Chapter 3: Case studies

3.1. The use of Copernicus Marine Service products to describe the State of the Tropical Western Pacific Ocean around the Islands: a case study

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Statement of main outcome: The Western Tropical Pacific Ocean remains one of the last frontiers for scientific research. This area of the ocean is exposed to strong variations at inter-annual to decadal scales forced by climate modes such as the El Niño Southern Oscillation, as well as long-term changes driven by global warming. These Pacific Island States lie in the main route of devastating storms and this area of the ocean lacks ocean observations. We have created a Copernicus Marine Atlas for the Pacific Ocean States, that delivers ocean data to address the needs of decision-makers and to meet climate directives. It responds directly to Fiji's requests at the 2017 United Nations Oceans Conference for the Sustainable Development Goal (SDG)14 (for life below water) and in the 2017 COP23 conference for SDG13 (on climate action). The Copernicus Marine Atlas for the Pacific Islands States shows sustained and drastic ocean warming, sea level rise, and a decrease in the base of the marine food chain (phytoplankton) in this area. The Pacific Big Ocean States are vulnerable to the changing marine environment and face unprecedented threats to the three pillars of sustainable development: economy, environment, and society.

Products used:

Ref. No.	Product name and type	Documentation
3.1.1	1.5.1 DUACS (Data Unification and Altimeter Combination System) delayed-time altimeter daily sea level products, Altimetry	http://climate.copernicus.eu/climate-data-store
3.1.2	GLOBAL_REANALYSIS_PHY_001_026 Reanalysis	PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-GLO-PUM-001-026.pdf QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-GLO-QUID-001-026.pdf
3.1.3	INSITU_GLO_TS_OA_REP_OBSERVATIONS_013_002_b *In situ* for the year 2017: INSITU_GLO_NRT_OBSERVATIONS_013_030 *In situ*	PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-INS-PUM-013-002-a.pdf; QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-INS-QUID-013-002a.pdf) for the year 2016: PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-INS-PUM-013.pdf QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-INS-QUID-013-030-036.pdf
3.1.4	GLOBAL_REP_PHY_001_021 *In situ*, remote sensing	PUM: http://marine.copernicus.eu/documents/QUID/CMEMS-GLO-QUID-001-021.pdf QUID: http://marine.copernicus.eu/documents/PUM/CMEMS-GLO-PUM-001-021.pdf
3.1.5	OCEANCOLOUR_GLO_CHL_L3_REP_OBSERVATIONS_009_065 Remote sensing	PUM: http://marine.copernicus.eu/documents/PUM/CMEMSOC-PUM-009-ALL.pdf QUID: http://cmemsresources.cls.fr/documents/QUID/CMEMS-OC-QUID-009-064-065-093.pdf

Fiji served as President of the UN General Assembly in 2017, linking climate (SDG13) and ocean (SDG14) as the foundation of blue economies for island and coastal states around the world. The resulting United Nations Oceans outcome statement stressed

> the importance of enhancing understanding of the health and role of our ocean and the stressors on its ecosystems, including through assessments on the state of the ocean, based on science and on traditional knowledge systems. We also stress the need to further increase marine scientific research to inform and support decision-making, and to promote knowledge hubs and networks to enhance the sharing of scientific data, best practices and 'know-how'. (UN 2017)

The Southern Pacific Ocean remains one of the last frontiers for scientific research. Few *in situ* monitoring systems exist to document the state of the Pacific Ocean. Indeed, accessing available fisheries data is compromised because of the competitive nature of the fishing industry (Transform Agorau, pers. comm.). The effective and growing Argo float network, with 3907 floats in February 2019 (http://www.argo.ucsd.edu/About_Argo.html), has truly revolutionised large-scale physical oceanography (Riser et al. 2016). The continuing limited capability of climate system models to adequately simulate ocean-climate coupling and dynamics, including the El Nino Southern Oscillation, underscores the importance of integrating the available data sets (Bellenger et al. 2014).

