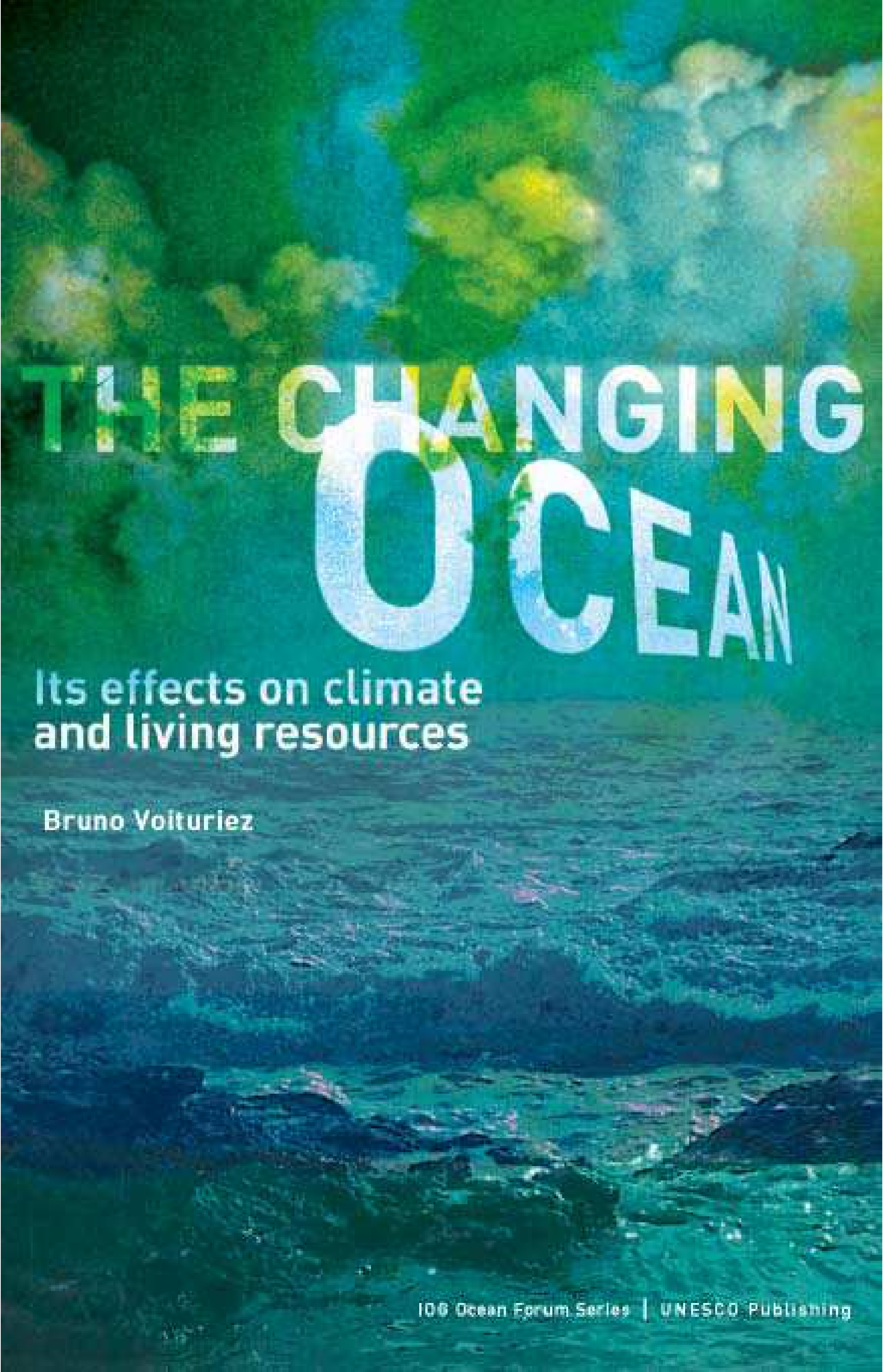

THE CHANGING OCEAN

Its effects on climate and living resources

Bruno Voituriez

IOC Ocean Forum Series | UNESCO Publishing

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Translated from French by Ray C. Griffiths

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Preface

The effect of the climate on living marine resources is a theme that concerns science as well as economics and politics. It is a global subject if ever there was one; its ramifications affect the life of nations and the future of the ocean itself. A great deal of research has been carried out on the links between the climate and fisheries, and today we are able to discriminate, in certain cases, between natural effects and human influences. But we must perfect our method of understanding, follow-up and prediction of the functioning and quantitative development of living marine resources. In this context which is, to say the least, uncertain, it is absolutely necessary to elaborate policies for the protection of marine resources.

The Intergovernmental Oceanographic Commission (IOC) of UNESCO has, since the 1960s, been encouraging the collection and sharing of scientific information and the adoption of an ecosystem approach to management of the marine environment. Notable progress has been made in the construction of the scientific basis for understanding and prediction of climatic phenomena, such as El Niño, and for achieving a clear view of the respective roles of human activities and natural phenomena.

The international network GOOS (Global Ocean Observing System) has been developed in this context in partnership with FAO, WMO, UNEP and other organizations. This global network is charged with gathering, processing and developing information concerning the oceans, for use by governments, industry, researchers and the general public. Co-operation, co-ordination and mutual assistance are the key words in this action which is aimed at giving the various stakeholders the capacity to take good and timely decisions to preserve the environment.

Following the *El Niño: fact and fiction* title in this same series, which analysed the components of this climatic phenomenon, so much talked about but so little understood, Bruno Voituriez here attempts to decipher the currents of this silent world and outlines the advances in the elucidation of its enigmas with each step in the progress in oceanography itself, the junior of the earth sciences. His effort of synthesis and popularization holds a special meaning for UNESCO which tries to go beyond the level of the specialists and give the greatest possible number of people access to information on domains that are so important for the future of the planet.

Patricio A. Bernal
Executive Secretary
Intergovernmental Oceanographic Commission

Understanding the ocean environment

The vital role of ocean behaviour in controlling climate and the distribution and abundance of living resources is well known, but poorly understood.

Much of the science involved is, at first sight, bewilderingly complex. Our imperfect knowledge also means that there is considerable uncertainty in predictions we make about climate or the variability of living resources. Yet, increasingly, we must use such predictions to underpin decision making in areas with vital, and sometimes very large, economic, social and safety implications.

Explaining this complex science to an audience outside of those with highly specialized scientific training and knowledge is essential. Decision makers must have an understanding of the scientific basis supporting their decisions. Non-specialists must have access to specialist knowledge conveyed in an understandable way if they are to make informed judgements.

As a leading worldwide provider of oceanographic and meteorological systems and services Fugro GEOS is engaged in providing the tools to monitor and predict the marine environment, and to link the resulting understanding of ocean processes to helping solve practical maritime engineering and marine environmental protection problems.

Our work requires that we effectively communicate oceanographic and meteorological knowledge to non-specialists. We are therefore very pleased to be associated with a book that so admirably achieves this objective.

Dr Ralph Rayner
Managing Director
Fugro Global Environmental and Ocean Sciences Limited[1]

Observing and modeling the ocean environment

The role of the oceans in climate is a critical issue facing us today, yet we are limited in our ability to collect the global observations needed to address this issue. Recent advances in both satellite and *in situ* observing systems, such as the Tropical Ocean Global Atmosphere Program/Tropical Atmosphere Ocean project array and Argo profiling floats, are contributing to our emerging capability to describe, understand and predict variability in the physical climate system. These advances and observations are helping to improve the quality of our climate models.

However, one of our greatest challenges is to understand how climate interacts with the planet's ecosystems. We have witnessed impacts of El Niño on fisheries and coral reefs. Decadal climate regime shifts in the North Pacific continue to have profound effects on the structure and productivity of ecosystems in the Gulf of Alaska and Bering Sea. New observing systems will help us to improve our understanding and management of our natural resources; especially for marine and coupled climate-ecosystem models that predict the impact of climate change on ecosystems and how ecosystem feedbacks influence climate variability.

Given its vital importance to the mission of the National Oceanic and Atmospheric Administration and the interests of the international community, we are pleased to sponsor the translation of this important book, and trust that it will contribute to a broader understanding of the oceans and climate change among the public at large.

Conrad C. Lautenbacher, Jr.
Vice Admiral, U.S. Navy (Ret.)
Under Secretary of Commerce
for Oceans and Atmosphere

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1 A brief history of oceanography

OCEANO-GEOGRAPHY

Wishing to give to the study of the oceans the aura of nobility they thought it lacked, the oceanographers of France, in the civil unrest of May 1968 which stimulated many minds the world over, wanted to become oceanologists. They wanted to show thereby that they had an ambition to understand the ocean and not simply to describe it. By analogy with geology, which can be defined as dynamical geography and which, on the spatial scales of geography, adds a temporal dimension, they conceived oceanology as signifying *dynamical oceanography* – an adolescent identity crisis somewhat late in coming which illustrates perhaps the late arrival of this science in France: the first French book on physical oceanography appeared only in 1965. In 1968, this semantic quarrel – *oceanography* for English speakers or *okeanologia* for Russian speakers – hardly made much sense any more, but the anecdote reveals a certain complex of the oceanographers of that time, when their science was the baby of the so-called geosciences or earth sciences. Moreover, it was a science born of meteorology, which itself had had great difficulty in being accepted as a science in the nineteenth century. Auguste Comte, a French philosopher for whom scientific positivism was a religion (he wrote *Catéchisme positiviste* in 1852), had such a faith in science that he thought that, like the movements of celestial bodies, it obeyed Newton's law of gravitation, and that social phenomena were also governed by similar laws. For Comte, no one in the universe could escape the laws of science. It was proof of great optimism or of great naivety to think that societies could allow themselves to be trapped in such a determinist carapace. For Comte, if science brings order to the universe, it follows that it has to show the way and be orderly itself. Hence his concern with a logical classification of the sciences and with their development, which, starting with mathematics, leads naturally to sociology by way of astronomy, physics, chemistry and biology. Meteorology, which, if one compares the movements of the atmosphere with those of the planets, paints *a priori* a picture of great disarray, could only be included in such a standardized classification with great difficulty; so it was excluded because of its indiscipline, so to speak! One may deduce that, for Comte, meteorology appeared to be an even softer science than sociology! A hundred years later, meteorology would get its revenge and put an end to the tyranny of the law, in Comte's view, by becoming the archetype of non-linear dynamical systems called chaotic and popularized by the meteorologist Edward Lorenz and his famous 'butterfly' effect.

