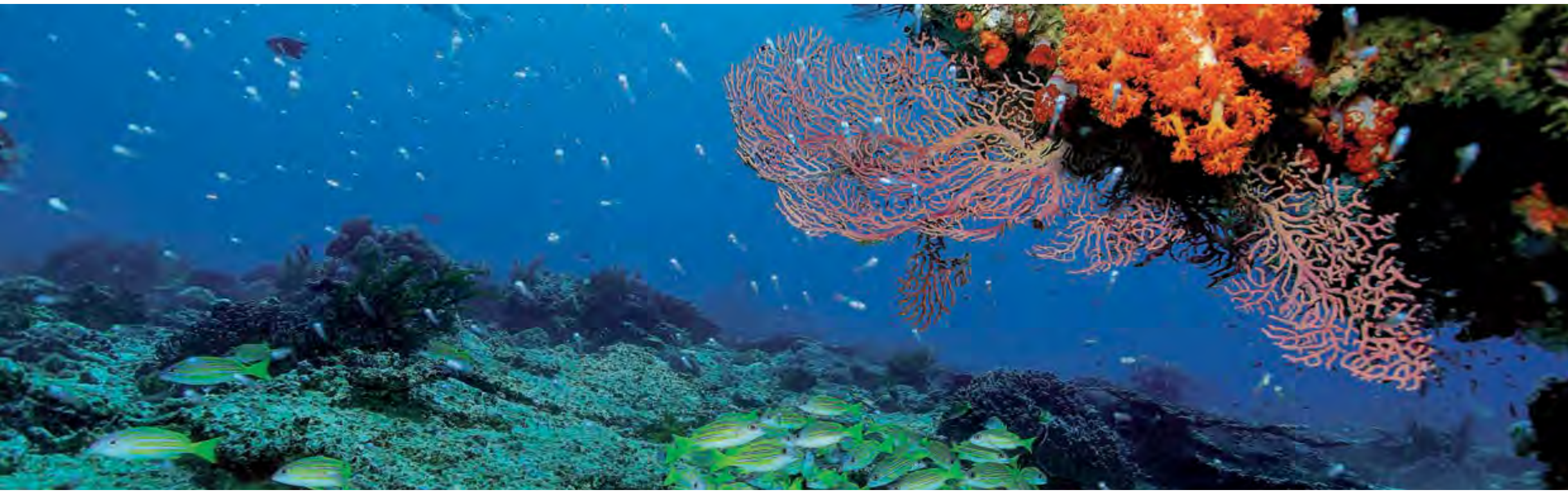
Chapter 8

Oceans: marine ecosystems and warming



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Gorgonians and shoals of fish in West Papua, Indonesia.

The oceans are at the heart of the globe's climate machine and are strongly hit by climate change. Numerous effects are observed today in the ocean environment: changes of water temperature and oxygen levels, acidification, rise in sea level, etc. These physical and biogeochemical changes and, to a lesser degree, extreme events, affect conditions of life in the oceans. The geographical distribution of species and the dynamics of ecosystems will be seriously disturbed in the coming decades and will affect fisheries at the world level. The movement of species towards the poles will lead in particular to a decrease in fishery resources in the tropics, compromising food security in numerous southern countries.

Ocean life subjected to environmental constraints

Warming and acidification

From 1971 to 2010, the oceans absorbed 90% of the increase in energy held in the world climate system. The temperature of this gigantic energy store is increasing as a result of global warming. According to the IPCC Fifth Assessment Report, warming of the surface of the seas has been an average of 0.11°C per decade from 1971 to 2010. The oceans also act as a carbon regulator by absorbing part of the carbon dioxide emitted as a result of anthropic activities. For a long time researchers thought that this storage of CO_2 had no special consequences for oceans and the organisms that live in them. But they realised about 15 years ago that the dissolution of CO_2 in seawater causes its acidification.

The role of the environment in ocean life

These physical and biogeochemical changes affect the conditions of life in the oceans. Indeed, the environment plays a dominant role in the dynamics of fish populations. This effect has been known since the work of Johan Hjort in the early 20th century. Studies of cores of marine sediments using scale deposits make it possible to estimate the abundance of fish for a period of more than 20,000 years. They have shown that the stocks of sardines and anchovies have varied considerably according to climatic conditions.

Raising a trawl net used for fish sampling off the Peruvian coast during an oceanographic programme run by the Instituto del Mar del Perú.