The Pacific Islands Meteorological Services Directors have repeatedly emphasised the need to include ocean forecasting and services in the suite of the WMO Global Framework for Climate Services (SPREP 2012), and the third Pacific Meteorological Council Meeting (SPREP 2017). As president of COP23, Prime Minister Frank Bainimarama has emphasised the importance of the climate and ocean connection and the need to protect ocean health to protect the planet: 'We are all in the same canoe' (https://cop23.com.fj/fijian-prime-minister-cop23-president-remarks-assuming-presidency-cop23/). The Copernicus Marine Service Atlas for Pacific Ocean States compiled by the author team responds directly to Fiji's requests at the 2017 United Nation Oceans for SDG 14, life below water and the 2017 COP23 for SDG13, climate action which goes beyond the Pacific.

The Copernicus Marine Service Atlas for the Pacific Ocean States goes beyond the unique compilation of CMIP3 climate model projections and data tools compiled by the Pacific Climate Change Science Program (PCCSP 2011, 2014). A complete overview of tropical Pacific observing network is available in the WMO publication library (GCOS 2014a, 2014b). Our study focuses on the application of the available CMEMS products to the Pacific domain defined by PCCSP.

The data sets available through the Copernicus Marine Service provide a valuable window on the under-observed Pacific Ocean and help build a foundation for providing ocean services, including food security, essential biological variables and indicators of ocean health, data to inform early warning systems and climate adaptation. To begin, we address the following key ocean variables:

- sea surface temperature, a much-needed variable for assessing coral reef health and bleaching and tropical cyclone forecasting
- ocean heat content trends for the upper 700 m depth, to monitor ocean warming and thermal volume changes contributing to sea level rise; to track changes in stratification, ocean currents, as well as marine ecosystems and human livelihoods. Moreover, this indicator is linked to the ocean's role as a major heat source for the global atmospheric circulation and has important implications for regional and global climates, including severe events.
- sea level trends from 1993 to 2017 to better inform climate adaptation and coastal planning. Sea level trend values in the entire Pacific Islands domain (Box 3) range between -0.5 mm y^{-1} and $+7.2$ mm y^{-1}, illustrating the non-uniformity of the sea level rise in this region.
- near-surface chlorophyll concentrations – as linked to phytoplankton populations – to assess ocean productivity and health as their changes can imply major impacts on ecosystem processes and biogeochemical cycling, which in turn can have significant implications for economy productivity and food availability.

To develop the Pacific case study, the domain was defined to encompass the 15 P-ACP (African, Caribbean and Pacific) countries defined by the EU Cotonou agreement and served by the EU's ACP secretariat (http://www.acp.int/) including: Cook Islands, Federated States of Micronesia, Fiji, Kiribati, Nauru, Niue, Palau, PNG, RMI, Samoa, Solomon Islands, Timor-Leste, Tonga, Tuvalu, and Vanuatu. The domain corresponded to that used for the Pacific Islands in the Pacific Climate Changes Science Program (Australia Bureau of Meteorology and CSIRO 2011). To explore the dynamics inside and outside the Western Pacific Warm Pool, the domain was further subdivided.

Global mean sea surface temperature, upper ocean heat content and mean sea level all show pronounced increasing trends over the last decades and with strong evidence that the positive trend is related to the increase in greenhouse gas concentration (Rhein et al. 2013). Nevertheless, the global surface and subsurface warming and global mean sea level rise is not spatially uniform (Meyssignac et al. 2016). Long-term warming of the western Pacific is a well-documented consensus in literature (Cane et al. 1997; Cravatte et al. 2009; Deser et al. 2010). Accordingly, the Copernicus Marine Service Atlas for the Pacific Islands area shows a significant surface and subsurface warming trend and sea level rise (Figures 3.1.1 and 3.1.2) at values close to and even exceeding the global mean warming and sea level rise rates (see Table 3.1.1, see also Chapter 1). The Western Pacific Islands area shows strong variability over various time scales (Merrifield et al. 2012; Han et al. 2014 Sun et al. 2017;). At inter-annual time scales, western tropical Pacific surface and subsurface temperatures, and sea level vary in synchrony with the modes of the El Niño Southern Oscillation (Figure 3.1.2; e.g. Wang et al. 1999; Ablain et al. 2017). The near-surface layers warm in the easternmost Box 2 during the 1997/1998 and 2015/2017 El Niño phase (shown in red) and cool during the 1998–2000, 2007/2008 and 2010/2011 La Niña phase (shown in blue, Figure 3.1.2(a)). Moreover, year-to-year changes for western tropical Pacific sea level are thermosteric driven: sea level rises as ocean temperatures rise (Figure 3.1.2(b,c)).