And the ocean? Its study was at that time still exclusively in the domain of geography. From the Greek sailor Pytheas, author of *Description of the Ocean,* who explored the North Atlantic right up to the Arctic in the fourth century BC, to the American Matthew Fontaine Maury and his *Physical Geography of the Sea* (1855), knowledge of the ocean followed the same path: that of explorers and sailors. Then, properly speaking, it was a question of oceano-geography. Their objectives were not always disinterested: it was also a search for new riches and commercial outlets, establishment of trading posts and, if necessary, conquest and colonization, as well as 'spreading the faith'; and – it cannot be denied – scientific curiosity. The ocean was, however, above all a power game; it was the business of sailors and navigators in the service of powers concerned with imposing their power and their sovereignty. The story of Henry the Navigator, son of King John I of Portugal, illustrates very well this mixture of styles which, bringing together in the same caravel the sailor, the soldier, the priest, the trader and, sometimes, the scholar, ensured the success of the expeditions and the conquest of the oceans by the Europeans, starting in the fifteenth century. A highly cultured mind and undoubtedly curious, but also 'Grand Master of the Order of Christ', concerned with combatting Islam and with circumventing it in order to make contact with the mysterious realm of Prester John in East Africa, in the first half of the fifteenth century Henry the Navigator organized the first exploration of the coasts of West Africa, down to the Gulf of Guinea. Supported by the king and financed by his

Order, he had nevertheless to make a profit from his undertaking, but trade and the necessity of trading posts to achieve this objective overcame the thirst for discovery. To see his entreprise through, he assembled at Sagres, on Cape Saint Vincent at the southern tip of Portugal, 'all the elements of a veritable research institute', according to the American historian Daniel Boorstin in *The Discoverers*: 'He brought together books and charts, vessel captains, pilots and sailors; cartographers and instrument makers; shipbuilders, carpenters and other artisans, to organize the voyages, examine the results obtained, launch ever far-reaching expeditions.' Was this the first oceanographic institution in the Western world? It would perhaps be excessive to assert it, but it was certainly at the same time a centre of innovation, of training in navigation and of capitalization of knowledge. A boost for the Europeans, from the Golden Age of Discovery with caravels designed and built in the port right next to Lagos.

The knowledge thus gained from the 'geography of the oceans' during the expeditions undertaken by Portugal and, subsequently, other European countries, was not the most widely shared in the world. Apart from the Vatican which, if it won souls by associating itself with the conquests of the European monarchies, lost on the other hand its power over men in Europe as a result of the protestant Reform and the development of scientific thought, both of which freed men from its tutelage. No power could prevent the diffusion of knowledge, the source of emulation amongst European scientists. Except in the domain of oceanography at that time: the geography of the oceans and the techniques of navigation were, quite rightly, considered as strategic, and oceanography could only be nationalistic. And so it remained to a very large extent up to the Second World War, in the mid-twentieth century, when the nature of the stakes changed and the progress of knowledge called for international co-operation, as was the case of meteorology 100 years earlier.

This oceano-geography was principally concerned with the ocean surface and its movements. For obvious reasons: the ocean is opaque to the human eye which is limited to admiring the changing reflections of the sky from its surface, and in any case to sail anywhere it was not really necessary to know what went on beneath a ship's draught. On the other hand, it was necessary to know sufficiently well the sea bed and its shoals to avoid a dramatic end to a sea voyage. Hence the interest in the third dimension (the vertical) of the ocean, which initially was only of concern to navigation and vessel safety: the container (the bottom) more than the content (the water). The overriding object was to have reliable bathymetric charts of coastal areas, so as to reduce as far as possible the risk of sinking. One therefore spoke of hydrography rather than oceanography and, for strategic reasons, the services in charge of it were generally attached to admiralties. It was still a question of geography, and interest in the properties of the oceanic fluid itself remained weak; this fluid was, after all, only salt water. Maury's *Physical Geography of the Sea,* published in 1855, mentioned above, closed this long chapter of oceano-geography. Maury was a naval officer, but owing to an accident while on duty which rendered him inapt for service at sea, he was made head of the US Navy's Depot of Charts and Instruments which later became the US Naval Observatory and Hydrographic Office. He was, very probably, the first to have the idea of compiling the data from ships' logbooks: wind strength and direction, sea state, cloud cover, temperature, atmospheric pressure, with a view to publishing wind and current charts (forerunners of the Pilot Charts) which proved very helpful for navigation. He also published the first attempt at a bathymetric chart of the North Atlantic Ocean for the purpose of laying submarine telegraph cables between the United States and Europe. He was also the initiator of marine meteorology and organized in Brussels in 1853, under the chairmanship of the Belgian mathematician Adolphe Quetelet, the first international meteorology conference. Ten countries took part and laid the foundation for an organization for the collection of meteorological data aboard ships. While a pioneer in this field, he was also often present as a founder of modern oceanography, particularly American. Yet he was a poor oceanographer and his book, despite its success with the general public, illustrated – to return to our initial idea – to what extent a good oceano-geographer could be a questionable oceanographer or oceanologist. In his book, Maury, who was a very religious man, seemed to be more concerned with exalting the wisdom and greatness of the designs of the Creator than with writing a rational text, and often referred to biblical texts for the purpose of explanation. This religious tone bothered the Europeans more than it did his compatriots who saw in his work rather a guarantee of seriousness. A pious work, perhaps, but certainly not a scientific one.

THE BIRTH OF OCEANOGRAPHY: THE MAJOR NATIONAL SCIENTIFIC EXPEDITIONS

Oceanography was born only when the ocean became an object of science; that is, when an interest emerged in the water and what it contained, and not just in the surface currents and the sea-bed topography for purposes of navigation. Scientific curiosity was not necessarily lacking, but it was up against two snags: the technical difficulty of taking samples and making subsurface measurements; and the need to have a vessel available. These difficulties ensured that oceanography was tied to the defence of national interests, as only governments and, most of the time, their admiralties, were in a position to provide such vessels.

Submarine telegraph cables play an important role in this story. The first one was laid in 1851 between France and the United Kingdom, and the first transatlantic cable dates from 1866. This new technological enterprise made people aware of the fact that, to ensure the success of the cable-laying, it was necessary to know the sea bed much better (topography, sediments, temperatures, currents). Those involved, like the collectors of living species, were helpers in the scientific search for truth, as will be seen later. They were very much involved in the beginning of the exploration of the deep ocean, symbolically marking the birth of oceanography, in which the British *Challenger* expedition was doubtless the best example.

Between December 1872 and May 1876, the *Challenger* plied the Atlantic, Pacific and Indian Oceans to study them and their depths. It was the first time that an expedition was dedicated exclusively to the ocean for its own sake. During this expedition, organized on the initiative of the Royal Society in co-operation with the British admiralty, which commissioned the vessel, the *Challenger* covered nearly 70,000 nautical miles (about 130,000 km), carried out 362 hydrographic stations, 492 bottom soundings and 133 dredges. The British decision to finance such an expedition was a result of questioning existing ideas of the ocean depths and the life they contained, at a time when the laying of submarine cables was taking place. It also corresponded to the British determination to affirm their supremacy in the ocean domain in the face of a foreseen challenge; one of the arguments advanced by Sir Charles Wyvill Thomson, the chief scientist of the expedition, was that Germany, Sweden and the United States were also preparing expeditions to explore the deep ocean and that the British Government should react to this foreign competition. The *Challenger* expedition was, for Victorian England, no doubt comparable to what was a century later the American conquest of the Moon under the Apollo programme in the face of competition from the Soviet Union. It was an oceanographic success.

Because of the lack of observations, practically nothing was known about the sea bed and the properties of the deep layers of the ocean. We undoubtedly knew more about the Moon's surface at the start of the

Apollo programme than we did about the deep ocean when the *Challenger* set off in December 1872. It was known, thanks to some rather imprecise measurements, that the temperature diminished with increasing depth and that the measured temperature could not be less than 4 °C, which corresponded to the maximum density of water, overlooking the fact that, under the effect of pressure, hence depth, water at a temperature of less than 4 °C could be denser than water at 4 °C at atmospheric pressure. In fact, the *Challenger* measured temperatures as low as 0.2 °C in deep water near Fernando de Noronha in the equatorial Atlantic Ocean.

It was known that sea water was salty, and the French chemist Antoine Lavoisier, at the end of the eighteenth century, had shown that this saltiness was due mostly to sodium chloride. From samples taken by the *Challenger,* William Dittmar, going much further with the chemical analysis, showed that 99% of the salts dissolved in sea water were of seven principal elements: sodium, calcium, magnesium, potassium, chlorine, bromine and sulphur, and that their relative abundances were constant. This was a fundamental result, as it was sufficient to measure any one of these abundances in order to find all the others and therefore the overall salinity and, finally, the density of a sample of sea water. The Dane Martin Knudsen in 1901 was therefore able to establish an equation of state of sea water which would allow going directly from the measurement of chlorine (chlorinity), the most abundant element and the easiest to measure chemically, to the density. This method became used universally to measure sea-water density – an essential parameter in ocean dynamics – until the 1960s, when it was replaced by direct measurement of the conductivity of a water sample without any sample manipulation.

The scientific crew of the *Challenger* comprised mostly biologists concerned to discover all they could about life in the deep ocean. Some years prior to the expedition, the British biologist Edward Forbes had put forward the hypothesis that, in the ocean, there were no living organisms at depths exceeding 500 m, the so-called azoic hypothesis. His reasoning was simple: listing the species collected by dredges on bottoms no deeper than a few hundred metres, he had observed that the number of species and individuals diminished more or less linearly with increasing depth. By extrapolation, he deduced that beyond a certain depth, which he put at 500 m, there should be no more life. A few previous isolated observations had already shown that life had been found well below a depth of 500 m and, in 1861, a submarine telegraph cable laid between Sardinia and North Africa at a depth of 1,500 m had been raised covered with invertebrates, thus throwing serious doubt on Forbes' azoic hypothesis. Nevertheless, a doubt remained as long as the greatest depths had not been reached. The evidence finally had to be faced: life was present everywhere, from the surface to the greatest depths yet sounded (8,000 m in the Marianas Trench in the Philippines); the deep ocean was not a lifeless fossil ocean.

Another scientific enigma found its epilogue with the *Challenger*: that of *Bathybius,* which was occupying many minds when Charles Darwin, by publishing his masterpiece *On the Origin of Species*, in 1859, laid down his theory of evolution. At this time, while preparing to lay the first transatlantic telegraph cable, H.M.S. *Cyclops* undertook a campaign of soundings and dredging in the Atlantic. It brought back a gelatinous substance which the very enthusiastic promoter of Darwinian ideas, the English biologist Thomas Huxley, identified as a very primitive form of life which he called *Bathybius*: a kind of protoplasm born of the primordial soup that, in his view, constituted the mud of the sea bed. This discovery came at just the right time to support the idea of the Darwinians, if not of Darwin himself, of the continuity of the cosmic evolution of the mineral world towards organic matter and life itself. With the *Bathybius* came the key to the origin of life. Exactly as, 100 years later, in 1953, the experiment of Harold Urey and Stanley Miller who synthesized organic matter in the laboratory from a reconstitution of what was thought to be the composition of the primitive Earth's atmosphere, 'verified' the hypothesis proposed by J. B. S. Haldane and A. I. Oparin in 1920. The idea was tempting and it is easy to understand the excitement it produced in scientific circles. John Buchanan, the chemist of the *Challenger,* tore it to pieces by showing that this substance was nothing more than a precipitate of calcium sulphate produced by the mixing of sea water with the alcohol used for the preservation of the samples.