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The environment particularly affects the conditions of reproduction of the various species. Fish lay large numbers of eggs and these are small (about 1 mm) and so they float. But 99% of the eggs die in the first few days and the lives of the remaining 1% are strongly conditioned by environmental factors. Recent studies carried out by IRD show that the number of parents counts for only 10% of the abundance of a population. The remaining 90% is related to the climate and ecosystem relations. The changes observed in the oceans thus have considerable influence on the life cycles of species. They also have effects on metabolism (growth, respiration, etc.), on interactions between species (prey-predator, host-parasite, etc.) and on habitats.

Knock-on effects on marine biodiversity

Water warming changes species distribution

Fish and marine invertebrates react directly to the warming of seawater by moving, generally to higher latitudes and deeper water. This migration means that they can be in habitats whose temperature matches their needs. It is observed for many species that the rate of movement towards the poles is more than 50 km per decade. Certain phytoplankton species have shifted by nearly 1,000 kilometres in several decades in reaction to the warming of the water. The migration rates recorded in a marine environment seem to be faster than those on land.

But the warming of seawater also changes the biological cycle and abundance of marine organisms, from plankton to large predators. The calendar of the numerous stages in biological development such as the reproduction and migration of invertebrates and fish—and also seabirds—has become earlier. In the last 50 years, plankton production

Myriads of hatching fish in New Caledonia.
The warming of seawater changes the dates of hatching and, more generally, the biological cycle of marine organisms.

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Box 14

The Humboldt Current ecosystem changed by increasing upwelling of cold water

The Humboldt Current off the shores of Peru and Chile is an enormously productive ocean ecosystem subjected to the climate disturbances of the Pacific. Substantial multidisciplinary work by IRD scientists (the Marbec, Locean and LEGOS units) and their partners makes it possible to assess the role of climate warming in the evolution of this ecosystem.

The Humboldt Current ecosystem is the world champion of fish production. It covers less than 0.1% of the total area of the world's oceans but supplies more than 10% of world fish captures. Its productivity results from an upwelling phenomenon bringing cold water rich in nutrient. This rich water enhances the growth of enormous phytoplankton and zooplankton populations supplying a food chain that includes numerous species of fish, birds and sea mammals.

However, this very rich ecosystem is subjected to extremely strong environmental constraints: biological activity and the poor ventilation of water lead to the formation of a layer of deoxygenated water that extends from several metres below the surface to a depth of 800 m.
The ecosystem includes the most extensive, intense, close to the surface minimum oxygen zone (MOZ) in the world. The zone results in the concentration of numerous fish species close to the surface where oxygen is more plentiful

Extension of the minimum oxygen zone

The impact of climate change on the Humboldt Current can already be seen.
While the world's oceans are warming, paradoxically the ocean zone bordering the coasts of Peru and Chile has been cooling for more than a century as a result of the intensification of upwelling. Rich in nutrients, this rising cold, deep water also increases the productivity of the system. This trend enhances the spread of the minimum oxygen zone.
The increase in the quantity of organic matter that is then broken down by bacteria increases oxygen consumption. Some fish species such as sardines cannot support the constraints of a reduced habitat and may in time disappear from the zone.

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Colony of cormorants on the island of Pescadores off the coast of Peru.
Fish, marine mammals and birds—the entire food chain along the coast of Peru is affected by climate change.

Off the Peruvian coast again, recent research shows that the warming of the water also increases the stratification of ocean water. In other words, the physical barrier between surface water and the deoxygenated zone becomes stronger (the barrier is linked to a difference in density between the warm, low density water at the surface and the cold, dense water at a deeper level). One of the results is that the characteristics of the rotating areas of surface water that form oases of life by deforming the barrier may change. These could directly affect fish populations.

Will boobies, cormorants or pelicans be the winners?