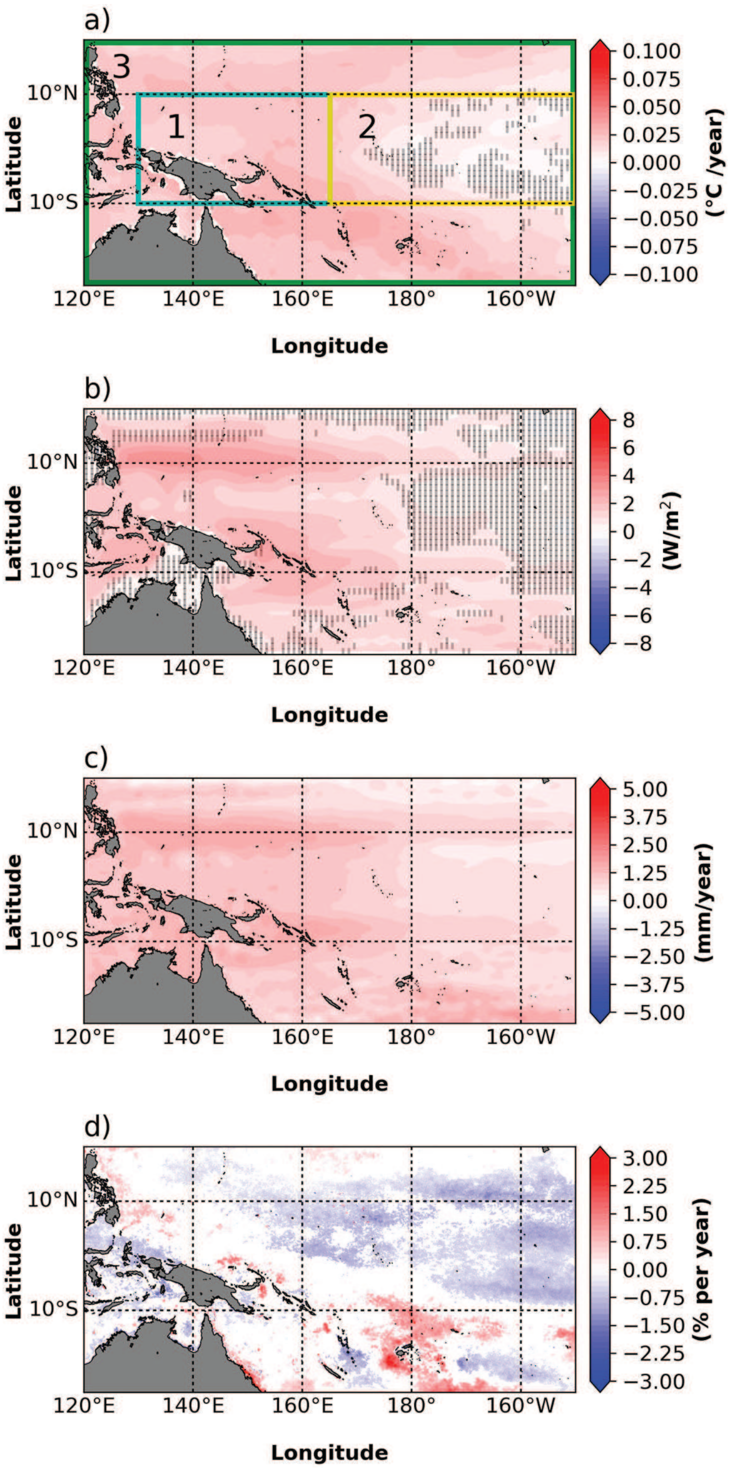

Figure 3.1.1. Regional trends of (a) sea surface temperature and (b) upper ocean (0–700 m) ocean heat content over the period 1993–2017 for the western tropical Pacific. The results are derived from a multiproduct approach (ensemble mean of product 3.1.2–3.1.4). Black dots indicate areas where the noise exceeds two times the signal. (c) Regional sea level trend (in mm y^{-1}) for the western tropical Pacific over the period January 1993–May 2017 (note to reviewer: will be up-dated until December 2017) as derived from re-processed satellite altimetry data (product reference 3.1.1). No Glacial Isostatic Adjustment correction is applied on the altimeter data. (d) Map of regional chlorophyll trend (September 1997–December 2017) in the western tropical Pacific as observed by remote sensing. Only statistically significant ($p < .05$) trends are shown, and are based on the CMEMS product 3.1.5. See Table 3.1.1 for the definition of the dataset, and access to related documentation. Regions for analysis are indicated in (a), i.e. Western Pacific Islands (blue, Box 1; 130°E–165°E; 10°S to 10°N to encompass the Western Pacific Warm Pool); Central Pacific Islands (yellow, Box 2: 165°E–150°W; 10°S to 10°N); and Entire Pacific Islands domain (green, Box 3 is consistent with domain used for the Pacific Climate Change Science Program).

