production in the region increased considerably during extreme El Niño years, with a mean production anomaly of +14 000 tonnes, equivalent to +2.3 percent of production in 2016, and +4.4 percent of mean production between 1950 and 2016.

FIGURE 8.10
Left panels: regional yearly global aquaculture production (in 1 000 t) per event category (upper panel) and type (lower panel) from Southern Europe. The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories or types



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

8.2.9 Western Africa

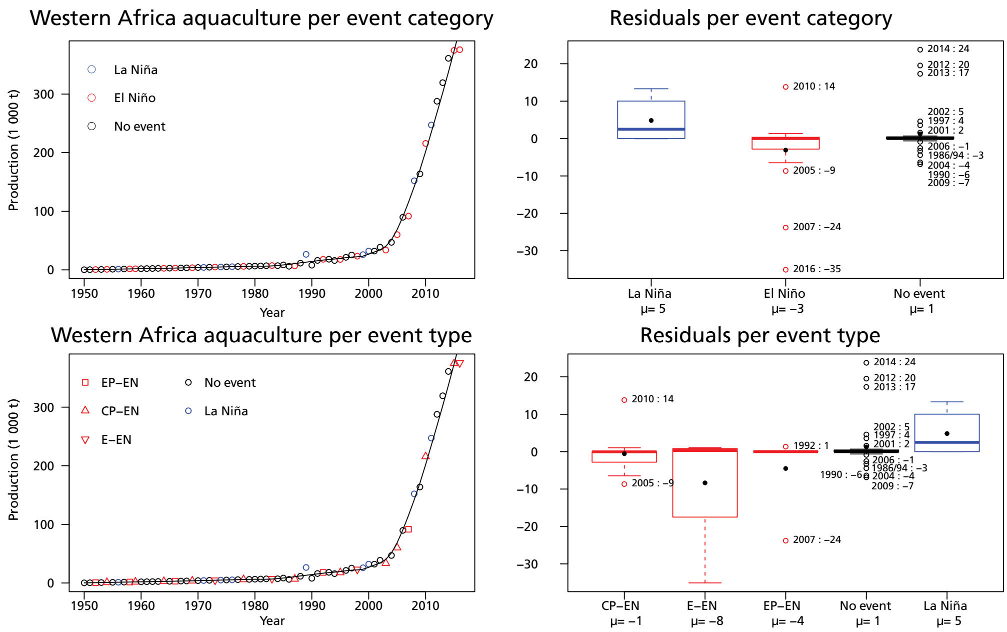
The Western Africa region (Figure 8.2) includes Benin, Burkina Faso, Cabo Verde, Côte d'Ivoire, the Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, the Niger, Nigeria, Saint Helena, Senegal, Sierra Leone and Togo. It extends across a total land surface area of 6.06 million km². The climate of the region is largely tropical and hot/warm with marked dry and wet seasons, but includes arid areas and hot, dry desert. ENSO variation affects climate in the region, but many impacts are limited to particular geographical areas (Davey, Brookshaw and Ineson, 2014). Temperature anomalies are mixed, with northern Mauritania showing positive temperature anomalies under El Niño between January and March, but negative anomalies between July and September. Positive temperature anomalies are apparent across the southwest and south of the region between February and April of El Niño years (Davey, Brookshaw and Ineson, 2014; Hao *et al*., 2018). Precipitation anomalies under El Niño conditions are negative across the south of the region between July and September. La Niña conditions are associated with cooling in the west of the region during January to March, and increased precipitation between July and September. River discharges in the region are greater during La Niña conditions (Ward *et al*., 2010). CP El Niño conditions are associated with more marked positive temperature anomalies in the north of the region (Graf and Zanchettin, 2012), and increased river discharge (Liang *et al*., 2016).

Aquaculture production in Western Africa was ranked ninth out of the different regions in 2016, with 0.35 percent of global production (Table 8.2). Annual aquaculture yield increased in the region from 213 tonnes in 1950 to 375 716 tonnes in 2016 (Figure 8.11). A total of 29 different aquaculture products were reported in 2016, with annual yields ranging between 2 tonnes (redbelly tilapia) through to 165 463 tonnes (North African catfish) with a mean ±SD annual yield of 12 956 tonnes ± 32 167 tonnes. Five species/categories accounted for >80 percent of aquaculture production in 2016 in Western Africa including North African catfish (44.0 percent), Nile tilapia (16.0 percent), Cyprinids nei (8.0 percent), torpedo-shaped catfishes (7.8 percent) and tilapias nei (6.4 percent).

Comparison of mean production anomalies in Western Africa showed no differences between different ENSO states or El Niño types (ANOVA p-value >0.05). Mean annual aquaculture yields increased on average by +1 000 tonnes under neutral conditions (2016: +0.3 percent; 1950 to 2016: +1.6 percent). Mean production increased by +5 000 tonnes during La Niña years – an equivalent of +10.2 percent of mean annual production between 1950 to 2016, and +1.3 percent of 2016 production. Mean production decreased by 3 000 tonnes on average across El Niño years, representing +0.8 percent of 2016 production or +6.1 percent of mean production between 1950 and 2016. CP El Niño was associated with a small mean decrease in regional aquaculture yields (−1 000 tonnes; 2016: −0.3 percent; 1950 to 2016: −2.0 percent). Annual production decreased considerably during both extreme El Niño (−8 000 tonnes; 2016: −2.1 percent; 1950 to 2016 −16.3 percent) and EP El Niño years (−4 000 tonnes; 2016: −1.1 percent; 1950 to 2016: −8.1 percent).

FIGURE 8.11

Left panels: regional yearly global aquaculture production (in 1 000 t) per event category (upper panel) and type (lower panel) from Western Africa. The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories or types



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

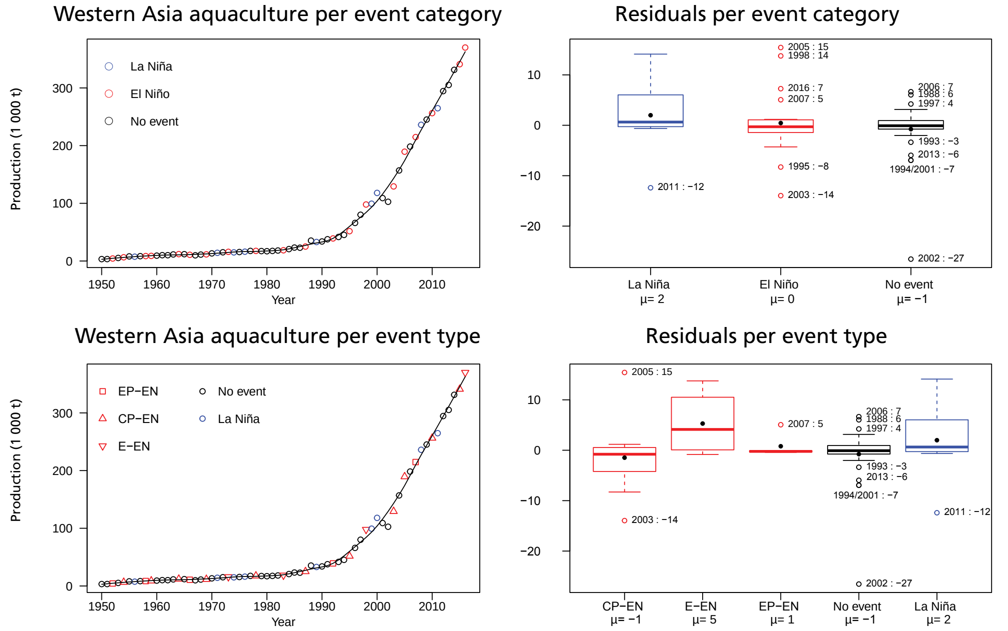
8.2.10 Western Asia

Western Asia extends over a land area of 4.8 million km² (Figure 8.2) and includes Armenia, Azerbaijan, Bahrain, Cyprus, Georgia, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, the Syrian Arab Republic, Turkey, the United Arab Emirates and Yemen. Climate in the region is diverse and includes temperate and Mediterranean climates through to extremely hot and arid deserts. Generally, there is little evidence for strong effects of ENSO on climate in Western Asia and Davey, Brookshaw and Ineson (2014) do not note any typical climatic shifts in the region. However, other authors (Hoell *et al*., 2018; Pagano *et al*., 2003) have concluded that El Niño conditions are associated with a tendency towards wetter than normal conditions during autumn and winter, and lower precipitation during La Niña. Indeed, droughts have been reported in Turkey following La Niña (Xoplaki *et al*., 2012), where the influence of the NAO on temperature, precipitation and streamflow is strong, with high NAO winters resulting in dry and cool conditions. Where they exist, relationships between ENSO and the climate indices are generally stronger for temperature indices than for the precipitation in the region (Donat *et al*., 2014). However, variation in precipitation (Karabork and Kahya, 2003) and streamflow in parts of Turkey is affected by ENSO (Kahya and Karabörk, 2001) but the signal is mixed and differs between northwest and eastern Turkey. Work to date indicates that there are no obvious effects of EP El Niño in terms of surface air temperature anomalies, but CP El Niños are associated with a positive temperature anomaly in southeast Iraq and Saudi Arabia (Graf and Zanchettin, 2012).

Ranked tenth in terms of its contribution (0.34 percent) to global aquaculture production in 2016 (Table 8.2), Western Asia saw increases in annual yield from 315 tonnes in 1950 to 370 014 tonnes in 2016 (Figure 8.12). A total of 44 different aquaculture species/categories were reported from Western Asia in 2016, with annual yields varying between <0.1 tonnes (marbled spinefoot) to 106 283 tonnes (rainbow trout) with a mean ±SD annual yield of 8 409 tonnes ± 22 625 tonnes. In 2016, five different species contributed more than 85 percent of all aquaculture production in Western Asia (rainbow trout: 28.7 percent; European seabass: 22.4 percent; gilthead seabream: 18.8 percent; common carp: 9.3 percent; whiteleg shrimp: 6.5 percent).

Aquaculture production in Western Asia was similar under different ENSO states or El Niño types (ANOVA p-value >0.05). A small negative anomaly was recorded during neutral conditions (–1 000 tonnes; 2016: –0.3 percent; 1950 to 2016: –1.3 percent) while aquaculture production in the region during La Niña years increased by +2 000 tonnes (2016: +0.5 percent; 1950 to 2016: +2.7 percent). There was no production anomaly apparent during El Niño years in Western Asia, when all types of events were combined into a single ENSO category. When considered individually, CP El Niño and EP El Niño were both associated with small 1 000 tonnes anomalies, negative in the case of CP El Niño and positive in the case of EP El Niño – equivalent to ±0.3 percent of 2016 production and ±1.3 percent of the 1950 to 2016 mean for the region. The anomaly associated with extreme El Niño in Western Asia was positive and larger (+5 000 tonnes) reflecting +1.4 percent of 2016 total production in the region, or +6.7 percent of the long-term (1950 to 2016) mean.

FIGURE 8.12
Left panels: regional yearly global aquaculture production (in 1 000 t) per event category (upper panel) and type (lower panel) from Western Asia. The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories or types



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

8.2.11 Central America

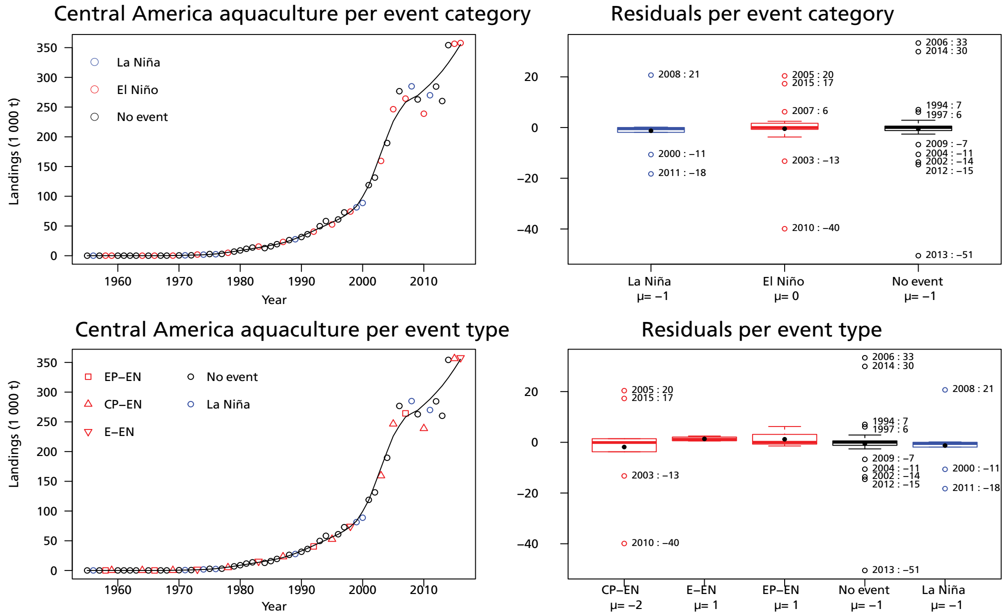
The Central America region (Figure 8.2) includes Belize, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua and Panama. It has a total land area of 2.4 million km². The regional climate is typically hot, humid and tropical, but also extends to temperate and desert areas, as well as cooler highlands. El Niño conditions are associated with cooler temperatures between December and April in the north of the region, and warmer conditions throughout the year in the southern part (Davey, Brookshaw and Ineson, 2014; Hao *et al*., 2018). The north of the region tends to be cooler between October and April and drier between December and February during La Niña conditions. The southern part of the region is typically colder in La Niña periods (Davey, Brookshaw and Ineson, 2014). EL Niño is associated with wet summers in Mexico during periods of low PDO and during winters of high PDO (Pavia, Graef and Reyes, 2006). River discharge is positively correlated with SOI in the region (Ward *et al*., 2010). Both EP and CP El Niños are associated with a positive temperature anomaly in southern central America. EP El Niño conditions result in positive precipitation anomalies in the southern part of the region (Graf and Zanchettin, 2012). The Río Grande showed increased discharge under EP El Niño during the developing phase, but it was similar to that seen under CP El Niño conditions during the mature and decaying phases (Liang *et al*., 2016). El Niño conditions have been seen to affect aquaculture production in the region, when La Niña restricted the supply of seed (Cornejo-Grunauer, 2002), but this was resolved through the development of hatcheries.

Information on aquaculture production in Central America first became available from 1955 (50 tonnes), increasing to 357 799 tonnes by 2016 (Figure 8.13). The region was ranked eleventh in terms of its contribution (0.33 percent) to global aquaculture production in 2016 (Table 8.2), when production was divided across 36 different aquaculture categories ranging in yields from 0.1 tonnes (Jaguar guapote) to 198 849 tonnes (whiteleg shrimp) with a mean ±SD annual contribution of 9 939 ± 35 199 tonnes. Five different species/categories accounted for 94 percent of aquaculture production in Central America in 2016 (whiteleg shrimp: 55.6 percent; tilapias nei: 18.7 percent; Nile tilapia: 14.5 percent; rainbow trout: 2.7 percent; Pacific bluefin tuna: 2.5 percent).

ENSO state had no measurable effect (ANOVA p-value >0.05) on aquaculture production in the Central America region (Figure 8.13, Table 8.2). El Niño events had no obvious effect on mean production, while La Niña and neutral periods were associated with small (–1 000 tonnes) negative anomalies (2016: –0.3 percent; 1955 to 2016: –1.3 percent). Production anomalies during both extreme and EP El Niño event types were minor (+1 000 tonnes; 2016: –0.3 percent; 1955 to 2016: –1.3 percent). CP El Niño events were associated with a slightly larger negative mean production anomaly in Central America (–2 000 t; 2016: +0.6 percent; 1955 to 2016: +2.5 percent).

FIGURE 8.13

Left panels: regional yearly global aquaculture production (in 1 000 t) per event category (upper panel) and type (lower panel) from Central America. The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (13 000 t) under each of the event categories or types



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

8.2.12 Eastern Africa

Covering a total land area of 6.05 million km², the Eastern Africa region (Figure 8.2) extends along the eastern coast of Africa and incudes the nations of Burundi, Comoros, Djibouti, Eritrea, Ethiopia, French Southern Territories, Kenya, Madagascar, Malawi, Mauritius, Mayotte, Mozambique, Réunion, Rwanda, Seychelles, Somalia, South Sudan, United Republic of Tanzania, Uganda, Zambia, Zanzibar and Zimbabwe, as well as the British Indian Ocean Territory. The region's climate is very varied, ranging from tropical monsoon-driven areas, subtropical, temperate highlands, through to hyper-arid, very hot deserts. Some regions experience multiple rainy seasons, others rainy and dry seasons and others minimal annual precipitation.

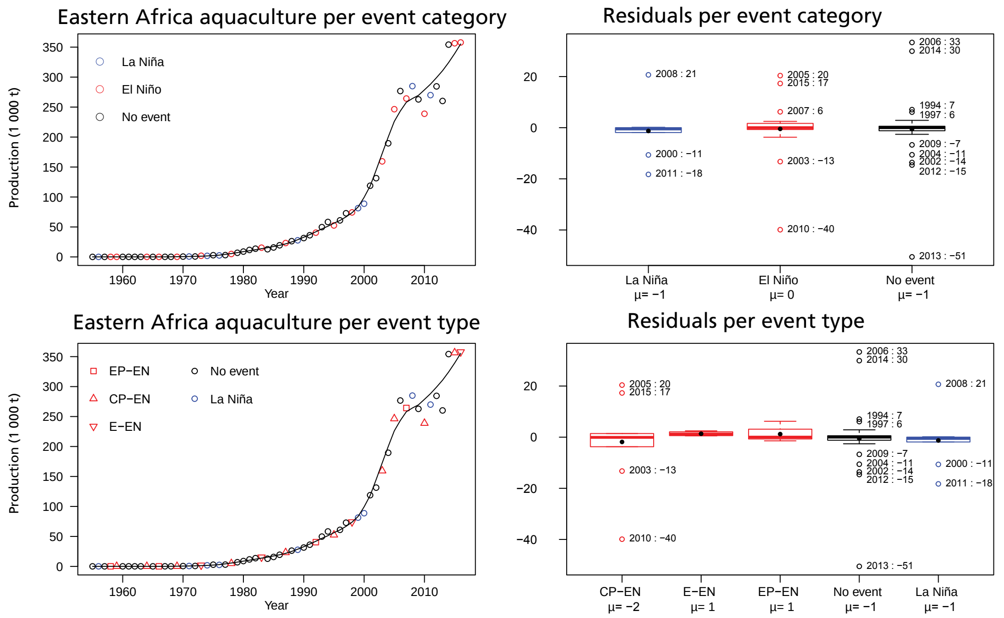
There is little evidence for ENSO effects on temperature in the region (Collins, 2011), but several authors indicate that El Niño years are associated with increased temperatures in the east and south of the region while La Niña events are associated with cooling (Davey, Brookshaw and Ineson, 2014; Hao *et al*., 2018). Effects of ENSO on precipitation in Eastern Africa are more complex – precipitation is reduced between June and August during El Niño in Ethiopia, Uganda and Kenya but increased between December and February in Kenya and United Republic of Tanzania. The main rainy season droughts in Ethiopia are more likely to occur during the years of warm ENSO events (Seleshi and Demaree, 1995). Precipitation decreases during December and February in La Niña years in Uganda, Kenya and northern United Republic of Tanzania, but increases in coastal southern United Republic of Tanzania. Rain also increases during June to August under La Niña in southern Sudan, northwest Ethiopia, Uganda and eastern United Republic of Tanzania (de Oliveira *et al*., 2018). Variability in the short rains in the African Great Lakes region is driven by ENSO, with El Niño years being associated with above normal rainfall in the short rains period (Kizza *et al*., 2009). Satellite-derived data indicates that there are clear associations between

ENSO and key limnological characteristics (lake surface temperature and chlorophyll a concentrations) across many of the African Great Lakes, but the scale, and the sign of the effect differs between lakes (Loiselle *et al.*, 2014). Positive temperature anomalies in the region were slightly less extensive during CP EL Niños relative to EP El Niños (Graf and Zanchettin, 2012).

Annual aquaculture production in Eastern Africa varied between 180 tonnes in 1950 and 334 853 tonnes in 2016 (Figure 8.14), when it was ranked twelfth in terms of its contribution (0.31 percent) to global aquaculture production (Table 8.2). In 2016, 26 different aquaculture species/categories were reported from the region, with annual contributions varying between <0.1 tonnes (giant river prawn) and 115 049 tonnes (Nile tilapia), with a mean ±SD annual contribution of 12 879 tonnes ± 31 198 tonnes. Five species/categories contributed more than 92 percent to total aquaculture production in Eastern Africa in 2016: Nile tilapia (34.4 percent), spiny *Eucheuma* (33.3 percent), North African catfish (13.8 percent), *Eucheuma* seaweeds nei (7.4 percent) and tilapias nei (3.6 percent). Annual aquaculture yields did not differ statistically by ENSO event category (ANOVA p-value >0.05) or type (Table 8.2, Figure 8.14). Mean anomalies in annual aquaculture production in Eastern Africa were small (+1 000 tonnes) in El Niño and neutral years, an amount equivalent to +0.3 percent of 2016 production, or +0.7 percent of the mean annual production between 1950 and 2016. La Niña events were associated with a slightly larger and negative (−3 000 tonnes) anomaly, representing −0.9 percent of 2016 production, or −2 percent of the mean annual production in Eastern Africa between 1950 and 2016. There was no apparent variation in aquaculture production in EP El Niño years, but the mean annual production anomaly during CP El Niño periods was +6 000 tonnes, (2016: +1.8 percent; 1950 to 2016: +4.0 percent). Production fell by −12 000 tonnes during extreme El Niño periods, equivalent to −3.6 percent of total aquaculture production in 2016 or −8.0 percent of mean production between 1950 and 2016 in Eastern Africa.

FIGURE 8.14

Left panels: regional yearly global aquaculture production (in 1 000 t) per event category (upper panel) and type (lower panel) from Eastern Africa. The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories or types



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

8.2.13 Eastern Europe

The Eastern Europe region (Belarus, Bulgaria, Czechia, Hungary, Republic of Moldova, Poland, Romania, the Russian Federation, Slovakia, Ukraine) is extremely large (approximately 18.1 million km^2), and somewhat of a misnomer, as it includes the Russian Federation, which extends from the east of continental Europe, across Eurasia to the Russian Far East (Figure 8.2). Climatic variation in the region is considerable, including Mediterranean areas to the south, continental and marine temperate, subarctic and tundra. Winters range between cool to frigid, and summers from cool and moist through to hot and dry.

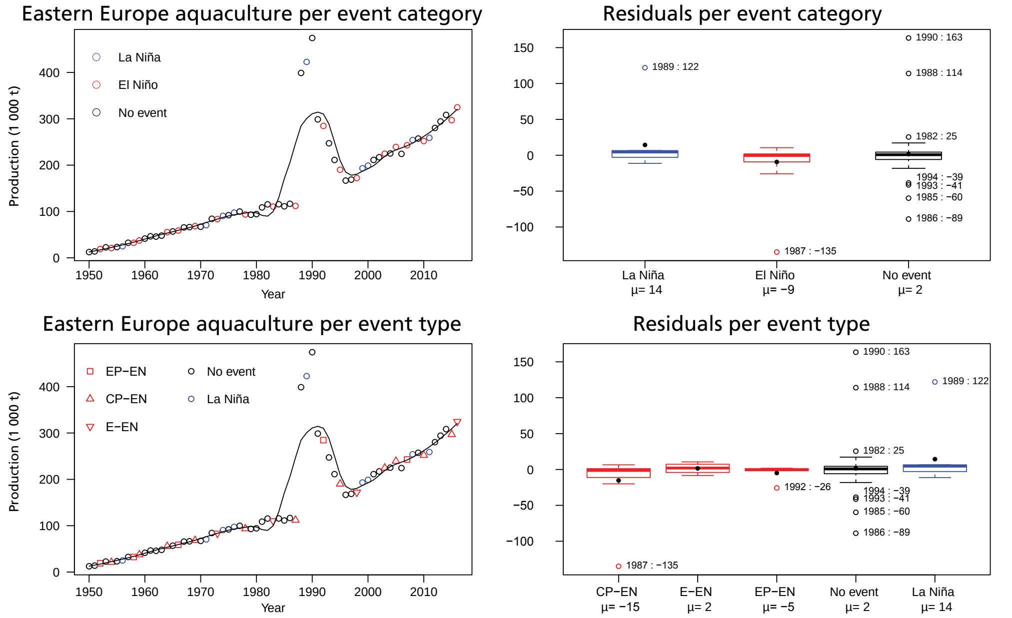
There is little evidence for large scale effects of ENSO on temperature or precipitation across the region (Hao *et al.*, 2018) but the western part of the region (northwest Russian Federation, Poland) is colder and wetter under El Niño during winter and spring, with the inverse under La Niña (Brönnimann, 2007; Davey, Brookshaw and Ineson, 2014). Most authors have suggested that there is little effect of ENSO on summer temperatures in the west of the region. However, extreme summer temperatures in 2010 led Sun, Li and Ding (2016) to re-examine relationships between ENSO and climate in the western Russian Federation. They showed that the relationship strengthened considerably after 1980 and that El Niño events in the Eastern Pacific were increasingly clearly associated with negative temperature anomalies, and La Niña with positive temperature anomalies in summer in the western Russian Federation. In the southern part of the Russian Federation Far East, El Niños under certain global atmosphere oscillation (GAO) conditions lead to reduced air temperatures and precipitation during winter months, and decreased precipitation but slightly increased air temperatures in summer (Byshev *et al.*, 2014). There is little evidence that ENSO affects river discharge in the region (Lee, Ward and Block, 2018; Ward *et al.*, 2010) beyond the extreme north of the Russian Federation Far East where maximum river discharge was positively correlated with the SOI, i.e. reduced during El Niño and increased during La Niña (Lee, Ward and Block, 2018).

Comparisons of conditions during CP and EP El Niños (Graf and Zanchettin, 2012) indicate that a marked negative temperature anomaly is apparent during CP El Niño that extends longitudinally from Poland to central Siberia mid-Russian Federation and latitudinally from the Arctic coast to the Black, Caspian and Aral seas. No such anomaly is present in this area during EP El Niños. CP El Niños are associated with a cold anomaly in the Amur region of the Russian Federation Far East. This anomaly continues and expands to the west and the north during EP El Niño (Graf and Zanchettin, 2012). Discharge in the Don River was consistently lower during EP El Niño compared to CP El Niño, but discharge anomalies were similar during the two different El Niño types in the Danube River (Liang *et al.*, 2016). Discharge anomalies in the Amur River basin are higher under CP El Niño conditions in the developing phase of the event, similar in both types during the mature phase, and then higher in EP El Niño conditions in the decaying phase of El Niño events (Liang *et al.*, 2016).

Aquaculture production in the Eastern European region increased from 12 440 tonnes in 1950 to 324 621 tonnes in 2016 but followed an unusual pattern (Figure 8.15) with a rapid increase in yields in the late 1980s, peaking at 474 278 tonnes in 1990, followed by a rapid fall in production and then subsequent gradual growth. In 2016, the region contributed 0.30 percent to global aquaculture production, resulting in it being ranked thirteenth in terms of regional contributions. At this time, a total of 55 different aquaculture products were reported from Eastern Europe, with annual yields ranging between <0.1 tonnes (chub) through to 140 471 tonnes (common carp) with a mean ±SD value of 5 902 tonnes ± 21 205 tonnes. In 2016, five different species/categories contributed more than 85 percent of all aquaculture production including common carp (43.3 percent), silver carp (17.7 percent), rainbow trout (15.9 percent), Atlantic salmon (4.0 percent) and freshwater fishes nei (2.9 percent).

Although mean annual production anomalies from aquaculture in Eastern Europe varied considerably by ENSO category and type (Figure 8.15, Table 8.2), they were not statistically different (ANOVA p-value >0.05). Neutral ENSO events were associated with a minor increase (+2 000 tonnes; 2016: +0.6 percent; 1950 to 2016: +0.7 percent) in aquaculture production, but production during La Niña events was on average +14 000 tonnes larger than average, representing +4.3 percent of 2016 production, and +4.6 percent of mean production between 1950 and 2016. Aquaculture production during El Niño events was reduced on average by –9 000 tonnes (2016: –2.8 percent; 1950 to 2016: –2.9 percent). CP El Niño conditions were associated with a considerable decrease (–15 000 tonnes) in aquaculture production in Eastern Europe, equivalent to –4.6 percent of total regional production in 2016, or –4.9 percent of the 1950 to 2016 annual mean. Aquaculture production during extreme El Niño years increased slightly (+2 000 tonnes; 2016: –0.6 percent; 1950 to 2016: –0.7 percent) in Eastern Europe, while production in the region fell by –5 000 tonnes during EP El Niño years, reflecting a reduction of –1.5 percent or –1.6 percent of the 2016 total and the 1950 to 2016 mean, respectively.

FIGURE 8.15
Left panels: regional yearly global aquaculture production (in 1 000 t) per event category (upper panel) and type (lower panel) from Eastern Europe. The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories or types



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

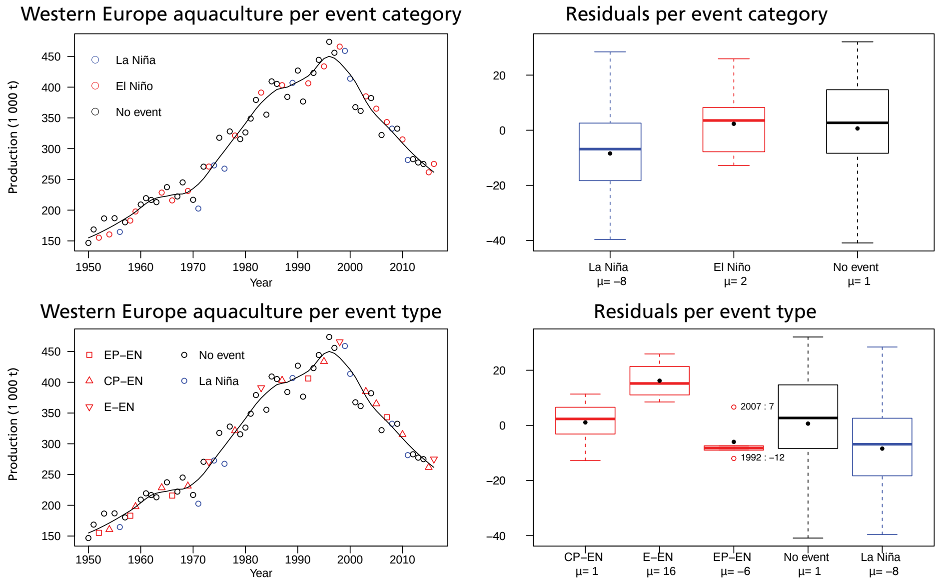
8.2.14 Western Europe

The region of Western Europe (total land area: 1.06 million km²) includes Austria, Belgium, France, Germany, Liechtenstein, Luxembourg, Monaco, the Netherlands and Switzerland (Figure 8.2). Its climate varies between temperate marine to the west, and temperate continental to the east and Mediterranean to the south. Winters are typically cool or cold, with rain or snow depending on location or altitude, and summers are cool to hot, with varying levels of precipitation from occasional showers, humid to frequent rain showers. As noted above for other European regions, evidence for major ENSO effects on weather in Western Europe is limited (Brönnimann, 2007). During El Niño events, the northwest of the region sees reduced precipitation during summer (Hao *et al*., 2018), while the southwest of the region sees warmer air temperatures between October and November (Davey, Brookshaw and Ineson, 2014). Wetter conditions are seen between August and November in southeastern France during El Nino, with the sign of the anomaly being reversed under La Niña (Davey, Brookshaw and Ineson, 2014). Streamflow in several rivers across Western Europe shows significant associations with ENSO variation (Su *et al*., 2018). River discharge shows mixed responses to ENSO, both by location and time of year but is typically higher during El Niño conditions and lower under La Niña (Donat *et al*., 2014; Lee, Ward and Block, 2018). There is little evidence for differences in precipitation or temperature anomalies in the region under EP or CP El Niños (Graf and Zanchettin, 2012).

Western Europe was ranked fourteenth in terms of its contribution (0.25 percent) to global aquaculture production in 2016 (Table 8.2). Production in the region grew from 146 700 tonnes in 1950, peaked at 465 869 tonnes in 1998 and then declined to 275 161 tonnes in 2016. In 2016, a total of 45 aquaculture species/categories were reported, with annual contributions varying between 1.6 tonnes (grayling) and 122 013 tonnes (blue mussel), and a mean ±SD annual yield of 6 115 tonnes ±20 779 tonnes. Five species/categories were associated with more than 84 percent of production in Western Europe in 2016 (blue mussel: 44.3 percent; Pacific cupped oyster: 23.4 percent; rainbow trout: 13.6 percent; Mediterranean mussel: 3.8 percent; common carp: 3.6 percent).

There was no measurable effect (ANOVA p-value >0.05) of the different ENSO event categories and types on aquaculture production in Western Europe (Table 8.2, Figure 8.16). Neutral events were associated with a mean increase of just +1 000 tonnes (2016: +0.4 percent; 1950 to 2016: +1.6 percent), while annual production during La Niña years was reduced on average by −8 000 tonnes – equivalent to −2.9 percent of 2016 production, and −13.1 percent of mean annual production in the region between 1950 and 2016. Aquaculture production in El Niño years increased on average by +2 000 tonnes (2016: +0.7 percent; 1950 to 2016: +3.3 percent). When considered as separate categories, aquaculture production in Western Europe increased by +1 000 onnes during CP El Niño years, and by +16 000 tonnes during extreme El Niño events. The latter represents +5.8 percent of 2016 production, or +26.2 percent of mean annual production in the region between 1950 and 2016. Conversely, mean aquaculture production was reduced by −6 000 tonnes during EP El Niño, equivalent to −2.2 percent of 2016 production, or −9.8 percent of annual mean aquaculture production in Western Europe between 1950 and 2016.