Numerous seabirds benefit from the plentiful 'forage fish' in the system. Although one might expect to find one species per niche, three species (boobies, cormorants and pelicans) coexist here in large numbers even though they seem to have precisely the same ecological niche, feeding on the same fish and nesting in the same places. However, recent work shows that the three species exploit the common resources in markedly different ways: the cormorant uses its excellent diving ability to feed on shoals of anchovies, even when they are comparatively deep; boobies use their network hunting strategy and flight capacity to benefit from anchovies even in very large areas; finally, pelicans—with poor flight and poor diving ability—hunt at night when the fish are in loose shoals but close to the surface.
By causing sudden frequent changes in prey distribution, the intrinsic climatic variability of the system gives the advantage to one or other of these three species in turn.
This is probably a key factor explaining the maintaining and coexistence of the three large bird populations.
By changing the structuring of the water masses and the habitat of forage fish, climate change calls into question the future pathway of this delicate ecological balance.
Will the boobies and cormorants, daytime hunters adapted to targeting fish clustered in the 'oases of life', lose ground to the night feeding pelicans?
Will cormorants that incidentally produce the best quality guano, still have opportunities to use their advantage as divers in a more stratified ecosystem?

End of the golden age

This fantastic productivity linked to upwelling is possible as the conditions of the ecosystem are currently optimal. As the work by IRD has shown, upwelling is not effective when the wind is too light and so the system is not very productive, but strong wind generates turbulence and scatters food and larvae.
The wind along the coasts of Peru and Chile is now moderate at approximately 5 metres per second.
The question of how the system will evolve in the future remains open. However, it is unlikely that the golden age of fish (currently the highest for the last 20,000 years) will continue in the future.

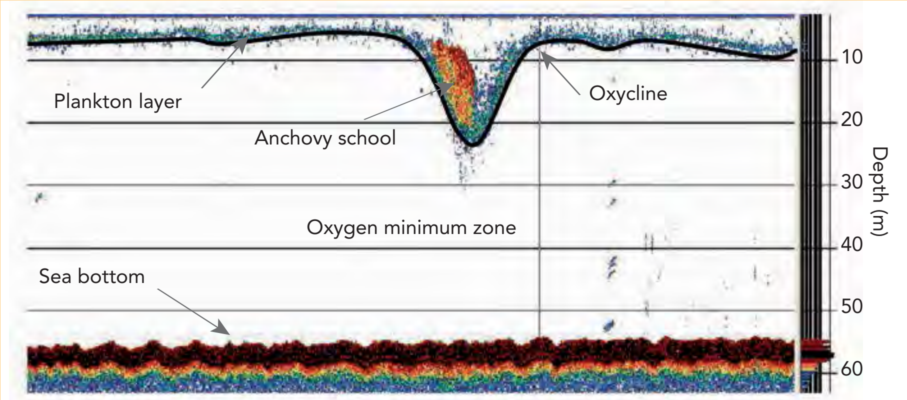

Figure 21.
An example of an acoustic echogram from Peru illustrating the intensification of the minimum oxygen zones.
The boundary (oxycline) between oxygenated surface water (black curve) and the MOZ is at a depth of less than 10 m. Organisms are therefore concentrated in a shallow surface layer. Zooplankton (blue and green dots) forms a shallow layer and a shoal of anchovies (red shape) is distributed in an internal wave where the oxycline is locally deeper. Anchovy can live when the oxycline is very close to the surface but other species like sardines are driven out of the system.
Source: IRD/Marbec.

has become earlier for numerous species, gaining an average of about 4 or 5 days in each decade. If the species that depend on this spring production do not shift their laying cycle at the same rate as plankton, their larvae may hatch too late when food is less abundant.

Chain effects of interactions between species

Knock-on effects resulting from interactions between species should also be taken into account in impacts related to climate change. Ecologists have long known that in trophic interactions (prey-predator) a change in the abundance and distribution of key consumers in food chains can have substantial repercussions on all the species that form part of these chains.

Changes in the environment and interactions may sometimes cause a higher density of fish at a local scale. For example, there is a well-established relationship between the duration of the plankton phase of larvae and water temperature: the warmer the water, the shorter the plankton phase because larvae develop more rapidly. Reducing the duration of the life of plankton strongly exposed to numerous predators reduces the death rate at this stage. As a result, the local development of fish is enhanced on condition that sufficient food of an appropriate size is available.

Understanding responses to climate change from organisms to ecosystems is thus a major challenge for research. Another level of complexity is also involved: adaptation. Indeed, species can adapt to changes in their environment or to new environmental niches. Long duration watches are thus needed to monitor the evolution of species.

Threats to coral ecosystems

Coral bleaching

A known impact on corals of the rise in water temperature is the coral bleaching phenomenon. When the temperature of seawater rises by a few degrees, corals expel zooxanthellae, microscopic algae, with which corals live in symbiosis. But these organisms provide them with nutrients that are essential for growth. Without them, corals lose their capacities and their colour and their white skeletons become visible. Bleaching can lead to the death of corals and have an impact on the very rich reef ecosystem.