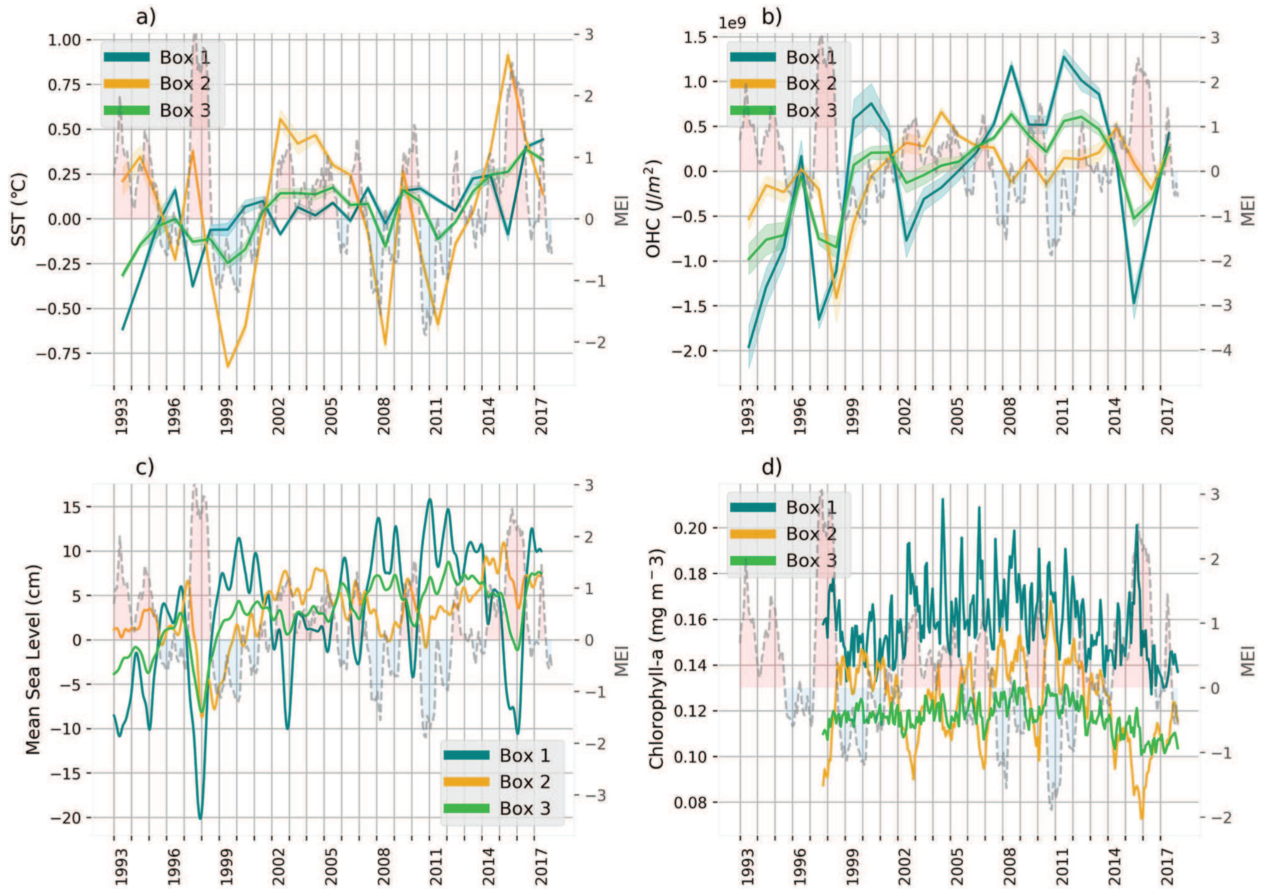

Figure 3.1.2. Averaged time series over the full area (green line, Box 3, full map area of Figure 3.1.1(a)), and the western (dark blue line, Box 1) and eastern (yellow line, Box 2) tropical Pacific Ocean for (a) sea surface temperature, (b) ocean heat content, (c) sea level and (d) Chlorophyll-a. The seasonal cycle had been removed from all time series (1993–2014 for (a)–(c), 1997–2014 for (d)). Details on box areas and data use is given in the caption of Figure 3.1.1. The Multivariate El Niño Southern Oscillation Index is used to describe the ENSO phase with the El Niño phase shown as red (positive) shaded areas and La Niña shown as blue (negative) shaded areas (Wolter and Timlin 2011, downloaded: https://www.esrl.noaa.gov/psd/enso/mei/).

We introduce chlorophyll concentration (Figure 3.1.1 (d) and Figure 3.1.2(d)) to provide a measure of the amount of phytoplankton present with its corresponding marine productivity on which the entire marine ecosystem depends, directly or indirectly. Ocean chlorophyll could be used by decision-makers to assess the health and productivity of natural resources and marine life that depend on phytoplankton. Reduced chlorophyll