FIGURE 8.16
Left panels: regional yearly global aquaculture production (in 1 000 t) per event category (upper panel) and type (lower panel) from Western Europe. The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories or types



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

8.2.15 Australia and New Zealand

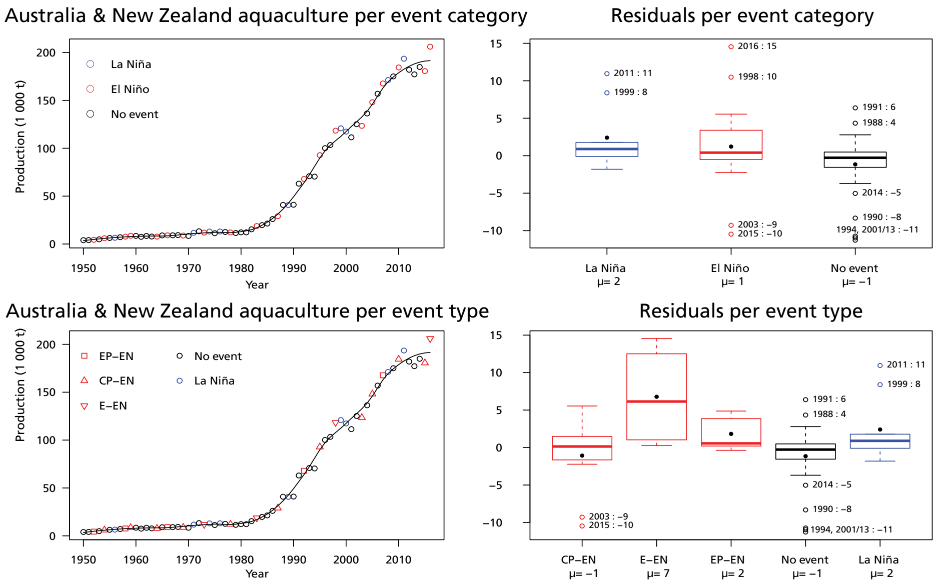
The climate of the region of Australia and New Zealand (Figure 8.2; land area: 7.9 million km²) varies considerably. Australia's climate is generally arid to semi-arid for much of the country, but there are temperate areas in the south and east and the north is tropical. New Zealand is temperate with marked regional contrasts between the North (semi-tropical) and South islands. ENSO has marked and variable effects on climate in the region (Davey, Brookshaw and Ineson, 2014; Hao *et al.*, 2018). Generally, under El Niño conditions, positive temperature anomalies are apparent across the north, east, south and west coasts of Australia in the austral spring–autumn (timing depends on location), but cold anomalies are apparent across the central north coast during austral winter and spring. Precipitation anomalies in Australia are negative under El Niño, occurring along the southern, western, northeastern and eastern coasts at different times of the year (Davey, Brookshaw and Ineson, 2014; Hao *et al.*, 2018). New Zealand exhibits negative temperature anomalies under El Niño between Austral autumn and spring, and drier conditions are found across the North Island and the northern part of the South Island. The very southern and southwestern regions of the South Island experience moderately wetter conditions under El Niño (Ummenhofer and England, 2007). Under La Niña conditions, northern Australia is warmer during austral winter and spring, but eastern Australia is cooler during the austral summer (Davey, Brookshaw and Ineson, 2014). Precipitation patterns during La Niña events see southwestern Australia being wetter from late autumn through to early summer, and eastern Australia being wetter between autumn and summer. La Niña is associated with warmer than average weather in New Zealand (Davey, Brookshaw and Ineson, 2014), and increased precipitation in the northwest of the North Island and along the western side of the South Island (Ummenhofer and England, 2007). Discharge patterns in rivers in Australia and New Zealand are commonly associated with ENSO variation (Su *et al.*, 2018). Australia shows a general pattern of reduced rainfall and streamflow under El Niño, but with regional differences between western and eastern Australia in terms of the timing and length of effects (Chiew *et al*., 1998). River discharge in Eastern Australia is positively correlated with SOI, indicating reduced flow under El Niño conditions (Ward *et al*., 2010). CP and EP El Niños result in distinct climatic conditions in Australia. EP El Niños are associated with warm anomalies across the western coast and the southeast of Australia (Graf and Zanchettin, 2012) and reduced precipitation over northeastern and southeastern Australia (Taschetto and England, 2009). Under CP El Niños, warm anomalies are recorded in the southwest of Australia (Graf and Zanchettin, 2012) and decreased rainfall over northwestern and northern Australia (Taschetto and England, 2009). Discharge in the Murray River basin is similar under EP and CP El Niño conditions (Liang *et al*., 2016).

The Australia and New Zealand region contributed 0.19 percent of global aquaculture production in 2016, leading it to be ranked fifteenth in terms of regional production. Annual aquaculture production rose from 4 000 tonnes in 1950 to 206 062 tonnes in 2016. In 2016, contributions were recorded from 21 different aquaculture species and categories, ranging from 8.5 tonnes (rainbow trout) up to 94 037 tonnes (New Zealand mussel), with a mean ±SD annual yield of 9 812 tonnes ± 22 785 tonnes per species/category. Five species/categories contributed more than 87 percent of total aquaculture production in 2016 (New Zealand mussel: 45.6 percent; Atlantic salmon: 27.2 percent; Chinook salmon: 6.3 percent; southern bluefin tuna: 4.3 percent; flat and cupped oysters: 4.0 percent).

There was no statistical support for differences in annual aquaculture production between different ENSO event categories or types (ANOVA p-value >0.05) but production anomalies are provided in Figure 8.17 and Table 8.2 for reference. Production anomalies from the Australia and New Zealand region were generally small (–1 000 tonnes to + 2 000 tonnes) for the different ENSO categories and CP/EP El Niños but there was a notable shift from average conditions under extreme El Niño, when production was increased on average by +7 000 tonnes, equivalent to +3.4 percent of 2016 production, or +11.7 percent of mean annual aquaculture production in the region between 1950 and 2016.

FIGURE 8.17

Left panels: regional yearly global aquaculture production (in 1 000 t) per event category (upper panel) and type (lower panel) from Australia and New Zealand. The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories or types



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

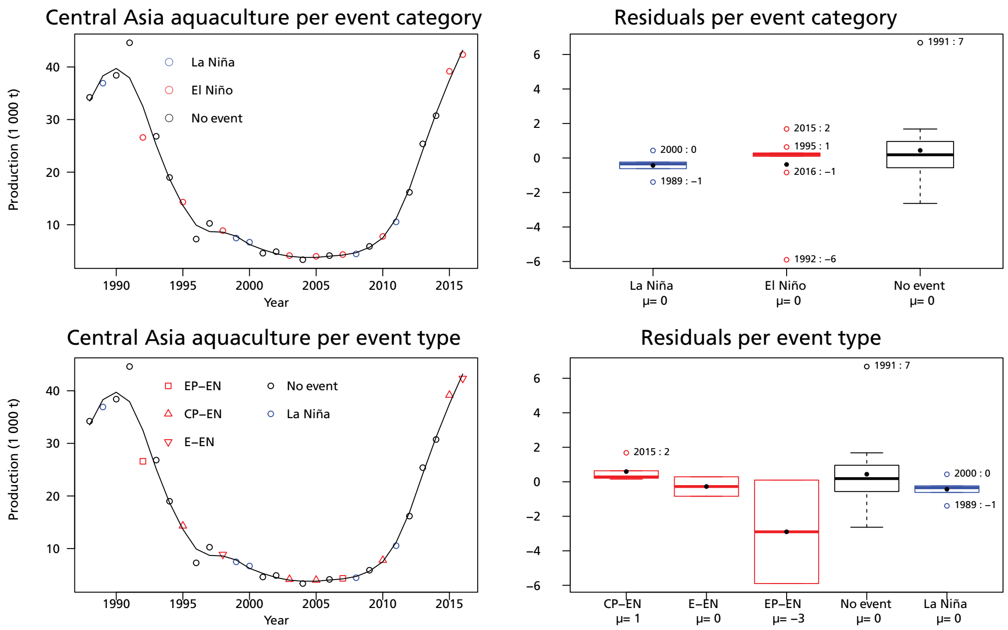
8.2.16 Central Asia

The Central Asian region (Figure 8.2) includes Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan with a total land area of 3.9 million km². The region's climate is largely semi-arid and arid, but also includes subtropical, temperate, dry continental, desert and polar upland areas. ENSO variation has strong impacts on precipitation in Central Asia, with El Niño being associated with wetter conditions, and La Niña with drier conditions (Hu *et al*., 2019), with the influence being particularly strong in Autumn (Mariotti, 2007). Ward *et al.* (2010) noted a negative anomaly between SOI and river discharge in the region, indicating increases under El Niño conditions. CP El Niño conditions are associated with a marked negative temperature anomaly in northwestern and northern Kazakhstan, in the north of the region (Graf and Zanchettin, 2012).

Central Asia made a minor (0.04 percent) contribution to global aquaculture production in 2016, resulting in it being ranked last of the different geographical regions considered in detail here (see Table 8.2). The earliest data available for aquaculture production from the region are from 1988, limiting the capacity to undertake statistical analyses, but the region has seen considerable variation in annual aquaculture production (Figure 8.18). In 2016, annual production data were provided for 17 different aquaculture species and categories, ranging from 18 tonnes (northern pike) through to 21 283 tonnes (silver carp), with a mean ±SD annual production of 2 491 tonnes ± 5 184 tonnes per species/category. Five species/categories represented almost 90 percent of total aquaculture production in Central Asia in 2016 (silver carp: 50.3 percent; freshwater fishes nei: 15.0 percent; grass carp: 10.9 percent; common carp: 9.2 percent; cyprinids nei: 3.8 percent). As noted above, the restricted time series makes statistical tests difficult, but yields were reduced by an average of −3 000 tonnes under EP El Niño, which reflects a reduction of approximately −7 percent of total production in 2016, and −17.6 percent of long-term (1998 to 2016) mean aquaculture production in Central Asia.

FIGURE 8.18

Left panels: regional yearly global aquaculture production (in 1 000 t) per event category (upper panel) and type (lower panel) from Central Asia. The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories or types



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

8.2.17 Regional aquaculture and ENSO – synthesis

Aquaculture production between 1950 and 2016 followed several different temporal patterns across the 16 broad geographical regions examined here. In the majority of cases, including the three Asian regions (Eastern, South-Eastern and Southern Asia) that together accounted for more than 90 percent of global aquaculture production in 2016, production was initially relatively low until an inflection point in the 1980s/1990s (or even the 2000s), after which production rapidly accelerated (Eastern Asia, Southern Asia, South America, Northern Europe, Western Africa, Western Asia, Central America, Eastern Africa, Australia and New Zealand). Other regions showed a pattern where production increased, peaked, and then followed an asymptote (Southern Europe) or even a recent decline following an earlier peak (Northern Europe, Western Europe). Two regions (Central Asia, Eastern Europe) showed unusual patterns during the 1980s and 1990s which likely reflect periods of political change following the break-up of the Soviet Union. Taken together with the information on the scale of aquaculture production over the period studied here, it is apparent that the aquaculture industry has developed significantly over the time series examined, but that the pattern of change has differed across regions.

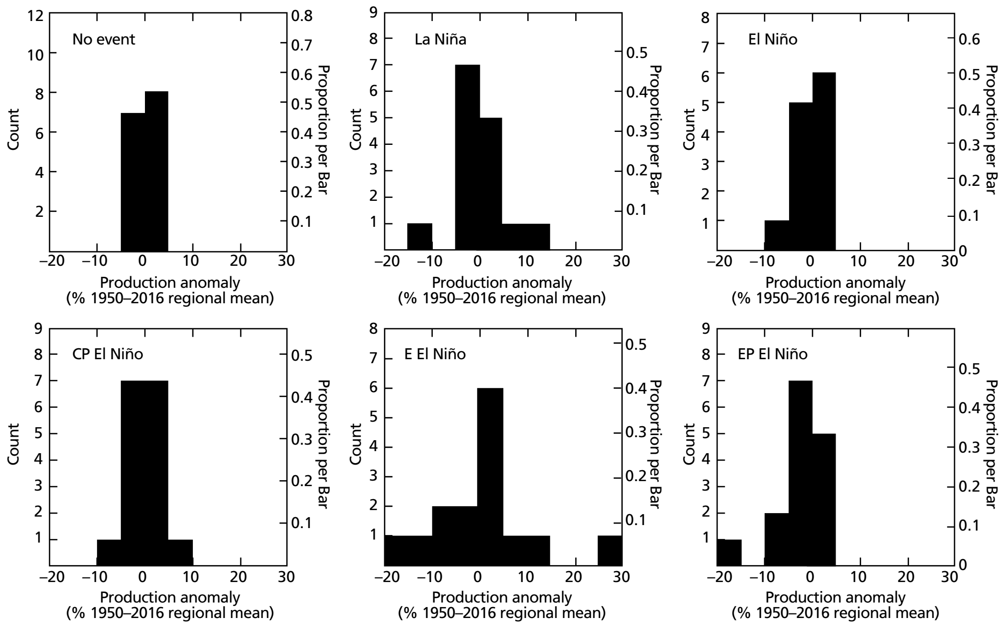
Regional aquaculture production anomalies varied between −428 000 tonnes and +136 000 tonnes (Table 8.2), with a mean ±SD anomaly of −7 510 tonnes ± 52 737 tonnes. There was no statistical evidence of differences in production under neutral, La Niña or El Niño conditions, or under CP, extreme or EP El Niño in any of the regions examined here. When anomalies were considered as percentage terms (relative to the 1950 to 2016 regional mean), they ranged between −17.6 percent and +26.2 percent (Figure 8.19), with a mean ±SD of −0.3 percent ± 5.4 percent. This indicates that at a global level, the average regional response to ENSO variation is minor. However, in terms of potential shocks to the food supply system, it is apparent that some ENSO conditions lead to considerable anomalies in a given region, if not at a global level. When the largest percentage production anomaly (relative to the 1950 to 2016 mean) was examined for the three ENSO categories within a particular region, it was most commonly associated with La Niña conditions (Table 8.2; Figure 8.19 and 8.20), both as negative (South-Eastern Asia −10.9 percent, South America −3.4 percent, Northern America −2.4 percent, Western Europe −13.1 percent) and positive (Northern Africa +5.5 percent, Southern Europe +3.1 percent, Western Africa +10.2 percent, Eastern Europe +4.6 percent) production anomalies.

Although in a previous section (8.1) we showed that there is little evidence that ENSO variation affects aquaculture production at a single global level when data are pooled for each country, it may be informative to consider potential effects and patterns at broad global scales. On average, during ENSO neutral events (Figure 8.20A) South America, Western Africa, Eastern Africa, South Asia, South-Eastern Asia and much of Europe showed minor (>0 percent to 5 percent) positive mean production anomalies, while Southern Europe, Northern Africa, Northern America, Central America, Eastern Asia and Australia and New Zealand all report minor (<0 percent to −5 percent) mean negative anomalies. No extreme production anomaly values were recorded under ENSO neutral conditions. La Niña conditions saw minor (<0 percent to −5 percent) negative mean aquaculture production anomalies across all of Asia apart from Western Asia, the Americas, and Eastern Africa, and marked (<−5 percent to −15 percent) negative mean production anomalies in Western Europe. Conversely, La Niña conditions were associated with minor positive (>0 percent to 5 percent) mean production anomalies for the most of Europe, Western Asia, Australia and New Zealand, and marked positive (5 percent to 15 percent) mean production anomalies in both Western and Northern Africa. Responses to El Niño events were more mixed, when all El Niño types were pooled into a single category. Central America, Northern Africa, Western Asia and Central Asia all showed no evidence for mean production anomalies. South America, Northern Europe, Eastern Europe, Southern Asia and South-Eastern Asia all showed minor (<0 percent to −5 percent) mean negative anomalies in annual aquaculture production under El Niño conditions, while Western Africa showed a marked (<−5 percent to −15 percent) negative mean production anomaly. Northern America, Western Europe, Eastern Africa and Eastern Africa all showed minor positive (>0 percent to 5 percent) mean production anomalies during El Niño years.

Inclusion of three different El Niño event types (Table 8.2, Figures 8.19 and 8.21) provided a more diverse set of production anomalies (relative to long-term regional mean annual production). Comparison across the 16 different regions showed that in half of the cases, production anomalies had different signs under CP and EP El Niños (Table 8.2, Figure 8.21). In terms of the different El Niño category types, the largest production anomalies (relative to the long-term mean) were typically associated with extreme El Niño (Table 8.2, Figures 8.19 and 8.21B), both as negative (South-Eastern Asia −10.9 percent, South America −4.6 percent, Northern Europe −6.4 percent, Eastern Africa −8 percent) and positive (Southern Europe +4.4 percent, Western Africa +16.3 percent, Western Asia +6.7 percent, Western Europe +26.2 percent, Australia and New Zealand, +11.7 percent) production anomalies.

FIGURE 8.19

Variation in mean percentage aquaculture production anomalies (relative to 1950 to 2016 regional mean) associated with different ENSO event categories or types of El Niño from all geographical regions

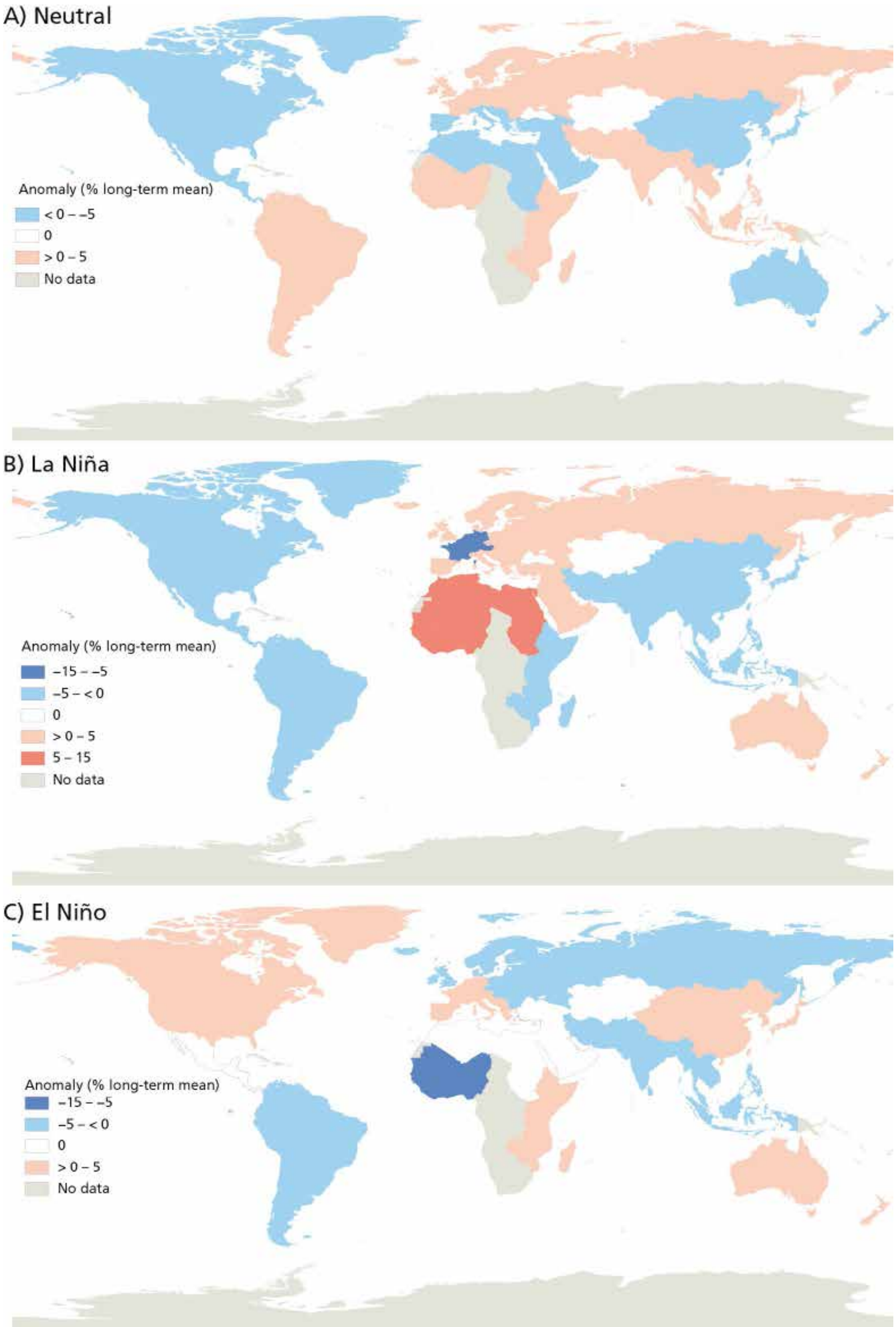


At an extra-regional level, CP El Niños were associated (Table 2, Figure 8.21A) with minor (<0 percent to −5 percent) negative mean production anomalies in Central America, Western Africa, Northern Europe, Eastern Europe, Western Asia, Southern Asia and Australia and New Zealand, and marked (<−5 percent to −15 percent) negative mean production anomalies in South America. Conversely, CP El Niños were associated with minor (>0 percent to 5 percent) positive aquaculture production anomalies in Eastern Asia, South-Eastern Asia, Western Europe, Southern Europe, North Africa, Eastern Africa, Northern America and Australia and New Zealand, and marked positive (5 percent to 15 percent) production anomalies in Central Asia, in contrast to the regions' response to the main ENSO categories (no anomaly). Production anomalies during extreme El Niño conditions were very variable (Figure 8.19), indicating the disruptive nature of such events across the world (Table 8.2, Figure 8.21B), including very marked (<−15 percent) production anomalies in Western Africa and marked (<−5 percent to −15 percent) production anomalies in Northern Europe, Eastern Africa and South-Eastern Asia. Extreme El Niño was associated with minor negative production anomalies in East Asia and South America. Very marked production anomalies (>15 percent) were recorded in Western Europe under extreme El Niño, while both Australia and New Zealand and Western Europe reported marked (5 percent to 15 percent) positive production anomalies, and Southern Asia, Northern America, Eastern Europe, Southern Europe and Northern Africa showed minor positive production anomalies. At a global level, EP El Niños were associated with more regions showing negative production anomalies (Table 8.2, Figures 8.19 and 8.21C), including Central Asia (<−15 percent), Western Africa and Western Europe (<−5 percent to −15 percent) and Eastern Asia, South-Eastern Asia, South Asia, South America, Northern Africa, Northern Europe and Eastern Europe (<0 percent to −5 percent). Positive aquaculture mean production anomalies (all less than 5 percent) were only seen in Northern America, Southern Europe, Western Asia and Australia and New Zealand, regions that make a relatively limited contribution to global aquaculture output.

Taken together, it appears that ENSO has no large-scale effect on aquaculture production when compared at the global or regional level, but some categories or event types may have the potential to shock the supply of aquaculture products more than others (La Niña and extreme El Niño), or may be associated with less positive anomalies at a regional scale (EP El Niño).

FIGURE 8.20

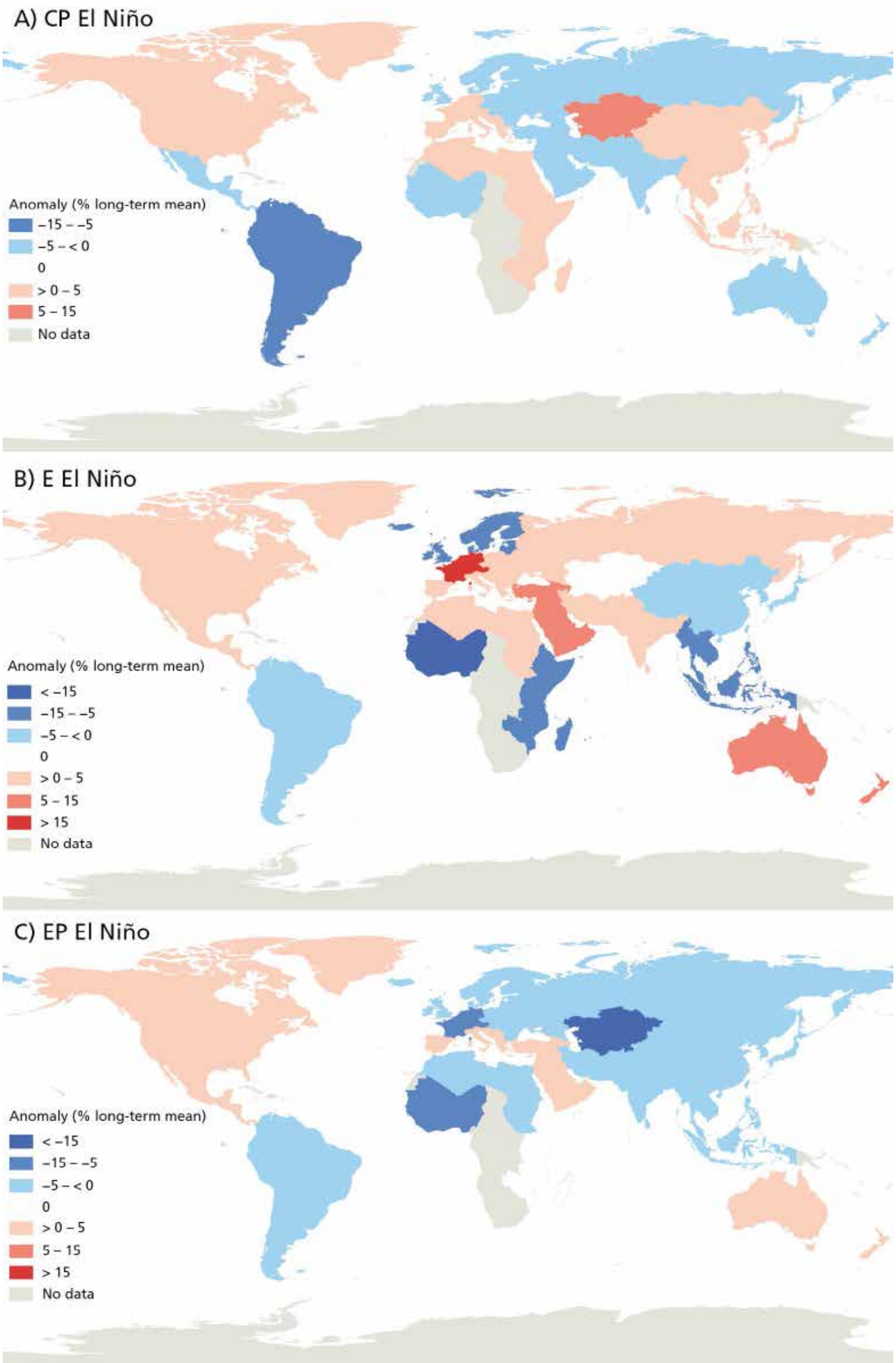
Geographical variation in mean regional aquaculture production anomaly associated with different ENSO categories (percent anomaly relative to regional mean long-term [typically 1950–2106] annual production): A) Neutral conditions, B) La Niña, and C) El Niño conditions. Note that anomalies were not estimated for regions with minor contributions to global aquaculture production in 2016 (Caribbean, Melanesia, Southern Africa, Middle Africa, Micronesia and Polynesia)



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a). Map conforms to United Nations World map, February 2020.

FIGURE 8.21

Geographical variation in mean regional aquaculture production anomaly associated with different El Niño conditions (percent anomaly relative to regional mean long-term [typically 1950–2016] annual production): A) CP El Niño, B) extreme El Niño, and C) EP El Niño conditions. Note that anomalies were not estimated for regions with minor contributions to global aquaculture production in 2016 (Caribbean, Melanesia, Southern Africa, Middle Africa, Micronesia and Polynesia)



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a). Map conforms to United Nations World map, February 2020.

8.3 TOP TEN AQUACULTURE PRODUCING COUNTRIES

KEY MESSAGES

- We described known climatic effects of ENSO variation and estimated ENSO effects on aquaculture production in the 10 countries with the largest aquaculture production in 2016.
- The ten largest aquaculture producing nations (as of 2016) were largely unaffected by ENSO variation, and there were no significant effects of ENSO event category or El Niño event type on aquaculture production in any country.
- Only in three cases did mean annual production anomalies associated with different ENSO conditions reach greater than 5 percent (Egypt, La Niña: +5.6 percent; Norway, extreme El Niño: –5.3 percent; Republic of Korea, EP El Niño: +5.6 percent.

Given the problems with pooling data at a regional level described above, we then concentrated on country-level analyses, assuming that putative impacts would be clearer at a national level, especially given that ENSO effects vary within regions and that the range of cultured species differs between countries (Table 3). The FAO aquaculture statistics for 2016 (FAO-FishStatJ., 2019b) include information from a total of 197 different territories, but production was focused in a limited number of countries, with more than 90 percent (97.6 million tonnes) being produced in only ten countries (Table 3) led by China (62.3 million tonnes; 57.6 percent) followed by Indonesia (16 million tonnes; 14.8 percent), India (5.7 million tonnes; 5.3 percent); Viet Nam (3.6 million tonnes; 3.3 percent), Bangladesh (2.2 million tonnes; 2.0 percent), the Philippines (2.2 million tonnes, 2.0 percent) the Republic of Korea (1.9 million tonnes; 1.7 percent), Egypt (1.4 million tonnes; 1.3 percent), Norway (1.3 million tonnes; 1.2 percent) and Japan (1.1 million tonnes; 1. percent). In terms of geographical distribution, the countries are strongly clustered in Asia, with the remaining two being located in either Africa (Egypt) or Europe (Norway). We estimated anomalies in aquaculture production for each country using the methodology used above. We do not present individual time series here for brevity's sake, but instead present the results for mean anomalies associated with the three ENSO event categories (no event/neutral, La Niña and El Niño) and the three different El Niño types (CP El Niño, extreme El Niño and EP El Niño). Given the variation in the scale of production between each country, we also present anomalies as percentages of, a) national aquaculture production in 2016, and b) mean aquaculture production over the entire time series (normally 1950 to 2016) from each country (Table 8.3).

Our results provide no evidence for any obvious variation in the effect of different ENSO categories or El Niño types on aquaculture production in any of the ten countries (ANOVA p-value >0.05 in all cases; see anomalies reported in Table 3). Although some large individual ENSO-related production anomalies were recorded, e.g. –159 000 tonnes under La Niña, and +138 000 tonnes during CP El Nino in China, these represented minor proportions of total aquaculture production in percentage terms, either relative to 2016 (La Niña: –0.3 percent; CP El Niño: +0.2 percent) or the longer-term (1950 to 2016) mean (La Niña: –1.0 percent; CP El Niño: +0.9 percent). Overall, the mean absolute anomaly (17 000 tonnes) from the ten countries under all ENSO conditions and El Niño types represented ±0.3 percent of their aquaculture production in 2016, or ±1.2 percent of mean national aquacultural production across the time series for each country.

Aquaculture production anomalies (i.e. relative to long-term national mean annual production) during neutral ENSO conditions (Table 8.3, Figure 8.22A) were generally associated with minor positive (>0 percent to 5 percent) production anomalies in six of the ten top aquaculture producing countries (responsible for 82 percent of global output in 2016, with lesser producers (Egypt, the Philippines and Republic of Korea) showing minor negative production anomalies (<0 percent to −5 percent). In contrast to the global pattern of mean regional anomalies, at a country level, La Niña conditions (Table 8.3, Figure 8.22B) were associated with an approximate geographical balance between positive and negative production anomalies. Four countries (China, Indonesia, Bangladesh and Japan), which together were responsible for 75.5 percent of global production in 2016, showed minor negative anomalies (<0 percent to −5 percent) during La Niña events. There was no apparent production anomaly associated with La Niña in the Republic of Korea. Five countries showed positive aquaculture production anomalies during La Niña events, four of which (India, Viet Nam, the Philippines and Norway) were minor (>0 percent to 5 percent) and one (Egypt) marked (5 percent to 15 percent). El Niño events were associated (Table 8.3, Figure 8.22C) with minor positive production anomalies in half of the top 10 aquaculture producers (China, India, Viet Nam, Republic of Korea and Japan), which together contributed 71 percent of global aquaculture production in 2016. On average, there was no apparent production anomaly in Egypt during El Niño events. Indonesia, Bangladesh and Norway (18.1 percent of global aquaculture production in 2016) all showed minor mean negative production anomalies during El Niño events.

When the three distinct types of El Niño were examined in terms of their effects on mean national aquaculture production anomalies (Table 8.3, Figure 8.23), most responses were minor, with individual countries showing both negative (<0 percent to −5 percent) and positive (>0 percent to 5 percent) anomalies under the three types of El Niño, and one country (Egypt) showing positive (CP El Niño), neutral (extreme El Niño) and negative (EP El Niño) anomalies. CP El Niño conditions (Table 8.3, Figure 8.23B) were associated with negative minor (<0 percent to −5 percent) mean annual production anomalies in Indonesia, India, Bangladesh, Republic of Korea, Norway and Japan while China, Viet Nam, the Philippines and Egypt displayed minor (>0 percent to 5 percent) positive production anomalies. Production anomalies during extreme El Niño events (Table 8.3, Figure 8.23B) were generally minor with both negative (China, Indonesia, Viet Nam and Bangladesh) and positive (India, the Philippines, Republic of Korea), indicating that the disruptive effects of extreme El Niño were less important at a national scale in these countries than as reported above for the regional scale. Only one country showed a marked production anomaly during extreme El Niño – Norway, where on average, production fell by 5.3 percent. There was no apparent production anomaly in aquaculture production associated with extreme El Niño in Egypt. EP El Niños were associated (Table 8.3, Figure 8.23C) with minor negative production anomalies (<0 percent to −5 percent) in six of the ten top aquaculture producing countries (China, Indonesia, India, Bangladesh, the Philippines and Egypt) which together contributed 83.1 percent of global aquaculture production in 2016. Minor positive production anomalies were seen in Viet Nam, Norway and Japan under EP El Niño conditions, while Republic of Korea showed a marked positive production anomaly of 5.6 percent.

Given the data analysed here, it is apparent that the ten largest aquaculture producing nations (as of 2016) are relatively unaffected by ENSO variation, with only three cases where mean annual production anomalies greater than 5 percent were recorded (Egypt, La Niña: +5.6 percent; Norway, extreme El Niño: −5.3 percent; Republic of Korea, EP El Niño: +5.6 percent.

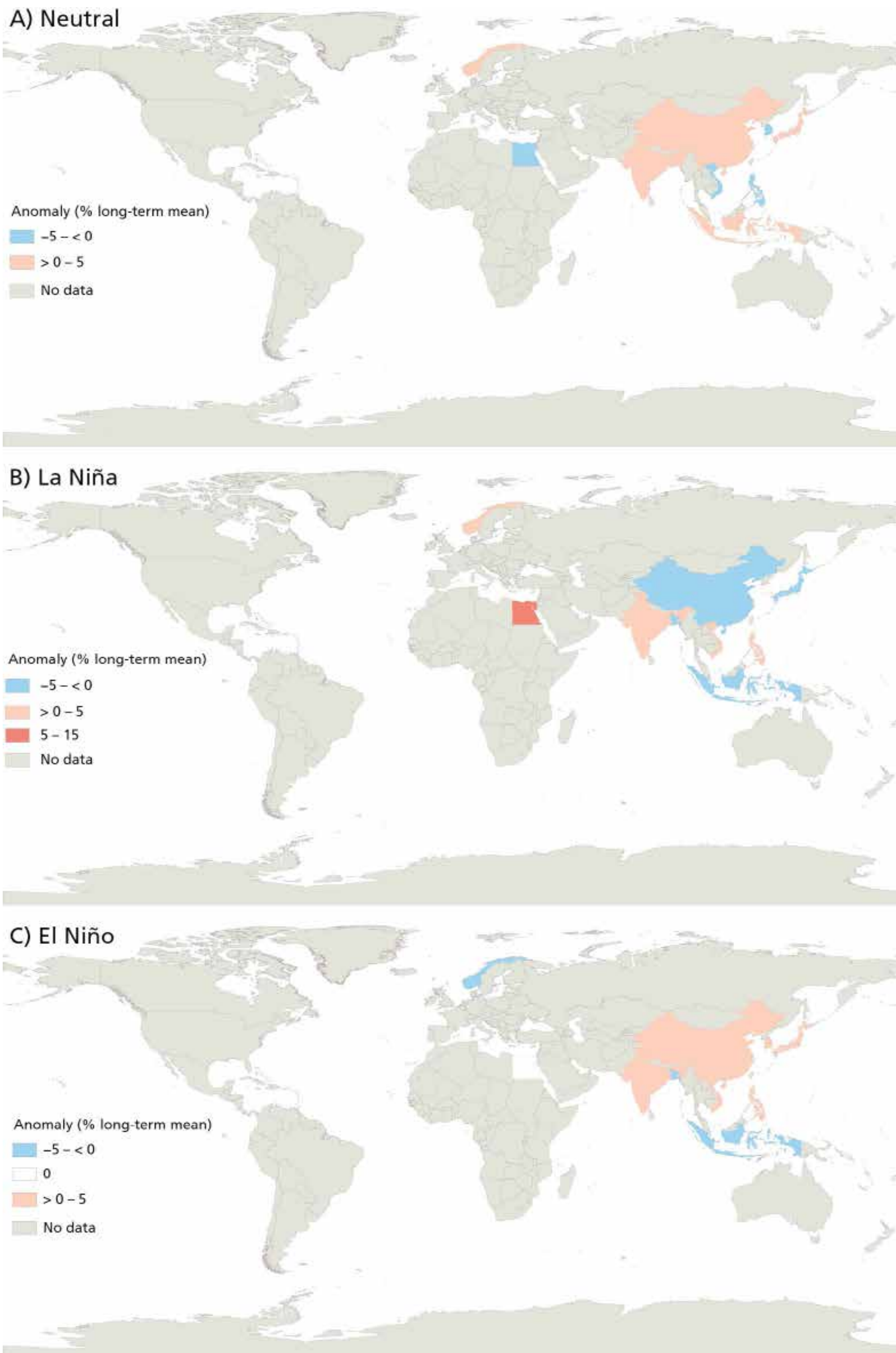
TABLE 8.3

Summary of the total yield (t) in 2016 is shown for the top 10 aquaculture producing countries, and their relative contribution to global aquaculture production (2016 %). Also shown is the summary of the mean anomaly (1950–2016) in aquaculture production (1 000 t) associated with different ENSO event categories or types of El Niño for each country. The percent change in yield relative to the total aquaculture yield reported for that country in (2016) or [relative to the long-term national mean] with values >±1% highlighted in bold. *Countries marked with an asterisk were considered as LIFDCs by FAO in 2016.