A decisive step had been taken which dissipated the mystery of the deep ocean. Obviously, a few hundred hydrographic stations, soundings and dredges would now seem small beer on the scale of the world ocean and they were certainly insufficient to describe the ocean completely. The distribution of these stations over the whole ocean nevertheless compensated for their low spatial density. It had become clear that life was present everywhere in the ocean from the surface to the bottom and that the deep layers, with their heterogeneous temperature and salinity, were not inert. The deep currents had never been measured directly, but it was quite clear that the differences in temperature measured from one place to another in the deep layers could only be explained by the movement of water masses. Only the details were missing; that is, the number of measurements and observations in the three dimensions of the whole ocean had to be greatly increased.

The race was on and the number of expeditions was about to increase. The competition was often fed by ulterior political motives. If the ships used on these expeditions were not actually fighting ships, they were often a clear expression of colonial power. And it is possible in the wake of the preceding era of major explorations – the so-called oceano-geographic expeditions – to propose a purely political reading of the history of the oceanography of this period. This is what the German oceanographer Matthias Tomczak did, not without good arguments, in a review of the major oceanographic expeditions since that of the *Challenger* presented at the Third International Oceanographic Congress at Woods Hole (Massachusetts) in 1980. The United Kingdom, the leading colonial power, certainly did not need to hide behind the *Challenger* expedition to express its territorial appetite, but the brilliance of such an unprecedented undertaking allowed it to assert its mastery of the seas. The other powers could not allow themselves the same luxury, except perhaps Monaco on a much smaller scale; Prince Albert of Monaco, between 1885 and 1914, was able to commission his own ships to explore the seas without any spirit of conquest. So, very often, the major marine powers could in their expeditions combine scientific exploration and colonial politics, very much to the advantage of oceanography which, without this nationalistic motivation, would otherwise never have acquired the necessary vessel resources. Unfortunately, this excluded international co-operation which, given the immensity of the ocean, would understandably also eventually prove itself indispensable. Nevertheless, it was necessary to wait till 1957–58 and the International Geophysical Year (IGY), which marked a revolution in the scientific study of the planet.

INTERNATIONAL CO-OPERATION: FROM THE INTERNATIONAL GEOPHYSICAL YEAR TO THE WORLD CLIMATE RESEARCH PROGRAMME AND THE INTERNATIONAL GEOSPHERE–BIOSPHERE PROGRAMME

The IGY, for eighteen months from July 1957 to December 1958, had as its objective an overall study of the Earth in all its components: solid earth, atmosphere, ocean, cryosphere. The date was chosen to correspond to a period of maximum solar activity. Initially conceived as the International Polar Year, following those of 1882–83 and 1932–33, it still gave pride of place to the polar regions, especially the Antarctic. Some seventy countries participated in it. The IGY benefited from the technological advances of the Second World War: rockets for the exploration of the upper atmosphere; probes for the exploration of the deep ocean; and satellites. The first satellites, *Sputnik* (Russian) launched in October 1957 and *Explorer* (American) launched in January 1958, were not put into orbit to meet the needs of the IGY (it was a time of intense Russian–American competition: the Cold War), but, by happy coincidence, the first scientific discovery of the space era was due to them: the discovery of the Van Allen radiation belt in the outer atmosphere (several hundred kilometres). We also owe to the IGY proof of the existence of the major mid-ocean ridges which encompass the globe and which would later be explained by plate tectonics.

The IGY was also an opportunity to set up observatories all over the planet, notably the famous station that the American Charles D. Keeling established on Mona Loa in Hawaii to measure the carbon dioxide in the atmosphere, which could detect and monitor the spectacular increase in the concentration of this greenhouse gas. On the political level, it inspired the Antarctic Treaty to preserve this continent from any attempt to use it for military purposes or other forms of exploitation. The Treaty was signed by twelve states on 1 December 1959. For oceanography, this marked its official entry into the geophysical sciences club. For the first time, independent national expeditions using one ship were replaced by a vast concerted multiship programme, co-ordinated and synchronized internationally.

This effort at co-ordination was particularly marked in the Atlantic, where five vessels simultaneously undertook some twenty transatlantic sections from 48° N to 48° S. This effort was also applied to the North Pacific and the intertropical Pacific Ocean. There was one particularly notable result: the discovery of the amplitude of the El Niño phenomenon. Whereas until then it had been perceived as a phenomenon confined to the coast of Peru, it was now seen as a major oceanographic and climatic perturbation on the scale of the whole Pacific Ocean. The International Geophysical Year was also the prelude to the creation in 1960 of the Intergovernmental Oceanographic Commission (IOC), within UNESCO; the IOC was where international concertation on the setting-up of international oceanographic programmes would take place. Such programmes would be developed to face the challenge of, *inter alia*, climate prediction and to answer the questions posed by the increasing concentration of greenhouse gases in the atmosphere. This aim was pursued through two global programmes which extended well beyond oceanography alone: the World Climate Research Programme (WCRP) and the International Geosphere–Biosphere Programme (IGBP). The WCRP is entirely dedicated to the physical system, the climate system, with a view to understanding and predicting it. The IGBP seeks to understand the system Earth, with a view to evaluating the impact that any global climate change might have on it. Besides the physical aspects, it is concerned with the ensemble of biogeochemical processes at work, and the functioning and dynamics of ecosystems. These programmes now mobilize most of the world's oceanographic research capacity. The panorama would not be complete without mentioning the main agent of the changes now occurring and who may be tomorrow their main victim: the human race. There is a special international programme: the Human Dimension of Global Environmental Change.

FROM OCEANOGRAPHY TO OCEANOLOGY: DYNAMICAL OCEANOGRAPHY

From the description of the physical, chemical and biological properties of the ocean initiated by the *Challenger* to a full understanding of it, a further big step had to be taken: to know the movements that control all the ocean's properties and determine their distribution. As navigation developed, sailors quickly got to know and exploit the surface currents. Thus, the Spanish explorer Juan Ponce de León, the 'discoverer' of Florida, was also the discoverer of the Gulf Stream, for which Benjamin Franklin produced the first chart in 1777 from information provided by ships plying between the British Isles and the American colonies. This work was later systematized by Maury in the Atlantic. But what was going on beneath the surface? To answer that question, the only data available were temperature measurements of the deep layers.

The first of such measurements were made, apparently, in 1751 in the Atlantic by Henry Ellis, captain of a British slave ship, using only rudimentary equipment. They afforded proof that, even in tropical regions, where the surface temperature reached 29 °C, the water temperature decreased steadily and markedly with increasing depth. The source of this cold water had therefore to be found. Naturally, the coldest water was in the polar regions. So, in 1791, the Anglo-American physicist Benjamin Rumford suggested that in these regions the water that was cooled at the surface would become denser than the underlying water, hence would sink and spread out at greater depths. The Frenchman François Arago went even further towards closing the loop: in his view, the spreading of cold water at depth from the polar regions towards the equator must be compensated at the surface by an inverse movement, from the equator towards the poles, and that the Gulf Stream is a tangible demonstration of that hypothesis. The idea was conceptually exact but would evidently become more complex as more and more temperature measurements were made and as they became more and more precise thanks to the use of, first, minimum thermometers, then of reversing thermometers which allowed rapid measurements to less than a hundredth of a degree in accuracy. The temperature distribution in the deep layers showed that the deep currents could not be reduced simply to the simple loops between the poles and the equator, as proposed by Arago, but followed far more tortuous paths.

The characterization of the deep layers by their properties (temperature, salinity) can, unfortunately, only give a qualitative image of oceanic circulation. The descriptive aspect still prevailed over the quantitative, hence the dynamical, aspect. The idea that came to mind immediately was that of measuring the currents themselves. The first such measurements were made in 1885 by the American John Pillsbury in the Gulf Stream, for obvious reasons; this current, with its unique characteristics, was truly a gift of God for understanding ocean dynamics and for testing methods of measurement and the validity of numerical models of oceanic circulation. The measurements were made from a ship at anchor during several months. The 'currentmeters' were, and still are in fact, anemometers (used for measuring wind speed and direction) transposed to the marine environment: the drift of the instrument is oriented in the direction of the current; it has a compass that records this direction and a rotor whose number of revolutions increases with increasing current speed. It is comparatively easy to measure wind speed on land, but it is another matter to measure a current from so unsteady a platform as a vessel at sea, even an anchored one, as was the case of Pillsbury. Therefore, the rather unreliable current measurements did not contribute much to the birth of dynamical oceanography. The Norwegian Harald U. Sverdrup, one of the fathers of dynamical oceanography, who was, with Martin Johnson and Richard Fleming, author of the first complete treatise of oceanography, *The Oceans, their Physics, Chemistry and General Biology,* published in 1942, said that the number of currentmeters exceeded the number of useful measurements. To obtain good current measurements it was necessary to operate from the only available stable platform: the ocean floor; and to deploy the currentmeters along cables laid on the ocean floor. This was an onerous and complex technology that was only successfully applied from the 1960s onwards. The development of techniques of satellite observation, global positioning and data transmission would lead later, as we shall see, to the deployment, at the sea surface and at depth, of thousands of floats; the movements of these floats by the ocean currents can be tracked with precision. This is a new oceanographic revolution opening the way to a kind of oceanography that would be as operational as meteorology now is.

As may be seen, the experimental approach by direct measurement of the oceanic circulation is recent. So, fortunately, such a long wait was not necessary to make progress in understanding ocean dynamics. The inadequacy of measurements is often productive when it stimulates the imagination, thought and theory. An ideal set of data or observations is rarely available for the understanding of a natural phenomenon. It is tempting and often intellectually more comfortable to be perpetually chasing 'missing' data that would explain everything, rather than to make the effort to integrate data and knowledge already acquired into a conceptually or theoretically coherent system. The Scandinavians have made such an effort; their oceanographic research was perhaps more disinterested or, at least, free of any of the colonial preoccupations that drove other European nations to outbid each other in the field. Two examples illustrate this idea: Ekman transport and the geostrophic method.

THE *FRAM* AND DRIFTING ICE IN THE ARCTIC

The Norwegian Fridtjof Nansen (who was the first person to cross the Greenland ice cap from east to west, in 1888, and was also, in 1922, a Nobel Peace prizewinner for his work on behalf of refugees at the League of Nations) noticed that the Arctic ice floe drifted from Siberia towards Spitzbergen. To study this drift and – why not? – thus reach the North Pole, he had a ship, the *Fram,* specially designed and built to allow itself to be trapped in the ice floe and drift with it. During this memorable expedition, which was a success, even if it did not reach the North Pole, Nansen observed that the drift of the ice, hence the ocean current, did not follow the wind direction, as common sense would suggest, but was at an angle of about 45° to it. Nansen put the question to the Norwegian physicist and meteorologist Vilhelm Bjerknes, who can be considered, based on his own work or that of his disciples, as the founder of ocean dynamics. He passed Nansen's problem to the young Swede Walfrid Ekman who published the answer in 1902, after determining the equilibrium between the surface-wind drag and the Coriolis force due to the Earth's rotation. It was the first dynamical theory of the generation of currents by the wind (see Chapter 2).