Table 3.1.1. Trend values and their uncertainties (90% confidence interval) of area mean Sea Surface Temperature (SST) and Ocean Heat Content (OHC) over the period 1993–2017 (ensemble approach from products 3.1.2–3.1.4), Sea Level over the period January 1993 to December 2017 (product ref. 3.5.1) and Chlorophyll concentration over the period September 1997–December 2017 (product ref. 3.5.5). Areas for Boxes 1 and 2 are given in Figure 3.1.1(a), and full domain covers the western tropical Pacific as shown in the maps of Figure 3.1.1. Note that the uncertainties related to the sea level internal variability are not included in the sea level trend uncertainties.

Variable	Western Pacific Islands Box 1 1993–2017 trend	Central Pacific Islands Box 2 1993–2017 trend	Entire Pacific Islands domain Box 3 1993–2017 trend
SST °C y^{-1}	+0.02 ± 0.01	+0.01 ± 0.02	+0.02 ± 0.01
OHC (0–700 m) W m^{-2}	+1.9 ± 1.5	+0.8 ± 0.7	+1.2 ± 0.7
Sea level mm y^{-1}	+4.8 ± 2.5	+2.8 ± 2.5	+3.5 ± 2.5
Chlorophyll % y^{-1}	-0.4 ± 0.02	−0.7 ± 0.001	−0.4 ± 0.001

concentration and associated decrease in primary production may negatively impact fish and marine life, important for food security and economic health of the Pacific Islands countries that dependent on fisheries.