Some Pacific reefs affected by marked periods of bleaching nearly 20 years ago have never returned to their initial state. Research at Indian Ocean coral sites that have suffered massive bleaching after the 1997-1998 El Niño climatic phenomenon also shows how the diversity, size and structure of fish communities follow the decline of coral reefs.

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Coral colony in the final stage after bleaching in the sea in Tahiti. The phenomenon is caused by an abnormal increase in water temperature causing the expulsion of micro-symbiotic algae.

However, researchers hold that these periods of mortality are difficult to forecast. Although heat stress is a factor in bleaching, a cascade of complex processes has not yet been elucidated. Recent studies on the state of the New Caledonian barrier reef also show that the bleaching phenomenon is little present there. Seawater temperature anomalies have perhaps not reached critical thresholds.

The impact of acidification on calcareous organisms

The acidification of seawater reduces available calcium, affecting marine organisms with calcareous shells or skeletons and especially corals. But research on the effects of acidification is only just beginning. If it is shown that the responses of corals and calcareous algae to acidification differ according to the species considered, much research will be required to gain better understanding of differences in vulnerability and specific capacity for adaptation.

Laboratory research has shown unexpectedly that several species will not be affected by the acidification of the oceans but will not survive warming of the water. However, global forecasts of the fate of coral reefs subjected to climate change are difficult in the present state of knowledge.

Ocean acidification may also reduce the probability of the survival of certain fishes and especially commercial species such as cod. This extra pressure is making further inroads on fish stocks that are already heavily exploited.

Box 15

Mapping risks to quantify the future vulnerability of atolls

Research on the massive extinctions of biodiversity on atolls in the South Pacific from 1993 to 2012 has made it possible to assess the vulnerability of these ecosystems to future climate change.

Massive deaths of benthic and pelagic species have occurred in several closed Pacific atolls in recent decades and were linked mainly with unusual but local climate conditions.
Scientists of the Entropie and Locean research units and their partners examined eight events of this type from 1993 to 2012 in 11 semi-closed lagoons of isolated atolls in French Polynesia and identified the environmental thresholds (temperature, wind, swell) beyond which the ecosystem was in danger.

The research led to quantifying the vulnerability of the atolls studied according to the thresholds that have triggered fish death periods in the past.

These results led to the mapping of risks used to identify the zones most vulnerable to future variations of temperature, swell and wind.
As the environmental thresholds may well be reached more often in the future as a result of climate change, climate evolution models can also give an idea of the future vulnerability of the systems.

An islet shore platform at Madang (Papua New Guinea).
Under pressure from climate change, environmental pressure and globalisation, the small island states in Oceania are seeking a model of sustainable development to match their specific context.

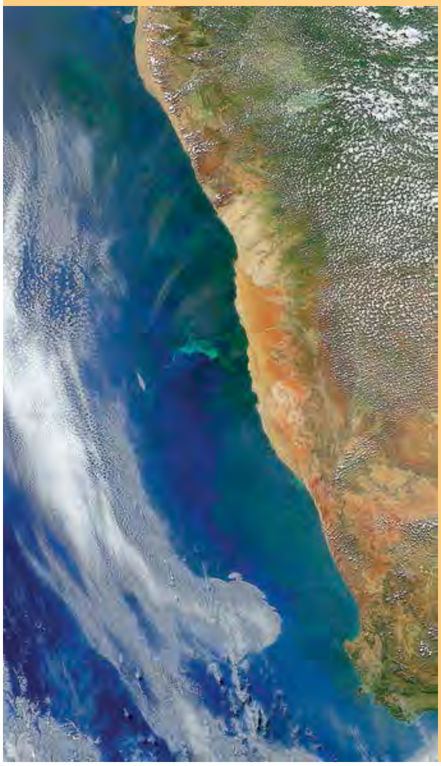
Modelling the effects of climate change on ecosystems

The first global models of the impact of climate change on life in the oceans assess the evolution of fish species distribution according to water temperature. These projections show the shift of species to higher latitudes. Depending on the climatic scenarios used, the tropical zone should see a 15% to 40% decrease in fish volumes in 50 years. More complex models using criteria other than temperature—such as ocean biogeochemical changes—are gradually improving predictions. However, it is difficult to apply these global estimates to local situations. Changes in temperature and acidification are unevenly distributed in the oceans.