			Mean anomaly (1 000 tonnes) (% of 2016 yield) [% of mean yield]					
Country *Five principal species/categories*	**(2016 yield) [mean yield] t**	**2016 %**	**No event**	**Strong La Niña**	**El Niño**	**CP El Niño**	**E El Niño**	**EP El Niño**
China *Japanese kelp (15.5%); grass carp (8.5%); cupped oysters nei (7.5%); Japanese carpet shell (6.6%); silver carp (6.3%)*	(62 318 378) [15 437 297]	57.63	+2 (+<0.1) [+<0.1]	−159 (−0.3) **[−1.0]**	+29 (+0.1) [+0.2]	+138 (+0.2) [+0.9]	−100 (−0.2) [−0.7]	−107 (−0.2) [−0.7]
Indonesia *Eucheuma seaweeds nei (60.6%); gracilaria seaweeds (8.5%); Nile tilapia (6.6%); Torpedo–shaped catfishes nei (4.8%); Milkfish (4.3%)*	(16 002 319) [1 781 236]	14.80	+13 (+0.4) [+0.7]	−1 (−<0.1) [−0.1]	−20 (−0.6) **[−1.1]**	−7 (−0.2) [−0.4]	−64 **(−2.0)** **[−3.6]**	−15 (−0.5) [−0.8]
India* *Catla (39.4%); roho labeo (15.8%); freshwater fishes nei (13.5%); whiteleg shrimp (8.1%); striped catfish (7.9%)*	(5 702 002) [1 279 420]	5.27	+5 (0.1) [0.4]	+3 (+0.1) [+0.2]	1 (<0.1) [0.1]	−13 (−0.2) **[−1.0]**	+47 (+0.8) **[+3.7]**	−14 (−0.3) **[−1.1]**
Viet Nam *Pangas catfishes nei (33.1%); freshwater fishes nei (12.8%); whiteleg shrimp (10.6%); cyprinids nei (10.5%); marine molluscs nei (7.3%)*	(3 581 069) [629 362]	3.31	−2 (−0.1) [−0.3]	+21 (+0.6) **[+3.3]**	+2 (+0.1) [+0.3]	+4 (+0.1) [+0.6]	−10 (−0.3) **[−1.6]**	+7 (+0.2) **[+1.1]**
Bangladesh* *Striped catfish (22.5%; tilapias nei (15.5%); roho labeo (11.9%); silver carp; 8.2; mrigal carp (7.7)*	(2 203 554) [416 003]	2.04	+4 (+0.2) **[+1.0]**	−3 (−0.1) [−0.7]	−6 (−0.3) **[−1.4]**	−1 (−0.1) [−0.2]	−12 (−0.5) **[−2.9]**	−12 (−0.5) **[−2.9]**
The Philippines *Elkhorn sea moss (59.1%); milkfish (16.4%); Nile tilapia (7.1%); spiny eucheuma (4.7%); tilapias nei (3.8%)*	(2 200 912) [761 188]	2.04	−2 (−0.1 [−0.3]	+11 (+0.5) **[+1.5]**	+4 (+0.2) [+0.5]	+8 (+0.4) **[+1.1]**	+4 (+0.2) [+0.5]	−6 (−0.5) [−0.8]
Republic of Korea *Wakame (26.7%); laver (nori) (22.0%), Japanese kelp (21.4%); Pacific cupped oyster (14.5%); Korean mussel (2.9%)*	(1 859 220) [628 246]	1.72	−2 (−0.1) [−0.3]	0 (–) [–]	+4 (−0.2) [−0.6]	−12 (−0.7) **[−1.9]**	+9 (+0.5) **[+1.4]**	+35 (+1.9) **[+5.6]**
Egypt *Nile tilapia (68.6%); mullets nei (11.2%); cyprinids nei (11.0%); common carp (3.6%); gilthead seabream (1.9%)*	(1 370 660) [213 652]	1.27	−3 (−0.2) **[−1.4]**	+12 (+0.8) **[+5.6]**	0 (–) [–]	+1 (+0.1) [+0.5]	0 (–) [–]	−1 (−0.1) [−0.5]
Norway (1957–2016) *Atlantic salmon (93.0%); rainbow trout (6.6%); blue mussel (0.2%); Atlantic halibut (0.1%); Atlantic cod (0.03%)*	(1 326 216) [322 649]	1.23	+4 (+0.3) [+1.2]	+2 (+0.2) [+0.6]	−5 (−0.4) **[−1.6]**	−3 (−0.2) [−0.9]	−17 **(−1.3)** **[−5.3]**	+1 (+0.1) [+0.3]
Japan *Laver (nori) (28.2%); yesso scallop (20.1%); Pacific cupped oyster (14.9%); Japanese amberjack (13.2%); silver seabream (6.3%)*	(1 067 995) [899 701]	0.99	+1 (+0.1) [+0.1]	−17 **(−1.6)** **[−1. 9]**	+3 (+0.3) [+0.3]	−5 (−0.5) [−0.6]	+16 **(+1.5)** **[+1.8]**	+10 (+0.9) **[+1.1]**

FIGURE 8.22

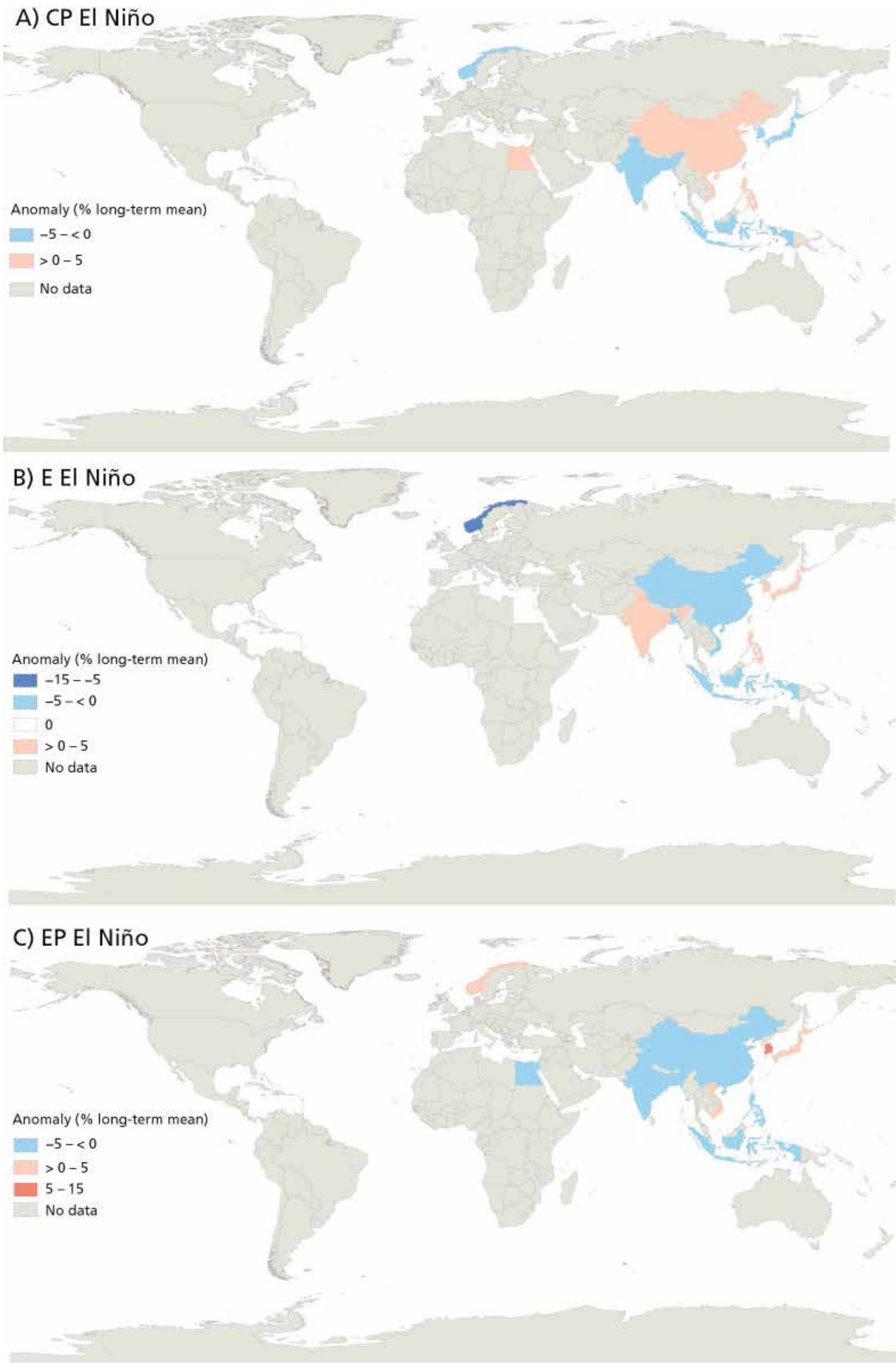
Variation in mean aquaculture production anomalies (percent anomaly relative to regional mean long-term [typically 1950–2016] annual production) in the ten largest aquaculture producing countries in 2016 associated with different ENSO event categories: A) Neutral conditions, B) La Niña and C) El Niño conditions



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a). Map conforms to United Nations World map, February 2020.

FIGURE 8.23

Variation in mean aquaculture production anomalies (percent anomaly relative to regional mean long-term [typically 1950–2016] annual production) in the ten largest aquaculture producing countries in 2016 associated with different El Niño event types: A) CP El Niño, B) extreme El Niño and C) EP El Niño conditions



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a). Map conforms to United Nations World map, February 2020.

8.4 ENSO AND KEY AQUACULTURE PRODUCTS

KEY MESSAGES

- We examined potential ENSO effects on the production of the aquaculture species/categories that dominated aquaculture production in 2016, including aquatic plants, and unfed (molluscs) and fed (crustaceans and finfishes).
- There were no measurable statistical effects of ENSO event category or El Niño event type on aquaculture production in any case.
- Generally, fish showed the least variation in production anomalies across the different ENSO categories and El Niño event types. Conversely, of the three groups of cultured animals, molluscs (unfed) showed the most variation in production anomalies, while the crustaceans, which included a range of ongrowing (unfed/fed) strategies were intermediate. Plants showed a similar amount of variation in production anomalies as molluscs.
- Put together, the most commonly cultured species showed relatively limited variation associated with ENSO, but plants and molluscs were the most affected groups. Of the different El Niño event types, CP El Niño (plants, molluscs) and extreme El Niño (molluscs, crustaceans, fish) were associated with the largest production anomalies.

Modern aquaculture has led to a diverse range of taxa being cultured across the world. In 2016, the FAO database included 438 different categories (FAO-FishStatJ., 2019b), some representing single species, others representing broader categories where results are pooled by taxonomy or function, e.g. marine mollusc nei (nei = not elsewhere included). In order to examine the potential effect of ENSO variation on production of key aquaculture products, we estimated production anomalies associated with the different ENSO event categories or types of El Niño for the five species/categories making the largest contribution to global aquaculture production for four broad categories that include unfed and fed taxa: aquatic plants (unfed), molluscs (unfed), crustaceans (fed) and fishes (fed). We also included two mollusc species from the southeast Pacific that are likely subject to ENSO fluctuations: *Mytilus chilensis*, the Chilean mussel (0.28 percent of total global aquaculture production in 2016) and *Argopecten purpuratus*, the Peruvian calico scallop (0.02 percent) as a means of testing the sensitivity of our approach. In the interests of brevity, we do not present figures for all species/categories, but show mean annual production anomalies associated with the three ENSO event categories (no event/neutral, La Niña and El Niño) and the three different El Niño types (CP El Niño, extreme El Niño and EP El Niño). We also present anomalies in percentage terms, both relative to annual production of that species or category in 2016, and relative to the long-term mean annual production for each species or category (Tables 8.4 to 8.7).

In each case, there was no statistical support for differences in production under the different ENSO categories or El Niño types (ANOVA p-value >0.05) for any of the species or categories examined (Tables 8.4 to 8.7). Anomalies varied between –169 000 tonnes (*Eucheuma* seaweeds nei under extreme El Niño) and +106 000 tonnes (Japanese kelp under EP El Niño), with a mean absolute production anomaly of 19 470 tonnes for the species/categories under all ENSO or El Niño conditions. Given that mean production in 2016 for the products examined here was 3.3 million tonnes, these anomalies represent on average +0.8 percent of 2016 production, indicating that ENSO variation had limited influence on aquaculture production of these key species. Furthermore, there was no statistical evidence of a measurable effect of ENSO variation on the two species of molluscs from southeast Pacific (Chilean mussel and Peruvian calico scallop) where ENSO effects are likely to be strongest (Table 8.4; Figures 8.19 and 8.20), yet some large shifts in production were apparent in percentage terms.

When each group was compared, some general patterns became apparent. For aquatic plants (Table 8.4), molluscs (Table 8.5) and fish (Table 8.7) mean relative production anomalies were qualitatively slightly larger in both absolute and percentage terms for La Niña than neutral or El Niño conditions. In crustaceans, where only four species were compared (Table 8.6), larger anomalies in both absolute and percentage terms were associated with El Niño conditions. The pattern was less clear for the different El Niño event types. All plant species/categories showed negative anomalies during extreme El Niño (Table 8.4), while fishes typically showed negative anomalies during extreme and CP El Niño events, and positive anomalies during CP El Niño.

The five most important (in terms of production) macroalgae species (Table 8.4) showed a mix of responses to ENSO neutral events, but as noted above, in all but one case showed negative production anomalies (relative to the long-term time series), with *Gracilaria* seaweeds showing a marked (–7.1 percent) and *wakame* a very marked (–15.1 percent) reduction in production. El Niño events resulted in positive minor production anomalies for all but two categories: *Gracilaria* seaweeds showed a minor negative production anomaly (–2.7 percent) while production of *wakame* increased on average by +5.7 percent during El Niño events. CP El Niño events (Table 8.4) were associated with positive production anomalies ranging from the minor (Japanese kelp, *Eucheuma* seaweeds nei, Elkhorn sea moss) to the marked (*wakame*, +12.5 percent). Production of *Gracilaria* seaweeds showed a marked (-5.4 percent) reduction in mean production during CP El Niño events. All macroalgae classifications showed negative production anomalies under extreme El Niño, with most being minor (< –5 percent), but the mean anomaly for *Eucheuma* seaweeds nei was more marked (–8.8 percent). EP El Niño events (Table 8.4) were associated with a mix of negative (*wakame*, Elkhorn sea moss) and positive (Japanese kelp, *Eucheuma* seaweeds nei, *Gracilaria* seaweeds) minor production anomalies.

All cultured mollusc categories (Table 8.5) showed minor production anomalies (relative to the long-term mean) during ENSO neutral events. Some categories showed very little evidence of major responses to ENSO variation (cupped oysters nei and Japanese carpet shell), while others saw quite distinct responses in terms of differences in the sign and scale of production anomalies across the different ENSO categories and EL Niño types (marine mollusc nei and Chilean mussel). La Niña conditions saw a mix of minor negative and positive production anomalies (Table 8.5), but marked and very marked positive anomalies were reported for the general marine mollusc nei category (+10.3 percent) and the Chilean mussel (+21.7 percent) respectively. Responses to the combined El Niño category (Table 8.5) were mixed, with both positive and negative minor production anomalies: however, on average, the general marine mollusc nei category showed a marked (–6.9 percent) reduction in production during El Niño events. CP El Niño conditions again resulted in both positive and negative minor production anomalies, with the Chilean mussel showing a marked negative anomaly and production being lower on average by –12.1 percent . Extreme El Niño events (Table 8.5) were associated with marked production anomalies in three different categories: scallops nei (–8.9 percent), marine mollusc nei (–10.3 percent) and the Chilean mussel (+21.7 percent). Mean production anomalies associated with EP El Niños were generally negative and minor (or zero), but the marine mollusc nei category showed a marked negative anomaly (–11.7 percent). The Peruvian calico scallop increased production on average by +5.8 percent during EP El Niño years.

Only four crustacean categories are included in Table 8.6, as the time series for the fifth most cultured crustacean (the oriental river prawn) was too short to calculate meaningful anomaly data. Under most ENSO categories, production anomalies were minor (positive and negative) but red swamp crayfish showed a marked positive anomaly (+7.8 percent) under El Niño. Marked responses were also seen under extreme El Niño (red swamp crayfish: + 22.5 percent; giant tiger prawn: –7.0 percent) and EP El Niño (white leg shrimp: +9.5 percent, giant tiger prawn: −6.3 percent). Red swamp crayfish showed positive production anomalies across all ENSO categories and El Niño types apart from ENSO neutral conditions.

We examined production anomalies in six different fish species (Table 8.7). The first five are the most cultured fishes globally, but are largely cultured in Asia. We also included Atlantic salmon as an additional species as it is cultured in different regions to the top five cultured species, including countries potentially susceptible to ENSO variation such as Chile. There was little evidence of major responses to variation in the different ENSO categories, as percentage differences to long-term mean production for each category/species. Neutral conditions (Table 8.7) resulted in mean production anomalies of between −0.2 and +0.6 percent in all but one case, Atlantic salmon which showed a mean annual production anomaly of +2.7 percent under neutral conditions. La Niña events resulted in minor (<0 to −5 percent) negative production anomalies in four species (silver carp, common carp, Nile tilapia and bighead carp), and a minor positive anomaly (+1.8 percent) in grass carp, the world's most cultured fish in 2016. Atlantic salmon showed no production anomaly during La Niña periods. Production anomalies were minor during El Niño periods for all species/categories, ranging between −0.6 percent and +0.8 percent, however Atlantic salmon had a larger and negative mean annual production anomaly of −4.0 percent. CP El Niño conditions were associated with minor positive production anomalies (+1 percent to +4.1 percent) for all species apart from Atlantic salmon which had a minor negative production anomaly (−2.8 percent) during CP El Niño periods (Table 8.7). During extreme El Niño, bighead carp showed no apparent anomaly, while grass carp, silver carp, common carp showed minor negative anomalies ranging between −0.5 percent and −4.4 percent. Two species had marked negative anomalies (Nile tilapia: −6.4 percent; Atlantic salmon: −9.2 percent) under extreme El Niño. All species showed minor negative production anomalies under EP El Niño (−0.2 to −4.1 percent).

We examined four different groups of cultured species/categories including those that are unfed (aquatic plants, marine molluscs, some crustaceans) and fed (some crustaceans and fish). Given that access to suitable food is likely an important controlling factor, and ENSO effects have been shown to limit aquaculture production in some species (Zeldis *et al.*, 2008), it might be expected that those taxa that are fed show less variation in production related to the different ENSO event categories or El Niño event types. Our results supported this idea. Generally, fish showed the least variation in production anomalies across the different ENSO categories and El Niño event types (Table 8.7). Conversely, of the three groups of cultured animals, molluscs (unfed) showed the most variation in production anomalies, while the crustaceans, which included a range of ongrowing (unfed/fed) strategies were intermediate. Plants showed a similar amount of variation in production anomalies as molluscs. Put together, the most commonly cultured species showed relatively limited variation associated with ENSO, but plants and molluscs were the most affected groups. Of the different El Niño event types, CP El Niño (plants, molluscs) and extreme El Niño (molluscs, crustaceans, fish) were associated with the largest production anomalies.

TABLE 8.4

Summary of the total yield (t) in 2016 is shown for key aquatic plants and their relative contribution to global aquaculture production (2016 %). Also shown is the mean anomaly (1950–2016) in aquaculture production (x 1 000 t) associated with different ENSO event categories or types of El Niño for each. The % change in yield relative to the total aquaculture yield reported for that region in 2016 is shown in parentheses, with values >±1% highlighted in bold.

			Mean anomaly (1 000 t) (% of 2016 yield) [% of mean yield]					
Aquatic plants *Five principal producers (% of global total for species/category)*	**(2016 yield) [mean yield] t**	**2016 %**	**No event**	**Strong La Niña**	**El Niño**	**CP El Niño**	**E El Niño**	**EP El Niño**
Japanese kelp *China (90.9%), Korea, Dem. People's Rep. (5.2%), Korea, Rep. of (3.7%), Japan (0.3%)*	(10 662 588) [3 030 910]	9.86	−16 (−0.2) [−0.5]	−35 (−0.3) **[−1.2]**	+26 (+0.2) [+0.9]	+37 (+0.4) **[+1.2]**	−105 **(−1.0)** **[−3.5]**	+106 **(+1.0)** **[+3.5]**
***Eucheuma* seaweeds nei (1985)** *Indonesia (99.1%), China (0.5%), Madagascar (0.2%), United Rep. of Tanzania (0.1%), Kiribati (<0.1%)*	(9 775 931) [1 924 570]	9.04	+21 (+0.2) **[+1.1]**	−21 (−0.2) **[−1.1]**	+18 (+0.2) [+0.9]	+86 (+0.9) **[+4.5]**	−169 **(−1.7)** **[−8.8]**	+3 (−0.0) [−0.2]
***Gracilaria* seaweeds** *China (67.5%), Indonesia (32.0%), Chile (0.3%). Viet Nam (0.2%)., the Philippines (<0.1%)*	(4 248 364) [448 399]	3.93	+11 (+0.3) **[+2.5]**	−34 (−0.8) **[−7.6]**	−12 (−0.3) **[−2.7]**	−24 (−0.6) **[−5.4]**	−16 (−0.4) **[−3.6]**	+19 (+0.5) **[+4.2]**
Wakame *China (73.6%), Korea, Rep. of (24.1%), Japan (2.3%)*	(2 063 492) [616 289]	1.91	−8 (−0.4) **[−1.3]**	−93 **(−4.5)** **[−15.1]**	+35 (+1.7) [+5.7]	+77 **(+3.7)** **[+12.5]**	−21 **(−1.0)** **[−3.4]**	−13 (−0.6) **[−2.1]**
Elkhorn sea moss (1965) *The Philippines (85.2%), Malaysia (13.5%), Solomon Islands (0.7%), Papua New Guinea (0.3%), India (0.1%)*	(1 526 491) [596 542]	1.41	−3 (−0.2) [−0.5]	+7 (+0.5) **[+1.2]**	+6 (+0.4) **[+1.0]**	+20 **(+1.3)** **[+3.4]**	−2 (−0.1) [−0.3]	−24 **(−1.6)** **[−4.0]**

TABLE 8.5

Summary of the total yield (t) in 2016 is shown for key cultured molluscs and their relative contribution to global aquaculture production (2016%). Also shown is the mean anomaly (1950–2016) in aquaculture production (x 1 000 t) associated with different ENSO event categories or types of El Niño for each. The % change in yield relative to the total aquaculture yield reported for that region in 2016 is shown in parentheses, with values >±1% highlighted in bold. NB. Where a year is given in parentheses, it indicates the first year in the time series when data were available.

			Mean anomaly (1 000 t) (% of 2016 yield) [% of mean yield]					
Mollusc *Five principal producers (% of global total for species/category)*	**(2016 yield) [mean yield] t**	**2016 %**	**No event**	**Strong La Niña**	**El Niño**	**CP El Niño**	**E El Niño**	**EP El Niño**
Cupped oysters nei *China (99.4%), Thailand (0.3%), Netherlands (<0.1%), Brazil (<0.1%), United States of America (0.1%)*	(4 684 550) [1 265 922]	4.33	−3 (−0.1) [−0.2]	−47 **(−1.0)** **[−3.7]**	+16 (+0.3) **[+1.3]**	+39 (+0.8) **[+3.1]**	+16 (+0.3) **[+1.3]**	−33 (−0.7) **[−2.6]**
Japanese carpet shell (1964) *China (98.7%), Italy (0.8%), Korea, Republic of (0.4%), United States of America (0.1%), Spain (<0.1%)*	(4 175 833) [1 182 687]	3.86	−3 (−0.1) [−0.3]	−8 (−0.2) [−0.7]	+6 (+0.1) [+0.5]	+4 (+0.1) [+0.3]	+7 (+0.2) [+0.6]	+10 (+0.2) [+0.8]
Scallops nei (1979) *China (>99.9%), Canada (<0.1%)*	(1 849 925) [706 567]	1.71	+17 (−0.9) [−2.4]	−22 **(−1.2)** **[−3.1]**	−22 **(−1.2)** **[−3.1]**	−1 (−0.1) [−0.1]	−63 **(−3.4)** **[−8.9]**	−22 **(−1.2)** **[−3.1]**
Marine mollusc nei *China (76.5%), Viet Nam (23.5%), Canada (<0.1%), Taiwan Province of China (<0.1%)*	(1 118 069) [359 883]	1.03	+3 (+0.3) [+0.8]	+37 (+3.3) [+10.3]	−25 **(−2.2)** **[−6.9]**	−13 **(−1.2)** **[−3.6]**	−37 **(−3.3)** **[−10.3]**	−42 **(−3.8)** **[−11.7]**
Sea mussels nei *China (79.6%), Spain (19.9%), United Kingdom of Gr. Britain and N. Ireland (0.4%), the Russian Federation (<0.1%), Portugal (<0.1%)*	(1 084 507) [422 060]	1.00	−4 (−0.4) [−0.9]	+2 (+0.2) [+0.5]	+6 (+0.6) **[+1.4]**	+16 **(+1.5)** **[+3.8]**	+10 (+0.9) **[+2.4]**	−18 **(−1.7)** **[−4.3]**
Chilean mussel *Chile (100%)*	(300 648) [41 476]	0.28	−1 (−0.3) **[−2.4]**	+9 **(+3.0)** **[+21.7]**	−1 (−0.3) **[−2.4]**	−5 **(−1.7)** **[−12.1]**	+9 **(+3.0)** **[+21.7]**	0 (–) [–]
Peruvian calico scallop (1974) *Peru (85.5%), Chile (14.5%)*	(24 522) [17 107]	0.02	0 (–) [–]	+1 **(+4.1)** **[+5.8]**	0 (–) [–]	0 (–) [–]	0 (–) [–]	+1 **(+4.1)** **[+5.8]**

TABLE 8.6

Summary of the total yield (t) in 2016 is shown for key cultured crustaceans and their relative contribution to global aquaculture production (2016%). Also shown is the mean anomaly (1950–2016) in aquaculture production (x 1 000 t) associated with different ENSO event categories or types of El Niño for each. The % change in yield relative to the total aquaculture yield reported for that region in 2016 is shown in parentheses, with values >±1% highlighted in bold. NB. Where a year is given in parentheses, it indicates the first year in the time series when data were available. Anomalies were not determined for the fifth most important crustacean (oriental river prawn) as the time series available was too short to allow analysis.

			Mean anomaly (1 000 t) (% of 2016 yield) [% of mean yield]					
Crustacean *Five principal producers (% of global total for species/category)*	**(2016 yield) [mean yield] t**	**2016 %**	**No event**	**Strong La Niña**	**El Niño**	**CP El Niño**	**E El Niño**	**EP El Niño**
Whiteleg shrimp (1969) *China (28.3%), Indonesia (14.6%), India (13.5%), Ecuador (12.3%), Viet Nam (11.1%)*	(4 132 963) [824 176]	3.82	−11 (−0.3) **[−1.3]**	−1 (<0.01) [−0.1]	+19 (+0.5) **[+2.3]**	0 (–) [–]	+26 (+0.6) **[+3.2]**	+78 **(+1.9)** **[+9.5]**
Red swamp crayfish *China (92.4%), United States of America (7.6%), Italy (<<0.1%)*	(894 709) [102 181]	0.83	−4 (−0.5) **[−3.9]**	+5 (+0.6) **[+4.9]**	+8 (+0.9) **[+7.8]**	+5 (+0.6) **[+4.9]**	+23 **(+2.6)** **[+22.5]**	+4 (+0.5) **[+3.9]**
Chinese mitten crab (1989) *China (>99.9%), Taiwan Province of China (<<0.1%), Korea, Republic of (<<0.1%)*	(748 805) [323 795]	0.69	+3 (+0.4) [+0.9]	−1 (−0.1) [−0.3]	−3 (−0.4) [−0.9]	−4 (−0.5) **[−1.2]**	−6 (−0.8) **[−1.9]**	+2 (+0.3) [+0.6]
Giant tiger prawn (1956) *Viet Nam (34.6%), Indonesia (18.7%), China (10.2%), Bangladesh (9.7%), India (8.1%)*	(705 177) [285 128]	0.65	+2 (+0.3) [+0.7]	+5 (+0.7) **[+1.8]**	−7 **(−1.0)** **[−2.5]**	+2 (+0.3) [+0.7]	−20 **(−2.8)** **[−7.0]**	−18 **(−2.6)** **[−6.3]**

Table 8.7

Summary of the total yield (t) in 2016 is shown for key cultured fishes and their relative contribution to global aquaculture production (2016 %). Also shown is the mean anomaly (1950–2016) in aquaculture production (x 1 000 t) associated with different ENSO event categories or types of El Niño for each. The % change in yield relative to the total aquaculture yield reported for that region in 2016 is shown in parentheses, with values ≥±1% highlighted in bold. NB. Where a year is given in parentheses, it indicates the first year in the time series when data were available.

			Mean anomaly (1 000 t) (% of 2016 yield) [% of mean yield]					
Fish *Five principal producers (% of global total for species/category)*	**2016 yield [mean yield] (t)**	**2016 %**	**No event**	**Strong La Niña**	**El Niño**	**CP El Niño**	**E El Niño**	**EP El Niño**
Grass carp *China (97.1%), Bangladesh (0.7%), Iran (Islamic Rep. of) (0.6%), Pakistan (0.5%), India (0.4%)*	(5 444 345) [1 398 083]	5.04	−4 (−0.1) [−0.3]	+25 (+0) **[+1.8]**	−1 (−0.02) [−0.1]	+14 (+0) **[+1.0]**	−7 (−0.1) [−0.5]	−29 (−0.5) **[−2.1]**
Silver carp *China (83.1%), India (7.6%), Bangladesh (3.8%), Iran (Islamic Rep. of) (2.3%), the Russian Federation (0.8%)*	(4 717 259) [1 581 174]	4.36	+6 (+0.1) [+0.4]	−56 **(−1.2)** **[−3.5]**	+3 (+0.1) [+0.2]	+37 (+0.8) **[+2.3]**	−17 (−0.4) **[−1.1]**	−57 **(−1.2)** **[−3.6]**
Common carp *China (74.0%), Indonesia (12.3%), Viet Nam (2.6%), Bangladesh (1.8%), the Russian Federation (1.5%)*	(4 054 695) [1 246 130]	3.75	+2 (+0.1) [+0.2]	−18 (−0.4) **[−1.4]**	+4 (+0.1) [+0.3]	+51 **(+1.3)** **[+4.1]**	−55 **(−1.4)** **[−4.4]**	−51 **(−1.3)** **[−4.1]**
Nile tilapia *China (29.9%), Indonesia (28.4%), Egypt (24.0%), Thailand (5.1%), the Philippines (4.1%)*	(3 918 092) [666 810]	3.62	+4 (+0.1) [+0.6]	−2 (−0.1) [−0.3]	−4 (−0.1) [−0.6]	+11 (+0.3) **[+1.6]**	−43 **(−1.1)** **[−6.4]**	−7 (−0.2) **[−1.0]**
Bighead carp *China (98.5%), Myanmar (0.39%), Iran (Islamic Rep. of) (0.3%), the Lao People's Dem. Rep. (0.3%), Nepal (0.2%)*	(3 161 494) [854 591]	2.92	−2 (−0.1) [−0.2]	−9 (−0.3) **[−1.1]**	+7 (+0.2) [+0.8]	+17 (+0.5) **[+2.0]**	0 (−) [−]	−10 (−0.3) **[−1.2]**
Atlantic salmon (1964) *Norway (54. 9%), Chile (23.7%), United Kingdom of Gr. Britain and N. Ireland (7.3%), Canada (5.5%), Faroe Islands (3.7%)*	(2 247 293) [598 512]	2.08	+16 (+0.7) **[+2.7]**	0 (−) [−]	−24 **(−1.1)** **[−4.0]**	−17 (−0.8) [−2.8]	−55 **(−2.5)** **[−9.2]**	−1 (−0.0) [−0.2]

8.5 SYNTHESIS – ENSO AND AQUACULTURE PRODUCTION

At a global level, aquaculture is now the principle source of fish and seafood for human consumers (FAO-FishStatJ., 2019b; FAO *et al*., 2019), providing employment, income and food security for poorer nations and communities (Subasinghe, Soto and Jia, 2009) and healthy dietary options for consumers worldwide (Thilsted *et al*., 2016). Although aquaculture is considered by some as an important means of adding resilience to the global food system (Troell *et al*., 2014), it is essential to examine potential issues regarding the long-term security of aquaculture production, and much interest has been directed at how climate change affects aquaculture, and the likely future challenges that face aquaculture in a warming world (Brander *et al*., 2018; Dabbadie *et al*., 2018; Froehlich, Gentry and Halpern, 2018). Beyond this, and following the lead from other essential food production sectors (Cottrell *et al*., 2019; Iizumi *et al*., 2014), there is also a pressing need to understand how sensitive the aquaculture sector is to ENSO, given its status as the dominant global climate phenomenon affecting the world through extreme weather events (Yuan, Wang and Hu, 2018) and changes in ecosystem state (Stenseth *et al*., 2002) during El Niño and La Niña modes. Studies in other food supply sectors have emphasised ENSO's capacity to act as a major source of shock to the food supply system (Cottrell *et al*., 2019; Iizumi *et al*., 2014), a system already subject to considerable stress.

Aquaculture is a key means by which humans access goods and services from the ecosystems that provide the human life-support system (Carpenter *et al*., 2009). These ecosystems, and the services they provide are inherently dynamic and ENSO is a key global driver of variation in the abiotic and biotic factors that do much to control primary and secondary production in aquatic systems, extending well beyond just the quality, volume and temperature of water needed for optimal production of cultured species (Boyd and Tucker, 2019). ENSO-associated extreme weather events such as droughts, TCs, storms and mass-precipitation events can result in widespread damage to the natural, physical, economic, and socio-cultural framework in which aquaculture operates (Hossain *et al*., 2002). For instance, the transition from El Niño to La Niña in 1997–1998–1999 led to flooding across Asia, with extensive flooding in India, Bangladesh, China and Japan (Kripalani and Kulkarni, 2002). Storms can lead to floods that overrun or destroy culture ponds (Casimiro *et al*., 2018; Tran *et al*., 2008), or aquaculture cages becoming damaged, with subsequent loss of stock (Gomez-Uchida *et al*., 2018).

Certain ENSO states can be associated with harmful algal blooms, with marked impacts on coastal aquaculture of both fish and molluscs (Allison, Badjeck and Meinhold, 2011; Díaz *et al*., 2019). In November 1987, following the 1987 El Niño (Tester *et al*., 1991), the toxic dinoflagellate *Gymnodinium breve* underwent a bloom in waters off North Carolina – the first record of *Gymnodinium breve* north of Florida, a range extension of >800 km. In the austral summer of 2016, following El Niño conditions, a major bloom of the alga *Pseudochattonella* led to deaths of approximately 27 million Atlantic salmon in the south of Chile, equivalent to more than 10 percent of Chilean annual salmon production, and leading to a loss of USD 800 million (Díaz *et al*., 2019; Yáñez *et al*., 2018). There have been suggestions (Kim *et al*., 1999) that ENSO variation was responsible for large-scale patterns in metal contamination in *Crassostrea virginica* from the Gulf of Mexico, however, this research has not been repeated in other systems.

Approximately 40 percent of all aquaculture production is lost to disease (Owens, 2019) and ENSO can affect both the susceptibility to, and the impacts of, disease (Allison, Badjeck and Meinhold, 2011; Pang and Liu, 2019) and parasites (Marcogliese and Cone, 1993; Mouritsen and Poulin, 2002) on cultured species (Lafferty *et al*., 2015). However, it is also important to include humans themselves in any consideration of how ENSO affects aquaculture production though disease, either through increased risks by eating infected or contaminated products, e.g. paralytic shellfish poisoning (Díaz *et al*., 2019) or cholera, or due to ENSO-associated shifts in exposure to other diseases such as malaria or dengue, an important issue in several key global regions for aquaculture including the Indian subcontinent, Mexico and South America (Colwell, 1996; Kovats *et al*., 2003).