THE GEOSTROPHIC METHOD

Bjerknes, again, established in 1898 a method called geostrophic (see Chapter 2) for calculating the wind in different layers of the atmosphere using simply the distribution of atmospheric pressure. The atmosphere and the ocean are both fluids. They have completely different characteristics, notably in their viscosity, so they operate on quite different time- and space-scales. Even so, they are fundamentally subject to the same dynamical laws. It was therefore logical to think that the method developed by Bjerknes for the atmosphere could be adapted to the ocean. This is what the Norwegians Björn Helland-Hansen and J. W. Sandström did successfully in 1909. With this method, ocean currents can be derived from the distribution of water density, which can be easily calculated from simple measurements of temperature and salinity. The validity of the method was tested by the German Georg Wüst in 1924; he compared the measurements of Pillsbury in the Gulf Stream with the current calculated by the geostrophic method, based on numerous measurements of temperature and salinity made in the Gulf Stream. The method, as we shall see later, rests on some simplifying hypotheses and is unable to account for variability of currents, but it provided a quantitative picture that did not require direct current measurements.

Thus was dynamical oceanography born, and without which it would not be possible to speak of oceanology. In effect, ocean dynamics control the distribution of the physical and chemical characteristics of the ocean hence, all together, the evolution and variability of the climate and therefore of the biological production of the oceans. Humanity does not live in the ocean and, except in special structures, will never live there, notwithstanding the undoubtedly worthy but illusory effort of some divers who would rival the fish. Human beings are naturally more sensitive to the variability of the atmosphere in which they live: we feel all its caprices directly through the senses and in real time. Of the ocean, we have involuntarily only a superficial knowledge, in the proper meaning of the term, when sailing. We do not perceive that 'upstream' it is largely the ocean and its dynamics, relayed by the atmosphere, that determine the rainfall and the fine weather and the more or less high fertility of marine ecosystems, hence the abundance of exploitable resources.

It is this essential role of ocean dynamics that this book seeks to explain and illustrate in order to facilitate a clear understanding of what is at stake and to create an awareness of the necessity of quickly establishing operational observing systems and the modelling of ocean dynamics, like those that have existed for a long time for the purpose of weather forecasting.

2 Driving forces of the ocean currents

The simple answer to the question ‘What causes ocean currents?’ is: ‘The energy received from the Sun and the rotation of the Earth.’

SOLAR ENERGY

Motion supposes a source of energy. On Earth, the almost exclusive source of energy is the Sun. The energy it emits is highly unequally distributed on the terrestrial surface: it is lowest in the polar regions and highest at the equator. And, because of the inclination of the Earth’s axis of rotation relative to its plane of rotation around the Sun, the energy received at any given point on Earth varies seasonally. It is this differential distribution, in space and in time, that sets the atmosphere and the ocean in motion. This is like central heating which starts from the principle, known for hundreds of years and applied by the Romans, that, in the gravitational field, a heated hence less dense fluid will have a tendency to rise, whereas inversely a cooled fluid can only sink. This is natural convection. So the boiler placed in the basement of a building is enough to supply all the radiators: the hot water in the circuit rises, but also becomes progressively cooler, attaining its lowest temperature at the highest point of the circuit, from which it can only sink under gravity and return to the boiler to replace the lost calories and start the loop once more. To speed up the thermal exchanges and to improve the circuit’s effectiveness, the system can be stimulated by means of an accelerator; this is known as forced circulation. Hot-air balloons, really bubbles of hot air rising in a cooler environment, also illustrate this principle. And this is the way the planetary heat machine works. But, in contrast to central heating, the planetary machine for the distribution of solar energy operates with two different fluids – the atmosphere and the ocean – that continually interact with each other, both obeying, overall, the same laws of dynamics, but with quite different physical properties. In the atmosphere, generally speaking, the hot air rises at the equator and the cold air descends in the polar regions, priming the atmospheric pump that transports the heat from the equator towards the poles. Symmetrically, the oceanic pump is primed by the sinking of ocean surface water cooled in the polar regions and which, at depth, returns towards the equator. This is known as the thermohaline circulation.

EARTH'S ROTATION AND CORIOLIS FORCE

Everyone can see at any time that the movements of the atmosphere, no more than those of the ocean, are not exclusively in a north–south direction from the poles towards the equator or reciprocally, as the preceding paragraph implies. The idea is complicated by the Earth's rotation around its own axis, which is manifested as a force acting on any body in motion on the Earth. Nothing, however, makes our senses aware of this rotation which nevertheless carries us along at 1,700 km an hour. When we move about, even by running, we feel no pernicious force dragging us to our right, in the northern hemisphere, or to our left, in the southern hemisphere. And yet, though undetectable at this scale, such a force exists. Its existence was shown at the time when the Earth's rotation around its own axis was demonstrated experimentally. Although Nicolaus Copernicus published in 1542 his conception of a system in which the Earth was a simple spinning top orbiting around the Sun, we had to wait till 1851 for an experimental verification of the Earth's rotation around its own axis. This experiment was carried out by Léon Foucault in the Pantheon in Paris. From the dome of the Pantheon, he suspended a 28 kg pendulum from a wire 67 m long, and set it in motion. He noticed that the plane of oscillation of the pendulum, to which a stylet was attached to mark the pendulum's trajectory across a bed of sand, traced a complete clockwise circle in thirty-two hours. In reality, it is the pendulum's plane that is fixed, relative to the stars, and it is the Earth that turns around the pendulum; but with the terrestrial reference with which we are familiar, it seems as if a force pushes the plane of the pendulum to the right. This is the Coriolis force that operates on any body in motion on a rotating solid. It is directed to the right of the motion in the northern hemisphere and to the left of it in the southern hemisphere. It is strongest at the poles, decreases with increasing latitude and is zero at the equator. It is the force that, applied to the atmosphere and to the ocean, makes their movements non-linear, but always in gyres of various sizes called anticyclones, depressions, cyclones, and so on.

OCEAN–ATMOSPHERE INTERACTION

The atmosphere and the ocean, once set in motion in this way, do not continue independently; they continually exchange energy, mechanically and thermodynamically, which affects their respective motions: they are said to form a coupled system.

MECHANICAL ENERGY EXCHANGE: DIALOGUE BETWEEN WIND AND SEA, EKMAN'S THEORY

The wind does not limit itself to just forming waves on the sea surface; it is a driver of ocean surface currents. If we compare a map of oceanic surface currents with a map of the prevailing winds, we find an excellent correspondence: the distribution of the major ocean currents is quite a good image of global atmospheric circulation. Thus, the trade winds that blow regularly from east to west in the subtropics, much to the satisfaction of sailors, drive the North and the South Equatorial Currents. And, in the temperate subpolar regions, corresponding to the dominant west winds, there is a drift (wind-driven) current that extends eastwards as the warm Gulf Stream in the Atlantic Ocean and as the warm Kuroshio (Japan Current) in the North Pacific Ocean (figure 1). Yet, as we have seen, Nansen had been surprised to find that sea ice did not flow exactly before the wind, but at an angle to the wind direction; this angle could be as much as 45°.

Ekman formulated an explanatory theory based on the hypothesis that the strength of the wind drag at the sea surface was in equilibrium with the Coriolis force, taking into account the viscosity of sea water; that is, the friction between the layers of surface water. He demonstrated that, in this simple system, the surface current flowed at an angle of 45° to the wind direction, that this angle increased with depth in the ocean, so could be conceived as a sort of spiral, known as Ekman's spiral, and finally, that the intensity of the current diminished exponentially with increasing depth, thus defining the so-called Ekman layer a few tens of metres thick limiting the surface-water layer subject to wind action. The Ekman theory applies on all scales and we shall see later the fundamental role it plays in the dynamics of marine ecosystems.

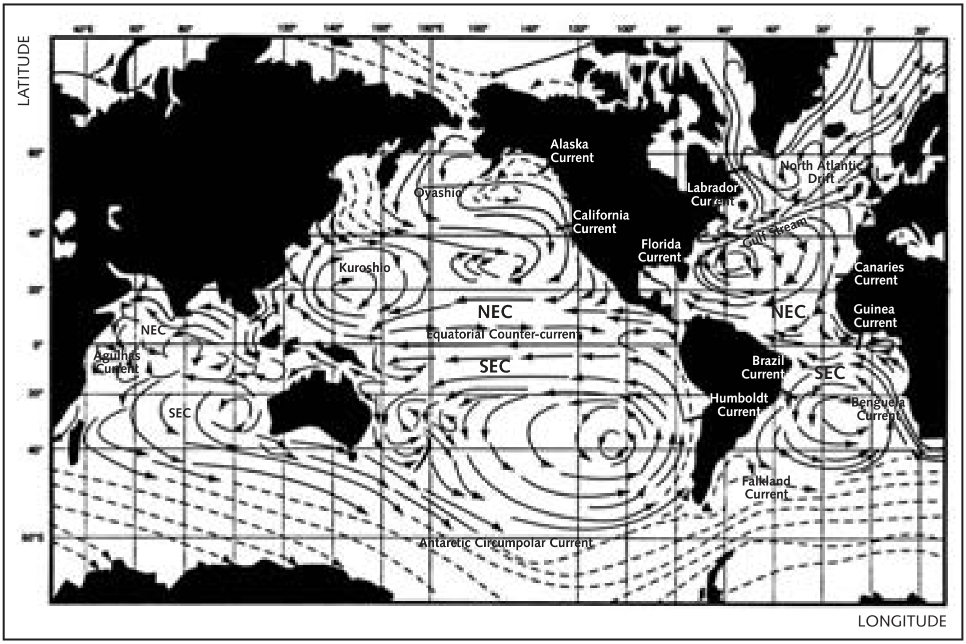


Figure 1
Map showing the principal ocean surface currents.
NEC: North Equatorial Current
SEC: South Equatorial Current
Source: Ocean Circulation/*The Open University, Pergamon Press, 1989.*

THERMODYNAMICAL EXCHANGES, DRIVERS OF THE THERMOHALINE CIRCULATION

The energy received from the Sun by the Earth is distributed in the various compartments of the system: the atmosphere, the ocean, the continental surfaces and the cryosphere (essentially the polar ice caps of the Antarctic and Greenland, and the ice floes). These ‘reservoirs’ have quite different capacities for the absorption of solar radiation, and some indications of the Earth’s radiation balance are required in order to understand clearly how the two fluids of the planetary heat machine, the atmosphere and the ocean, behave in redistributing this energy that is so unevenly distributed by latitude. On average, the Earth receives from the Sun approximately 340 W/m^2 (watts per square metre) of energy. A third of this is reflected directly back into space by the atmosphere and is thus lost to the climate system. The atmosphere, although rather transparent to the solar radiation, only absorbs 20%. The remaining 50% reaches the

Earth's surface where it is absorbed: 32% by the ocean and 18% by the continents. So the ocean is the principal receiver of solar energy. The ocean, like the continents, returns a part of this absorbed energy to the atmosphere which ends up receiving 30% of its energy directly from the Sun, 25% from the continents and 45% from the ocean. The atmosphere, contrary to what might be intuitively thought, is thus warmed mainly at its base and not directly by the Sun; it is the ocean that provides nearly 50% of the atmosphere's energy. The transfer of energy from the ocean to the atmosphere occurs principally by radiation and evaporation.