Close modelling of marine ecosystems is needed in particular to assess the effects of the interactions between the various components of the environment. IRD has been working for about 15 years on modelling ecosystems to develop generic models that can be used by a broad research community in the South and the North. These models also make it possible to explore and predict the future dynamics of marine ecosystems. This is difficult in terms of model validation and calibration but is essential today to gain understanding of the evolution of the marine environment in a context of global change (Box 16).

Box 16

A virtual laboratory for the evaluation of the impact of climate change on marine ecosystems



Developed by the Marbec unit, the OSMOSE model (*Object-oriented Simulator of Marine ecOSystem Exploitation*) gives a detailed representation of the life cycles of numerous species and their interactions. Growth, predation, reproduction, migration, causes of mortality and other dynamic processes are assigned parameters according to physiological and environmental constraints.

The cold Benguela current flows northwards along the coast of Namibia.

The model can be considered as a virtual laboratory able to evaluate, for example, the impacts related to the fishing of predators or the warming of the oceans. The OSMOSE E2E (*end-to-end*) model was developed in particular to integrate the main components of marine ecosystems, addressing features ranging from the physical, biogeochemical and biological aspects to economic scenarios of fisheries.

The model is used to study the synergic or antagonistic effects of fishing and the environment in various environments, for example upwelling ecosystems (Benguela, Humboldt), temperate ecosystems (Strait of Georgia, Gulf of Lion) and tropical ecosystems (Gulf of Mexico, Sine Saloum delta). For example, the results of simulations of the southern Benguela upwelling ecosystem show that the combined effect of the factors fishing and wind force always leads to a smaller biomass of small pelagic fish than is given by the addition of the separate effects.

The impact on fisheries and world food security

Fishing is our last industrial scale harvesting activity applied to wild resources that is sensitive to environmental fluctuations. And pressure on the resource is increasing as human consumption is growing as a result of population increase and changes in dietary behaviour. Today, fish is the main source of animal protein for a billion people in the world. However, the deep-seated disturbances to marine ecosystems expected in the coming decades will affect fisheries at the world level even more and compromise food security in numerous countries in the South.

Projections of potential global capture in 2055 were performed for about a thousand harvested sea fish and invertebrates. They showed that the warming of the water can lead to a large-scale redistribution of global catch potential, with an average increase of 30% to 70% in high latitudes and a decrease of as much as 40% in the tropics.

Other more recent simulations integrate the biochemical and ecological effects in impact evaluation. The acidification of the oceans and the decrease in oxygen content may reduce potential capture by 20% to 30% in comparison with simulations performed without taking these factors into account. In addition, the changes that affect the phyto-plankton community could reduce capture projections by about 10%.

Seine fishing for *Sardinella aurita* off Joal in Senegal.
The northward movement of sardinellas caused by the warming of seawater is changing fishery charts.

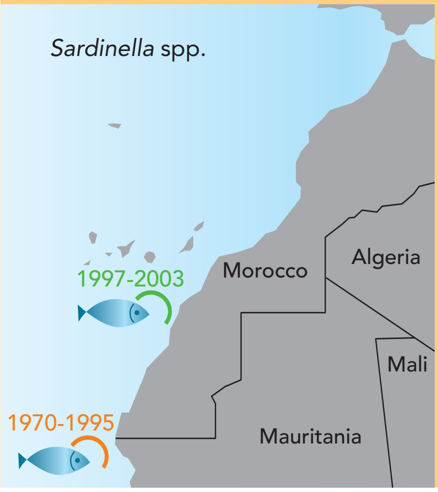
© IRD/V. Turmine

Box 17

Sardinellas are moving northwards along the north-west coast of Africa

Modelling of the distribution of sardinellas according to environmental features confirms the distinct trend for this genus found off the West African coast to migrate northwards. Its passage along the Moroccan coastline makes it a new resource for Moroccan fishing today.