The previous paragraphs highlight how ENSO can affect aquaculture directly by affecting the capacity of the ecosystem to support production. However, there are several means by which ENSO can also affect aquaculture production indirectly, e.g. by affecting the price and availability of feed (Ubilava, 2014), the health of aquaculture workers, their families and customers (Kovats *et al*., 2003; Lafferty, 2009), as well as demand for the product (Cobon *et al*., 2016) relative to other foods (Ambikapathi *et al*., 2017; Anderson *et al*., 2018).

We used national-level aquaculture production data (FAO-FishStatJ., 2019b) to examine whether ENSO variation affects aquaculture production. Using a non-linear regression to calculate production anomalies associated with three broad ENSO categories (neutral/no event, La Niña and El Niño) and with three different types of El Niño events (CP El Niño, extreme El Niño and EP El Niño). We estimated annual production anomalies from a long-term (typically 1950 to 2016) time series at a range of different scales – global (all countries pooled), geographical regions (data pooled for countries within those regions), national (for the ten nations that led aquaculture production in 2016), and finally for those species/categories that dominated aquaculture production in 2016. Mean annual anomalies (tonnes) were estimated for the different ENSO categories and types of El Niño and converted into percentage anomalies relative to either reported production in 2016, or the mean annual production calculated from the long-term time series.

The lack of a marked global, regional national or species/category-level response from the aquaculture sector to ENSO may reflect a number of potentially interacting factors. Our inability to detect statistically robust differences between ENSO categories or El Niño event types in each of the regions may reflect reality (there are no differences), or that an effect exists, but due to issues with the data analyses, we failed to detect a difference (a type II error in statistical terms). The frequency of different ENSO events was unbalanced (no event = 38, La Niña = 9, El Niño = 20; CP El Niño = 11, EP El Niño = 5, extreme El Niño = 4). They also occurred at different times over the time series, which given the marked changes in production trajectories seen in many regions, may affect our results (although our statistical approach minimizes this risk). A further issue is that we pooled annual production data from a number of countries, regions and processes. Countries pooled together in a region often have distinct climates and differ both in terms of economic development and in the species cultured, as well the habitats in which aquaculture activities take place. As such, climatic and production responses to ENSO may differ within a given region, dampening any putative pattern that might be apparent at the level of the individual country, subregion or locality. A further factor is that aquaculture technology has advanced rapidly over the study period, and resistance to ENSO-associated abiotic climatic shifts has likely increased as technology and aquaculture techniques have improved, and demand for products has increased (Klinger and Naylor, 2012). Finally, we assume that the production values reported to the FAO are reliable, and the ENSO classifications we have used for a given year are correct and reflect the period associated with aquaculture production. In some cases, where actual production data are not available, they are estimated using expert opinion by FAO staff.

The remarkable growth of aquaculture production over the past 70 years means that the prevailing pattern seen in most of the cases examined was a persistent year-on-year increase in aquaculture production. These data clearly reveal a common pattern of a rapidly expanding sector and act as a reminder of the capacity of well-managed aquaculture operations to maintain and increase production despite exposure to substantial natural environmental variation, a testimony to the many developments in scientific, technical and human capacity building made in the field over the past decades. These data do not, however, provide information on those cases where aquaculture systems have failed, which may be more informative to the questions raised here. As such, data pooled at the global, regional or national level may not be sufficient to identify responses to ENSO variation, and future studies may have to examine results at a higher level of resolution. Future research should consider which factors are driving variation in aquaculture production and examine how ENSO affects them, e.g. variation in water temperature or provision of natural food for unfed species. It is likely that we also need to examine production at a less broad temporal scale that would allow direct comparison with ENSO indices (e.g. Niño-3.4 or SOI), rather than classifying individual years into particular ENSO categories or El Niño types as we have done. Such data are not readily available, unlike the FAO data used here, but may be available at a national level or from particular aquaculture facilities (where harvesting occurs throughout the year).

Another key issue is how ENSO affects interactions between aquaculture and other sectors, both in the present and in the future. As human populations grow, demands for land and water to support agriculture and urban development will grow, and aquaculture will likely face increasing competition for space and access to water in the future (Harrod *et al*., 2018a). ENSO affects water temperature, volume and currents and in non-marine settings, the availability of water itself. Like all culture-based food production sectors, aquaculture has significant environmental impacts (Clavelle *et al*., 2019), the most marked being on local water and sediment quality (Quiñones *et al*., 2019) and the effective removal of pollutants is essential to maintain production (Boyd and Tucker, 2019). ENSO has the potential to affect the capacity of water to remove waste products generated by aquaculture activities, and models used to estimate carrying capacity and select sites for aquaculture facilities (Sainz *et al*., 2019) need to take this into account, and to consider the full diversity of El Niño events. Furthermore, if mass-mortality events occur due to ENSO events (León-Muñoz *et al*., 2018), there need to be robust and transparent plans for the disposal of mortalities, the latter being essential to minimize conflict with stakeholders (Quiñones *et al*., 2019).

The aquaculture sector competes with other food production sectors and with the nature-based human support system for space, water and food. For instance, its capacity to add resilience to the global food supply system is limited (Troell *et al*., 2014) by problems associated with the supply of the feed that fuels more than 70 percent of global production of cultured fish and crustaceans. About 68 percent of these direct-fed species are currently dependent upon the use of commercially manufactured aquaculture feeds (Tacon and Metian, 2015). This production has largely been reliant on wild-captured pelagic forage fishes such as anchovies and sardines (Froehlich *et al*., 2018), which themselves are characteristically sensitive to climatic variation such as ENSO (Bertrand *et al*., 2004; Lehodey *et al*., 2006). These fish represent approximately one third of all global landings (Froehlich *et al*., 2018) and are rendered into fish oil and fishmeal to provide the essential fatty acids, amino acids and micronutrients required to maximize growth and product quality in cultured species (D'Abramo, 2019; Tacon and Metian, 2015). Increasingly, direct-feeding is not just used with obligate carnivorous fishes such as salmon, but also to omnivorous taxa such as cyprinids and crustaceans (Froehlich *et al*., 2018; Tacon and Metian, 2015). Rendered products from forage fishes have historically been extremely important in agriculture, but aquaculture became the dominant user of fishmeal and fish oil from forage fish in the 2000s (Froehlich *et al*., 2018), and these sectors compete for access to forage fishes, which are also extremely important for direct (Tacon and Metian, 2009) and indirect (e.g. dietary supplements: Klinger and Naylor, 2012) human consumption. Although the direct-fed aquaculture and agricultural sectors are increasingly seeking to use alternative and less costly sources to fulfil their demands for fishmeal and oil, including plant-based alternatives (see below) and use of materials derived from so called non-food fishes or from fishery by-products (Tacon and Metian, 2015; Zhang *et al*., 2019), they still remain heavily reliant on already fully or overexploited forage fishes (Essington *et al*., 2015). These small pelagic fishes are typically derived from industrial fisheries and given their status as canonical case studies of the impacts of variation in ENSO (Barber and Chavez, 1983; Bertrand *et al*., 2004; Chavez *et al*., 2008) and other climatic drivers, will continue to be highly affected by ENSO variation (see Section 6.1.3; Lehodey *et al*., 2006), and therefore must be considered in any assessment of how ENSO affects aquaculture, as has been done for climate change (Bakun *et al*., 2015).

The rapid development of the fed-aquaculture sector in China, by far the leading world aquaculture producer (>57 percent of global production in 2016: Table 8.3) has driven demand for fishmeal and fish oil, and the country is the leading user of forage fish (Froehlich *et al*., 2018), even though Chinese aquaculture production of fish and crustaceans is dominated by omnivorous carps (Tacon and Metian, 2015). Although there is extremely high demand for fish from capture fisheries for human consumption in China, production has increasingly been used to provide feed for the aquaculture sector (Zhang *et al*., 2019), and today half of China's trawler fleet catch (3.0 million tonnes) in China's EEZ is of fish and other taxa used as aquaculture feed directly or indirectly after reduction to fish oil or fishmeal. The reliance on non-forage fishes is likely to increase in the future, further complicating efforts to understand how aquaculture food supply and ultimately production, is sensitive to ENSO variation.

Technological developments have potentially reduced exposure to potential ENSO-driven variation in the supply of fishmeal and fish oil. For instance, the use of alternative materials has allowed Atlantic salmon producers in Norway to make considerable recent reductions (1990 to 2013) in the use of fishmeal (65 to 24 percent) and fish oil (19 to 11 percent) (Ytrestøyl, Aas and Åsgård, 2015). Furthermore, there is much interest regarding shifts to alternative feeds in aquaculture (Hall, 2015) including diets based on insect meal, macroalgae, microbes, and especially plant materials (Hall, 2015; Klinger and Naylor, 2012) in some key sectors (Naylor *et al*., 2009). Although moves to plant-based aquaculture feeds has great potential to limit the ecological impacts of aquaculture and exposure to ENSO-driven variation in the availability of forage fish (Section 6.1.3; Lehodey *et al*., 2006), it must be recognized that these agricultural crops are subject to demand to feed humans and agricultural livestock (Troell *et al*., 2014), and are themselves susceptible to climatic variation (Anderson *et al*., 2018; Hall, 2015; Iizumi *et al*., 2014) and their relative economic attractiveness as an alternative to fishmeal can be affected by ENSO variation (Ubilava, 2014).

Aquaculture has been seen as a means by which extra resilience can be added to global food security (Troell *et al*., 2014), however, the sector is potentially exposed to ENSO-associated impacts that limit its capacity to add resilience, including sensitivity to temperature fluctuation, reliance on wild fish and terrestrial crops for feed, access to high quality water and secure spaces for culture activities, and likely competes with other key sectors for these things, a situation that will only intensify with ongoing climate change (Dabbadie *et al*., 2018; Harrod *et al*., 2018a). Given the data at hand however, we have not shown any obvious large-scale impact of ENSO variation on aquaculture production at a global level. We have, however, shown that major shifts in production can be associated with certain ENSO conditions and have highlighted several issues of interest that are worthy of increased focus and that require consideration by the aquaculture sector and those who rely on its products.

9 ENSO and inland capture fisheries

KEY MESSAGES

- Inland capture fisheries make a relatively small (5.7 percent in 2016) contribution to global aquaculture and fisheries production but play an essential role in the provision of global food security. They provide access to food, employment and income to some of the world's most vulnerable populations especially in LIFDCs and land-locked developing countries.
- Inland fisheries are distributed globally, but are concentrated in the tropics and subtropics, often in ecosystems with known sensitivity to the climatic impacts of ENSO variation. However, there is little information on how fishery production is affected (in marked contrast to coastal marine systems).
- We examine potential effects of ENSO on inland fisheries production at a series of different levels including global, regional and national levels, as well as at the level of the most commonly captured species.

Inland fisheries are distributed globally (on every continent apart from Antarctica) and operate almost everywhere that freshwater fishes are found, including streams, rivers, floodplains, lakes, reservoirs and wetlands (Funge-Smith, 2018; Welcomme, 2001). Although widely distributed, inland fisheries are concentrated in the tropics and subtropics (Funge-Smith and Bennett, 2019). Inland capture fisheries (hereinafter referred to as inland fisheries) make a relatively small (5.7 percent) contribution to total annual global fisheries and aquaculture catch (198.7 million tonnes in 2016) (FAO-FishStatJ., 2019b), but they play a fundamental role in the provision of global food security (Funge-Smith and Bennett, 2019; Lynch *et al*., 2016). Inland fisheries provide ready access to food, employment and income to some of the world's most vulnerable populations (Vannuccini *et al*., 2018), especially in LIFDCs and land-locked developing countries (Funge-Smith and Bennett, 2019), with more than 90 percent of inland fishery catches being directly consumed by humans (Welcomme *et al*., 2010). In 2016, McIntyre, Reidy Leirmann and Revenga (2016) estimated that wild captured fish from lakes and rivers provided the equivalent of the total animal protein consumption of approximately 160 million people worldwide. Furthermore, they showed that more than 80 percent of nutritional dependence on freshwater fisheries is seen in those nations with below global median gross domestic product, and where alternative animal protein sources are likely not to be available, due to cost. Inland fisheries are also important for recreation, more so in the global north than in developing countries, but harvesting of wild fishes associated with recreational fishing can be of such intensity that it can lead to overexploitation (Cooke and Cowx, 2004; Embke *et al*., 2019).

Given their importance as a source of food security, and in the context of enhancing resilience to potential shocks, it is important to understand how inland fisheries production is affected by climatic variation (Allison, Andrew and Oliver, 2007) such as ENSO. Most studies detailing fisheries responses to natural climatic cycles such as ENSO are from marine systems (Stenseth *et al*., 2002). There is a considerable literature detailing physical responses to ENSO variation from freshwater ecosystems across the world, including the key regions supporting inland fisheries (Funge-Smith, 2018). However, more detailed information regarding how ENSO affects freshwater fishes and their fisheries themselves is less common, but includes information from Oceania (Harris *et al*., 1988), North America (Casselman, 2002; Fitzgerald *et al*., 2001; Gunn, 2002) and South America (Lima, Kaplan and Doria, 2017; Mol *et al*., 2000; Oliveira *et al*., 2015; Rabuffetti *et al*., 2017; Smolders *et al*., 2000) and others (Milton *et al*., 2005).

As seen in aquaculture (Chapter 8), the effects of climatic variation on inland fisheries have been studied, especially in the context of anthropogenic climate change (Harrod *et al*., 2018b, 2018a; Harrod, 2016; Myers *et al*., 2017; Paukert *et al*., 2016). These authors commonly cite ENSO-associated climatic events as indicators of future conditions for inland fisheries under continued anthropogenic-driven climate change. ENSO has the potential to affect fish production in inland fisheries due to the pronounced controlling influence climate has on physical, chemical and biological processes in freshwater ecosystems and the terrestrial catchments that support them. However, much of the variation in abiotic conditions seen within freshwater ecosystems, and subsequent biotic and ecological responses can be associated with two main features of ENSO-associated climatic variation: precipitation and air temperature. Variation in streamflow, water level and residence time in a given freshwater system is typically a function of precipitation in that catchment. Extreme events such as floods or droughts affect limnological conditions in these ecosystems, with subsequent ecological responses (Bouvy *et al*., 2003; Phlips *et al*., 2007). ENSO is the primary driver of variation in the global precipitation record (Trenberth *et al*., 2014), explaining 38 percent of the interannual variance in globally averaged land precipitation and approximately 8 percent of the space–time variability of precipitation at a global level (New *et al*., 2001). This in turn affects river discharge (Ward *et al*., 2010), with >35 percent of all rivers worldwide being subject to the influence of ENSO (Su *et al*., 2018), affecting residence time and the intensity of flooding (Schöngart and Junk, 2007) and the flood pulse that is key in supporting production in floodplain fisheries (Rabuffetti *et al*., 2017; Räsänen and Kummu, 2013). Water levels are also affected by variation in air temperature, e.g. in catchments supplied by glacial or snow melt. Long-term data from two New Mexico rivers showed that during warmer El Niño years, spring flows during snowmelt were significantly increased, and reduced during cooler La Niña years (Molles and Dahm, 1990).

ENSO effects also extend to surface air temperature (Davey, Brookshaw and Ineson, 2014). Air and water temperatures at a given location are typically strongly related (Arai, 1981) and as such ENSO-derived shifts in air temperature are transmitted to water bodies and the taxa inhabiting them. Water temperature drives most physico-chemical and biological processes in aquatic systems, with impacts on almost every component of the ecology of freshwater fish across different levels of biological organization (Brett, 1970). This includes oxygen and food availability (and requirements), habitat use, growth and production, reproductive investment, predation risk and mortality rate, the prevalence and impact of parasites and pathogens, effects on fish behaviour and that of fishers themselves (for detailed discussions see Harrod *et al*., 2018b; Harrod, 2016). As most fishes are obligate poikilotherms or thermal conformers and almost every aspect of their lives is affected by the temperature of the surrounding water, different lineages of fish tend to have distinct temperature preferences and limits. Magnuson, Crowder and Medvick (1979) classified North American freshwater fishes into different guilds according to their temperature preferences. This approach has been widely used in temperate regions, and most information on thermal tolerances of freshwater fishes is from the temperate northern hemisphere. As such, information on temperature preferences and requirements of fishes from subtropical and tropical regions is lacking. However, many tropical and subtropical fishes face less variation in water temperature than their temperate counterparts, and other abiotic factors are more important.

Fish from tropical river systems have been classified into broad guilds based on various features of their ecology, including their sensitivity to low dissolved oxygen (DO) concentrations, trophic ecology and their migratory behaviour (Welcomme, 1979; Regier *et al*., 1989). Here, blackwater fishes are often benthivorous, adapted to low DO concentrations and make short-distance lateral migrations from the main river channel into flooded riparian areas to spawn and feed. Fish from the whitefish guild require higher concentrations of DO, tend to be piscivorous or planktivorous and undertake characteristic long-distance longitudinal seasonal migrations to avoid low DO concentrations and to spawn. Greyfishes are intermediate generalists with some physiological adaptation to low DO concentrations. In temperate, subtropical and tropical systems, inland fisheries exploit assemblages made up of a mix of the different guilds present in a given location. Each guild present in a particular fishery will show potentially different responses to the environmental shifts associated with ENSO variation, complicating attempts to provide a simple measure of the effects of ENSO on inland fisheries. For example, in Lake Ontario and other eastern North American lakes, a positive temperature anomaly is apparent in El Niño years and a negative one in La Niña (Casselman, 2002). El Niño warming led to a loss of cold-adapted lake charr from shallow lakes due to the lack of a cool thermal refuge (Gunn, 2002). Unusually warm winters associated with El Niño disrupted the phenology of cool-water fishes (yellow perch) in North America (Fitzgerald *et al*., 2001), while other cool-water species such as northern pike showed peak year class strength during moderate El Niño events. Warming associated with El Niño benefited warm-water fishes (smallmouth bass) (Casselman, 2002) which showed strong recruitment during EL Niño years, but reduced recruitment during La Niña years.

One challenge with understanding how ENSO affects freshwater ecosystems is that although an increasing body of evidence supports the role that ENSO and other climatic factors play at regional and extra-regional scales, impacts are often modulated at a local level by site-specific factors, reflecting both variation in the natural setting and levels of human influence. This can complicate the search for general patterns regarding effects of ENSO on fish production at a catchment level, e.g. catches from local fisheries located in different parts of the Lower Amazon showed distinct responses to ENSO variation (Pinaya *et al*., 2016). Such site-specific shifts in response to ENSO variation can also affect the search for general patterns at a national level. In their research on rivers in New Zealand, an area typically considered to be outside the direct influence of ENSO, Scarsbrook *et al*. (2003) showed that ENSO was not only correlated with flow at a national level, but also with a series of key physicochemical parameters associated with water quality (e.g. concentration of DO and total phosphorous, *p*H, and conductivity). Importantly, they showed that both the strength and the sign of the relationships between ENSO and water quality variables differed between individual streams. Similar patterns have been reported in the relationship between ENSO and lake physiochemistry and phytoplankton dynamics, where local features can affect the intensity and even the sign of any relationship (Cozar *et al*., 2012; Loiselle *et al*., 2014).

As noted above, ENSO variation is largely associated with shifts in precipitation and air (water) temperatures, but extreme weather events are also commonly associated with strong ENSO events. These can range from moderate increases in hydrological characteristics, e.g. discharge, through to events that completely transform catchments such as droughts leading to loss of freshwater ecosystems and their associated fisheries, through to floods in otherwise dryland rivers which can result in long-fragmented river networks being transformed into a single, major river, reconnecting previously isolated sub-habitats (Arthington and Balcombe, 2011). ENSO-associated extreme weather can open the door to phase shifts, by changing water levels, impacting native primary producers and allowing invasive species to become established (Ogutu-Ohwayo *et al*., 2013). Extreme events associated with ENSO typically enhance existing issues affecting yields, but also affect the lives of fishers, their families and their communities, to the point of affecting health (Kovats *et al*., 2003), diet and food security (Ajaero, 2017; Pinho, Marengo and Smith, 2015).

Seasonal environmental variation is the main driver of growth and distribution of fishes (Wootton, 1990), and the evolution of their life histories is closely linked to these generally predictable patterns. This in turn has been exploited by humans through fisheries, which commonly target fishes as they make predictable seasonal movements between and within habitats. This is particularly clear in fisheries from large river systems, which show a characteristic synchrony between the hydrological and fish reproductive cycles. This has not only driven the evolution of fish diversity in these systems (Wootton, 1990) but also has an important influence on the abundance of target species for riverine fisheries (Oliveira *et al*., 2015; Stassen *et al*., 2010). In neotropical rivers, capture production of some key species is positively associated with increased water levels (Oliveira *et al*., 2015; Rabuffetti *et al*., 2017; Stassen *et al*., 2010) while other target species (Milton *et al*., 2005) thrive in years with less water availability. Such interannual variation in conditions and fisheries yields also affects socio-economic dynamics of fishers and the wider community (Pinho, Marengo and Smith, 2015), including consumption patterns (Ambikapathi *et al*., 2017). As such, the well-recognized capacity of ENSO to modify the intensity and timing of key seasonal patterns in precipitation and hydrology in river basins worldwide, means that ENSO represents a potentially major disruptive influence on inland fisheries and on those who rely on them for income, food and employment.

Although it is clear that ENSO variability has considerable potential to affect the capacity of inland fisheries to provide goods and services – including maintenance of food security – to our knowledge, no systematic assessment has been made of the effects of ENSO on inland fisheries production. This likely reflects several factors, including the fact that variability associated with ENSO changes across time and space (Kovats *et al*., 2003; Ward *et al*., 2010) and that ENSO is a remarkably complex phenomenon (Takahashi *et al*., 2011), with Wyrtki (1975) observing that no two ENSO events are the same.

As noted above, inland fisheries exploit wild fish from a variety of freshwater ecosystems, with the largest yields being associated with lake and river fisheries (Funge-Smith, 2018). In order to consider the possible complexities involved with reliably demonstrating ENSO-derived variation in inland fisheries production, we can consider the case of river fisheries, which dominate the sector in many regions. Many of the world's large river systems (e.g. Amazon, Ganges, Mekong, Niger, Orinoco, Paraná) support important floodplain fisheries, which can be extremely productive – e.g. 50 kg ha^{-1} to 400 kg ha^{-1} in Bangladesh (Craig *et al*., 2004). These fisheries rely on the seasonal flood pulses that affect the magnitude and timing of river discharge and result in the flooding of riparian habitats such as the floodplain (the flood pulse concept – Junk, Bayley and Sparks, 1989), leading to an expansion of available habitat from the main river channel to a complex network of numerous lakes, wetlands and connecting smaller rivers and streams, providing access to nursery and foraging habitats with diverse and productive food webs fuelled by a number of autochthonous and allochthonous energetic pathways. This allows increased secondary production and fisheries yields (Lima, Kaplan and Doria, 2017; Stassen *et al*., 2010; Welcomme *et al*., 2016). ENSO effects on precipitation in these large river catchments affect discharge (Räsänen and Kummu, 2013; Su *et al*., 2018; Ward *et al*., 2010) and the timing and magnitude of the flood pulse (Schöngart and Junk, 2007), raising the clear potential for ENSO-associated variation in precipitation to affect floodplain fishery production. Indeed, this has been seen in several important fisheries species (Fernandes *et al*., 2009; Pinaya *et al*., 2016; Rabuffetti *et al*., 2017), which might raise hopes for general common response to a given ENSO event. However, floodplain systems and their fisheries are remarkably complex (Hoggarth *et al*., 1999) and different species within the same tropical river fish assemblage can show distinct responses to hydrological variation (Lima, Kaplan and Doria, 2017), and local catches from sites located across a wider system can show different responses to ENSO variation e.g. lower Amazon (Pinaya *et al*., 2016). These factors combined increase the difficulties involved in developing a general model to predict fisheries yields to ENSO-derived flood pulse variation (Hoggarth *et al*., 1999; Lima, Kaplan and Doria, 2017) and will likely complicate the search for a common approach to how inland fisheries production responds to ENSO variation.

Using a similar approach to that used in previous sections, we examine whether different ENSO event categories, and different El Niño event types show any patterns of influencing annual production from inland capture fisheries. Firstly, we examine evidence for effects at a global level, pooling data for different species, regions, and countries. We also examine whether the overall taxonomic composition of the global inland fisheries catch became more similar in years associated with different ENSO categories or El Niño events types using permutation-based multivariate analysis of variance (PERMANOVA) and visualized shifts in community composition using principal coordinate analysis (PCoA) (Anderson, Gorley and Clarke, 2008).

We then examined similar patterns in LIFDCs and land-locked developing countries, reflecting their importance in terms of global food poverty. In a subsequent section, we examine evidence for a potential ENSO influence on inland fisheries production at the level of FAO inland fishery subregions, as well as the ten countries that in 2016 were responsible for producing 68 percent of global inland fisheries production. Finally, we examined putative ENSO effects on the ten species/categories that contributed most to global inland fishery production as reported in 2016 (FAO-FishStatJ., 2019b). Such an analysis is important if we wish to insulate ourselves as much as possible from shocks to the food production system (Badjeck *et al*., 2010; Cottrell *et al*., 2019). This has become increasingly pressing, given that recent evidence has confirmed previous suspicions that ENSO events have become increasingly more extreme in recent decades (Grothe *et al*., 2019).

9.1 GLOBAL INLAND CAPTURE FISHERY PRODUCTION

KEY MESSAGES

- At a global level, annual inland fisheries yield increased in a linear manner from 1.9 million tonnes in 1950 to 11.3 million tonnes in 2016.
- Comparison of annual inland fishery production anomalies between 1950 and 2016 showed no statistical effect of ENSO variation at a global level, nor in LIFDCs or land-locked developing countries.
- Mean annual production anomalies associated with each ENSO category or El Niño type were minor at a global level, with a maximum of +1.2 percent during La Niña and +1.4 percent during extreme El Niño.
- There was clear evidence of considerable temporal shifts in the taxonomic structure of the global inland fishery catch but this was not affected by ENSO.
- Production anomalies in LIFDCs were minor, but most marked during EP El Niño (−1.7 percent).
- Production anomalies in land-locked developing countries were most notable during extreme El Niño (−3.0 percent) and EP El Niño (+3.1 percent) events.

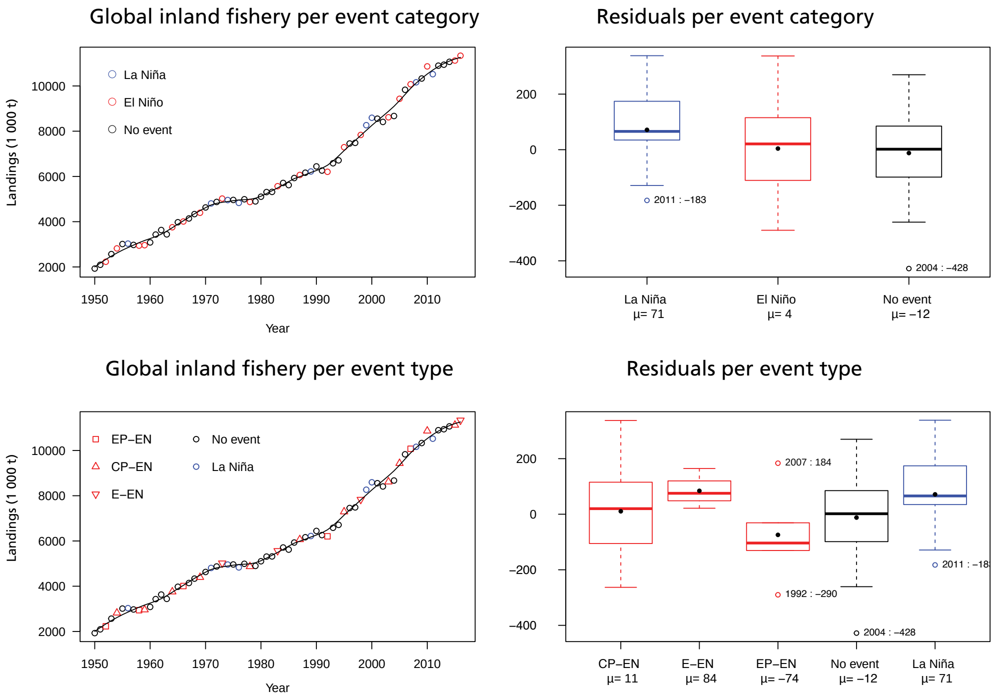
The FAO database (FAO-FishStatJ., 2019b) included catch data from inland fisheries from 127 different countries/territories in 2016. National fisheries yields (2016) varied between 1 tonne and 1.45 million tonnes, with a mean ±SD national contribution of 47 342 tonnes ± 180 413 tonnes. Data were available for 341 different species/categories captured from inland waters, with contributions ranging from

1 tonne to 5.97 million tonnes and a mean ±SD annual yield in 2016 of 33 246 tonnes ± 327 428 tonnes. At a global level (Figure 9.1), annual inland fisheries yield increased in a linear manner from 1.9 million tonnes in 1950 to 11.3 million tonnes in 2016 (cf. Figure 8.1, and the exponential-like increase seen in aquaculture).

There was no apparent statistical difference in global inland fishery production during different ENSO categories or El Niño event types (ANOVA p-value >0.05). Mean inland fisheries production (Table 9.1: Figure 9.1 during neutral events was reduced by −12 000 tonnes, equivalent to −0.1 percent of 2016 global inland fisheries production, and −0.2 percent of mean global production between 1950 and 2016. La Niña events were associated with a minor increase in mean annual global inland fisheries production of +71 000 tonnes (2016: +0.6 percent; 1950 to 2016: +1.2 percent), while catches during El Niño years increased on average by only +4 000 tonnes (2016: <+0.1 percent; 1950 to 2016: +0.1 percent). Capture anomalies were positive for both CP El Niño (+11 000 tonnes; 2016: +0.1 percent; 1950 to 2016: +0.2 percent) and extreme El Niño (84 000 tonnes; 2016: +0.7 percent; 1950 to 2016: +1.4 percent), but negative for EP El Niño (−74 000 tonnes; 2016: −0.7 percent; 1950 to 2016: −1.2 percent).

FIGURE 9.1

Left panels: variation in annual global inland fisheries production (in 1 000 t) per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories or types



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

TABLE 9.1

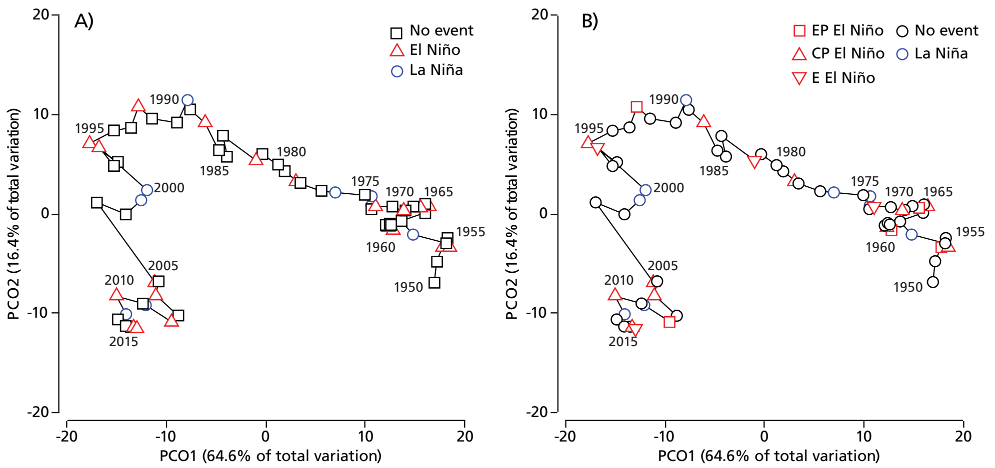
Summary of the total yield (t) in 2016 for global inland fisheries production, and the relative contribution to global inland fisheries production (2016%) of two groups of countries where access to inland fisheries-derived fish protein is particularly important for food security (LIFDCs and land-locked developing countries). Also shown is the mean anomaly (1950–2016) in inland fisheries production (x 1 000 t) associated with different ENSO event categories or types of El Niño. The % change in yield relative to the total inland fisheries yield in 2016 is shown in parentheses, with values ≥ ±1% highlighted in bold.

			Mean anomaly (1 000 t) (% 2016 yield) [% mean yield]					
Region/country *Five principal species contributing to production in 2016*	**(2016 yield) [mean yield] Tonnes**	**% 2016**	**No event**	**Strong La Niña**	**El Niño**	**CP El Niño**	**E El Niño**	**EP El Niño**
Global *Freshwater fishes nei (52.6%); cyprinids nei (6.8%); tilapias nei (3.9%); freshwater molluscs nei (2.7%); silver cyprinid (2.4%)*	(11 336 924) [6 127 479]	100	-12 (-0.1) [-0.2]	+71 (+0.6) **[+1.2]**	+4 (+0.0) [+0.1]	+11 (+0.1) [+0.2]	+84 (+0.7) **[+1.4]**	-74 (-0.7) **[-1.2]**
LIFDCs *Freshwater fishes nei (47.7%); cyprinids nei (13.6%); silver cyprinid (5.2%); tilapias nei (4.3%), Nile perch (3.9%)*	(5 157 178) [2 535 823]	45.5	-9 (-0.2) [-0.4]	+29 (+0.6) **[+1.1]**	+13 (+0.3) [+0.5]	+34 (+0.7) **[+1.3]**	+25 (+0.5) **[+1.0]**	-43 (-0.8) **[-1.7]**
Land-locked developing countries *Freshwater fishes nei (33.1%); Lake Malawi sardine (8.6%); tilapias nei (7.9%); cyprinids nei (7.3%); Nile perch (7.2%)*	(1 276 731) [609 492]	11.3	-2 (-0.2) [-0.3]	+6 (+0.5) **[+1.0]**	+2 (+0.2) [+0.3]	+2 (+0.2) [+0.3]	**-18** **(-1.4)** **[-3.0]**	**+19** **(+1.5)** **[+3.1]**

PERMANOVA showed that neither ENSO category (Pseudo $F_{2,66}$ = 0.37, P = 0.93) or El Niño event type (Pseudo $F_{1,66}$ = 0.42, P = 0.98) had an obvious effect on the composition of global inland fishery catch, but time was strongly associated (Pseudo $F_{1,66}$ = 88.1, P = 0.0001) with changes in catch composition (Figure 9.2).