A body radiates as a function of its temperature. The visible radiation we receive from the Sun corresponds to a body with a temperature of 6,000 °C, which is the surface temperature of the Sun. The Earth, whose average temperature is 15 °C, emits radiation in the infrared part of the electromagnetic spectrum which, unlike direct solar radiation, is easily absorbed by the atmosphere, which in turn is heated: this is the natural greenhouse effect which ensures a livable temperature on the Earth's surface (15 °C, on average), instead of the -18 °C that the atmosphere would have if it were transparent to infrared radiation – but which we should not withstand.

When sea-surface temperature exceeds that of the atmosphere, the ocean evaporates and transmits to it, in the form of water vapour, the energy that this vapour releases when it condenses at altitude during the induced convection. This phenomenon is particularly intense in the equatorial region, and the cumulo-nimbus clouds in the doldrums (which the first navigators and the pioneers of aviation feared, and competitors in the round-the-world sailing races still fear) are the sign of the intense evaporation of the ocean in these regions where the sea-surface temperature is maximal. This is the Intertropical Convergence Zone (ITCZ) where the north and south trade winds converge. In this way, the tropical ocean is really the boiler of the climate system: it is there that the atmosphere gets most of the energy that sets it in motion. The driving of the surface currents by the wind is only the return to the ocean of the energy that the atmosphere had borrowed from it.

The atmosphere well illustrates the central heating system taken as an example: the boiler (the tropical ocean) at the base of the system activates the convection, or setting in motion, of the atmosphere. The opposite is true for the ocean, in which the least-dense warm layers are at the surface and, at depth, there is no source of heat capable of priming the convective pump.

DEEP CONVECTION: THERMOHALINE CIRCULATION

The ocean, in which the temperature decreases from the surface to the bottom, is in a normally stable situation, so that only a very powerful 'refrigerator' rather than a boiler could disturb it enough for the sea-surface temperature to decrease to the point that the surface layer would become denser than the underlying water and therefore sink to great depth. This situation would be very unlikely if the ocean were not salty. Like the temperature, the salinity determines the density of the sea water: the saltier the water the denser it is. There are some regions in the world where the conjunction of high salinity and strong cooling allow the surface water to attain densities such that the water sinks to the bottom of the ocean. This is the driver of the deep ocean circulation. Without this, we should have a two-layered ocean: an upper layer a few tens of metres thick and subject to wind action, overlying the rest of the ocean – an almost motionless body of water.

Evaporation, the transfer of water from the ocean to the atmosphere, cools the ocean and increases its salinity, a double reason why the density of surface water increases. The Gulf Stream, for example, transports hot and relatively salty water from the tropics of the North Atlantic Ocean towards high latitudes. In the course of its travels, evaporation is intense, so it cools. It becomes carried by the North Atlantic Drift which thus carries salty water towards the Arctic; this water progressively cools and becomes denser. When sea ice forms, at a temperature of around -2 °C, the salinity increases further, as the ice that is formed consists of fresh water, the salt remaining in the sea water. In this way, very high densities are achieved, so the water becomes much denser than the underlying water and sinks, right there, until it reaches its depth of hydrostatic equilibrium which is determined mainly by its *in situ* temperature (2.9 °C) and salinity (34.9 PSU). These properties amount to an identity card allowing this water to be traced during its progression across the ocean. It is even given a name: North Atlantic Deep Water (NADW) which can be traced at a depth of 3,000 m right down to the Antarctic (figure 2). An analogous mechanism exists in the southern hemisphere, in the Weddell Sea, along the coast of Antarctica, where Antarctic Deep Water (AADW) is formed (with a temperature of 0 °C and a salinity of 34.7 PSU); it is even denser than the NADW mentioned above and literally carpets the ocean floor.

These waters flow very slowly and finally meet and mix and warm up, rising in a diffuse way towards the sea surface to become incorpo-

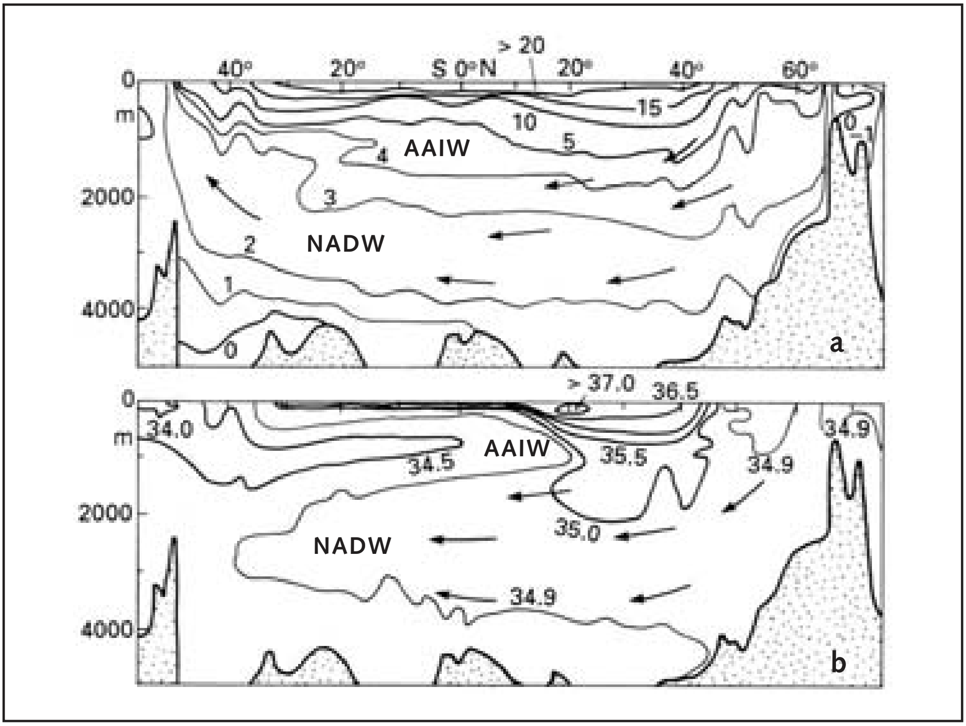


Figure 2

North–south section in the western Atlantic Ocean showing the temperature *(a)* and the salinity *(b)* as a function of depth.

AAIW: Antarctic Intermediate Water
NADW: North Atlantic Deep Water

Source: M. Tomczak and J. S. Godfrey, Regional Oceanography: An Introduction, *Oxford, Pergamon Press, 1993.*

rated into the surface circulation, and sooner or later will reach the North Atlantic convection zone, thus starting again to sink and to undertake a new voyage that will last several hundred years. This circulation, a sort of conveyor belt, was proposed by Broecker in 1985 and is illustrated in figure 3.

SUBDUCTION ZONES

Deep-ocean convection is not the only mechanism by which ocean water masses are created. All of them acquire their properties at the sea surface, as a result of their exchanges with the atmosphere (radiation, evaporation, precipitation) which determine their temperature and salinity. But during their journey in the ocean currents they may come up against less-dense

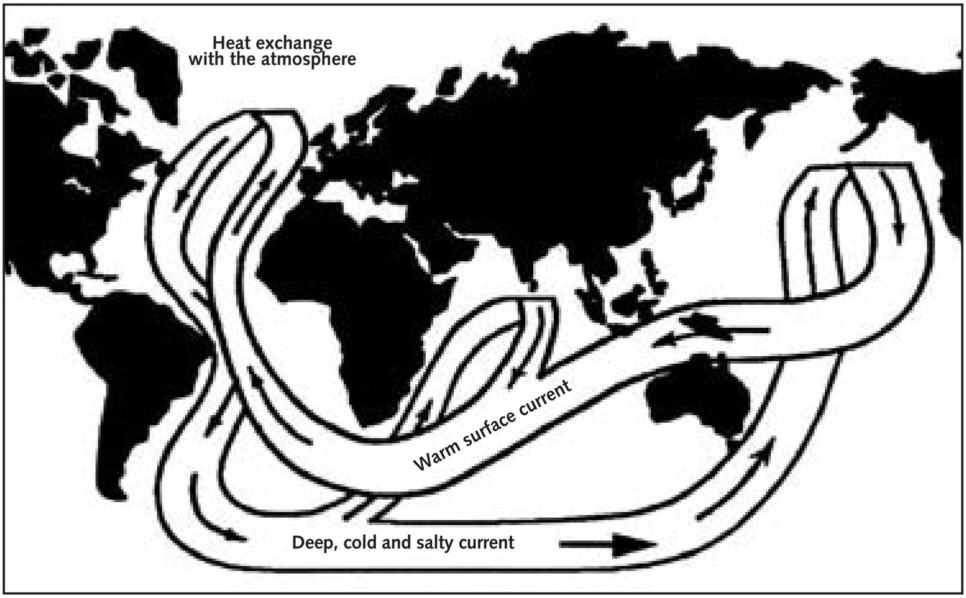


Figure 3
The 'conveyor belt', a diagrammatic representation of the world ocean circulation
The warm and salty surface water is driven into the North Atlantic and the Norwegian Sea where it is cooled. Its density increases causing it to sink to great depths and return to the South Atlantic, then the Indian and Pacific Oceans. This deep water diffuses slowly back towards the surface where it is taken up by the surface current and carried back to the North Atlantic.
Source: Broecker et al., Nature *315, 1985, pp. 21–6.*

water, so they will 'dive' under it until they reach their equilibrium depth. Take, for example, the history of NADW. When it reaches the Antarctic continent, it will become caught up in an ascending movement known as the Antarctic Divergence (described in Chapter 4). By mixing with surface water, as well as undergoing the effects of precipitation and heat exchange with the atmosphere, it will lose the identity it had acquired and mostly conserved while at depth and thus acquire a new identity (a lower temperature and salinity, hence a lower density). In the great Antarctic Circumpolar Current which, driven by the wind, girdles the Antarctic continent from west to east and, in agreement with Ekman's theory, is carried northwards (at an angle to the left of the wind direction, as in the southern hemisphere) until it comes into contact with warmer and less-dense water of subtropical origin. Whereupon it sinks to a depth of 800 m, in accordance with its acquired properties (T = 4 °C, S = 34.3 PSU), at which it will, with its new properties, continue its northward flow, becoming known as Antarctic Intermediate Water (AAIW). It can be traced in the Atlantic Ocean as far as 20 °N where it is seen as a tongue of relatively low-salinity water between the surface water and the NADW which is moving southwards (figure 2).