Figure 22.
Evolution of the area of distribution of *Sardinella* spp. in Morocco.
Source: Institut national de recherche halieutique



The Lemar unit is developing a forecasting system combining geographic information system (GIS) techniques and the use of satellite data to model the distribution of marine fish.
The method is based on estimating the existing relations between the effective presence of species in a given place and the corresponding environmental features.
Researchers used global databases to collect records of the presence of as many species as possible in a zone stretching from West Africa to the North-East Atlantic.
They also assembled 30 years of monthly sea surface temperature data and other oceanic and bathymetric parameters.
This information was cross-referenced to construct environmental envelopes for each species.
Each envelope was then projected on series of environmental data (1981 to 2013) to model the potential distribution of the fish studied and to trace the evolution of the northern and/or southern boundary of their distribution zone.

The results show the evolution of the distribution zone of each species in time, with a clear northward migration trend. For example, monitoring the small pelagic *Sardinella* that prefer comparatively cold water shows the appearance of new stock in Moroccan waters north of Cap Blanc, the usual limit of the thermal front.

Northward migration was confirmed by microchemical analysis of **otoliths** of these fish in the Senegal-Mauritania-Morocco zone.

Sardinella, a new resource for Morocco

Whereas the shifting of species is often considered to be a constraint, especially as regards food security, it can also be a source of economic opportunities as has been shown by the scientists of the Prodig unit and their partners at the *Institut national de recherche halieutique* in Morocco.
The expansion of the stock of Senegalese/Mauritanian sardinellas into Moroccan water has resulted in captures totalling some 50,000 tonnes per year in the Dakhla and Laâyoune regions of Morocco.
Some operators in the Moroccan small pelagics sector have profited from this new feature.
They have made agreements with a proportion of the sardine fleet owners to ensure supply of raw material.
They have also modified sardine processing and packing methods to match the physical and organoleptic features of sardinellas.

A shoal of yellowfin tuna in the Indian Ocean.
Fish volumes in the tropics will probably decrease by 15 to 40% over the next 50 years.

The shifting of species has changed the map of fisheries

The decrease in fish stocks is currently changing the map of fisheries and this has direct effects on food security and the global economy. Fisheries products are one of the most traded renewable resources in the world and more than two-thirds of the total fish catch is in fisheries zones in countries in the South. The decrease in catch sizes in this zone will induce the reorganisation of the entire world fish market system and greatly affect the tropics.

IRD, with the Secretariat of the Pacific Community (SPC) and French, Australian and American partners, has studied the response of fish biomass to climate change in the Pacific using the various IPCC scenarios. Modelling showed that the rise in surface water temperature—more marked in the west of the ocean basin—appears to be causing tuna to migrate towards Polynesia in the east. The catch of bonito, in the tuna group and forming 90% of catches, will be strongly affected. The catch zones would thus be moving away from the Melanesian coasts, the Solomon Islands and Papua-New Guinea. The shifting of the fish out of the territorial waters of these countries will be a significant economic loss, especially as the fishing rights paid by the large international fishing operators form a substantial income for these small island states.

In such a changing context, fisheries management must take into account the vulnerability of the species caught more than ever. An ecosystem approach to fisheries resources, in other words an approach capable of integrating environmental factors in the evaluation of fish stocks, is thus becoming a major issue for the prevention of the rapid extinction of species.

Box 18

EuroMarine: from genes to ecosystems in changing oceans

The European marine science network EuroMarine was launched in 2014. With 66 member organisations in 22 countries, the network has been designed to give a say to the entire European marine science community. The initiative followed the experience of three former European excellence networks (Eur-Oceans, Marine Genomics Europe and MarBEF) and scientific management is shared between IRD and the CNRS.

One of the aims of EuroMarine is to promote cutting-edge science on climate change in particular through understanding and modelling marine ecosystems in changing oceans. It supports the identification and development of emerging scientific topics in particular by funding calls for competitive bids.

Increased risks of pollution

A little known effect of climate change is the risk of increased contamination of fish by natural pollutants in upwelling zones. IRD scientists and their partners have demonstrated the natural release of contaminants—especially heavy metals—from deep water to the surface as a result of the intensification of upwelling off the Atlantic coast of Morocco. Metal trace elements such as cadmium then accumulate in the aquatic food chain, in zooplankton, molluscs and fish and then reach the final consumers such as sea mammals, birds and humans. The consequences for human health are all the more worrying as a large proportion of catches are from upwelling zones.

Finally, the movement of fish stocks is one of the most visible results of climate change in live animals. Understanding and anticipating the redistribution of marine species at the global scale as a result of rising water temperature provide important information for fisheries planning and marine conservation.

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