FIGURE 9.2

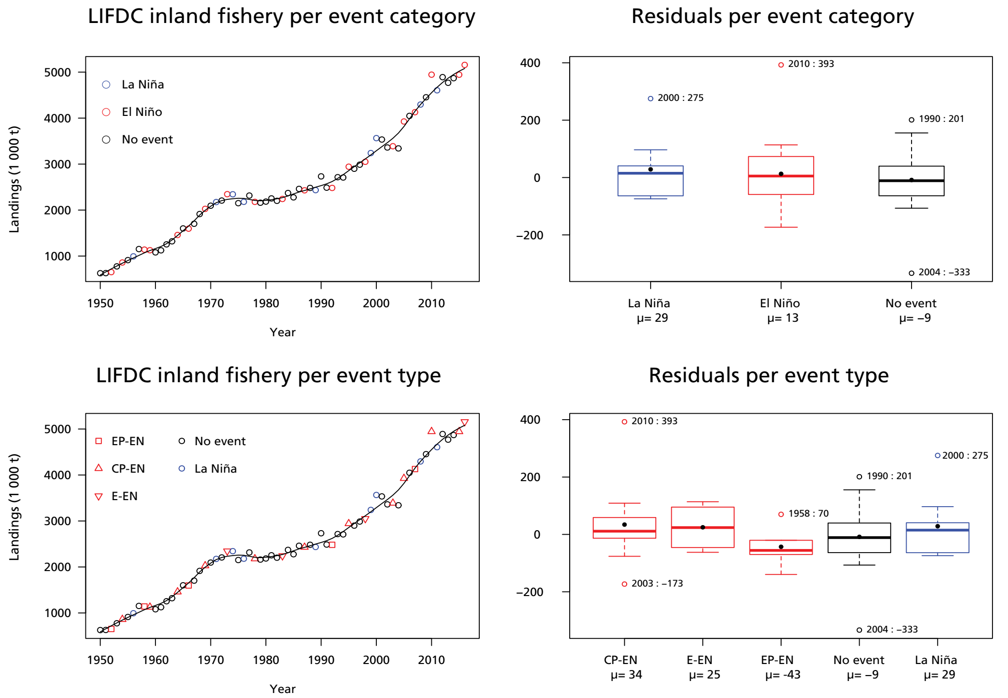
Canonical analysis of principal coordinate (PCoA) ordinations showing how taxonomic composition of total annual global inland fishery catch shifted over the period 1950–2016 (Bray-Curtis dissimilarity), where markers closer together reflect years with more similar catch compositions. Individual markers show years, and are joined with a line that follows the 1950–2016 time series. The results show a clear temporal evolution of the global inland fisheries catch, with no evidence that catches during years associated with particular A) ENSO categories or B) El Niño event types were more similar



Almost half (45.5 percent) of all inland fishery production in 2016 was derived from LIFDCs (Table 9.1). Annual inland fisheries production in these countries increased in a linear pattern from 627 102 tonnes in 1950 to 5.2 million tonnes in 2016 (Figure 9.3), with mean annual production over this period of 2.5 million tonnes. In 2016, a total of 99 different species/categories contributed to LIFDC inland fisheries production, with five species contributing approximately 75 percent of total catch in 2016 (Table 9.1). Production anomalies were statistically similar for both the three different ENSO categories, and the different El Niño types (ANOVA p-value >0.05). Mean production anomalies were negative and relatively small during neutral events (–9000 tonnes; 2016: –0.2 percent; 1950 to 2015: –0.4 percent), but positive during both La Niña (+29 000 tonnes; 2006: +0.6 percent; 1950 to 2016: +1.1 percent) and El Niño events (+13 000 tonnes; 2016: +0.3 percent; 1950 to 2016: +0.5 percent). Inland fishery production in LIFDCs was associated with a positive anomaly of +13 000 tonnes (2016: +0.7 percent; 1950 to 2016: +1.3 percent) under CP El Niño conditions, and a similar but slightly smaller positive anomaly during extreme El Niño periods (+25 000 tonnes; 2016: +0.5 percent; 1950 to 2016: +1.0 percent). LIFDC inland fishery production anomalies under EP El Niño resulted in an average reduced catch of –43 000 tonnes, equivalent to –0.8 percent of 2016 production, or –1.7 percent of the annual mean for the period 1950 to 2016.

FIGURE 9.3

Left panels: variation in annual inland fisheries production in LIFDCs (in 1 000 t) per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories or types

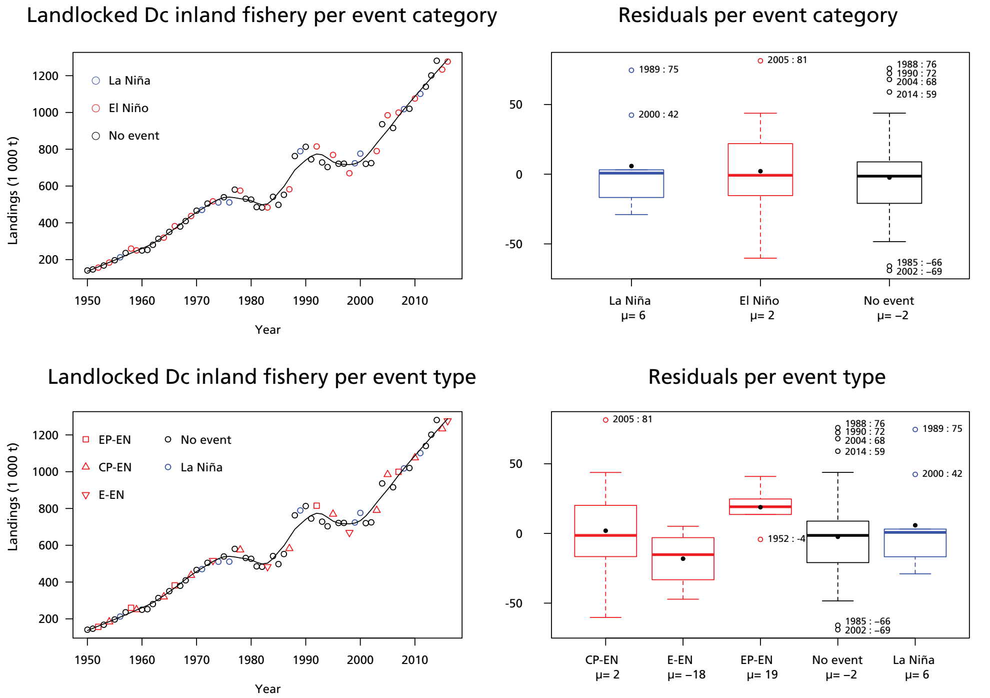


Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

Production from land-locked developing countries made a limited (11 percent) contribution to total global inland fishery production in 2019 (Table 9.1). Over the period 1950 to 2016 annual production increased in a generally linear pattern (Figure 9.4) from 140 850 tonnes to 1.3 million tonnes, with mean annual production over the same period being 609 492 tonnes. There was no evidence for statistical differences in annual production under different ENSO events or El Niño types (ANOVA p-value >0.05). Neutral conditions were associated with a minor negative mean production anomaly (–2 000 tonnes; 2016: –0.2 percent; 1950 to 2016: –0.3 percent). Production during La Niña periods increased on average by +6 000 tonnes (2016: +0.5 percent; 1950 to 2016: +1.0 percent). El Niño was associated with minor positive anomalies (+2 000 tonnes; 2016: +0.2 percent; 1950 to 2016: +0.3 percent). An identical mean anomaly was recorded for CP El Niño. Production during extreme El Niño was reduced on average by –18 000 tonnes, equivalent to –1.4 percent of 2016 production and –3.0 percent of mean production for the 1950 to 2016 period, indicating a possibly wider impact. Conversely, EP El Niño conditions were associated with a positive mean annual production anomaly of +19 000 tonnes (2016: +1.5 percent; 1950 to 2016: +3.1 percent).

FIGURE 9.4

Left panels: variation in annual inland fisheries production in land-locked developing countries (in 1 000 t) per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories or types



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

9.2 REGIONAL INLAND FISHERY PRODUCTION

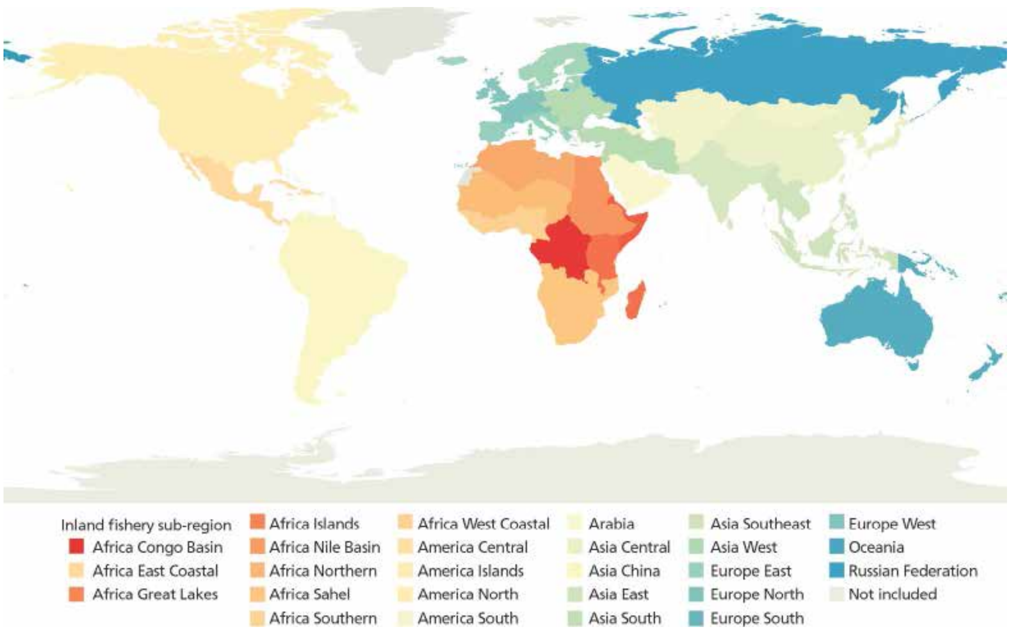
KEY MESSAGES

- We described known climatic effects of ENSO variation and estimated ENSO effects on inland fisheries production across 25 broad geographical subregions that include countries that display common characteristics, e.g. relating to climate, geography and economic status, as well as fisheries that extend across national boundaries.
- There was no significant effect of ENSO event category or El Niño event type on inland fisheries production in any of the subregions, but production anomalies associated with the different ENSO conditions and extreme El Niño event types varied between −18.8 percent and +34.9 percent.
- The sign or strength of production anomalies differed for many subregions under ENSO, including those that provide the bulk of inland fishery production, and again, as seen for the aquaculture sector, La Niña was associated with more extreme production anomalies than neutral or El Niño events.
- Comparison of mean annual inland fisheries production values during the different El Niño event types indicated quite distinct responses, with switches in the sign and scale of anomalies at a subregional, and extra-subregional scale. Extreme El Niño saw particularly large numbers of inland fisheries subregions with negative production anomalies.

In order to examine the potential influence of ENSO on inland fisheries production, it is important to consider likely regional level effects, especially given that inland fisheries production is concentrated in certain geographical regions (Funge-Smith, 2018; Funge-Smith and Bennett, 2019) and that particular ENSO events have markedly different consequences for ecosystems situated in different geographical locations (Lee, Ward and Block, 2018; Su *et al*., 2018; Ward *et al*., 2010). It is less simple to define which level of geographical resolution is suitable for such analyses. Capture statistics held in the FAO database for inland fisheries are reported at a national level, not at the level of individual fisheries or basins, which would be optimal. Furthermore, national data aggregates information from a range of different habitat types and fishing gears, each of which may respond differently to ENSO-associated variation.

A further issue is that many inland fisheries operate in basins that extend across national boundaries, reducing the utility of national level data. In previous work using FAO-derived data on inland fisheries (Funge-Smith, 2018; Harrod *et al*., 2018a) it has proved useful to gather information at the level of subregional clusters that include countries that display common characteristics, e.g. relating to climate, geography and economic status, as well as fisheries that extend across national boundaries. As such, we examined the putative impact of ENSO variation on inland fisheries production in each of 25 different FAO subregions (Figure 9.5, Table 9.2), where reported inland fishery yields in 2016 ranged between 200 tonnes (Africa: East Coast) and 2.7 million tonnes (Asia South). Many of these subregions broadly overlap with the regions used in Section 8, but are not always directly comparable. In many cases, information on ENSO effects on local climate and water availability for the countries included in each subregion is given above in section 8.2. Where information has not been provided previously, it is provided in this section.

FIGURE 9.5
FAO Inland fishery subregions used to calculate inland fishery production anomalies following Funge-Smith (2018)



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a). Map conforms to United Nations World map, February 2020.

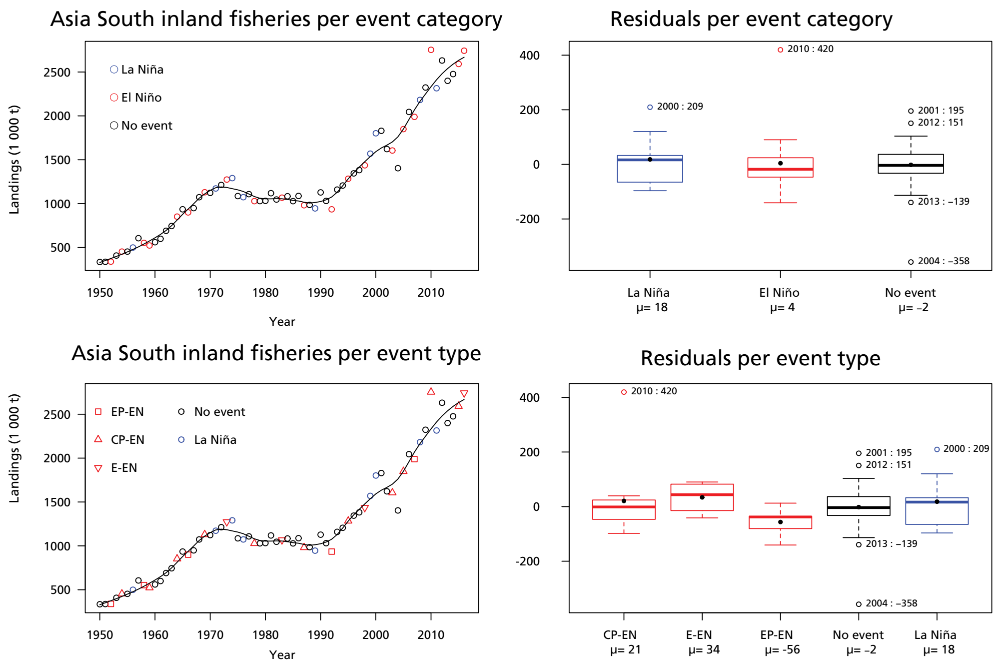
9.2.1 Asia South

The six countries (Bangladesh, Bhutan, India, Nepal, Pakistan, Sri Lanka) located in the subregion of Asia South (Table 9.2, Figure 9.5) contributed 24.2 percent of global inland fishery catch in 2016, with a total land area of 4.13 million km². ENSO-related effects on climate and water availability are reported in Section 8.2.3. Annual inland fisheries production in the subregion (Figure 9.6) increased from 334 905 tonnes in 1950 to 2.7 million tonnes in 2016, with an initial linear rise from the 1950s until 1970, after which it stabilized, and then declined slightly, and then increased again in a linear fashion from the 1990s until 2016. In 2016, yields from 17 different inland fisheries products were reported from the subregion, with contributions ranging from 1 tonne (copper mahseer, representing 0.00004 percent of regional contribution) through to 1.6 million tonnes for the general freshwater fishes nei category (58.6 percent). Mean ±SD annual contribution in 2016 was 161 332 tonnes ± 399 403 tonnes. Five species/categories contributed to 94 percent of total inland fisheries catch in the Asia South subregion in 2016 (freshwater fishes nei: 58.6 percent; cyprinids nei: 21.7 percent; snakeheads nei: 5.5 percent; Hilsa shad: 5.3 percent; freshwater siluroids nei: 2.8 percent).

There were no statistical differences in production anomalies associated with either ENSO event category or El Niño event type (ANOVA: P >0.05). As in previous sections, we discuss mean production anomalies to inform discussion about the likely scale of responses to ENSO events. Neutral ENSO conditions were associated (Table 9.2) with a minor (−2 000 tonnes) mean production anomaly from inland fisheries in the Asia South subregion, equivalent to −0.1 percent of 2016 production, or −0.2 percent of mean production in the subregion between 1950 and 2016. Mean production anomalies during La Niña and El Niño conditions were both positive, but differed in terms of their scale (La Niña: +18 000 tonnes; 2016: +0.7 percent; 1950 to 2016: +1.4 percent; El Niño: +40 00 tonnes; 2016: +0.2 percent; 1950 to 2016: +0.3 percent). Mean production anomalies for both CP El Niño (+21 000 tonnes; 2016: +0.8 percent; 1950 to 2016: +1.7 percent) and extreme El Niño (+34 000 tonnes; 2106: +1.2 percent; 1950 to 2016: +2.7 percent) were both positive. EP El Niño conditions were associated with a considerable negative inland fishery production anomaly (−56 000 tonnes) in the Asia South subregion, a value equivalent to −2 percent of total 2016 yield in the region, or −4.5 percent of mean production in the period 1950 to 2016.

FIGURE 9.6

Left panels: variation in annual inland fisheries production from the Asia South FAO subregion (in 1 000 t) per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories or types



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

TABLE 9.2
Summary of the total yield (t) in 2016 for inland fisheries production, and the relative contribution to total global inland fisheries production (2016%) of different FAO inland fisheries subregions. Also shown is the mean anomaly (1950–2016) in inland fisheries production (x 1 000 t) associated with different ENSO event categories or types of El Niño. The % change in yield relative to the total inland fisheries yield in 2016 is shown in parentheses, with values >±1% highlighted in bold. Two regions with minor (<0.04%) of total global inland fisheries production in 2016 (America islands: 4 056 t; Africa East Coast: 200 t) are not shown, but showed no evidence for anomalies. No data were reported from the Arabia subregion. Countries marked with * were categorised as LIFDCs by the FAO in 2016, while those marked with # are considered as land-locked developing countries.

			Mean anomaly (x1 000 t) (% 2016 yield) [% mean yield]					
Inland fishery subregion: *Country*	**(2016 yield) [mean yield] t**	**2016 %**	**No event**	**Strong La Niña**	**El Niño**	**CP El Niño**	**E El Niño**	**EP El Niño**
Asia South *Bangladesh*, Bhutan#, India*, Nepal*#, Pakistan*, Sri Lanka*	(2 742 637) [1 250 058]	24.19	-2 (-0.1) [-0.2]	+18 (+0.7) **[+1.4]**	+4 (+0.2) [+0.3]	+21 (+0.8) **[+1.7]**	+34 **(+1.2)** **[+2.7]**	-56 (-2.0) **[-4.5]**
Asia Southeast *Brunei Darussalam, Cambodia, Indonesia, the Lao People's Dem. Rep. #, Malaysia, Myanmar, the Philippines, Singapore, Thailand, Timor-Leste, Viet Nam*	(2 398 941) [1 088 964]	21.16	+7 (+0.3) [+0.6]	+14 (+0.6) **[+1.3]**	-18 (-0.8) **[-1.7]**	-30 **(-1.3)** **[-2.8]**	-29 **(-1.2)** **[-2.7]**	+19 (+0.8) **[+1.7]**
Asia China *China, China, Hong Kong SAR, China, Macao SAR, Taiwan Province of China*	(2 003 422) [966 110]	17.67	-7 (-0.3) [-0.7]	+16 (+0.8) **[+1.7]**	+9 (+0.4) [+0.9]	+7 (+0.3) [+0.7]	+80 **(+4.0)** **[+8.3]**	-44 (-2.2) **[-4. 6]**
Africa Great Lakes *Burundi*#, Kenya*, Malawi*#, Rwanda*#, United Rep. of Tanzania*, Uganda*#*	(1 028 191) [558 123]	9.07	-3 (-0.3) [-0.5]	+2 (+0.2) [+0.4]	+6 (+0.6) **[+1.1]**	+6 (+0.6) **[+1.1]**	+5 (+0.5) [+0.9]	+15 **(+1.5)** **[+2.9]**
Africa West Coast *Benin*, Cameroon*, Côte d'Ivoire*, Equatorial Guinea, Ghana*, Guinea*, Guinea-Bissau*, Liberia*, Nigeria*, Sierra Leone*, Togo**	(571 940) [254 200]	5.05	-1 (-0.2) [-0.4]	+6 **(+1.1)** **[+2.4]**	-1 (-0.2) [-0.4]	-2 (-0.4) [-0.8]	+12 **(+2.1)** **[+4.7]**	-8 **(-1.4)** **[-3.2]**
Africa Nile Basin *Egypt, Ethiopia*, South Sudan*#, the Sudan**	(349 959) [152 705]	3.09	+3 (+0.9) **[+2.0]**	-11 **(-3.1)** **[-7.2]**	-1 (-0.3) [-0.7]	+1 (+0.3) [+0.7]	-2 (-0.6) **[-1.3]**	-3 (-0.9) **[-2.0]**
America South *Argentina, Bolivia (Plurinat. State of)#, Brazil, Chile, Colombia, Ecuador, French Guyana, Guyana, Paraguay#, Peru, Suriname, Uruguay, Venezuela (Bolivarian Rep. of)*	(338 643) [255 490]	2.99	0 (-) [-]	-6 **(-1.8)** **[-2.3]**	+3 (+0.9) **[+1.2]**	+10 **(+3.0)** **[+3.9]**	-5 **(-1.5)** **[-2.0]**	-7 **(-2.1)** **[-2.7]**

			Mean anomaly (x1 000 t) (% 2016 yield) [% mean yield]					
Inland fishery subregion: *Country*	**(2016 yield) [mean yield] t**	**2016 %**	**No event**	**Strong La Niña**	**El Niño**	**CP El Niño**	**E El Niño**	**EP El Niño**
Africa Sahel *Burkina Faso*#, Chad*#, Gambia*, Mali*#, Mauritania*, the Niger*, Senegal**	(317 975) [205 123]	2.81	-1 (-0.3) [-0.5]	+1 (+0.3) [+0.5]	+1 (+0.3) [+0.5]	+6 (+1.9) [+2.9]	-13 (-4.1) [-6.3]	0 (-) [-]
Africa Congo Basin *Central African Republic*#, the Congo, the Democratic Republic of the Congo*, Gabon*	(309 288) [178 103]	2.73	-2 (-0.7) [-1.1]	+2 (+0.7) [+1.1]	+3 (+1.0) [+1.7]	+3 (+1.0) [+1.7]	-2 (-0.7) [-1.1]	+5 (+1.6) [+2.8]
The Russian Federation	(292 890) [112 917]	2.58	-6 (-2.1) [-5.3]	+6 (+2.1) [+5.3]	+8 (+2.7) [+7.1]	+7 (+2.4) [+6.2]	-3 (-1.0) [-2.7]	+21 (+7.2) [+18.6]
Africa Southern *Angola, Botswana#, Lesotho*#, Mozambique*, Namibia, South Africa, the Kingdom of Eswatini#, Zambia#, Zimbabwe*#*	(217 622) [87 066]	1.92	+1 (+0.5) [+1.2]	+1 (+0.5) [+1.2]	-1 (-0.5) [-1.2]	0 (-) [-]	-5 (-2.3) [-5.7]	0 (-) [-]
America Central *Belize, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua*, Panama*	(203 945) [69 706]	1.80	-3 (-1.5) [-4.3]	+2 (+1.0) [+2.9]	+3 (+1.5) [+4.3]	+2 (+1.0) [+2.9]	+9 (+4.4) [+12.9]	-1 (-0.5) [-1.4]
Asia West *Iran (Islamic Rep. of), Iraq, Israel, Jordan, Lebanon, Palestine, the Syrian Arab Republic*, Turkey*	(158 091) [87 694]	1.39	0 (-) [-]	+4 (+2.5) [+4.6]	-2 (-1.3) [-2.3]	-7 (-4.4) [-8.0]	+5 (+3.2) [+5.7]	+5 (+3.2) [+5.7]
Asia Central *Afghanistan*#, Armenia#, Azerbaijan#, Georgia, Kazakhstan#, Kyrgyzstan*#, Mongolia#, Tajikistan*#, Turkmenistan#, Uzbekistan*#*	(91 206) [37 257]	0.81	0 (-) [-]	+13 (+14.3) [+34.9]	-5 (-5.5) [-13.4]	-7 (-7.7) [-18.8]	-2 (-2.2) [-5.4]	0 (-) [-]
Europe Eastern *Belarus, Bulgaria, Czechia, Hungary, Republic of Moldova, Montenegro, Poland, Romania, Serbia, Slovakia, Slovenia, Ukraine*	(62 075) [44 529]	0.55	+1 (+1.6) [+2.2]	0 (-) [-]	-1 (-1.6) [-2.2]	-2 (-3.2) [-4.5]	-1 (-1.6) [-2.2]	-1 (-1.6) [-2.2]
America North *Canada, United States of America*	(53 934) [103 210]	0.48	0 (-) [-]	-1 (-1.9) [-1.0]	+1 (+1.9) [+1.0]	-1 (-1.9) [-1.0]	+2 (+3.7) [+1.9]	+4 (+7.4) [+3.9]

			Mean anomaly (x1 000 t) (% 2016 yield) [% mean yield]					
Inland fishery subregion: *Country*	**(2016 yield) [mean yield] t**	**2016 %**	**No event**	**Strong La Niña**	**El Niño**	**CP El Niño**	**E El Niño**	**EP El Niño**
Europe Northern *Denmark, Estonia, Finland, Iceland, Latvia, Lithuania, Norway, Sweden*	(44 423) [37 910]	0.39	0 (-) [-]	-1 (-2.3) [-2.6]	0 (-) [-]	-1 (-2.3) [-2.6]	-1 (-2.3) [-2.6]	+2 (+4.5) [+5.3]
Asia East *Japan, Democratic People's Republic of Korea*, the Republic of Korea*	(42 140) [124 087]	0.37	0 (-) [-]	-3 (-7.1) [-2.4]	+2 (+4.8) [+1.6]	+6 (+14.2) [+4.8]	-1 (-2.4) [-0.8]	-5 (-11.9) [-4.0]
Africa Islands *Madagascar**	(30 461) [31 278]	0.27	0 (-) [-]	0 (-) [-]	+1 (+3.3) [+3.2]	+1 (+3.3) [+3.2]	+1 (+3.3) [+3.2]	+1 (+3.3) [+3.2]
Europe Western *Andorra, Austria, Belgium, Channel Islands, Faroe Islands, France, Germany, Ireland, Liechtenstein, Luxembourg, Netherlands, Switzerland, United Kingdom of Gr. Britain and N. Ireland*	(26 888) [29 230]	0.24	0 (-) [-]	0 (-) [-]	0 (-) [-]	+1 (+3.7) [+3.4]	-1 (-3.7) [-3.4]	0 (-) [-]
Oceania *Australia, Fiji, French Polynesia, Micronesia (Federated States of), New Zealand, Papua New Guinea, Samoa, Solomon Islands*	(17 949) [11 022]	0.16	0 (-) [-]	0 (-) [-]	0 (-) [-]	-1 (-5.6) [-9.1]	0 (-) [-]	0 (-) [-]
Africa North *Algeria, Libya, Morocco, Tunisia*	(16 702) [2 880]	0.15	0 (-) [-]	0 (-) [-]	0 (-) [-]	0 (-) [-]	0 (-) [-]	0 (-) [-]
Europe Southern *Albania, Bosnia and Herzegovina, Croatia, Cyprus, Greece, Italy, Former Yugoslav Republic of Macedonia, Malta, Portugal, Spain*	(13 281) [23 705]	0.12	0 (-) [-]	+1 (+7.5) [+4.2]	0 (-) [-]	0 (-) [-]	+1 (+7.5) [+4.2]	0 (-) [-]

9.2.2 Asia Southeast

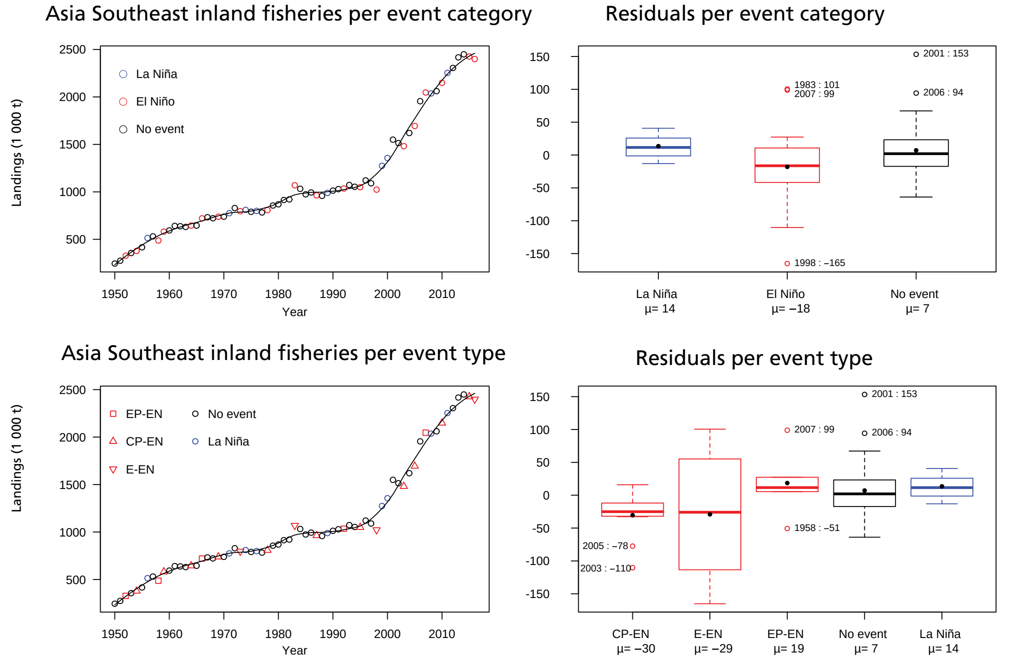
Eleven countries (Brunei Darussalam, Cambodia, Indonesia, the Lao People's Democratic Republic, Malaysia, Myanmar, the Philippines, Singapore, Thailand, Timor-Leste, Viet Nam) constitute the Asia Southeast inland fisheries subregion (Table 9.2, Figure 9.5), with a total land area of 4.36 million km^2. ENSO influences on climate and water availability in the subregion are described in Section 8.2.2.

The Asia Southeast subregion contributed 21.2 percent of global inland fisheries production in 2016. Reported annual inland fisheries production in the subregion (Figure 9.7) increased from 244 892 t in 1950 to ~2.4 million t in 2016, with a notable acceleration in capture rate following the late 1990s: mean ±SD annual production over the period was 1 088 964 tonnes ± 595 594 tonnes. In 2016, five different species/categories accounted for 82 percent of the total inland fisheries yield in the Asia Southeast subregion, with the general freshwater fisheries nei category dominating recorded catch (72.6 percent), followed by striped snakehead (3.0 percent), Nile tilapia (2.3 percent), freshwater molluscs nei (2.3 percent) and the Asian redtail catfish (1.8 percent).

Inland fisheries production anomalies were statistically similar between both ENSO event categories and event types (Figure 9.7; ANOVA p-value >0.05). Mean inland fisheries annual production increased by +7 000 tonnes during ENSO neutral periods in the Asia Southeast subregion (Table 9.2), a value equivalent to +0.3 percent of production in 2016, or +0.6 percent of mean production for the period 1950 to 2016. On average, production anomalies during La Niña conditions were double that of neutral periods (La Niña: +14 000 tonnes; 2016: +0.6 percent; 1950 to 2016: +1.3 percent). El Niño conditions were associated with a mean decrease in inland fisheries production of −18 000 tonnes, reflecting −0.8 percent of 2016 production in the subregion, or −1.7 percent of mean production between 1950 and 2016. Mean production anomalies for both CP (−30 000 tonnes) and extreme El Niño (−29 000 tonnes) were similar, reflecting reductions in mean annual production of −1.2 percent to −1.3 percent relative to 2016 or −2.7 percent and −2.8 percent to long-term mean inland fisheries production in the Asia Southeast subregion. Conversely, EP El Niño conditions were associated with a positive production anomaly of +19 000 tonnes (2016: +0.8 percent; 1950 to 2016: +1.7 percent).

FIGURE 9.7

Left panels: variation in annual inland fisheries production from the Asia Southeast FAO subregion (in 1 000 t) per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories or types



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

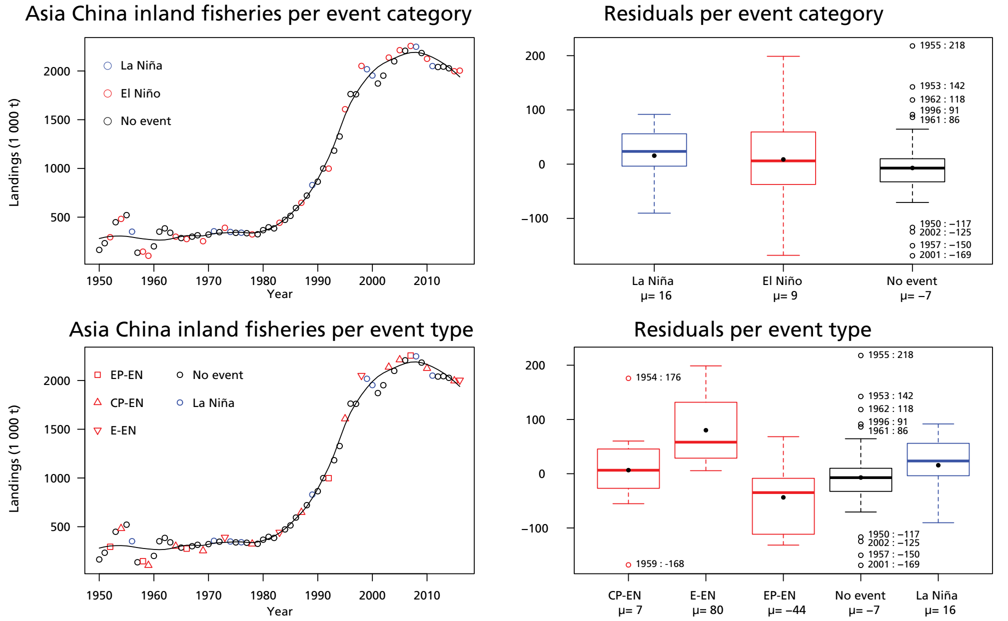
9.2.3 Asia China

The Asia China subregion (Figure 9.5) is made up of China, China, Hong Kong SAR, China, Macao SAR and Taiwan Province of China and has a total land area of 9.33 million km². It overlaps largely with the region of East Asia detailed in Section 8.2.1, and details of the climate response of the region to ENSO variation can be found there. The Asia China subregion was ranked third in terms of inland fisheries yield in 2016 (Table 9.2), with a total contribution of 17.7 percent to global inland fisheries catch. Annual reported catch in the subregion increased (Figure 9.8) from 164 359 tonnes in 1950 to 2.0 million tonnes in 2016, with a noticeable apparent increase in the annual yields in the mid-1980s, followed by a levelling off and reduction in catches after about 2005. Mean reported inland fisheries yield during the period 1950 to 2016 in the Asia China subregion was 966 110 tonnes ± 785 706 tonnes. In 2016, 72.4 percent of captures by mass related to the general freshwater fishes nei category and 11.8 percent to the freshwater molluscs nei category.

Inland fisheries production in the Asia China subregion between 1950 and 2016 was statistically similar between all ENSO event categories and EL Niño types (ANOVA p-value >0.05). Mean anomalies for the main ENSO categories ranged between –7 000 tonnes (neutral conditions) through to +16 000 tonnes during La Niña events (Table 9.2), the latter reflecting +1.7 percent of mean annual inland fisheries production in the subregion between 1950 and 2016. The most notable mean production anomaly was associated with extreme El Niño events, where inland fisheries production in the Asia China subregion increased by +80 000 tonnes – equivalent to +4.0 percent of 2016 production, or +8.3 percent of mean regional inland fisheries yield between 1950 and 2016. CP El Niño anomalies were minor (+7 000 tonnes), while EP El Niño events were associated with a mean reduction of –44 000 tonnes (2016: –2.2 percent; 1950 to 2016: –4.6 percent).