Significant trends, both positive and negative, have been reported on a regional basis, for both chlorophyll concentration and primary production (Mélin et al. 2017; Racault et al. 2017), and some of the most pronounced trends have been reported for the eastern and western Pacific region. In the western Pacific area (Box 1 of Figure 3.1.2(d), blue line), large variations from year-to-year characterise the chlorophyll concentrations, highlighting the need for regular monitoring services. River run off coincident with ITCZ and SPCZ dynamics in the equatorial coastal areas like that of northern Papua New Guinea explains the greater high-frequency variability than open ocean regions. In the central Pacific (Box 2 of Figure 3.1.2(d), yellow line), a reduction of chlorophyll concentration since the year 1997 is recorded at a rate of ∼−0.7%/year which is either linked to decadal or longer variability (as observed in the northern Pacific e.g. Sun et al. 2017) or the impact of climate change. Chla is strikingly well correlated with the Central Pacific El Niño signal with high Chla associated with the negative (La Niña) phase of ENSO as seen in 1998, 1999, 2007 and 2010, and a lower Chla associated with the positive (El Niño) phase of ENSO as seen in 2015. For the entire Pacific Islands (green line, Box 3, Figure 3.1.2(d)), Chla mimics that of the western Pacific (blue line, Box 1) with a lower amplitude due to the weaker correlation with Central Pacific ENSO events (yellow line, Box 2). In the Fijian Archipelago, with the inverse, Chla concentration is increasing between 0% and 2% per year (Figure 3.1.1(c)), indicating a high positive response of phytoplankton, or/and a shift in phytoplankton composition (Dupouy et al. 2018).

Given that time series from remote sensing used here is only 18 years long, and the dominant signature is decadal scale variability (Gregg et al. 2017), this time series is admittedly too short to disentangle the effect of interannual variability and longer-term climate change. Nevertheless, this series demonstrates (1) the correlation between Chla and ITCZ in the western Pacific due to coastal areas in large Pacific Islands in the Western Pacific (Box 1), (2) the strong correlation between Chla and La Niña phase due to the equatorial upwelling enrichment in the Central Pacific (Box 2) and (3) less correlation for the entire region due to smoothing of the ENSO or ITCZ effects as demonstrated by the reduced variability (Box 3). The variability around the long-term trend appears visually to be inversely related to the MEI (Figure 3.1.2(d), yellow line).

The State of the Pacific Ocean case study is a demonstration of how Copernicus Marine Service products might be used to inform decision-making in a region that regards itself as data poor, especially for ongoing monitoring of biological variables. The perception of data poverty results from limited capacity to access, display and analyse data (Holland 2018). The Copernicus Marine Services State of Pacific Ocean challenges those perceptions of data poverty by demonstrating the richness of the data available to inform decision-making in the Pacific Islands.

Our hope is that the State of the Pacific Ocean atlas serves as a springboard to begin stakeholder engagement and dialogue on how to use the available data to inform decision-making. In the 2018 Pacific Island Forum Leaders meeting, the Pacific leaders of the 16 Forum member countries prioritised climate change and blue economies. Optimising utilisation of the available data requires further dialogue at the science policy interface to generate the robust products required to inform decision-making.

The Pacific Islands Forum Marine Sector Working Group (MSWG) has prioritised the need to document data available for the Pacific Islands domain. A first step will be to show the products to the MSWG and other stakeholders to engage them in collaborative discussions about how the data might be used. The long-term goal is to produce data products that would inform decision-making for the blue economies of the Pacific. The data is available to inform decision-making on an annual basis through the World Ocean Atlas, and could become useful on more refined time scales, quarterly to weekly to inform climate and ocean outlooks. One step might be to transform the data products provided here into real time data available to the Forum Fisheries agency, Honiara, Solomon Islands for display in their fisheries monitoring facility. Another step for the MSWG would be developing real time data displays that provide the more than 20 years of context for physical ocean monitoring (GCOS 184)

Future needs for the Copernicus data include refining the approach to finer time scales with the eventual goal of providing real time data and information services and short-term two-week forecasts. The data products are available through CMEMS, but (i) regionalisation (e.g. downscaling) and (ii) cross-validation between products (e.g. link the consolidated products with the non-consolidated ones) are required. The data products shown are subset of the data available for the Pacific Islands to launch the much-needed dialogue with the key stakeholders and champions. With the successful launch of this Pacific Ocean Atlas, other ideas and innovations will emerge for research products and applications.

The Copernicus Marine Services State of Pacific Ocean analysis of available data demonstrates that the ocean surrounding the Pacific Islands is warmer, has higher heat content, with sea level rising at rates higher than the global mean and a decline in chlorophyll content.