THE GEOSTROPHIC HYPOTHESIS

In the ocean, as in the atmosphere, the currents induce pressure differences. We are much more familiar with this idea for the atmosphere we live in, thanks to meteorology whose job it is to know the caprices of the weather. The meteorological maps that we see in all weather forecasts are maps of atmospheric pressure, and we all know what kind of weather to expect when a depression arrives or an anticyclone (zone of high pressure) grows. The atmospheric pressure at a point on the ground represents the weight of the atmosphere directly over this point. The pressure differences from one point to another simply represent the distribution of air masses with different properties (temperature, humidity) due to the movements of the atmosphere. Logically, in accordance with the principle of communicating vessels, which holds that a fluid seeks an equilibrium such that at any given depth the pressures are the same, the movements of the atmosphere, and therefore the wind, should be from high to low pressure under the action of the pressure force which is proportional to the pressure difference. But this is not what is observed; the wind turns around the centres of high and low pressure. In the northern hemisphere, the direction of rotation is clockwise in anticyclones and anticlockwise in depressions. The opposite is true in the southern hemisphere and it is, of course, the Coriolis force that explains this. We can describe, to a close approximation, the movements of the atmosphere and show that they conform to the hypothesis that at any given point the pressure and the Coriolis forces are in equilibrium. In a pressure field associated with, say, a depression (figure 4), the pressure force will be directed to the centre of the low-pressure area and perpendicular to the isobars (lines of equal atmosphere pressure); the Coriolis force, under the equilibrium hypothesis, will be the same but in the opposite direction. As the Coriolis force is perpendicular to the direction of movement and to the right in the northern hemisphere, the wind will necessarily be tangent to the isobars and oriented in an anticlockwise direction. Based on this hypothesis, and inverting the problem, we can see that, from a simple map of atmospheric

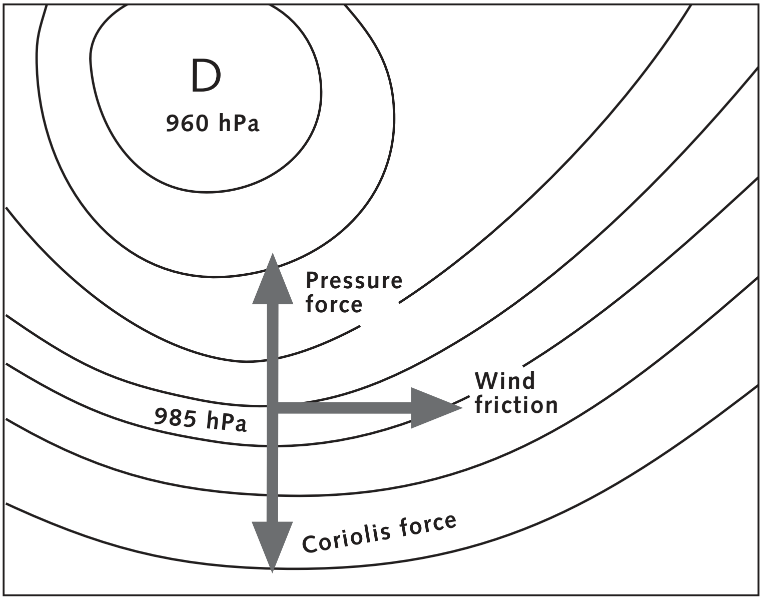


Figure 4
Diagram of the pressure field, the Coriolis force, winds and currents in the northern hemisphere.
In the absence of the Earth's rotation, the winds would blow from a zone of high pressure to a zone of low pressure (D). The Coriolis force drives the wind to the right in the northern hemisphere (and to the left in the southern hemisphere). In a state of geostrophic equilibrium, the pressure force equals and opposes the Coriolis force. The wind is tangential to the isobars and turns anticlockwise around a centre of low pressure (as in the diagram). The opposite is true around a high-pressure centre. And the situation is also inverted in the southern hemisphere.
The diagram is also applicable to the ocean where, to a first approximation, a high-pressure zone corresponds to an elevation of the sea surface, and vice versa.

pressure, it is possible to reconstitute the wind field associated with it. This is obviously an approximation that ignores friction and turbulence and supposes that vertical movements are negligible and that, in fact, the system is in equilibrium. Even so, this method is still powerful enough for analysing the average state of the atmosphere at any given moment.

This method was developed by Bjerknes in 1898 and adapted to the ocean by Helland-Hansen and Sandström in 1909. As in the atmosphere, the ocean currents, by moving water masses, induce differences in hydrostatic pressure. Applying the geostrophic method, we can deduce the corresponding average currents. Measuring the pressure at a given depth in the ocean is not simple. In effect, we do not measure it; we calculate it from measurements of temperature and salinity (from which we deduce the water density) made with the help of probes in the water column. In this way, for a given depth, we can calculate the weight of the column of water above the chosen depth; that is, the hydrostatic pressure. And from the pressure field thus calculated, we can deduce the currents.

MAJOR SUBTROPICAL ANTICYCLONIC CIRCULATIONS

As an example, we can take the anticyclonic circulation of the tropical North Atlantic; this is associated with the Azores atmospheric anticyclone (figure 1). Around this anticyclone, in accordance with the geostrophic hypothesis, the wind blows in an anticlockwise direction in a loop comprising, on the northern side, westerly winds, and on the southern and eastern sides, the familiar trade winds. They drive the surface currents: the North Atlantic Drift westwards on the northern side, the Canaries Current along the west coast of Africa, the North Equatorial Current on the southern side, and finally, on the western side, the Gulf Stream, which closes the loop. In accordance with Ekman's theory, the water of these currents will also be carried towards the right; that is, towards the centre of this great gyre where it will pile up, raising the sea-surface height, hence a zone of high pressure. The Azores atmospheric anticyclone thus creates its own oceanic mirror-image. The interest of the geostrophic method is that, from simple measurements of temperature and salinity which largely define the hydrostatic-pressure field, we can reconstitute this anticyclonic oceanic circulation without concerning ourselves with the original causes.

These subtropical gyres are the oceanic response to the major atmospheric anticyclones, such as that of the Azores. There is an analogous symmetrical situation in the South Atlantic around the Saint Helena anticyclone: the South Equatorial Current is driven westwards by the trade winds on the northern side of the anticyclone; it is then extended southwards by the Brazil Current and entrained by the Antarctic Circumpolar Current; the loop is then completed by the Benguela Current and returned to the south-east trade-wind zone. Even though the two oceans differ in size, there is a similar situation in the Pacific, with the North and South Equatorial Currents, the California and the Humboldt Currents, homologous with the Canaries and the Benguela Currents, and the Kuroshio in the Pacific Ocean, equivalent to the Gulf Stream in the North Atlantic.

The geostrophic method and the analysis of ship drift made it possible to acquire an overall knowledge of the planet's ocean currents long before good current measurements were available.

UNDULATIONS OF THE THERMOCLINE, CONVERGENCE AND DIVERGENCE

The ocean is, as we have seen, in a generally stable configuration: it receives its heat energy through the sea surface and special forcing conditions must occur to create deep convection. Without these conditions, the ocean would consist of two separate layers: a surface layer of water that is warm, thanks to solar energy, and homogeneous, thanks to mixing due to the wind stress; and an underlying layer of cold water extending down to the bottom. This situation is always found in the tropics where the abundance of solar energy easily maintains a warm and homogeneous and more or less thick surface layer. The two layers are separated by a zone in which the temperature decreases rapidly with increasing depth: this the thermocline (from the classical Greek verb *clinein,* to incline). In a sharp thermocline, the temperature can change at a rate exceeding 1 °C per metre. You can experience this phenomenon in certain lakes, for example, where, in summer while bathing, you can have your shoulders in warm water and your feet in cool water. The thermocline is, necessarily, also a pycnocline, a zone in which the density increases very rapidly with increasing depth, since the density increases as the temperature decreases. This strong density gradient limits considerably vertical water movement and mixing across the thermocline, which therefore acts as a kind of physical barrier between the warm surface layer and the cool deep layer. In the temperate regions, where the flux of solar energy received by the ocean varies according to the season, a thermocline becomes established near the surface in summer. This thermocline is analogous to that in the tropics and will be destroyed by winter cooling and increased wind, facilitating vertical mixing with the underlying water down to the permanent, but less sharp, thermocline at a greater depth (several hundred metres). Only the deep convection of the polar regions mentioned above can break down this deep thermocline.

As we saw in the geostrophic hypothesis, the currents can be derived from the hydrostatic pressure field. The hydrostatic pressure at a given depth does not only depend on the height of the water column above it, but also on the density and thickness of the water masses present. At two points at the same depth, the hydrostatic pressure is not necessarily the same unless, under the geostrophic hypothesis, there is no current between the two points. On the other hand, from the pressure difference between the two points, we can deduce the current flowing between them. Nevertheless, the difference in the height of the water column basically reflects the pressure difference between the two points, hence reciprocally, any current corresponds to the effective differences in sea-surface height. We saw in the example of anticyclonic circulation discussed in a preceding paragraph that, owing to the Ekman drift, the water accumulates at the centre of the anticyclonic gyre, thus raising the effective sea-surface height there relative to the edge of the gyre. In the Atlantic and Pacific Oceans, the trade winds in the northern and southern hemispheres drive the North and South Equatorial Currents from east to west from one side of the ocean to the other, inducing a difference in sea level of about a metre between the two sides of the ocean. At a given latitude, the slope of the sea surface (the pressure gradient) associated with a current is positively related to the intensity of the current, and if the current is in geostrophic equilibrium, the slope will be, as we have seen, perpendicular to the direction of the current (figure 4). In a section across the Gulf Stream, sea-surface height can differ by a metre over 100 km.

In the tropics, where there is a permanent thermocline, the surface currents act principally on the warm, homogeneous layer above the thermocline, so the pressure differences induced are reflected principally by the differences in thickness of the surface layer. Zones of high pressure correspond to thick homogeneous layers, and vice versa. So the depth of the thermocline can be considered, to a first approximation, as an indicator of the pressure field, hence of the currents. For example, a temperature section across the equatorial current system in the Atlantic shows that the thermocline varies according to the currents (figure 5). The troughs (convergences) and the crests (divergences), which are the extremes of the pressure field, also correspond to changes in the current. For example, the separation between the South Equatorial Current, which flows westwards, and the Equatorial Counter-current, which flows in the opposite direction, is marked by a trough in the thermocline (thick homogeneous layer and high pressure) at 3°–4° N. Referring anew to the geostrophic hypothesis that is serving as a guide, this is fairly easy to understand. Imagine an observer on a crest of the sea surface (pressure maximum): they will see the current to the right of the pressure gradient; that is, to the east looking northwards, it will be the Equatorial Counter-current, and to the west, looking southwards, it will be the South Equatorial Current. The same reasoning applies if the observer stands on

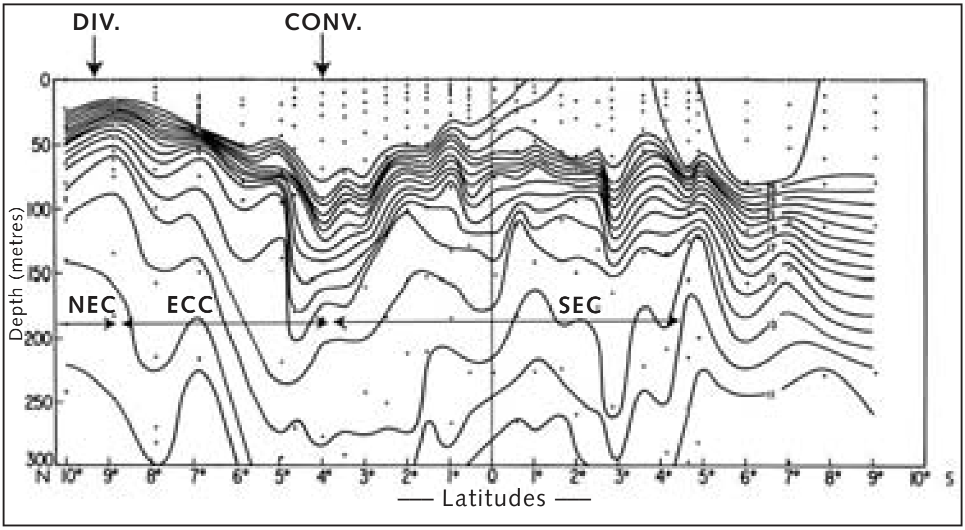


Figure 5
Distribution of temperature as a function of depth along the 25° W longitude in the Atlantic Ocean in August 1963.
DIV.: divergence
CONV.: convergence
SEC: South Equatorial Current
NEC: North Equatorial Current
ECC: Equatorial Counter-current
Source: Proceedings of the Symposium on Oceanography and Fishery Resources of the Tropical Atlantic, *Abidjan, 20–28 October 1966, UNESCO, 1968.*

the crest of the thermocline around 9° N, between the North Equatorial Current and the Equatorial Counter-current. This variation in the depth of the thermocline due to the ocean currents is central to biological production, for, as we shall see, the thermocline is not only a pycnocline, but also a ‘nutricline’; that is, a barrier to the diffusion of the nutrient salts essential to biological production towards the sea-surface water. We speak of convergence whenever, at the interface between two currents, the thermocline sinks, and of divergence when it rises.