FIGURE 9.8

Left panels: variation in annual inland fisheries production from the Asia China FAO subregion (in 1 000 t) per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories or types



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

9.2.4 Africa Great Lakes

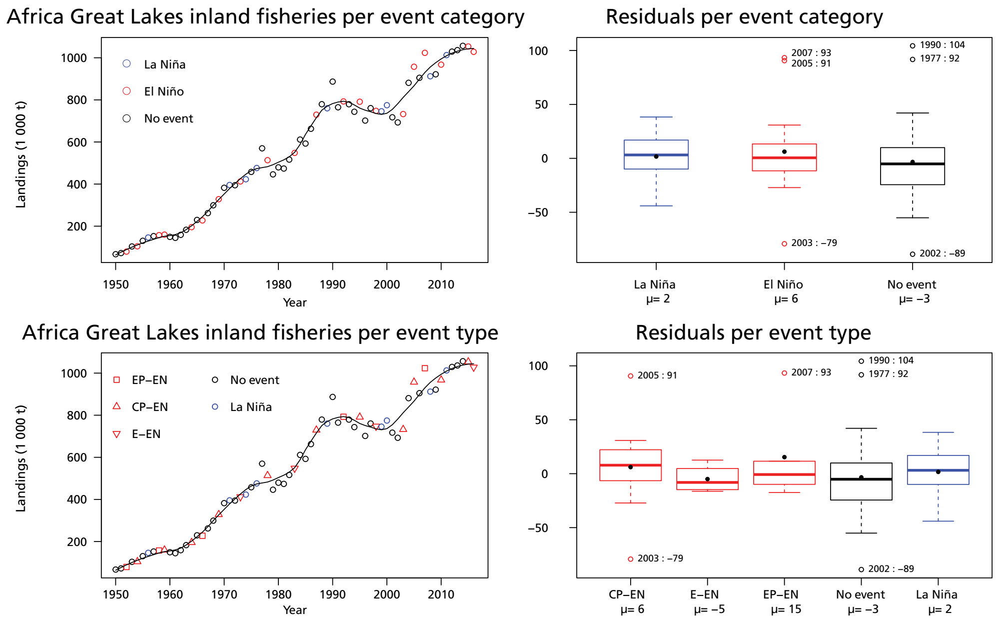
The Africa Great Lakes subregion (total land area: 1.79 million km²) includes six different countries (Burundi, Kenya, Malawi, Rwanda, the United Republic of Tanzania and Uganda), all of which are LIFDCs and four of which are classified by the FAO as land-locked, low income countries (Table 9.2, Figure 9.5). Climatic responses to ENSO are described in Section 8.2.12. Inland fisheries production in the subregion is extremely important for food security and in 2016 represented 9.1 percent of total global production. Estimated annual inland fisheries production in the Africa Great Lakes subregion increased from 66 900 tonnes in 1950 to 1.03 million tonnes in 2016 in a generally linear fashion, albeit with some evidence for a plateau during the 1990s (Figure 9.9). Mean ±SD annual inland fisheries yield in the subregion for the period 1950 to 2016 was 558 123 tonnes ± 312 570 tonnes. A total of 43 different species and categories were recorded from the subregion's inland fishery in 2016, with the five highest ranked species accounting for 68 percent of the total catch (silver cyprinid: 26.0 percent; Nile perch: 16.1 percent; Lake Malawi sardine: 10.6 percent; tilapias nei: 7.8 percent; cyprinids nei: 7.3 percent).

No statistical evidence was apparent for differences in annual inland fisheries production in the Africa Great Lakes subregion between either different ENSO event categories or types (ANOVA p-value >0.05) during the period 1950 to 2016. Production anomalies associated with the three ENSO event categories (Table 9.2) ranged between –3 000 tonnes (neutral conditions) and +6 000 tonnes (El Niño), the latter representing +1.1 percent of mean annual production between 1950 and 2016.

When the different El Niño event types were considered, anomalies ranged between −5 000 tonnes (extreme El Niño) and +15 000 tonnes (EP El Niño), the latter being equivalent to +1.5 percent of 2016 annual production and +2.9 percent of 1950 to 2016 mean production in the Africa Great Lakes subregion.

FIGURE 9.9

Left panels: variation in annual inland fisheries production from the Africa Great Lakes FAO subregion (in 1 000 t) per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories or types



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

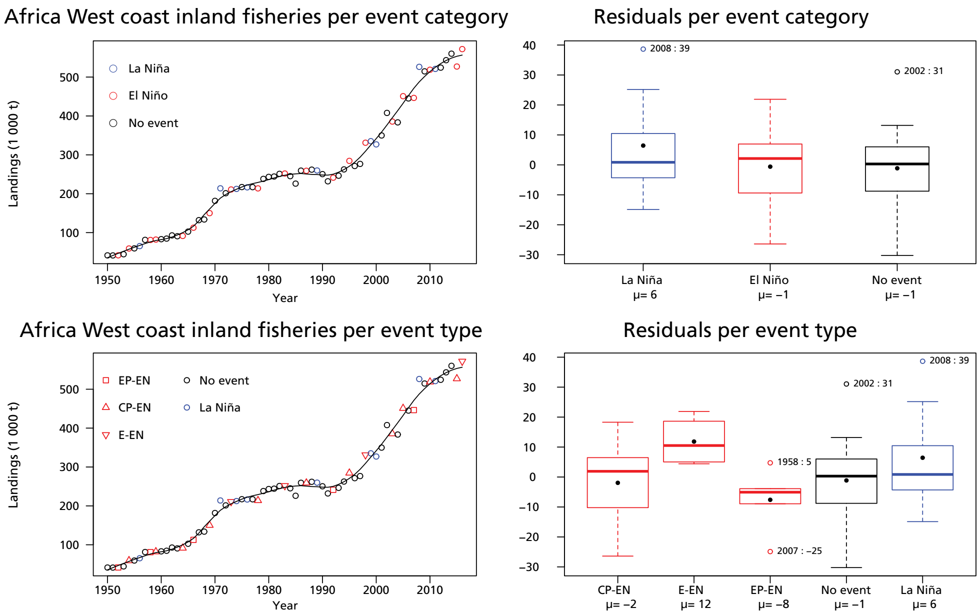
9.2.5 Africa West Coast

Of the eleven countries (Benin, Cameroon, Côte d'Ivoire, Equatorial Guinea, Ghana, Guinea, Guinea-Bissau, Liberia, Nigeria, Sierra Leone, Togo; total land area: 2.56 million km²) forming the Africa West Coast subregion (Table 9.2, Figure 9.5), all but one were classified as LIFDCs by FAO in 2016 (FAO *et al.*, 2019). The climatic response to ENSO variation for much of the subregion is described in sections 8.2.9, but does not include information for Cameroon and Equatorial Guinea. Cameroon's climate varies from tropical in coastal areas, through to semiarid and hot in the north of the country, while the climate is tropical, hot and humid. Annual estimated inland fisheries catch in the subregion increased from 41 487 tonnes in 1950 to 571 940 tonnes in 2016 (Table 9.2, Figure 9.10), representing 5.1 percent of global inland fisheries production, with a mean ±SD annual yield of 254 200 tonnes ± 152 253 tonnes. Captures in the subregion increased relatively linearly over this period, although there was an apparent slowing of the increase between the 1970s to late 1990s, followed by a marked acceleration in the rate by which annual catches increased. In 2016, a total of 29 species/categories were reported from inland fisheries from the Africa West Coast subregion, with the five highest ranked contributing 68 percent by mass (freshwater fishes nei 36.2 percent; tilapias nei 15.5 percent; torpedo-shaped catfishes nei: 7.4 percent; elephantsnout fishes nei: 4.6 percent; North African catfish: 4.4 percent).

There was no apparent statistical difference in mean capture anomalies between ENSO event categories or the different event types in the Africa West Coast subregion over the period 1950 to 2016 (ANOVA p-value >0.05). Maximum mean annual capture anomalies varied under the three ENSO event categories was +6 000 tonnes, seen during La Niña events, and equivalent to an increase of +1.1 percent relative to the 2016 total catch, or +2.4 percent of the mean catch between 1950 and 2016. The most notable shift in annual inland fisheries yields was seen during extreme El Niño, when they increased on average by +12 000 tonnes, i.e. +2.1 percent of 2016 catch and +4.7 percent of the mean annual yield between 1950 and 2016. Mean annual production decreased by −8 000 tonnes during EP El Niño periods (2016: −1.4 percent; 1950 to 2016: −3.2 percent).

FIGURE 9.10

Left panels: variation in annual inland fisheries production from the Africa West Coast FAO subregion (in 1 000 t) per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories or types



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

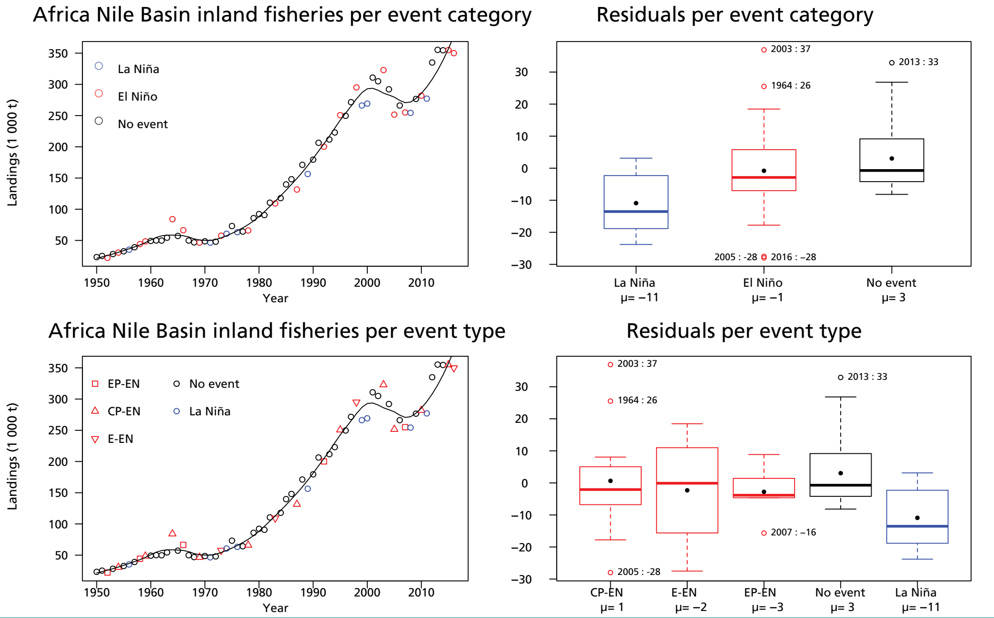
9.2.6 Africa Nile Basin

The Africa Nile Basin subregion includes four countries (Egypt, Ethiopia, South Sudan and the Sudan; total land area: 4.37 km^2), of which three are LIFDCs (Table 9.2, Figure 9.5). The climate of the subregion was described previously in 8.2.6 and 8.2.12. Total inland fisheries production in 2016 was 349 959 tonnes (3.1 percent of global total), increasing from 23 300 tonnes in 1950 (Figure 9.11). Inland fisheries catches in the subregion showed a pattern of slow but consistent increases over time, slowed during the first decade of the 2000s, but then increased again from 2012. Mean ±SD annual inland fisheries production in the period 1950 to 2016 was 152 705 tonnes ± 111 100 tonnes. In 2016, 31 different species/categories were reported in inland fisheries statistics from the Africa Nile Basin, with the five top ranked species/categories contributing 78.7 percent (Nile tilapia: 36.3 percent; freshwater fishes nei 18.9 percent; mudfish: 8.2 percent; mullets nei: 7.8 percent; tilapias nei 7.4 percent).

Mean annual inland fisheries capture anomalies in the Africa Nile Basin subregion were statistically similar between ENSO event categories and event types (Figure 9.11: ANOVA p-value >0.05). Capture anomalies associated with different ENSO event types (Table 9.2) ranged between –11 000 tonnes (La Niña) and +3 000 tonnes (neutral conditions) Mean production anomalies during La Niña were minor (–3.1 percent) relative to 2016 annual production, but marked (–7.2 percent) when estimated relative to mean regional annual production between 1950 and 2016. Mean annual capture anomalies were broadly similar across the three El Niño event types (Table 9.2), ranging between –3 000 tonnes (EP El Niño) and +1 000 tonnes (CP El Niño).

FIGURE 9.11

Left panels: variation in annual inland fisheries production from the Africa Nile Basin FAO subregion (in 1 000 t) per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories or types



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

9.2.7 America South

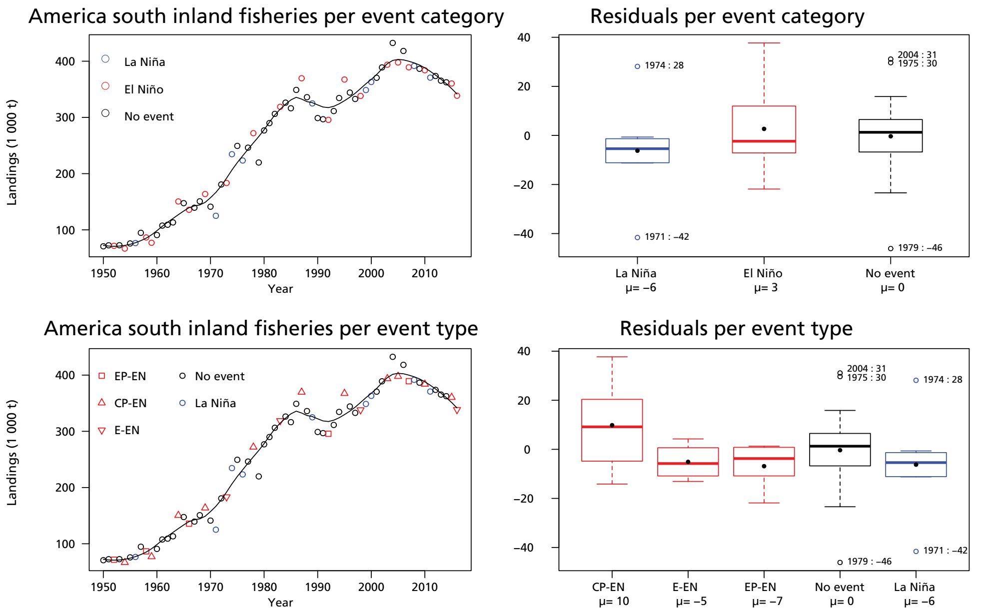
The America South subregion includes 13 different countries (Argentina, Plurinational State of Bolivia, Brazil, Chile, Colombia, Ecuador, French Guyana, Guyana, Paraguay, Peru, Suriname, Uruguay and Bolivarian Republic of Venezuela), two of which are classified as land-locked developing countries (Table 9.2, Figure 9.5). The subregion has a total land area of 17.52 million km^2. Details of the subregion's climate and effects of ENSO variation are given in section 8.2.4.

The subregion contributed approximately 3 percent to total global inland fisheries production in 2016. Annual production increased from 70 700 tonnes in 1950 to 338 643 tonnes in 2016 (Figure 9.12), with a mean ±SD annual yield of 255 490 tonnes ± 117 466 tonnes recorded between 1950 and 2015. Annual inland fishery yields in the subregion (Figure 29) increased over time until the mid-1980s, after which they showed an apparent plateau (with considerable interannual variation) until the early 2000s, after which there has been an apparent year on year decrease in inland fisheries production. In 2016, a total of 71 species/categories were reported in the inland fisheries catch statistics from the America South subregion, of which the five top ranked contributed approximately 67 percent (characins nei: 41.2 percent; prochilods nei: 10.7 percent; freshwater fishes nei: 5.7 percent; freshwater siluroids nei: 5.0 percent; laulao catfish: 4.3 percent).

There was no measurable statistical effect of ENSO event category or event type on inland fisheries production between 1950 and 2016 in the America South subregion (Table 9.2, Figure 9.12). Annual mean production anomalies associated with the three ENSO event categories varied between −6 000 tonnes (La Niña) and +3 000 tonnes (El Niño), the former reflecting 1.8 percent of 2016 production in the region, or 2.4 percent of mean annual production between 1950 and 2016. Production anomalies during different El Niño event types ranged between a mean annual reduction of −7 000 tonnes (EP El Niño; 2016: −1.1 percent; 1950 to 2016: −2.7 percent) and an increase of +10 000 tonnes (CP El Niño; 2016: +3.0 percent; 1950 to 2016: +3.9 percent).

FIGURE 9.12

Left panels: variation in annual inland fisheries production from the America South FAO subregion (in 1 000 t) per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories or types



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

9.2.8 Other subregions

Of the 23 different subregions included in Table 9.2, a considerable number (16) made minor (< 3 percent) individual contributions to total global inland fishery production in 2016. Mean annual production in 2016 for these subregions was 79 741 tonnes (1950 to 2016 mean = 50 515 tonnes). Given their reduced individual contribution to global production, we do not provide a detailed examination of these subregions beyond commenting on a subregion where access to fish from inland fisheries is known to be particularly important for food security (Africa Congo Basin) or where anomalies were particularly large in terms of annual production (Asia Central, Asia East, the Russian Federation). There was no statistical evidence that inland fishery production differed between different ENSO categories or event types (ANOVAs, P >0.05) in any of the 16 subregions with a contribution to global production <3 percent.

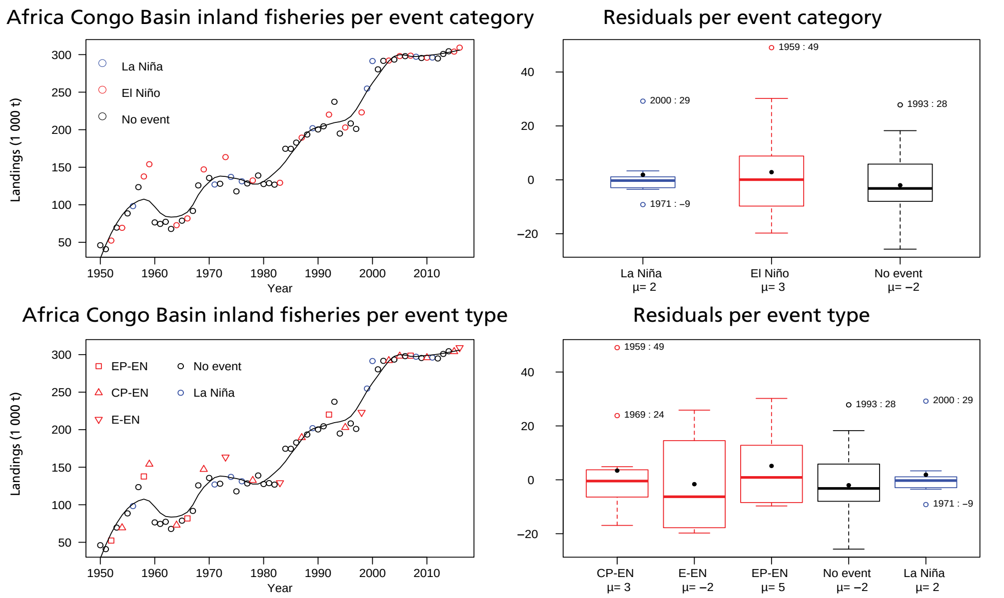
In 2016, FAO estimates suggested a total inland fisheries production of 292 890 tonnes in the Africa Congo Basin subregion, representing 2.7 percent of the global total (Table 9.2). This subregion (Figure 9.5) is made up of four countries (Central African Republic, the Congo, the Democratic Republic of the Congo and Gabon). The climate of the region and responses to ENSO have not been previously described in this work, and as such will be examined briefly here. The entire subregion is tropical, and includes areas with hot, humid climates, those with marked wet and dry seasons, highland areas that are cooler, and vary in terms of their humidity from drier to more humid. Climate is very complex in the region (Farnsworth *et al*., 2011) but there are some general patterns. The southern part of the Democratic Republic of the Congo is typically warmer during El Niño between December and April, while the Central African Republic is typically drier during the July to September period during El Niño events (Davey, Brookshaw and Ineson, 2014). The northeast of the Congo Basin and coastal west Africa showed a mean positive air temperature anomaly of >1 °C as well as some evidence of a mild precipitation deficit during the 2015/16 El Niño (Burton, Rifai and Malhi, 2018).

La Niña events are associated with cooling in the south of the Democratic Republic of the Congo during April and May (Davey, Brookshaw and Ineson, 2014), while in equatorial West Africa, La Niña is associated with increased precipitation (Nicholson and Selato, 2000). Ward *et al*. (2010) showed that Congo River discharge was positively correlated with SOI, and so the discharge is lower during El Niño. Discharge in the Congo River is lower during El Niño events, but only about 10 percent of the variance in flow is associated with ENSO variation (Amarasekera *et al*., 1997), and flow is reduced between September and November during El Niño periods (Lee, Ward and Block, 2018). There is little information on the subregion's response to different category types, but the area of the subregion located south of the equator shows a positive temperature anomaly during EP El Niño. However, this anomaly is not present during CP El Niño events (Graf and Zanchettin, 2012). River discharge in the Congo basin is reduced during EP relative to CP EL Niño (Liang *et al*., 2016).

FAO estimates of inland fisheries production in the subregion are likely to represent a significant underestimation (possibly by up to 75 percent), which is noteworthy given the importance of fish in the diet of the region (Fluet-Chouinard, Funge-Smith and McIntyre, 2018). There was little evidence (Table 9.2, Figure 9.13) for any large production anomalies associated with the different ENSO event categories in the subregion, with mean anomalies ranging between –2 000 tonnes and +3 000 tonnes. The largest production anomaly in the Africa Congo Basin subregion was during EP El Niño events, where production increased on average by +5 000 tonnes, equivalent to +1.6 percent of 2016 production or +2.8 percent of mean annual production in the region between 1950 and 2016. However, it is important to note that the reliability of production data from this subregion is sub-optimal (Fluet-Chouinard, Funge-Smith and McIntyre, 2018).

FIGURE 9.13

Left panels: variation in annual inland fisheries production from the Africa Congo Basin FAO subregion (in 1 000 t) per event category (upper panel) and type (lower panel). The black solid line depicts the LOESS smoothing function adjusted to the data to calculate the residuals. Right panels: residuals of landings (in 1 000 t) per event category (upper panel) and type (lower panel). μ values reflect the mean anomaly (positive or negative) for yield (1 000 t) under each of the event categories or types



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a).

As a whole, mean inland fisheries production anomalies in the 16 subregions with individual contributions to global catch in 2016 < 3 percent, were small (mean = 0.4 tonnes). However, some individually large anomalies were recorded (Table 9.2: range: −13 000 tonnes to +21 000 tonnes). As inland fisheries production in these subregions is typically relatively limited on a global scale, these extreme anomalies can represent large shifts in percentage terms. Production anomalies in the Africa Sahel subregion were generally low (0 or +1 000 tonnes) but extreme El Niño (−13 000 tonnes) and CP El Niño (+6 000 tonnes) events were associated with moderate or marked percentage shifts in production, especially the EP El Niño which represented a mean reduction of −4.1 percent relative to 2016 production, or −6.3 percent of mean production between 1950 and 2016. Production anomalies in the Russian Federation (2.58 percent of global inland fisheries production in 2016) were moderate in terms of the three ENSO categories (range −6 000 tonnes to +8 000 tonnes), but were more marked in terms of percentage shifts, especially from the long-term average for the subregion (−5.3 to +7.1 percent). The subregion also displayed a considerable range in production anomalies relative to the three El Niño event types (Table 9), with a maximum mean positive shift during EP El Niño of +21 000 tonnes. This reflects a very marked percentage increase in production of +7.2 percent relative to the 2016 total, or +18.6 percent of the long-term regional mean annual inland fishery catch. Inland fisheries production in the Asia Central subregion (Table 9.2) was very limited in global terms (0.81 percent of 2016 production), yet production anomalies were considerable, ranging between −5 000 tonnes (El Niño) and +13 000 tonnes (La Niña). In percentage terms, El Niño conditions were associated with very marked reductions of −5.5 percent in inland fisheries production relative to the 2016 total, or −13.4 percent to the regional long-term mean annual production. Inland fishery production during La Niña saw a very marked mean increase of +14.3 percent relative to 2016 production, or +34.9 percent relative to the regional long-term mean – the largest percentage anomaly reported here from the different inland fishery subregions (Table 9.2).

9.2.9 Regional inland fisheries production and ENSO

Inland fisheries production has typically increased markedly across the different subregions examined here (although the Asia East, Russian Federation, Europe South and Europe West subregions all saw reduced catches over time). Of those subregions where catches increased, annual production time series have been very dynamic, showing a range of different trajectories over the periods considered, suggesting that modern inland fisheries have evolved in contrasting ways across the different subregions (compare Figures 9.6 to 9.13). For many subregions, production showed a typically linear increase, with some cyclical fluctuations around the curve and periodic plateaus. Several of the most productive subregions saw rapid growth in the latter part of the time series, including Asia South subregion (Figure 9.6) in the 1990s, Asia Southeast in the 2000s (Figure 9.7) and Asia China (Figure 9.8) which showed a very steep acceleration in catch between the mid-1980s until 2005, after which it flattened, and declined slightly.

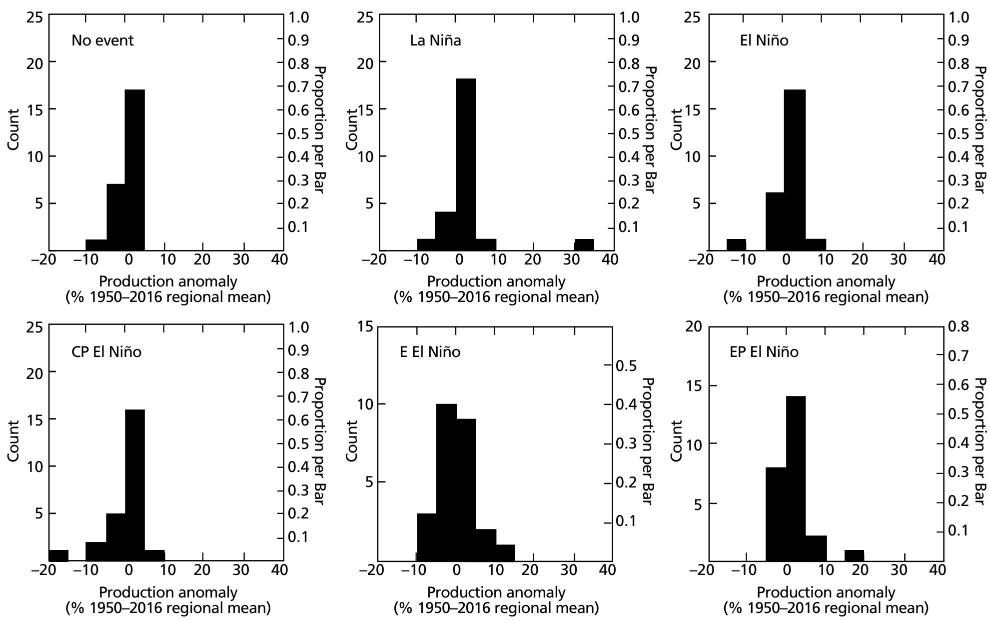
Annual mean inland fisheries production anomalies associated with ENSO categories and different El Niño types ranged between −56 000 tonnes and +80 000 tonnes (Table 9.2) with a very small mean ±SD anomaly of +746 tonnes ± 11 264 tonnes. There was no evidence of systematic statistical differences in inland fisheries production during neutral, La Niña or El Niño conditions, or between CP, extreme or EP El Niño in any of the subregions examined here. When anomalies were considered in percentage terms (relative to the 1950 to 2016 regional mean), they ranged between −18.8 percent and +34.9 percent (Figure 9.14), with a mean ±SD of +0.3 percent ±4.8 percent, indicating that at a global level, the overall average regional response in the inland fisheries sector to ENSO variation is minor. When individual anomalies are considered, it becomes apparent that in certain regional settings, ENSO variation can be very considerable (Table 9.2, Figure 9.14), raising the potential for shocks to the food supply system.

When responses to the different ENSO categories were examined within each subregion, the largest percentage production anomaly (relative to the 1950 to 2016 mean) was most commonly associated with La Niña conditions (Table 9.2; Figure 9.14), both as negative and positive production anomalies, with particularly marked percentage anomalies being recorded in Asia Central (+34.9 percent), Africa Nile Basin (−7.2 percent), the Russian Federation (+5.3 percent), Asia West (+4.6 percent) and Europe Southern (+4.2 percent). El Niño conditions were also associated with individually large mean annual inland fisheries production anomalies: the Russian Federation (+7.1 percent), America Central (4.3 percent) and Asia Central (−13.4 percent).

Next, we examined how ENSO variation affects inland fishery production at a broad global scale (Figure 9.15). We compared the mean production anomaly (relative to the average annual production for the 1950 to 2016 period) for a subregion for years associated with each of the different ENSO categories. On average, ENSO neutral events were associated with zero production anomalies for more than half of the subregions examined (Figure 9.15A, Table 9.2). Seven subregions showed minor (<0 percent to −5 percent) negative mean inland fisheries production anomalies during ENSO neutral conditions, while just one, the Russian Federation showed a marked (−5 percent to −15 percent) negative response. Four subregions showed (>0 percent to 5 percent) positive mean production anomalies under ENSO neutral conditions (Asia South, Africa Nile Basin, Africa Southern and Europe East).

FIGURE 9.14

Variation in mean percentage inland fisheries production anomalies (relative to 1950–2016 regional mean) associated with different ENSO event categories or types of El Niño from all geographical subregions



Under La Niña conditions, zero anomalies were recorded from six of the subregions (Table 9.2, Figure 9.15B), including Europe East, Europe West, Asia East and Oceania. Minor (<0 percent to −5 percent) mean annual negative anomalies were seen in both North and South America, Europe North and Asia East. The Africa Nile Basin subregion, however, showed a marked negative anomaly (−5 percent to −15 percent). Apart from Asia East, inland fishery capture anomalies were positive across Asia during La Niña conditions, with mean capture anomalies ranging between minor (>0 percent to 5 percent) (Asia South, Southeast, China, West) through to very marked (>15 percent) in Asia Central. La Niña conditions were associated with marked (5 percent to 15 percent) positive mean annual inland fisheries anomalies in the Russian Federation. Minor positive mean annual production anomalies were also recorded in America Central, Europe South and most of sub-Saharan Africa. El Niño conditions (Figure 9.15C, Table 9.2) were associated with zero production anomalies for all of Europe apart from the Europe Eastern subregion, as well as Africa Northern and Oceania. Minor (<0 percent to −5 percent) negative mean annual inland fishery anomalies were seen in six subregions during El Niño conditions including the productive Asia Southeast subregion, as well as lesser contributors (Africa West Coastal, Africa Nile Basin, Africa Southern, Asia West, and Europe East). On average, Asia Central showed a marked negative production anomaly during El Niño (in contrast to La Niña). El Niño conditions were associated with positive minor (>0 percent to 5 percent) mean annual production anomalies across Asia South, Asia China and Asia East, as well as America South, America Central and America North, Africa Sahel, Africa Congo Basin, and Africa Islands. The Russian Federation subregion saw marked positive (>5 percent to <15 percent) mean annual production anomalies during CP El Niño.

When the different El Niño types were considered, CP El Niño (Figure 9.16A, Table 9.2) saw a complex pattern of production anomalies across different global regions. Africa Southern and Africa Northern and Europe South all showed no apparent effect, with zero production anomalies. Minor (<0 percent to −5 percent) negative production anomalies were apparent in Asia Southeast, Africa West Coastal, Europe East, America North and Europe North. Marked (−5 percent to −15 percent) negative mean annual production anomalies were associated with CP El Niño in inland fisheries in Asia West and Oceania, while very marked (<−15 percent) negative mean annual production anomalies were seen in Asia Central. In terms of positive anomalies, CP El Niño was largely associated with minor (>0 percent to 5 percent) positive mean annual production anomalies (Asia South, Asia China, Africa Great Lakes, Africa Nile Basin, America South, Africa Sahel, Africa Congo Basin, America Central, Africa Islands and Europe West). The Russian Federation subregion saw marked positive (>5 percent to <15 percent) mean annual production anomalies during CP El Niño.

During extreme El Niño, inland fisheries production in Africa Northern and Oceania were similar to that of the long-term mean, i.e. there was no apparent production anomaly (Figure 9.16B, Table 9.2). Negative mean annual production anomalies were seen in many of the inland fishery subregions under extreme El Niño conditions, including minor (<0 percent to −5 percent) anomalies in Asia Southeast, Africa Nile Basin, America South, Africa Congo Basin, the Russian Foundation, Europe East and Europe North. Marked (−5 percent to −15 percent) negative anomalies were apparent in Africa Sahel, Africa Southern and Asia Central. Minor (>0 percent to 5 percent) positive mean annual production anomalies were seen in Asia South, Africa West Coastal, America North, and Africa Islands during extreme El Niño years. Asia China, America Central and Asia West all recorded marked (>5 percent to 15 percent) anomalies during extreme El Niño events.

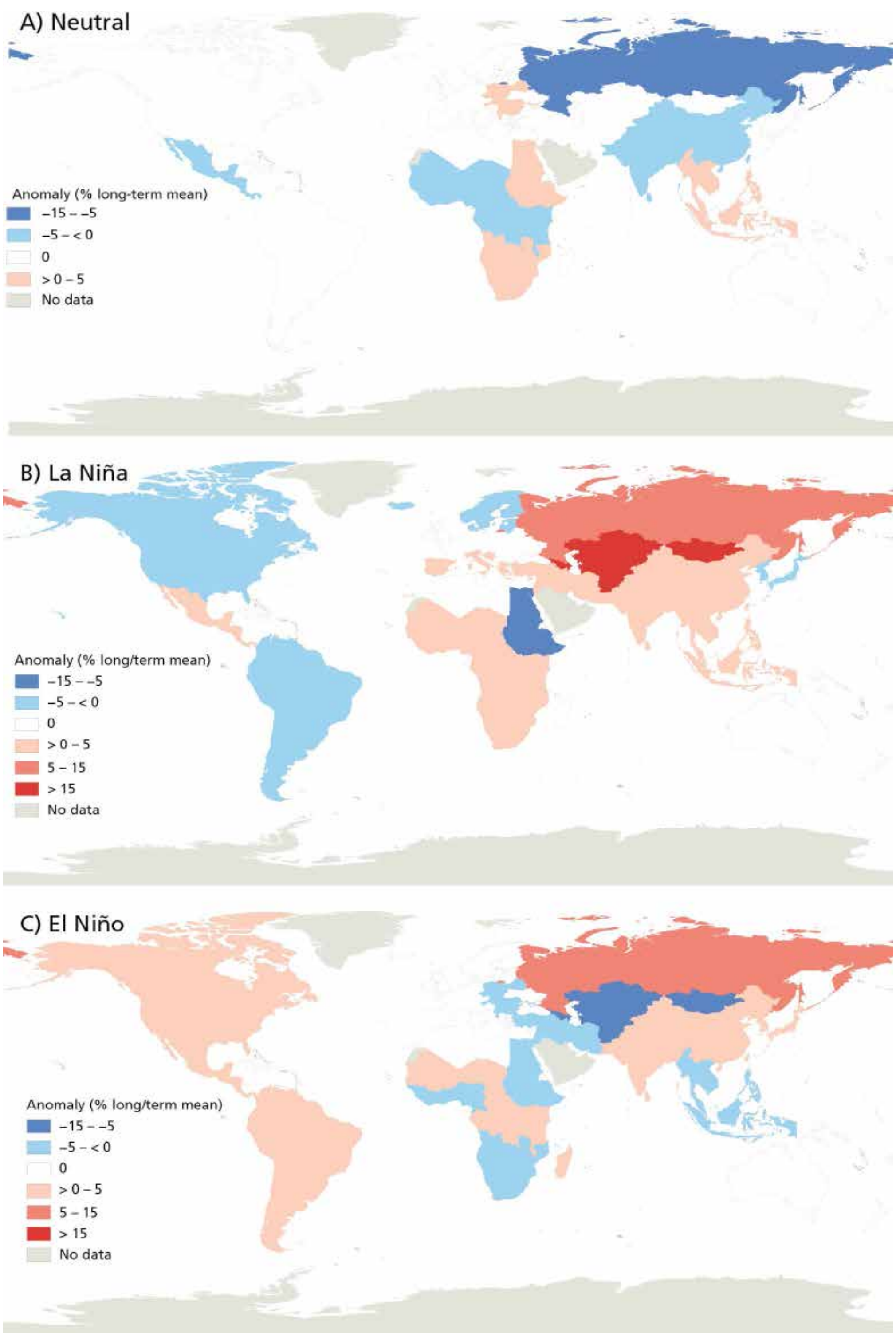
Many inland fisheries subregions (Africa Sahel, Africa South, Asia Central, Europe West, Oceania, Africa Northern and Europe South) showed zero production anomalies during EP El Niños (Figure 9.16C, Table 9.2), although in general, these regions are not overly productive in global terms (6.2 percent of total global production in 2016). Negative anomalies were limited to minor (<0 percent to −5 percent) values, but were widespread, and included key inland fisheries subregions (Asia South, Asia China, Africa West Coastal, Africa Nile Basin and America South) as well as lesser producers (America Central, Europe East, Asia East) (Figure 9.16C, Table 9.2). Positive inland fisheries production anomalies were seen in eight subregions during EP El Niño. Asia Southeast, Africa Great Lakes, Africa Congo Basin, America North and Africa Islands subregions had minor (>0 percent to 5 percent) mean annual production anomalies during EP El Niños, while Asia West and Europe North had marked (>5 percent to 15 percent) positive anomalies and the Russian Federation showed a very marked positive anomaly (>15 percent) response in terms of mean annual inland fisheries production.