3.2. Review of the use of ocean data in European fishery management and monitoring applications

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Statement of main outcome: Operational oceanographic data is potentially of great value for use in the monitoring and management of marine living resources due to the close coupling between the physiology of marine organisms and their environment. However, while oceanographic data is invaluable in understanding the processes governing the dynamics and behaviour of these organisms from a historical perspective, it has generally not been used in the day-to-day management of fisheries resources. We discuss the reasons for this situation and highlight emerging results, such as dynamic ocean management and marine ecological forecasting, that are starting to reverse this tendency. Finally, we discuss what can potentially be done to improve the uptake of this information.

Ref. No.	Product name and type	Documentation
3.2.1	SST_GLO_SST_L4_NRT_ OBSERVATIONS_010_001 SST_GLO_SST_L4_REP_ OBSERVATIONS_010_011	PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-OSI-PUM-010-001.pdf QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-OSI-QUID-010-001.pdf
3.2.2	GLOBAL_ANALYSIS_FORECAST_ PHY_001_024_MONTHLY Model	PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-GLO-PUM-001-024.pdf QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-GLO-QUID-001-024.pdf

Marine organisms are coupled to their physical environment in a way that, as terrestrial mammals, is hard for us to comprehend. Most marine organisms are ectotherms ('cold blooded'), meaning that their body is at the same temperature as the surrounding environment: as a consequence, their metabolisms, and therefore their food requirements, growth rates, reproductive development and activity rates are all directly modulated by the temperature of their surroundings (Pörtner 2002). In addition, the concentration of dissolved oxygen at the surface is strongly temperature-dependent (higher temperature waters contain less oxygen) while below the surface the consumption of oxygen by other organisms can lead to areas of critical oxygen depletion (Breitburg et al. 2018). Salinity can play an important role in limiting the fitness and distribution of organisms, particularly in and around regions of transition between fresher and saltier waters e.g. from the high salinity North Sea (surface salinity of approximately 33–35) to the low salinity Baltic Sea (surface salinity 2–15) (Pecuchet et al. 2016). Variations in seawater pH and its resulting impacts on carbonate concentration have also been shown to affect both shell-forming organisms (e.g. coccolithophores, shellfish) and higher organisms (e.g. fish) (Dupont and Pörtner 2013).

This tight linkage between the physical environment and marine organisms has long been recognised within both the science and management of living marine resources. Oceanographic data therefore can potentially play an important role in informing these activities (Tommasi et al. 2017). Here we review how operational oceanographic products are currently used in these fields, with a particular focus on the CMEMS product catalogue. We focus on three different applications of this information, according to the timescale in question, i.e. understanding the historical perspective, evaluating the current state of the system and looking towards the future. Finally, we examine potential future directions and how collaboration between these two fields can best be fostered.

Firstly, historical oceanographic data play a key role in developing our scientific understanding of marine organisms and ecosystems: indeed, an entire sub-discipline of oceanography ('fisheries oceanography') has evolved at the interface of fisheries science and physical/chemical/biological oceanography that focuses on resolving these questions. One of the most prominent applications of such historical data is in cataloguing and understanding changes in the context of climate change and climate variability: a review performed in the lead up to the last IPCC report (AR5) identified 1700 such examples of observed responses to climate change in marine systems, including around 800 in European waters (Poloczanska et al. 2013). Large-scale indices have been used to link climate variability to ecological consequences in the ocean, including the North Atlantic Oscillation, the Atlantic Multidecadal Oscillation (Nye et al. 2014), the North Atlantic Subpolar Gyre intensity (Hátún et al. 2009), the El Niño Southern Oscillation (Chavez et al. 2002) or the Indian Ocean Dipole (Saji et al. 1999). The oceanographic data sets underlying these studies are diverse in nature and often reflect what is available to the authors, rather than being selected from either the global marketplace or from a systematic catalogue such as the CMEMS portal. In particular, the most impactful and important results are those that are based on long time series of both biological and physical observations (e.g. Boyce

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