OCEANIC GYRES

The geostrophic hypothesis that has been our guide in the preceding descriptions gives the ocean circulation a peaceful image, in which the currents are long quiet-flowing rivers. A true picture if we are thinking of the average circulation, but false if we are there in reality, as satellite images of the ocean surface show (figure 6); in these images we see only tortuous, filamentous, swirling trajectories. The average currents allow us

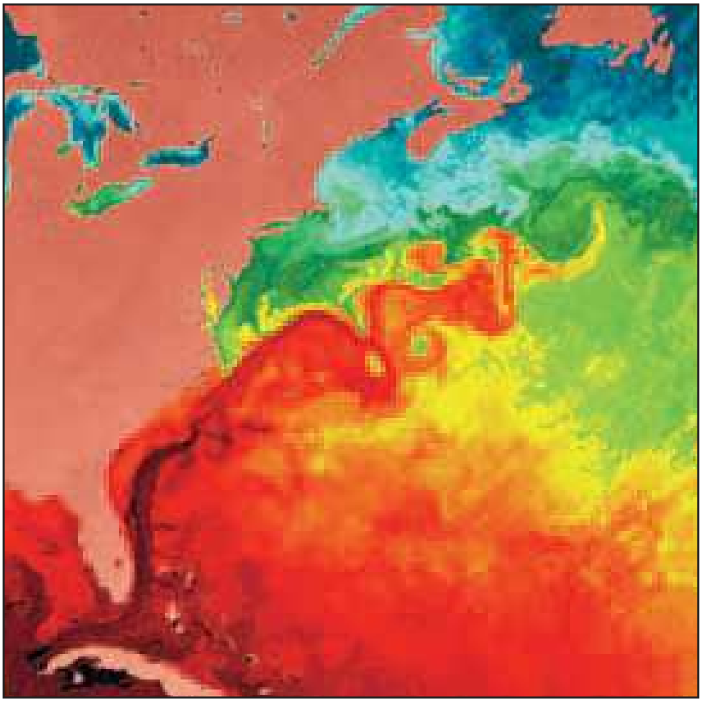


Figure 6
Sea-surface temperature of the Gulf Stream measured by satellite (April 1982).
The temperatures increase from blue to red. On the northern edge of the Gulf Stream there is a warm anticyclonic eddy, and on the southern edge (in green) a cold cyclonic eddy.
Source: Remote-sensing Group, Division of Meteorology and Physical Oceanography, Rosenstiel School of Marine and Atmospheric Sciences, Miami, Florida.

to evaluate the large-scale transport of mass and heat which the local, instantaneous values of the currents (which can even be counter to the average flow) can completely mask. The ocean is turbulent. Turbulence can be defined as an agitation such that the fluid, instead of quietly following the mean current, never stops fluctuating in every direction. Agitation facilitates mixing, hence the transfer of heat and salinity throughout the fluid. This turbulence occurs on all scales, so we can say that the eddies of the Gulf Stream shown in figure 6 are manifestations of the turbulence associated with this current, and even that they constitute the fundamental turbulent structure of the Gulf Stream. In the 1960s, some people even proposed the creation of a special kind of oceanography in which the ocean would be regarded as an assemblage of elementary fluid particles acting with each other. The so-called mesoscale eddies, such as the Gulf Stream eddies of several tens of kilometres in diameter just mentioned, have a life of about 100 days. They play an important role in mixing and in the transport of heat and dissolved properties (salinity, nutrients). Hence the need to take them into account in the models, which obliges us to develop models with a very high spatial resolution (say, 10 km) to represent the eddies clearly and to demand a high power of computation, the lack of which long held back the development of such models. The existence of these turbulent structures was suspected for a long time: ship drift and the observation of the trajectories of floating objects suggested their existence. But the traditional oceanographic expeditions with only one vessel, which did not at all meet the criteria of unity of place and time so dear to the French playwrights of the seventeenth century, were quite incapable of identifying these small, mobile and ephemeral structures.

We had to wait until the 1970s and the MODE and POLYMODE experiments, between 1972 and 1977, which saw, in a small part of the Sargasso Sea (600 square km), an exceptional concentration of means (six vessels, anchored buoys, floats) to evaluate the importance of these structures in the transfer of energy and to assess the difficulty of sampling them by traditional methods. The problem would have been virtually unsolvable without the space revolution of the 1980s which gave almost instantaneous access to the whole of the ocean: if six vessels for 600 square km were necessary, how many would be needed for all the eddies in the ocean, which the satellites now show us daily?

3

Oceanic variations, climatic variations

VARIATION IN THE CLIMATE SYSTEM

The climate system is a machine for converting and distributing the energy that the Earth receives from the Sun. It is a complex system with many parts. The Sun does not provide a strictly constant flow of energy. Its twenty-two-year cycle brings us a period of maximum activity every eleven years, as occurred during the International Geophysical Year 1957–58. It can also have relatively feeble periods, as in the seventeenth century when there was a time of greatest cold during the 'Little Ice Age' when the solar cycle appeared to be lulled by a low level of radiation (the Maunder cycle). In the northern hemisphere, the mean temperature was 1 °C lower than it is now. Between the extremes, the corresponding variation in solar energy is only 0.1% and its impact on climate variation was long underestimated. The parameters of the Earth's orbit around the Sun vary, so that the energy received from the Sun, and its distribution over the Earth's surface, fluctuate on time-scales from 10 to 100,000 years. This explains the successive Ice Ages and interglacial periods (cf. pp. 56–59). The proportion of solar energy absorbed and returned to the atmosphere by the continents depends on the properties of their surface and their vegetation. The cryosphere (mostly the polar ice caps of Greenland and the Antarctic, and sea ice) reflects back into space a quantity of energy that depends on the state of the ice and especially the area of the ice-covered surface and is thus lost to the climate system. And finally, the motions of the ocean and the atmosphere depend on the ensemble of these variations in the planetary energy balance.

All these components of the climate system thus evolve continually, each at its own speed and each quite different from the others. Any variation or disturbance of one of them affects the others, each reacting at its own speed. The climate system ceaselessly seeks an equilibrium it can never attain; it does this no matter what the time-scale of observation is. For us, the essential point is that the system should remain sufficiently stable to be able to keep within a range and speed of variation that we can live with. An increase in the concentration of greenhouse gases in the atmosphere could compromise our situation.

DYNAMICAL FACTORS: THE ATMOSPHERE AND THE OCEAN

The atmosphere and the ocean are the two fluids of the planetary heat machine. By ensuring the transfer and distribution of thermal energy, they are the dynamic factors. Being permanently in contact with each other, they continually exchange energy and are inseparable. The association they form determines the planet's climate. The great difficulty we have in deciphering this coupling arises from the fact that they have quite different characteristics and reaction speeds.

The atmosphere has almost no 'memory'. It responds very quickly to the perturbations it is subject to. This is why weather forecasting is so difficult. At the present time, meteorological services make weather forecasts up to seven days in advance. In spite of the progress in modelling the atmosphere, it appears that it will always be impossible to make a weather forecast of more than two or three weeks in advance. A weather forecast starts from a given state of the atmosphere, based on observations, and thanks to models based on the physical laws that govern the dynamics of the atmosphere, calculates what this state will be one, three or seven days later. It is therefore virtually certain that weather forecasting will reach a limit in time; that is, a time by which the state of the atmosphere will be totally unrelated to what it was at the initial instant. Beyond this time limit, however good the observations and the models might be, it becomes impossible to forecast the weather. This time limit appears to be about fifteen days.

The ocean has a much longer response time and therefore a much better 'memory'. It plays a double role: to supply some of its energy to the atmosphere and to distribute the remainder directly, by its currents, on a planetary scale. At any given place, the quantity of energy exchanged with the atmosphere depends on the ocean's sea-surface temperature, hence the amount of heat it has transported to that point. The part of the ocean to be considered in climate processes depends on the time-scale chosen. If the only concern is forecasting weather less than two weeks in advance, the models only require the sea-surface temperature to determine the energy exchanges between the ocean and the atmosphere. During these two weeks the change in sea-surface temperature is too small to have a significant impact on the heat exchanges; it would be pointless to complicate the models by incorporating ocean dynamics into them. Weather-forecasting models are strictly atmospheric. On a climatic scale, on the other hand, the dynamics must be taken into account: it is the ocean, the slower of the two partners, that imposes its rhythm on climate variability. Regarding interannual variation, as manifested by the El Niño phenomenon, for example, the top several hundred metres of the equatorial ocean are the predominant factor. Beyond the interannual time-scale, the whole of the ocean circulation, from the surface to the bottom, must be taken into account, as the cycle covers several centuries. In effect, the ocean memorizes for several centuries the 'signature' of previous climatic events. Up to a point, the Earth's present climate depends on the cooling during the 'Little Ice Age' between the sixteenth and nineteenth centuries. Even if the ocean dampens climate variations, it returns the effects decades or even hundreds of years later.

Climate-forecasting models, whatever the time-scales considered, are forced to couple the very different but interactive dynamics of the ocean and the atmosphere. And that is not easy.

INTERANNUAL VARIABILITY: THE EL NIÑO PHENOMENON

Alfonso Pezet, on behalf of the Geographical Society of Lima, presented a communication on 'The Counter-current El Niño on the Coast of Northern Peru' in London in 1895. This was a historic occasion. First of all, because it marked the scientific recognition of the El Niño current. Then because Pezet started by broaching the question of the relations between the ocean and the atmosphere. 'That this warm current be the cause of abundant rainfall in an arid region of Peru seems to be a fact,' he wrote. This coastal current was best known by Peruvian fishermen who with much pleasure observed, generally around Christmas time, that it brought tropical species that changed their usual diet. Hence the name El Niño (The Christ Child) that they had affectionately given it. It is thanks to the International Geophysical Year of 1957–58, which was an El Niño year, that the extent of the phenomenon was demonstrated. The El Niño coastal current familiar to the Peruvian fishermen is in fact only the appendix, in the eastern Pacific Ocean, of a major perturbation of the whole of the equatorial Pacific.