As seen for the aquaculture sector (Chapter 8), there is little compelling evidence that ENSO has a large-scale global or regional effect on inland fisheries production. However, the sign or strength of production anomalies differed for many subregions under ENSO, including those that provide the bulk of inland fishery production, and again, as seen for the aquaculture sector, La Niña was associated with more extreme production anomalies than neutral or El Niño events. Comparison of mean annual inland fisheries production values during the different El Niño event types indicated quite distinct responses, with switches in the sign and scale of anomalies at a subregional, and extra-subregional scale. Extreme El Niño events were associated with particularly large numbers of inland fisheries subregions with negative production anomalies.

The subregions producing the majority (2016: >77 percent) of inland fishery production (Asia South, Asia Southeast, Asia China, Africa Great Lakes and Africa West Coastal) at times showed common responses. Asia South and Asia China always showed anomalies of the same sign, but Asia Southeast had anomalies with the opposite sign to the other two main Asian producing subregions in all but one of the three ENSO categories, and for all El Niño event types. Inland fisheries production anomalies in the Africa Great Lakes subregion always showed the same sign seen in Asia South and Asia China, while the sign of anomalies in the Africa West Coastal subregion were similar in four out of six comparisons.

FIGURE 9.15

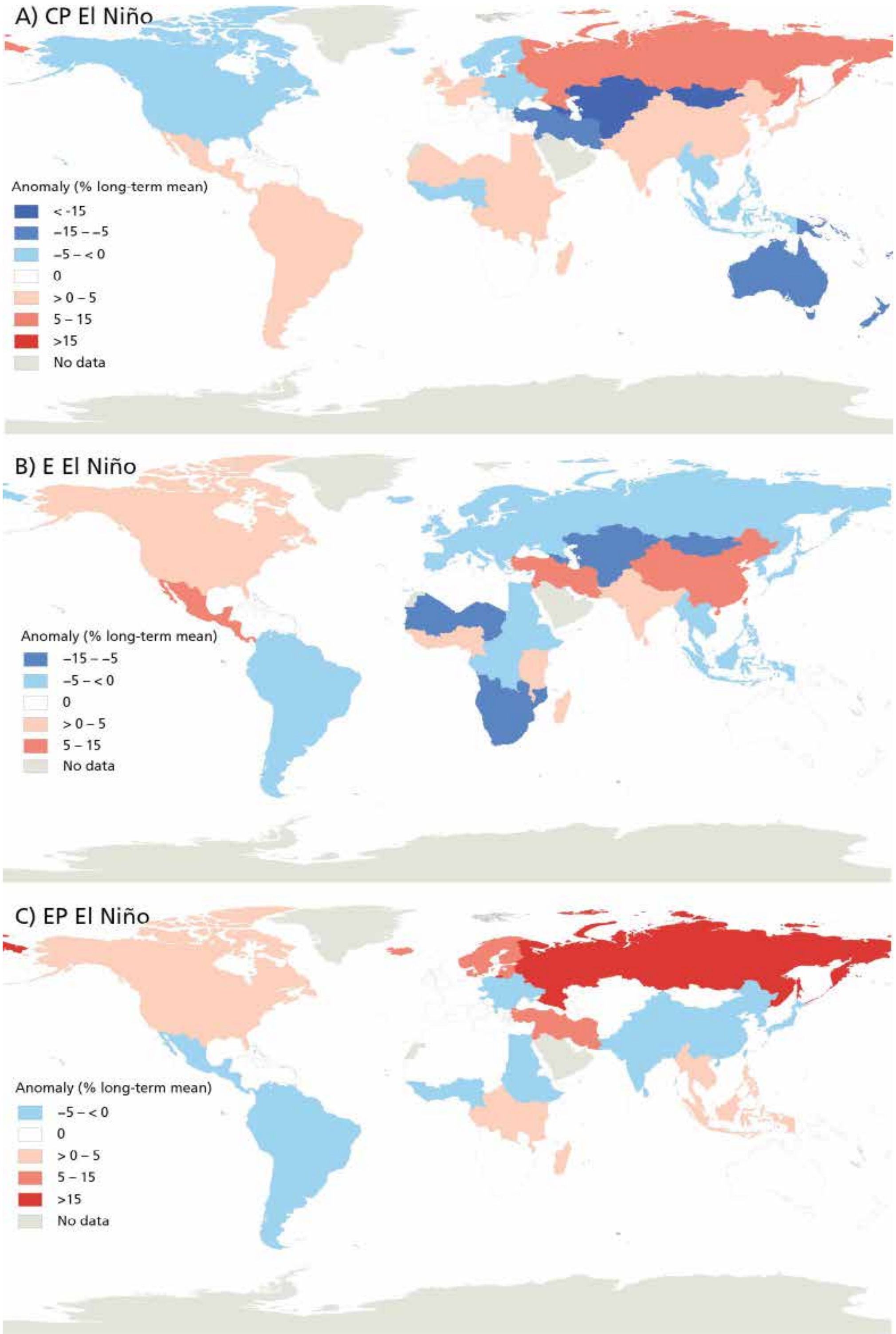
Geographical variation in mean inland fishery production anomalies associated with different ENSO categories (percent anomaly relative to regional mean long-term [typically 1950–2106] annual production): A) Neutral conditions, B) La Niña and C) El Niño conditions. Note that data are not shown for regions with minor (America islands, Africa East Coast), or zero (Arabia) contributions to global inland fishery production in 2016



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a). Map conforms to United Nations World map, February 2020.

FIGURE 9.16

Geographical variation in mean inland fishery production anomalies associated with different El Niño event types (percent anomaly relative to regional mean long-term [typically 1950–2106] annual production): A) CP El Niño, B) extreme El Niño and C) EP El Niño conditions. Note that data are not shown for regions with minor (America islands, Africa East Coast), or zero (Arabia) contributions to global inland fishery production in 2016



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a). Map conforms to United Nations World map, February 2020.

9.3 LEADING INLAND FISHERY PRODUCING COUNTRIES

KEY MESSAGES

- We estimated ENSO effects on production in the 10 countries that dominated inland fisheries production in 2016.
- There were no significant effects of ENSO event category or El Niño event type on inland fisheries production in any country.
- However, some considerable (−14.4 percent to +8.3 percent) production anomalies were associated with the different El Niño event types in the countries, indicating that certain El Niño conditions have the potential to shock inland fisheries production at a national level.
- Most countries reported catch composition at a low level of taxonomic resolution: conversely, more highly detailed catch composition data were available from Uganda. Multivariate analysis showed that the extreme El Niño of 1983 had very marked effects on inland fisheries in that country, with production shifting markedly to drought resistant species.

Although the FAO statistics included data on inland fisheries production from 197 different countries in 2016, production was particularly concentrated in a limited number of countries, with the ten largest producers contributing approximately 68 percent of global production in 2016 (Table 9.3; cf. aquaculture, when the top ten nations were responsible for more than 90 percent of production in 2016). Of these ten nations, six are included in the countries with the ten highest human populations in 2016 (FAO-FishStatJ., 2019c), and five countries are LIFDCs (India, Bangladesh, Uganda, Nigeria, United Republic of Tanzania). Five (Bangladesh, Myanmar, Cambodia, Uganda, United Republic of Tanzania) are classified by the FAO as least-developed countries, i.e. low-income countries confronting severe structural impediments to sustainable development, and highly vulnerable to economic and environmental shocks. Furthermore, one country (Uganda) in the ten leading producers is land-locked, limiting access to marine fishes.

Given the importance of these countries in terms of production, and the potential role of inland fisheries in supporting food security, we examined whether there was any marked sensitivity to ENSO variation in terms of inland fisheries production. We used the same approach employed in previous sections, where we examined variation in long-term (1950 to 2016) national annual inland fisheries records relative to ENSO state (Table 9.3). In no case was there statistical support for differences in production anomalies between ENSO event categories or event type (ANOVA p-value >0.05). As such, we concentrate on mean annual production anomalies associated with the different ENSO states as an indication of the potential for climate variation to disrupt the supply of food derived from inland fisheries.

With a total estimated inland fisheries production of 2.0 million tonnes in 2016, China was ranked first in terms of contribution to global inland fisheries supply. However, the results are essentially identical to those previously described for the Asia China subregion (see Section 9.2.3), reflecting the fact that China as a country contributes > 99.99 percent of the subregion's inland fishery catch. As such, they are not considered in more detail here and the reader is directed to Section 9.2.3. Across the ten countries, the mean absolute production anomaly associated with the three principal ENSO categories was 4 766 tonnes, but individual anomalies ranged between −8 000 tonnes (Cambodia: El Niño) to +16 000 tonnes (China: La Niña). In percentage terms relative to 2016 production (Table 9.3), the largest production anomaly was +2.7 percent (the Russian Federation: El Niño), and relative to long-term production, −5.7 percent (Cambodia: El Niño).

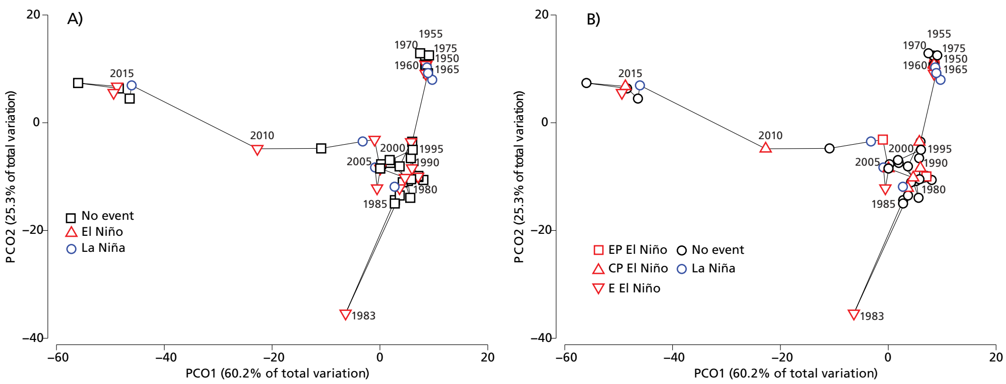
Neutral ENSO conditions were associated with minor (<0 percent to −5 percent) negative mean annual anomalies relative to national long-term mean in six of the ten countries (Figure 9.19A, Table 9.3), no anomaly in one (Myanmar), and with minor (>0 percent to 5 percent) positive anomalies in three countries, all of which were located in southern or southeastern Asia. La Niña conditions (Figure 9.19B) saw minor (<0 percent to −5 percent) negative mean annual anomalies in inland fisheries production in India, Uganda and United Republic of Tanzania, while minor positive production anomalies were recorded in the remaining seven countries. El Niño events were associated with a minor (<0 percent to −5 percent) negative mean production anomaly in Indonesia, and marked mean production anomaly in Cambodia (Figure 9.19C). In all remaining eight countries, El Niño was associated with minor positive (>0 percent to 5 percent) annual mean inland fisheries production anomalies.

Absolute inland fisheries production anomalies associated with the three different El Niño types averaged 13 767 tonnes, but ranged between −49 000 tonnes (India: EP El Niño) and +80 000 tonnes (China: extreme El Niño). In percentage terms, mean anomalies were generally lower during CP El Niño conditions (Table 9.3), but similar during both extreme El Niño and EP El Niño years. Particularly notable anomalies recorded in India and associated with El Niño event types were more considerable, ranging between −49 000 tonnes (EP El Niño) and +28 000 tonnes (CP El Niño). In percentage terms, this represents a mean reduction during EP El Niño years of −3.4 percent relative to 2016 production, and −8.2 percent in terms of the 1950 to 2016 national mean. Conversely, Bangladesh saw the greatest production anomaly during extreme El Niño, where catch increased by a mean of +38 000 tonnes, an equivalent of +3.6 percent of Bangladeshi inland fishery production during 2016, or +6.9 percent of national long-term mean annual capture. Myanmar saw moderate (−7 000 tonnes) reductions in mean annual inland fisheries catch during CP El Niño (Table 9.3), an amount equivalent to −2.8 percent of 1950 to 2016 mean annual catch. Conversely, EP El Niño events were associated with a mean increase of +13 000 tonnes, an increase of +1.5 percent over 2016 production, or +5.3 percent of the long-term mean annual production in Myanmar. CP El Niño (−10 000 tonnes) and extreme El Niño (−20 000 tonnes) events were both associated with negative production anomalies in Cambodia, which were equivalent to −2.0 percent and −3.9 percent of 2016 production and −7.2 percent and −14.4 percent of 1950 to 2016 mean annual production, respectively. In Indonesia, production anomalies were minimal during both CP and EP El Niño events, but extreme El Niño conditions were associated with a mean decrease of −24 000 tonnes. This decrease was equivalent to −5.6 percent of 2016 production in Indonesia, or −8.3 percent of mean national annual inland fishery production between 1950 and 2016. Production anomalies were generally minimal in Uganda, however, catches during EP El Niño increased on average by +14 000 tonnes, which in percentage terms reflects +3.6 percent of 2016 national inland fisheries production, or +7.1 percent of the long-term national average annual catch. Nigeria also saw very moderate production anomalies apart from during extreme El Niño periods, when catches increased by a mean of +9 000 tonnes, equivalent to +2.4 percent of total inland fisheries production in 2016, or +7.5 percent of the mean annual catch for the period 1950 to 2016. Catch anomalies in the Russian Federation ranged between −3 000 during extreme El Niño (equivalent to approximately −1 percent of catch in 2016 and of the long-term national mean) and +21 000 tonnes during EP El Niño, with the latter reflecting increased mean catches of +7.2 percent to +8.0 percent of either national catch in 2016, or of the long-term mean annual catch respectively.

Following the approach used to examine possible shifts in global catch composition during different ENSO event categories and El Niño types, we aimed to examine temporal shifts in catch composition in the main inland fishery producers. However, our analyses were limited to Uganda as this was the only country with a long-term time series where catches were reported in more taxonomic detail than other countries (which often pool fish into the general freshwater fishes nei category). As seen in the global inland fisheries data, the principal driver for variation in Uganda (Figure 9.17) was time (PERMANOVA p-value = 0.0001) rather than either ENSO state or El Niño event type (PERMANOVA p-value >0.8 in all cases). However, in the Uganda data, 1983 – a very strong extreme El Niño year associated with widespread drought – was clearly distinct from other years. Examination of the catch composition in 1983 showed large reductions in the reported production of the tilapias nei category and the freshwater fishes nei category, but a very large (order of magnitude) increase in the production of African lungfishes and torpedo shaped catfishes nei relative to the previous year. Both lungfishes and torpedo shaped catfishes are characteristically drought resistant and were likely increasingly targeted during the drought conditions driven by the extreme El Niño in 1983.

FIGURE 9.17

Canonical analysis of principal coordinate (PCoA) ordinations showing how taxonomic composition of inland fishery catch in Uganda shifted over the period 1950–2016 (Bray-Curtis dissimilarity), where markers closer together reflect years with more similar catch compositions. Individual markers show years, and are joined with a line that follows the 1950–2016 time series. The results show a clear temporal evolution of the inland fisheries catch in Uganda, with little evidence that catches during years associated with particular A) ENSO categories or B) El Niño event types were more similar. However, production during the 1983 extreme El Niño was very different (note its distance from the other markers) due to increased reliance on drought-resistant fishes such as lungfish and torpedo shaped catfishes



Although on a country by country basis, we were unable to identify statistical differences in inland fisheries production associated with the different ENSO categories or El Niño types, it was apparent that under specific conditions mean annual production anomalies could be considerable. Eight of the ten countries had production anomalies greater than 5 percent (Table 9.3, Figures 9.18 and 9.19). Only in one case (Cambodia: El Niño) was one of the three basic ENSO categories associated with a marked (< −5 percent to −15 percent) anomaly (Figure 9.18). For the three different El Niño types (Figure 9.19), extreme El Niño was associated with marked production anomalies in five of the ten countries (China: +8.3 percent; Bangladesh: +6.9 percent; Cambodia: −14.4 percent; Indonesia: −8.3 percent; Nigeria: +7.5 percent), EP El Niño in three (India: −8.2 percent; Uganda: +7.1 percent; the Russian Federation: +8.0 percent), and CP El Niño, in one country (Cambodia: −7.2 percent).

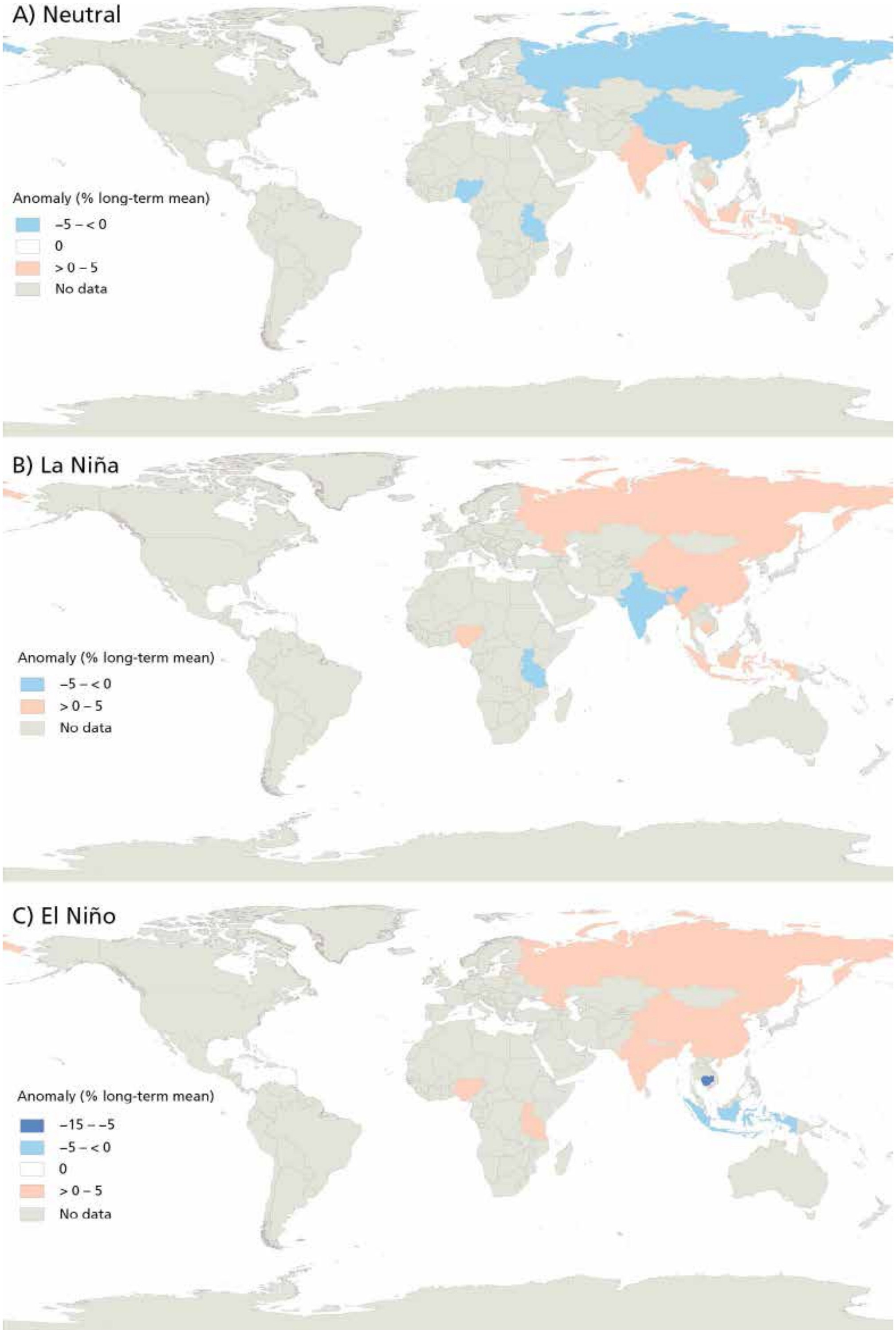
TABLE 9.3

Summary of the mean anomaly (1950–2016) in inland fisheries production (x 1 000 t) associated with different ENSO event categories or types of El Niño in the top ten countries ranked by total inland fisheries production (2016). Countries marked with * are categorized as LIFDCs by FAO, while those marked with # are considered as land-locked developing countries.

			Mean anomaly (x 1 000 t) (% 2016 yield) [% mean yield]					
Country *Five principal species/categories contributing to production in 2016*	(2016 yield) [mean yield] Tonnes	2016%	No event	Strong La Niña	El Niño	CP El Niño	E El Niño	EP El Niño
China *Freshwater fishes nei (72.5%); freshwater molluscs nei (11.8%); Oriental river prawn (6.0%); Siberian prawn (6%); Chinese mitten crab (2.4%)*	(2 003 333) [965 007]	17.67	-7 (-0.4) [-0.7]	+16 (+0.8) [+1.7]	+9 (+0.5) [+0.9]	+7 (+0.4) [+0.7]	+80 (+4.0) [+8.3]	-44 (-2.2) [-4.6]
India* *Cyprinids nei (40.7%); freshwater fishes nei (38.6%); snakeheads (=murrels) nei (10.4%); freshwater siluroids nei (5.3%); Natantian decapods nei (1.9%)*	(1 462 063) [599 092]	12.90	+4 (+0.3) [+0.7]	-4 (-0.3) [-0.7]	+2 (+0.1) [+0.3]	+28 (+1.9) [+4.7]	-7 (-0.5) [-1.2]	-49 (-3.4) [-8.2]
Bangladesh* *Freshwater fishes nei (81.5%); hilsa shad (13.4%); freshwater crustaceans nei (5.1%)*	(1 048 242) [551 861]	9.25	-6 (-0.6) [-1.1]	+13 (+1.2) [+2.4]	+6 (+0.6) [+1.1]	-1 (-0.1) [-0.2]	+38 (+3.6) [+6.9]	-5 (-0.5) [-0.9]
Myanmar *Freshwater fishes nei (100%)*	(886 780) [245 946]	7.82	0 (-) [-]	+2 (+0.2) [+0.8]	0 (-) [-]	-7 (-0.8) [-2.8]	+4 (+0.5) [+1.6]	+13 (+1.5) [+5.3]
Cambodia *Freshwater fishes nei (99.9%); freshwater crustaceans nei (0.1%)*	(509 350) [139 175]	4.49	+4 (+0.8) [+2.9]	+4 (+0.8) [+2.9]	-8 (-1.6) [-5.7]	-10 (-2.0) [-7.2]	-20 (-3.9) [-14.4]	+6 (+1.2) [+4.3]
Indonesia *Freshwater fishes nei (10.7%), striped snakehead (10.6%); Asian redtail catfish (9.9%); Nile tilapia (8.2%); snakeskin gourami (6.1%)*	(432 475) [290 189]	3.81	+2 (+0.5) [+0.7]	+3 (+0.7) [+1.0]	-5 (-1.2) [-1.7]	+1 (+0.2) [+0.3]	-24 (-5.6) [-8.3]	-3 (-0.7) [-1.0]
Uganda*# *Silver cyprinid (22.3%); cyprinids nei (18.9%); Nile perch (17.7%); nurse tetra (14.1%); tilapias nei (12.9%)*	(389 244) [197 461]	3.43	-1 (-0.3) [-0.5]	-5 (-1.3) [-2.5]	+4 (+1.0) [+2.0]	0 (0) [-]	+1 (+0.3) [+0.5]	+14 (+3.6) [+7.1]
Nigeria* *Tilapias nei (18.0%); Freshwater fishes nei (11.6%), torpedo-shaped catfishes nei (10.6%); elephantsnout fishes nei (7.0%); North African catfish (6.6%)*	(377 632) [120 482]	3.33	-1 (-0.3) [-0.8]	+5 (+1.3) [+4.1]	+4 (+1.1) [+3.3]	-1 (-0.3) [-0.8]	+9 (+2.4) [+7.5]	-3 (-0.8) [-2.5]
United Republic of Tanzania* *Silver cyprinid (35.7%); Nile perch (21.9%); mouthbrooding cichlids (12.3%); freshwater fishes nei (9.0%); tilapias nei (8.4%)*	(312 039) [199 784]	2.75	-1 (-0.3) [-0.5]	-4 (-1.3) [-2.0]	+3 (+1.0) [+1.5]	+4 (+1.3) [+2.0]	0 (0) [-]	+3 (+1.0) [+1.5]
The Russian Federation *Chum salmon (18.7%); pink salmon (9.8%); crucian carp (9.4); freshwater bream (8.3%); northern pike (6.5%)*	(292 890) [260 877]	2.58	-6 (-2.1) [-2.3]	+6 (+2.1) [+2.3]	+8 (+2.7) [+3.1]	+7 (+2.4) [+2.7]	-3 (-1.0) [-1.1]	+21 (+7.2) [+8.0]

FIGURE 9.18

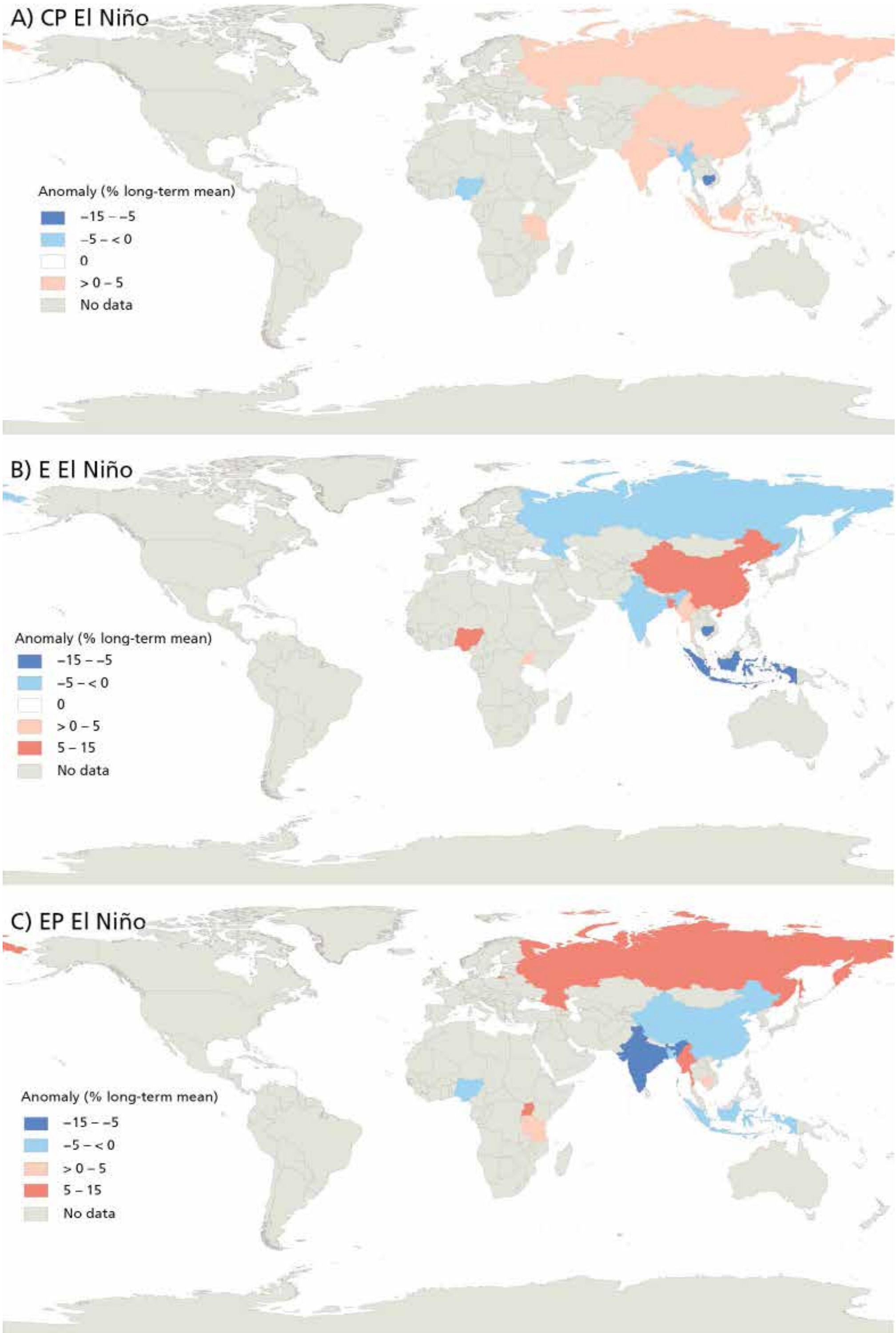
Variation in mean inland fishery production anomalies (percent anomaly relative to regional mean long-term [typically 1950–2106] annual production) in the ten largest inland fishery producing countries in 2016 associated with different ENSO event categories: A) Neutral conditions, B) La Niña and C) El Niño conditions



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a). Map conforms to United Nations World map, February 2020.

FIGURE 9.19

Variation in mean inland fishery production anomalies (percent anomaly relative to regional mean long- term [typically 1950–2106] annual production) in the ten largest inland fishery producing countries in 2016 associated with different El Niño event types: A) CP El Niño, B) extreme El Niño and C) EP El Niño conditions



Source: FishStatJ v3.5 (FAO-FishStatJ., 2019a). Map conforms to United Nations World map, February 2020.

9.4 ENSO AND THE LEADING SPECIES/CATEGORIES CONTRIBUTING TO INLAND FISHERY PRODUCTION

KEY MESSAGES

- We examined potential ENSO effects on the production of the species/categories that dominated (>75 percent) inland fisheries production in 2016.
- There were no measurable statistical effects of ENSO event category or El Niño event type in any case.
- Production anomalies were generally larger for the leading species/categories during El Niño events than those seen for La Niña or ENSO neutral conditions.
- There was no obvious pattern in capture anomalies associated with the three different types of El Niño, but absolute anomalies were generally larger during extreme and EP El Niños than those seen during CP El Niño years.

Beyond considering potential geographical patterns in inland fisheries responses to ENSO variation, we also included an examination of key inland fishery categories contributing to global catch, following the approach used in previous sections. From a total of 341 different species and categories, ten species contributed approximately 76 percent to global inland fisheries catch in 2016 (Table 9.4). There were no obvious statistical differences (ANOVA p-value >0.05) or general patterns in common in production anomalies between the different ENSO categories or event types for each of these ten species/categories. Mean production anomalies for the ten species were associated with the three main ENSO categories ranged between −8 000 tonnes (no event: cyprinid fishes nei) and +42 000 tonnes (La Niña: cyprinid fishes nei), with an overall mean production anomaly of 3 700 tonnes. Production anomalies associated with the three different El Niño event types were larger on average (10 000 tonnes) and varied between −32 000 tonnes (EP El Niño: cyprinids nei) and +61 000 tonnes (extreme El Niño: freshwater fishes nei).

The general freshwater fishes nei category represented 52.6 percent of global inland fisheries catch in 2016. Catches were reported from 126 different countries but five (China, Myanmar, Bangladesh, India and Cambodia) contributed more than 71 percent of global catch in 2016. Capture anomalies for this taxonomically diverse category were most marked for La Niña (+42 000 tonnes) and extreme El Niño (+61 000 tonnes), representing +1.3 percent of global yield of the freshwater fishes nei category in 2016, and +1.9 percent of the 1950 to 2016 annual mean yield for the category. The second largest contributing category, cyprinids nei, represented 6.8 percent of global inland fisheries catch in 2016, and although extended to 35 different countries was largely dominated (93 percent of total) by contributions from India, Uganda, Nigeria, Islamic Republic of Iran and the Philippines (Table 9.4). Noteworthy capture anomalies were only reported from the different El Niño event types. CP El Niño events were associated with a mean global increase in production of cyprinids nei by +15 000 tonnes. This represents +1.9 percent of 2016 production for this category, or +6.3 percent of mean annual global production between 1950 and 2016. Inland fishery captures of the cyprinids nei category during extreme El Niño and EP El Niño events fell on average by −22 000 tonnes and −32 000 tonnes respectively (Table 9.4). Extreme El Niño conditions were associated with a reduction in catch by −2.8 percent relative to 2016 global catch, and −9.3 percent relative to mean annual capture of the cyprinids nei category over the period 1950 to 2016. Percentage anomalies were even more marked for EP El Niño, with a decrease of −4.1 percent compared to the 2016 catch and −13.5 percent compared to the 1950 to 2016 average.

A total of 24 countries contributed to global inland fisheries production of tilapia nei in 2016, the third largest (3.86 percent) inland fishery category contributing to inland fishery production (Table 9.4). Of these, a geographically diverse collection of five countries (Mexico, Nigeria, Uganda, Sri Lanka and the Philippines) together contributed almost 75 percent of total catch in 2016. Catch anomalies associated with the three ENSO categories were minimal (Table 9.4: –1 000 tonnes to 0 tonnes), but each of the different El Niño category types were associated with absolute percentage anomalies > ±1 percent relative to 2016 catch, and ±3.2 percent to 6.3 percent relative to the 1950 to 2016 mean annual catch. The fourth largest contributing category to inland fisheries production in 2016 was freshwater molluscs nei (Table 9.4), with a total contribution of 2.68 percent. Catches were distributed over only five different countries and there was no evidence for any large-scale capture anomalies associated with either ENSO event categories or El Niño event types.

The silver cyprinid (*Rastrineobola argentea*) represented the fifth largest contributor to worldwide inland fishery catch in 2016 (2.36 percent). This fishery operates in Lake Victoria, with catches divided between the United Republic of Tanzania, Uganda, Kenya and Rwanda (Table 9.4). Generally, ENSO category-associated production anomalies were small (–1 000 tonnes to + 3 000 tonnes), but anomalies during extreme El Niño (–7 000 tonnes; 2016: –2.6 percent; 1976 to 2016: –7.9 percent) and EP El Niño (+11 000 tonnes; 2016: +4.1 percent; 1976 to 2106: +12.5 percent) events were more notable, suggesting that this important fishery is susceptible to ENSO-associated effects. Capture fisheries for Nile tilapia (*Oreochromis niloticus*), the sixth largest contributor to global inland fisheries catch, contributed approximately 2 percent of global inland fisheries catch in 2016, and were reported from 12 different countries, five of which contributed more than 98 percent (Table 9.4). Generally, ENSO or El Niño-associated capture anomalies were limited (–3 000 tonnes to +3 000 tonnes) apart from CP El Niño which was associated with an increased mean yield of +7 000 tonnes, representing an increase in percentage terms of +3.1 percent relative to 2016 catch, or +7.9 percent to the long-term mean annual catch.

The Nile perch (*Lates niloticus*) fishery was the seventh largest single contributor to global inland fisheries catch in 2016 (Table 9.4). Fishery returns for Nile perch were contributed by nine different African countries in 2016, with five contributing >90 percent of the total catch. Capture anomalies for the three ENSO categories ranged between –3 000 tonnes and +4 000 tonnes, representing between –1.5 percent and +1.9 percent of the 2016 catch and –1.7 percent and +2.2 percent of the 1950 to 2016 mean catch. Anomalies were slightly larger for CP El Niño (+5 000 tonnes; 2016: +2.4 percent; 1950 to 2106: +2.8 percent) and EP El Niño (–6 000 tonnes; 2016: –2.9 percent; 1950 to 2106: –3.3 percent), but considerably larger for extreme El Niño, where mean annual yields were increased by +15 000 tonnes. This represented an increase of +7.2 percent compared to 2016 and of +8.4 percent relative to mean annual production between 1950 and 2016.

Data for the combined category snakeheads (murrels) nei were only available from 1987, but in 2016 this category contributed 1.42 percent of global inland fisheries catch (Table 9.4), with the entire fishery distributed between four geographically dispersed countries. Production anomalies associated with the different ENSO categories varied between –6 000 tonnes (La Niña) and +7 000 tonnes (El Niño), which in percentage terms represented considerable shifts in production (La Niña; 2016: –3.7 percent; 1987 to 2016: –8.1 percent; El Niño; 2016: –4.3 percent; 1987 to 2016: –9.5 percent). Of the three El Niño event types, production anomalies during extreme El Niño were the largest (Table 11), with mean increase in annual yield of +23 000 tonnes, i.e. +14.3 percent of 2016 or +31.1 percent of 1987 to 2016 mean annual snakehead nei catch.

Hilsa shad (*Tenualosa ilisha*) contributed 1.28 percent to global total inland fisheries production in 2016 (Table 9.4). Although yield data were available from both Bangladesh and India, Bangladeshi production accounted for more than 96 percent of the total in 2016. Production anomalies were limited for all ENSO categories (range: –2 000 tonnes to +4 000 tonnes) representing between –1.4 percent and +2.8 percent of 2016 production, and −1.8 percent and +3.6 percent of 1984 to 2016 mean annual production. All El Niño category types were associated with positive anomalies, with values ranging between +2 000 tonnes during extreme El Niño (2016: +1.4 percent; 1984 to 2016: +1.8 percent) through to +6 000 tonnes during EP El Niño events (2016: +4.1 percent; 1984 to 2016: +5.4 percent).

When the patterns were compared across the ten most important inland fishery capture species/categories in 2016, inland fisheries production anomalies were generally larger during El Niño events than those seen for La Niña or ENSO neutral conditions (Table 9.4). There was no obvious pattern in capture anomalies associated with the three different types of El Niño, but absolute anomalies were generally larger during extreme and EP El Niños than those seen during CP El Niño years.

TABLE 9.4

Summary of the mean anomaly (1950–2016) in inland fisheries production (1 000 t) associated with different ENSO event categories or types of El Niño in nine species/categories that make the largest contribution to inland fisheries production (ca. 75%). Where years are shown in parentheses, this identifies the first year where data were available to calculate anomalies. Anomalies were not determined for the tenth most important (by yield) category (oriental river prawn) as the time series available is too short to allow for analysis.

			Mean anomaly (1 000 t) (% 2016 yield) [% mean yield]					
Inland fisheries species/category *Five principal countries contributing to production in 2016*	**(2016 yield) [mean yield] t**	**2016%**	**No event**	**Strong La Niña**	**El Niño**	**CP El Niño**	**E El Niño**	**EP El Niño**
Freshwater fishes nei *China (24.3%), Myanmar (14.9%), Bangladesh (14.3%), India (9.5%), Cambodia (8.5%)*	5 965 052 [3 285 331]	52.62	-8 (-0.1) [-0.2]	+42 (+0.7) [+1.3]	-1 (-0.0) [-0.0]	-17 (-0.3) [-0.5]	+61 (+1.0) [+1.9]	-16 (-0.3) [-0.5]
Cyprinids nei *India (76.8%), Uganda, (9.5%), Nigeria (3.0%), Iran (Islamic Rep. of) (2.0%), the Philippines (1.9%)*	775 826 [236 855]	6.84	+3 (+0.4) [+1.3]	-3 (-0.4) [-1.3]	-4 (-0.5) [-1.7]	+15 (+1.9) [+6.3]	-22 (-2.8) [-9.3]	-32 (-4.1) [-13.5]
Tilapias nei *Mexico (27.9%), Nigeria (15.5%), Uganda (11.5%), Sri Lanka (10%), the Philippines (9. 5%)*	438 072 [220 474]	3.86	-1 (-0.2) [-0.5]	0 (-) [-]	0 (-) [-]	-8 (-1.8) [-3.6]	+7 (+1.6) [+3.2]	+14 (+3.2) [+6.3]
Freshwater molluscs nei *China (77.9%), the Philippines (17.8%), India (1.2%), Japan (0.9%), Fiji (0.8%)*	303 736 [219 546]	2.68	+2 (+0.7) [+0.9]	+1 (+0.3) [+0.5]	-3 (-1.0) [-1.4]	-3 (-1.0) [-1.4]	-3 (-1.0) [-1.4]	-2 (-0.7) [-0.9]
Silver cyprinid (1976) *United Rep. of Tanzania, (41.7%), Uganda (32.5%), Kenya (25.8%), Rwanda (0.1%)*	267 364 [88 150]	2.36	+1 (+0.4) [+1.1]	+3 (+1.1) [+3.4]	-1 (-0.4) [-1.1]	-3 (-1.1) [-3.4]	-7 (-2.6) [-7.9]	+11 (+4.1) [+12.5]
Nile tilapia *Egypt (52.1%), Indonesia (17.2%), Mali (13.3%), the Sudan (9.2%), Kenya (6.8%)*	227 779 [104 911]	2.01	-1 (-0.4) [-1.0]	+2 (+0.9) [+1.9]	+3 (+1.3) [+2.9]	+7 (+3.1) [+6.7]	-1 (-0.4) [-1.0]	-3 (-1.3) [-2.9]
Nile perch *Uganda (33.2%), United Rep. of Tanzania (33.0%), Kenya (13.5%), Nigeria (6.5%), Mali (5.2%)*	207 544 [179 450]	1.83	-3 (-1.5) [-1.7]	+2 (+1.0) [+1.1]	+4 (+1.9) [+2.2]	+5 (+2.4) [+2.8]	+15 (+7.2) [+8.4]	-6 (-2.9) [-3.3]
Snakeheads(= murrels) nei (1987) *India (94.0%), Nigeria (5.4%), Uzbekistan (0.6%), Turkmenistan (<0.01%)*	161 430 [73 918]	1.42	-2 (-1.2) [-2.7]	-6 (-3.7) [-8.1]	+7 (+4.3) [+9.5]	+3 (+1.9) [+4.1]	+23 (+14.3) [+31.1]	+4 (+2.5) [+5.4]
Hilsa shad (1984) *Bangladesh (96.7%), India (3.3%)*	145 606 [110 704]	1.28	-2 (-1.4) [-1.8]	-2 (-1.4) [-1.8]	+4 (+2.8) [+3.6]	+4 (+2.8) [+3.6	+2 (+1.4) [+1.8]	+6 (+4.1) [+5.4]

9.5 SYNTHESIS – INLAND FISHERIES AND ENSO

KEY MESSAGES

- Our data indicate that there is no wide-scale effect of ENSO on inland fisheries at the global, subregional or national level, or at the level of the species/categories that currently dominate global inland fisheries production.
- However, certain ENSO conditions and El Niño event types were associated with considerable production anomalies, and where more detailed catch composition data were available, we were able to show production shifts during a major extreme El Niño-associated drought.
- This, and the well reported impacts of ENSO variation on freshwater ecosystems and on fisheries production at a local level, raises a number of questions that should be examined before it is definitely concluded that ENSO does not affect inland fishery production.
- We suggest that the way that inland fisheries data are typically reported (annually, national level, low taxonomic resolution) may limit our capability to identify effects of ENSO-derived variation in inland fisheries production and we provide suggestions for future studies.

In terms of percentage contribution by biomass to global food supply, inland fisheries are ranked relatively low compared to other sectors including agriculture, aquaculture and marine capture fisheries (Froehlich *et al.*, 2018; Funge-Smith, 2018). However, inland fisheries play an important and often undervalued role in the provision of food, employment and income to many people, especially in some of the world's least wealthy countries and communities (FAO *et al.*, 2019; Fluet-Chouinard, Funge-Smith and McIntyre, 2018; Funge-Smith and Bennett, 2019). Given their role in maintaining food security and the provision of employment, there is a pressing need to understand which factors challenge the long-term persistence of inland fisheries.

Many obstacles exist to the continued supply of food, employment and income from inland fisheries. These include a number of interacting anthropogenic stresses such as habitat degradation, introduction of invasive species, shifts in the availability of water due to competing demands from irrigation, industry and domestic supply, river regulation, construction of barriers to fish movement, pollution and climate change (reviewed in Harrod *et al.*, 2018a). Here, we have examined the potential for ENSO-associated climatic variation to affect inland fisheries production, which given the well-recognized potential sensitivity of inland fisheries to climate change (Allison, Andrew and Oliver, 2007; Harrod *et al.*, 2018b; Harrod, 2016; Paukert *et al.*, 2016) seems clear. However, although several individual studies exist, there has been little wide-scale focus on the issue of ENSO in inland fisheries, even though ENSO variation plays a key regulating role in freshwater ecosystems and has been shown to markedly affect other sectors of the global food supply system (Cobon *et al.*, 2016; Cottrell *et al.*, 2019; Iizumi *et al.*, 2014).

Here, following the approach used in previous chapters, we used FAO-derived information presented at the level of individual nations (FAO-FishStatJ., 2019b) to examine how inland fisheries production varied across three broad ENSO categories (neutral/no event, La Niña and El Niño) and three different types of El Niño events (CP El Niño, extreme El Niño and EP El Niño). We estimated annual production anomalies from a long-term (typically 1950 to 2016) time series at a range of different scales – global (all countries pooled), geographical regions (data pooled for countries within inland fisheries subregions), national (for the ten nations that dominated inland fisheries production in 2016), and finally for those species/categories that dominated production in 2016. Mean annual anomalies (tonnes) were estimated for the different ENSO categories and types of El Niño and converted into percentage anomalies relative to either reported production in 2016, or the mean annual production calculated from the long-term time series. We also examined evidence for shifts in the composition of the inland fishery catch in years associated with different ENSO or El Niño conditions at a global and national (Uganda) level.

Our results indicate that ENSO has no large-scale measurable effect on inland fisheries production at global, regional or national level, nor on the production of the key species/categories that contribute most to global production. The main driver of change in inland fisheries production, and of catch composition appeared to be time, rather than ENSO state. However, it was apparent that certain ENSO categories (particularly La Niña) or event types (particularly extreme El Niño) were associated with larger production anomalies of both signs in percentage terms, indicating that they have the potential to disrupt the supply of products from inland fisheries by either reducing or increasing production, but that effects differ considerably at the extra-regional or extra-national scale. Differences seen between the subregions and countries examined here highlight the fact that responses to ENSO events differ considerably across space and time (Fan *et al*., 2017) and that a given global ENSO event has contrasting effects in different locations (Whitfield *et al*., 2019). We showed that the extreme El Niño of 1983 led to marked shifts in the composition of the Ugandan inland fisheries catch towards drought- resistant species, but our ability to examine this for other major producing nations was limited by the taxonomic resolution at which annual production is reported.

The lack of a clear effect of ENSO variation on inland fisheries production is unexpected, more so than for the aquaculture sector (Chapter 8), where operators have more capacity to control conditions affecting production. As noted in Chapter 8, our inability to identify large-scale effects of ENSO on inland fisheries production may reflect two extremes: one, that there is no effect, or alternatively that, due to whatever reason, we are unable to demonstrate an effect at the global, regional and national levels that we examined (a type II error).

A lack of statistical power to show actual effects likely reflects issues with the way data were collected, aggregated or analysed. Alternatively, effects of ENSO variation are relatively subtle and become overwhelmed by the influence of other confounding factors. Robustly demonstrating relationships between climatic variation and fish stock dynamics is not simple at the best of times (Wooster, 2002), and this likely extends to similar approaches attempting to link global, regional and national inland fisheries production to ENSO. We discussed several statistical issues related to the lack of marked differences in aquaculture production between ENSO categories or El Niño event types that extend to our analyses of inland fisheries production. These include the pooling of data from different countries, catchments and individual fisheries which may have distinct climates and differ in terms of habitats and species fished, as well as the techniques and gears used and levels of economic development. A further issue is that almost all inland fisheries activities take place against a background of anthropogenic modification e.g. climate change, river regulation, pollution, invasive species, habitat modification and loss (Harrod *et al*., 2018a) and these factors likely interact with, modify and possibly even confound effects of ENSO-related disturbance (Teo and Marren, 2015), further affecting our ability to show consistent impacts on inland fisheries production. Some earlier studies have shown that ENSO effects on fish production can be most marked when temporal lags or multi-year effects are considered. We did not include such factors in our analyses but they may be important given that effects on fisheries production may become apparent after a particular ENSO event, for example in species that recruit to the fishery at greater ages or sizes (Harris *et al*., 1988; Stassen *et al*., 2010).

A common pattern across many of the subregions and countries examined in this study has been a rapid and marked increase in production, indicating that in most cases, many more fishes are removed today than in previous years. A key issue, that likely varies over space and time, is the unknown form of the relationship between reported inland fisheries production and the actual biomass of fish and other taxa available for exploitation, and the amount actually removed by capture fisheries. As noted in Chapter 8, we assumed that production values reported to the FAO are reliable (Ye *et al*., 2017), but understand that in some cases estimates reflect informed guesses made by FAO experts. Our analyses have shown that not only has the scale of fisheries production typically increased markedly, but also the composition of catches has shifted over time both at global and national (Uganda) levels. Such increases in production in inland fisheries have been supported by considerable technological advances over the times series studied here, with major developments in gear, vessels and fishing aids such as echosounders and GPS (Marchal *et al*., 2007). This has possibly allowed fisheries production to remain high to support increased demand, even when fish abundance has fallen in response to ENSO and other detrimental influences, further confounding our attempts to show clear patterns between ENSO variation and inland fisheries production. This is further complicated because fish from inland fisheries commonly do not enter the formal market system and are not recorded (Welcomme, 2011). Such under-reporting can be very significant, with household survey models indicating that actual capture production is approximately 65 percent higher than that officially reported (Fluet-Chouinard, Funge-Smith and McIntyre, 2018).

Our analytical approach assumes that 1) the ENSO classifications we have used for a given year reliably represent conditions as encountered in the particular geographical region under study, and 2) that ENSO is the principal driver of climatic variation experienced by its fisheries. ENSO is recognized as the dominant global climate phenomenon affecting the world through both extreme weather events (Yuan, Wang and Hu, 2018) and changes in ecosystem state (Stenseth *et al*., 2002). However, ENSO acts differently across regions and even countries, meaning that multiple responses to a given event will be apparent at global, regional or country levels (or within a particular inland fisheries species or category) as reported from both agricultural systems (Cobon *et al*., 2016) and fisheries operating in different parts of the same wider ecosystem (Pinaya *et al*., 2016). Beyond this, cyclical drivers of climatic variation other than ENSO may have a larger influence on inland fisheries production in a given location, such as the NAO (Blenckner and Hillebrand, 2002) or the IOD (Pervez and Henebry, 2015). A major drought in 2005 had widescale detrimental impacts on fisheries in the Amazon and was not associated with ENSO (Tomasella *et al*., 2013). Clearly such major events or even less-marked responses to alternative climatic drivers can affect statistical analyses examining the existence of ENSO-derived impacts on inland fisheries and future analyses should include these other potential influences.

Although our results suggest the contrary, given the well-reported impacts of ENSO on freshwater and terrestrial ecosystems at a local, national and regional level, we feel that it is prudent not to discount the potential for ENSO variation to significantly affect inland fisheries production, and its crucial support for global food security. These effects range from marked shifts in precipitation and temperature through to extreme events that affect numerous components in the life of fish, and that of their prey and predators, fishers and those who rely on inland fishery products for food. ENSO is classically associated with extreme weather events such as floods or droughts that can radically affect the landscape in which fisheries operate. A hint of this is seen in the clear shift in the catch composition from Uganda during the 1983 extreme El Niño event when great increases were seen in the reported production of highly-drought resistant species such as lungfish and torpedo-shaped catfishes (e.g. *Clarias* spp.). Our ability to highlight this taxonomic and functional shift is a direct consequence of production data from Uganda being reported to a higher taxonomic resolution than in many other major inland fishery production nations. These nations typically pool species into general categories, for example, in the Asia South subregion, 58.6 percent of production in 2016 was reported as freshwater fishes nei while in the Asia China subregion, 84 percent of production was listed as either freshwater fishes nei or freshwater molluscs nei in the same year. Biological diversity in the tropical regions that support much of inland fisheries production is characteristically high and likely includes species that show distinct responses to the abiotic and biotic variation associated with ENSO, but this is hidden when production is reported with an insufficient level of taxonomic resolution.

In summary, ENSO effects clearly have the potential to affect inland fisheries production through often major effects on aquatic and terrestrial habitats worldwide. However, our results indicate that large-scale ENSO-associated impacts are not general, but that certain ENSO events can lead to major production anomalies in percentage terms at regional and national levels, as well as major shifts in national catch composition following extreme events such as an ENSO-associated drought. Given the importance of inland fisheries for the provision of food, employment and income, and their role in food security, as well as a number of studies that have reported ENSO effects at the level of the catchment or individual fishery, we suspect that our results indicating a lack of large-scale effects of ENSO variation on inland fisheries production require further confirmation. As such, we recommend that future studies are undertaken to examine this question using high resolution (temporal, spatial and taxonomic) catch data recorded at a timescale relevant to variation in ENSO indices and local environmental conditions rather than annual summaries recorded at a national level. Analysis of such data from catchments and fisheries representative of different geographical regions, likely represents the best opportunity for identifying how ENSO affects inland fisheries.

10 Summary, lessons learned and perspectives for ENSO preparedness in a warmer world

KEY MESSAGES

- Scientific knowledge is much greater with respect to the physical impact of ENSO than it is on the consequences of ENSO on fish, capture fisheries, aquaculture and related human activities. Robust information is lacking for these sectors.
- ENSO impacts on fisheries and aquaculture are weak globally but can be severe regionally (e.g. in the HCS) and locally, or during certain ENSO types.
- Responses to ENSO will vary depending on ENSO types and their contrasting effects (positive/negative) on fish, fisheries and aquaculture along the supply chain. Impacts will also depend on the reliance of the fishers/fish farmers and industry on the affected resources and existing coping mechanisms.
- In a given ocean region, coping/adaptation measures should be tailored to ENSO event types and to the existing institutional and socio-economic context.
- ENSO early warning should specify the expected type of event and, as far as possible, the expected regional impacts to enable appropriate adaptation and DRR action(s).
- Warning mostly concerns El Niño events but La Niña can have as much positive or negative impact, depending on the region.
- Current evidence suggests that at a global level, ENSO impacts on food security are largely due to impacts on agriculture rather than on capture fisheries or aquaculture, although there is evidence of negative impacts on the local livelihoods, safety at sea and on land, and food security of artisanal fishers and fish workers.
- ENSO events generally worsen the effects of climate change on fish, fisheries and aquaculture.
- The combination of global warming and ENSO events will dramatically impact coral reefs with consequences for the fish supply chain.
- Successful adaptation in the fisheries and aquaculture sector need to consider three main domains of interventions, namely: institutional adaptation, livelihoods adaptation and risk reduction and management for resilience. Regardless of how adaptation is approached, building adaptive capacity is imperative.
- Different types of adaptation practices have been documented or recommended in this publication to address ENSO events. Evaluations of success are, however, often missing which makes it difficult to assess success. Assessment of past and ongoing efforts is recommended.

Climate change exerts a number of biophysical impacts on aquatic environments, namely: sea level changes; coastal erosion; sea temperature changes; ice melting; changes in storm frequency and intensity; alteration of the hydrological cycle and rainfall patterns; stratification changes (e.g. alterations to upwelling efficiency); thermohaline circulation changes; increased riverine nutrients discharge leading to marine eutrophication; increased ocean acidification; ocean deoxygenation (e.g. expansion of oxygen minimum zones) and coastal hypoxia; and sediment changes. These alterations affect fish, fisheries and aquaculture-dependent communities and the ecosystems they depend on by altering primary production, species abundance, behaviour and distribution, biodiversity, and ultimately catchability (Barange *et al*, 2018) as well as by increasing physical risks to the sector (e.g. risks to life, loss and damage to assets). Combined with global warming, the projected increase of extreme ENSO events is expected to strengthen ENSO impacts on climate, fisheries and aquaculture dependent livelihoods and ecosystems.

At a global scale, ENSO impact on fisheries and aquaculture is minor (Figure 5.6), representing a 1 percent variation in global marine and inland fisheries landings and global aquaculture production (but can exceed 3.5 percent during extreme El Niño). These global effects are dominated by the effects on the HCS fisheries, mainly the anchoveta (*Engraulis ringens*) fishery which supplies about 50 percent of fishmeal and fish oil globally. Moreover, multidecadal to millennial regime shifts in eastern boundary (upwelling) marine ecosystems (e.g. Salvatteci *et al*., 2019) may be influenced by climate change, but do not seem to be influenced by ENSO. In fact, at global level, ENSO impacts are mostly felt through agriculture: climate variability (including ENSO-induced droughts and floods) has been proved to be a key driver for global challenges to food security, especially in areas where agricultural systems are sensitive to precipitation and temperature, and where high proportions of the population depend on agriculture for their livelihoods (FAO *et al*., 2018). However, at national and local levels, certain ENSO events have severe consequences for the industry and the livelihoods of the people dependent on fisheries or aquaculture. For example, the severe declines in anchoveta catch during the 1972/73 ENSO event in Peru put a halt to the operations of 1 500 fishing vessels and 200 processing plants and over 100 000 people became unemployed. This was followed by another extreme loss of employment during the 1997/98 ENSO, leading some authors to argue that ENSO events could cause long-lasting to permanent unemployment (OECD, 2010). Also, in inland fisheries fluctuations in production and major shifts in national catch composition following extreme events such as an ENSO-associated drought are mirrored by changes in fishing activity and catch with consequences for food security. Aquaculture is impacted by climate change and ENSO through direct impacts on the supporting ecosystems and aquaculture capital goods (i.e. infrastructure), as well as on agriculture and fisheries systems providing inputs to aquafeeds (Porter *et al*., 2014). The mechanisms and negative impacts of climate change on agriculture have been identified with higher evidence, confidence and consensus than those of fisheries and aquaculture (Porter *et al*., 2014), yet the main impacts on and risks to fisheries and aquaculture are rather well understood and consensual. For instance, the alteration of marine fish distribution and mobility in connection with habitat changes is identified as the main effect of climate change on fisheries (FAO, 2018).

In describing the consequences of ENSO events, media, scientists and other commentators often adopt a disasters-related discourse, suggesting that ENSO episodes systematically cause or manifest as disasters. Conversely, Goddard and Dilley (2005) suggest that disaster-related losses are not necessarily more or less during any of the ENSO phases, seemingly (i) because forecast accuracy improves as the weather becomes more extreme, and (ii) due to actions taken based on those forecasts, namely standard DRR actions (Kelman, 2017). For this reason, ENSO early warning systems should be clearly associated with the "expected type of event", as the different ENSO types impact fish and fisheries very differently. And these early warning systems should be accompanied by effective DRR and disaster management measures specific to each type of ENSO. This Technical Paper provides some key elements to elaborate such specific measures.

Given that over 40.3 million people in the world are directly engaged in fisheries, and over 19.3 million people are engaged in aquaculture (FAO, 2018), negative impacts of climate change and ENSO on fish, fisheries and aquaculture have a negative effect on many communities, and therefore adaptation and mitigation efforts should be human centred (Barange *et al*., 2018). Nonetheless, ecosystem protection beyond the human dimension should also be carried out. For instance, Edgar *et al*. (2010) argue that marine protected areas with adequate management and related compliance are predicted to improve but not eliminate ecosystem impacts caused by increasing thermal anomalies associated with El Niño and global climate change (Edgar *et al*., 2010), while also – depending on the species and local conditions – creating "spill-over" catches in surrounding areas.

Since the 2015 Paris Agreement, adaptation has been attributed the same level of priority as mitigation. The Agreement also recognizes for the first time the vulnerabilities of food production systems to the adverse impacts of climate change and the importance of safeguarding food security and ending hunger. Together with the 2030 Agenda for Sustainable Development and the Sendai Framework for Disaster Risk Reduction 2015–2030, the Paris Agreement provides a way forward for addressing future El Niño and La Niña events. The Sendai Framework for Disaster Risk Reduction 2015–2030, for example, recommends to substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to people by 2030. The Sustainable Development Goals 2015–2030 aim to strengthen resilience and adaptive capacity to climate-related events (e.g. goal 13, targets 13.1, 13.2 and 13.3), whereas the Paris Agreement is the primary legally binding global instrument that deals with climate change.

As seen in chapters 6 to 9, adaptation and/or coping strategies can be differentiated by: spatial scale (e.g. international, national, local); temporal scale (e.g. short-term, medium-term, long-term); sector (e.g. small-scale, large-scale, capture fisheries, aquaculture, post-harvest); actors (e.g. fishers, fish farmers, fish workers, fishing companies, management authorities); or by type of impacts (e.g. changes in fish distribution and species abundance). Building on the aforementioned treaties, recent studies have emerged for adaptation in the fisheries and aquaculture sector (OECD, 2010; Barange *et al*., 2018). Poulain, Himes-Cornell and Shelton (2018) use the following categorization as part of a suggested FAO fisheries and aquaculture adaptation toolbox, which splits adaptation into three non-mutually exclusive areas as follows:

1. Institutional adaptation comprises the actions of public bodies, that address policy, legal and institutional issues including public investments and incentives; they also include the planning, and management of fisheries and aquaculture in a manner that addresses the dynamic nature of natural systems and societal needs in the face of climate change, following the principles of the ecosystem approach to fisheries or the ecosystem approach to aquaculture.
2. Livelihood adaptation includes a mix of public and private activities, within or among sectors, most commonly through diversification strategies within or outside the sector to reduce vulnerability.
3. Risk reduction and management for resilience include a mix of public and private activities that promote early warning and information systems, improve risk reduction (DRR) strategies and enhance response to shocks (Watkiss, Ventura and Poulain, 2019).

These three categories have been adapted for this publication and some adaptation measures have been documented in the previous chapters 6 and 8. Table 10.1 below provides selected examples of relevant adaptations in the context of ENSO.

TABLE 10.1
Adaptation options for fisheries and aquaculture

Type of intervention	Examples
Public policies	• Mainstream fisheries and aquaculture in regional, national and local adaptation policies and plans. • Build political support for management change. • Promote public investments in research, capacity building, sharing best practices and trials, communication.
Legal matters	• Establish or strengthen mechanisms for protecting tenure and access rights. • Adaptive regulation to address ENSO-related events.
Institutional design/ set-up	• Improve cross-sectoral coordination. • Build capacity of institutions to integrate research, management and policy. • Encourage partnership between science and policy institutions so that research is developed at relevant scales for decision-making and includes local knowledge. • Enhance institutional cooperation agreement(s) between countries to enhance the capacity of fleets to move across national boundaries in response to changes in species distribution.
Planning and management	• Consider ENSO/climate change in management practices e.g. the ecosystem approach to fisheries and to aquaculture (EAF, EAA) including adaptive fisheries management and co-management. • Integrated coastal zone management. • Flexible seasonal rights. • Redistribution of rights among neighbouring municipalities to share responsibilities. • Risk-based zoning and siting through risk analysis. • Temporal and spatial planning to permit stock recovery during periods when climate is favourable. • Transboundary stock management to take into account changes in distribution. • Aquaculture area management plans to minimize climate-related risks.
Livelihoods	• Diversify patterns of fishing or fish farming activities with respect to the species exploited, location of fishing grounds or farms and gear used. • Improve or change post-harvest techniques/practices and storage. • Improve product quality: ecolabelling, reduction of post-harvest losses. • Invest in aquaculture (e.g. mud crab, seaweed, fish cages, oysters). • Diversify markets and fish products, access to higher-value markets. • Diversify livelihoods (e.g. switching between rice farming, tree crop farming and fishing in response to seasonal and interannual variations in fish availability).
Early warning	• Set up or improve monitoring, early warning, and communication systems (including identification of ENSO types) with responses tailored to ENSO type warnings. • Collaborative monitoring. • Information to anticipate price/market variability. • Extreme weather forecasting.
Pooling/risk sharing	• Risk insurance. • Personal savings. • Access to credit. • Social protection and safety nets for the most vulnerable. • Sharing of property and risks among community members.
Prevention	• Aquaculture zoning and area management. • Safety at sea and vessel stability. • Effective management of natural barriers to provide a natural first line of protection from storm surges and flooding. • Coastal zone management permitting movement of fish along with sea level rise.
Preparedness and response	• Develop and disseminate guidebooks and training packages on disaster needs assessment and response in the sector. • Rehabilitate ecosystems. • Shock contingency response funds.

Source: adapted from Poulain, Himes-Cornell and Shelton, 2018; FAO, 2018.

Early warning systems are especially useful to adapt to events such as ENSO. In particular, as ENSO types will impact fish and fisheries and aquaculture livelihoods and ecosystems differently, ENSO-oriented warnings and coping/adaptation measures should be tailored to the type of event they intend to address. It is the case in Peru where the official El Niño and La Niña predictions are issued separately for the coastal region and the central Pacific (ENFEN, 2015; L'Heureux *et al*., 2017), as the impacts in this country from the ocean warming or cooling are very different depending on where they take place. For example, El Niño warming along the coast can lead to extreme precipitation in the arid coast, while El Niño warming in the central Pacific tends to reduce precipitation in the Andes (Sulca *et al*., 2018). However, the ocean warming/cooling pattern in the tropical Pacific associated with different ENSO types is currently not well predicted, even at a one-month lead (Ren *et al*., 2019). Hence, even though the prediction of the strong 2015/2016 El Niño was relatively good in a broad sense, the warming in the coastal zone was weaker than predicted – relative to the central Pacific region – and the observed coastal precipitation in Peru was much weaker than expected (L'Heureux *et al*., 2017). In fact, global climate models have long-standing difficulty simulating the climate in the eastern Pacific (Adam, Schneider and Brient, 2018; Zuidema *et al*., 2016) and, considering that climate feedbacks are non-linear in this region (Ding *et al*., 2018; Takahashi, Karamperidou and Dewitte, 2019), this likely negatively affects forecast skill. Orlove, Broad and Pettyl (2004) studied the response of fishers to ENSO forecasts in Peru, and Broad, Pfaff and Glantz (2001) studied misinterpretation of forecasts for forecast users within the Peruvian fisheries sector during the 1997–98 El Niño season. Both these studies highlight not only the challenges in producing good forecast information, but also the importance of delivering accurate and timely communication, and to support the uptake and use of forecasts to improve decisions. This supports the need for investing in the whole weather chain, including communication, end user response (Watkiss, Ventura and Poulain, 2019), as well as safety at sea. Safety at sea is particularly important for capture fisheries given that the latter is probably one of the most dangerous occupations in the world.

Another important set of adaptation options relates to management and planning. As previously recommended, management responses have to adapt to the type of El Niño to avoid over- or under-reactions. Planning, monitoring, research, evaluation and learning have a major role to play in informing future fisheries management strategies, such as EAF, including adaptive management or co-management. [Iterative] adaptive management is well suited to the highly variable HCS and ENSO-associated impacts on species abundance and distribution (Bertrand, Vögler, & Defeo, 2018). It is also well suited to anticipate and respond to important emerging threats such as MHWs. In particular, the use of collaborative monitoring and learning between fisherfolk, scientists and management authorities, etc., can inform fisheries policy and regulation over time (e.g. to change catch limits, including between species) and ensure that proposed interventions are appropriate and effective (Watkiss, Ventura and Poulain, 2019; Dunstan *et al*, 2018).

Whereas some attention has been given to the economic impact of ENSO events, less is known about their implications for people (e.g. in terms of poverty and food) and for people's adaptation strategies. Yet at national/local level, ENSO events can have profound effects on the livelihoods of fishing and fish farming communities. The severity of the impacts of ENSO will depend on the ENSO types (i.e. the exposure), the degree of dependence on affected resources (e.g. sensitivity) and on existing national and local capacities to cope with, adapt to or take advantage of the changes they experience (i.e. the adaptive capacity). The findings of the Badjeck (2008) study in Peru suggest that fishers were vulnerable to external shocks because of their strong reliance on fishing activities. Specialized and localized fisheries are indeed likely to be more vulnerable to climatic hazard, and to ENSO in particular (Bertrand, Vögler and Defeo, 2018). In response to climate variability, human fishery systems/SSF have developed a variety of strategies including intensification of effort, diversification of species, migration (following the fish), occupational pluralism and exit (the strategy of last resort). Not all strategies are sustainable in the long-run. More intense fishing or diversification of target species about which little is known are examples of high-risk, long-term strategies (OECD, 2010). Cinner *et al.* (2018) have recently identified five key domains to help local and national governments, development agencies, and non-governmental organizations develop communities' adaptive capacity. These include the assets that fishers and aquaculture stakeholders can draw on during times of change: financial assets (e.g. savings, credit or insurance); technological and service resources (e.g. social protection, education) that individual fishers or communities can access as they need. These can be critical in times of change. For example, in Peru, at the time of the 1997/98 El Niño event, the recently privatized social security and health organization for industrial fishers – which relied on a percentage of the catch – was depleted quickly as a result of decreasing catches, leaving fishers without a safety net and access to financial resources to cope with the difficult economic situation (OECD, 2010).

The other domains of adaptive capacity are: the flexibility to change strategies for individuals or rules, boundaries, partners for organizations, either temporarily or permanently; the capability to organize and act collectively (e.g. to exchange information or promote cooperation to adapt to changes in fish catches or weather patterns); learning to recognize and respond to the effects of climate change (e.g. learning about new fishing grounds, gears, etc.); and the agency to decide whether to change one's behaviour or not. These domains are cross-cutting and need to be considered across the three main adaptation categories identified above (institutions, livelihoods and risk reduction and management for resilience).

While our knowledge of ENSO and adaptation grows, planned adaptation that results from a policy decision remains a challenge, as it has to address climate risks that vary dynamically and non-linearly over time. The literature (see for example Watkiss, Ventura and Poulain, 2019) identifies no or low regret adaptation frameworks, or early adaptation frameworks, to help identify and prioritize key adaptations in the fisheries and aquaculture sector that are likely to have good returns on investments. An example of these is given below:

- Interventions that address current climate impacts and early trends and generate net social and/or economic benefit. Weather and climate services for fisheries, including early warning systems, are often classified in this category, as these have been found to have good benefit-to-cost ratios. Benefits arise from the use of information to improve decisions (the value of information), which reduces losses/enhances gains, provided investments are made along the whole weather chain (i.e. forecast accuracy, communication and end user response in addition to meteorological infrastructure).
- Early interventions to ensure that adaptation is considered in early decisions that have long lifetime or a risk of lock-in, i.e. long-lived investment that will be exposed to future change such as vessel replacement and infrastructure development.
- Early adaptation steps to help inform longer-term change, e.g. planning, monitoring, pilots and research so that appropriate decisions can be brought forward or delayed. These provide economic benefits from the value of information, learning and option values.

In the national context, all the above options may be needed and they are not mutually exclusive. Where a formalized appraisal is needed, conventional decision-support methods such as cost-benefit analysis or multi-criteria analysis can be used for short-term, low and no regret adaptation. For options that involve longer-term decisions, where uncertainty becomes important, a more detailed set of appraisal methods is applicable. These include decision making under uncertainty methods. There is emerging guidance available on the application of these approaches (Watkiss, Ventura and Poulain, 2019) though to date there has been a low application for fisheries and aquaculture.

To conclude, different types of adaptation and DRR practices have been documented or recommended in this publication to address the effects on fisheries and aquaculture of the different types of ENSO. Evaluations of success are, however, often missing which render it difficult to assess success. Assessment of past and on-going efforts is recommended.

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This FAO Technical Paper synthesizes current knowledge on the impact of El Niño Southern Oscillation (ENSO) events on fisheries and aquaculture in the context of a changing climate. Fisheries and aquaculture are essential parts of the global food system. The recent discovery that ENSO is far more diverse than previously recognized highlights a pressing need to synthesize the impact of the different ENSO types on fisheries and aquaculture. The overall aim of this Technical Paper is to provide relevant, up-to-date information and help decision-makers identify the most appropriate interventions according to the diversity of ENSO types. In addition, the possible effects of climate change on these sectors can be partly illustrated by the current effects of ENSO events, which are themselves affected by climate change.

The Technical Paper describes the diversity of ENSO events (Chapter 2), ENSO forecasting (Chapter 3) and ENSO in the context of climate change (Chapter 4). It includes a global overview and regional assessment of ENSO impact (Chapters 5 and 6) and a focus on coral bleaching and damage to reefs and related fisheries (Chapter 7). Finally, it synthesizes the lessons learned and the perspectives for ENSO and preparedness in a warmer ocean (Chapter 10).

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