OCEAN–ATMOSPHERE COUPLING IN THE EQUATORIAL PACIFIC

The trade winds that blow from east to west in the whole of the equatorial Pacific drive the warm sea-surface water of the South Equatorial Current; this motion is compensated, on the eastern side and along the equator, by the upwelling of colder water. Temperature differences therefore arise between the two sides of the Pacific Ocean. A corresponding difference in sea height, which is higher in the west by 50 cm to 1 m. So, also in the west, in the Indonesian region, there is a vast reservoir of warm water in which the sea temperature exceeds 29 °C. It is here that the ocean transfers a maximum amount of energy to the atmosphere; the convection there is very intense. The air, hot and charged with humidity following contact with the ocean, rises; during this ascension, the water vapour condenses, giving rise to well developed cumulo-nimbus clouds, and is a source of precipitation that generously soaks the Indonesian region. This convection is the ascendant branch (with a low atmospheric pressure) of an atmospheric circulation cell along the equator (figure 7). The descending branch of this cell, linked to the ascending branch by a west–east current at altitude, lies east of the area of coolest oceanic water which corresponds to high atmospheric pressures and a supply of dry air: rainfall is rare on the desert coasts of Peru and northern Chile. The trade winds, which blow from east to west over the ocean surface, complete this circulation cell, known as a Walker Cell. Overall, the intensity of the trade winds and of this Cell is proportional to the difference in atmospheric pressure between the eastern and western Pacific. To describe it, we use a simple index: the difference in atmospheric pressure in Tahiti (zone of high pressure) and in Darwin, Australia (zone of low pressure). This is called the ‘Southern Oscillation Index’ or SOI. When the index is high, the Walker Cell is very active, and vice versa.

Describing the exchanges between the ocean and the atmosphere in this cell, Jakob Bjerknes (the son of Vilhelm Bjerknes mentioned in Chapter 1) indicated: ‘To an increase in the pressure gradient at the base of the Walker Cell, there is a corresponding strengthening of the easterly winds along the equator and therefore sea-surface temperature difference between the eastern and western equatorial Pacific Ocean. This chain reaction shows that the intensification of the Walker Cell generates an increase in the ocean-temperature difference which, in turn, activates even more the atmospheric circulation. The opposite occurs if the point of departure taken is the weakening of the Walker Cell.’ We are in a positive-feedback system that operates in a loop until a perturbation makes it see-saw, without us knowing whether the ocean or the atmosphere was the cause of the perturbation. This ‘pas de

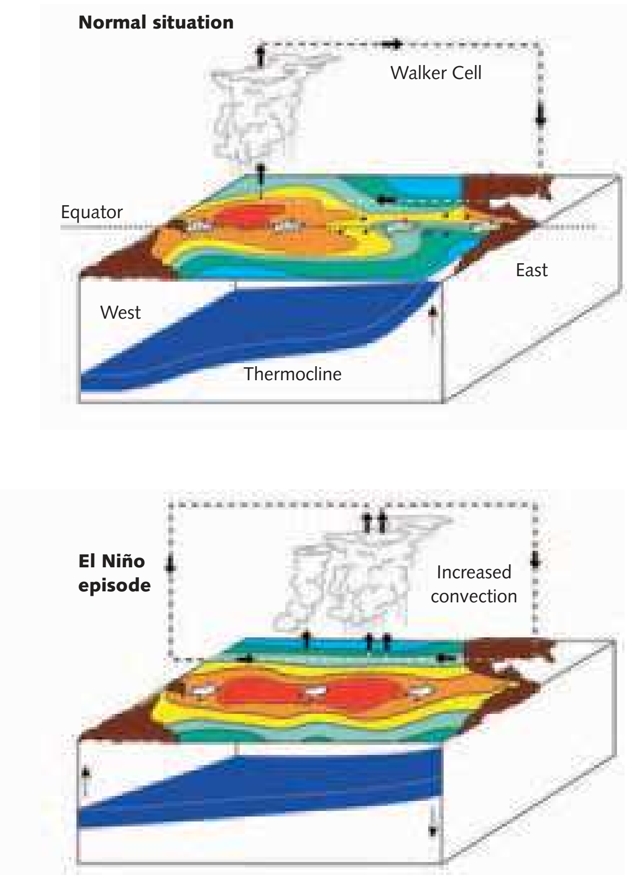


Figure 7

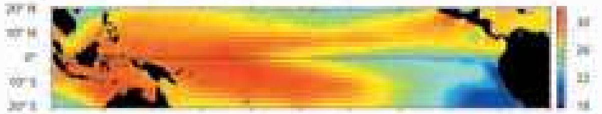
Evolution of the ocean–atmosphere coupling in the equatorial Pacific Ocean.

Normally, the trade winds induce upwelling of cold water off Peru and an accumulation of warm surface water in the western Pacific, increasing the west–east difference in sea-surface height by 50 cm to 1 m. Consequently, the thermocline reaches the sea surface in the upwelling zone, but is at about 200 m depth off Indonesia. The atmospheric circulation is characterized by a strong ascent of air over Indonesia, with strong rainfall, whereas the subsequent descent of air creates very arid conditions between Easter Island and the South American continent between Ecuador and northern Chile. In certain El Niño years, the relaxation of the trade winds brings about a displacement of the mass of warm water and of the associated atmospheric circulation towards the central Pacific Ocean. The thermocline shoals in the west and deepens in the east.

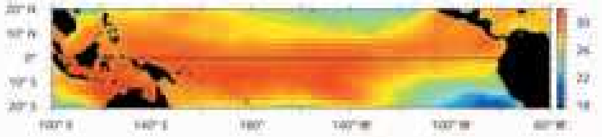
Source: Images kindly provided by the NOAA/PMEL/TAO Project Office, Michael J. McPhaden, Director.

December 1988 under La Niña conditions

December 1990 under ‘normal’ conditions



December 1997 under El Niño conditions

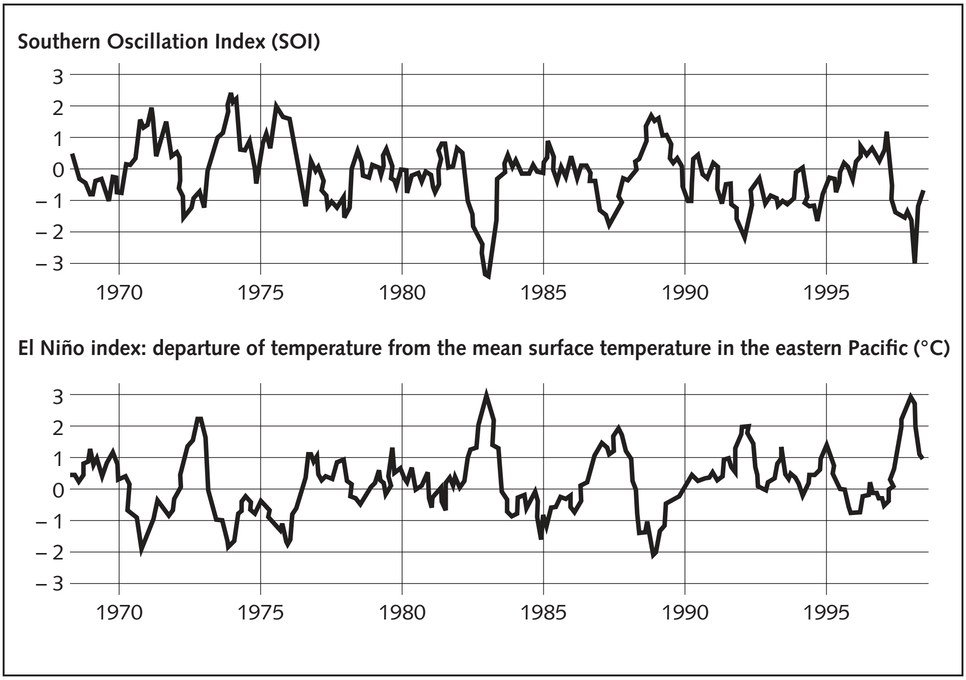


Sea-surface temperature charts of the equatorial Pacific Ocean.

The temperature colour scale is given on the right-hand side of each chart. There is, qualitatively, a similarity between the La Niña and the normal conditions, with a thermal minimum along the equator which extends the coastal upwelling. Nothing like this occurs during an El Niño, in which there is a band of warm water along the equator from one side of the Pacific to the other.

Source: Images kindly provided by the NOAA/PMEL/TAO Project Office, Michael J. McPhaden, Director.

deux' described by Bjerknes between the Walker Cell and its oceanic counterpart, which links the southern oscillation to the east–west thermal gradient in the equatorial Pacific, is known as ENSO (El Niño–Southern Oscillation). This oscillation can be characterized starting either from the atmospheric component, using the SOI, or from the oceanic component, using the sea-surface temperature anomalies in the eastern equatorial Pacific, or even the sea-level anomalies along the equator (figure 8).



Southern Oscillation Index (SOI)

El Niño index: departure of temperature from the mean surface temperature in the eastern Pacific (°C)

Figure 8

ENSO as shown by the Southern Oscillation Index and the El Niño index from 1968 to 1998.

The evolution of these two indices shows that ENSO has a period of two to seven years with an average of four years. The 1980s and 1990s show an increased activity, with five El Niños (1982–83, 1986–87, 1991–93, 1994–95, and 1997–98) and three La Niñas (1984–85, 1988–89, 1995–96). The two strongest El Niños of the century (1982–83, 1997–98) occurred during these fifteen years, as well as an extended El Niño from 1991 to 1995.

The Southern Oscillation Index is the difference in atmospheric pressure at sea level between Tahiti and Darwin. The El Niño index is the difference, in the eastern Pacific, between the mean temperature (°C) at a given time and the long-term mean sea-surface temperature.

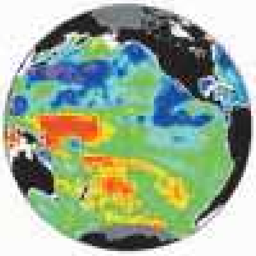
EL NIÑO: THE WARM PHASE OF ENSO

El Niño corresponds to the dismantling of the system just described, the Walker Cell and its oceanic counterpart. When the southern oscillation index diminishes, the system of the Walker Cell and its oceanic equivalent weakens: the intensity of the trade winds and the South Equatorial Current decreases (figure 7). The situation may even be inverted: westerly winds and an eastward-flowing ocean current appear at the equator. With nothing to retain the warm water accumulated in the Indonesian region, this water flows eastwards carrying with it the zone of atmospheric convection, hence rains. To the east, the temperatures increase by 4–5 °C. The slope of the sea surface also decreases, the sea level increasing in the east and decreasing in the west (figure 9).

Such is El Niño whose more or less calamitous climatic manifestations regularly make the newspaper headlines; it is a ‘sudden qualitative leap’ that turns upside down the heat exchange between the two fluids in a zonal direction, owing to the dislocation of the Walker Cell, but also in a latitudinal direction from the equator towards the poles. In effect, the abnormal accumulation of warm water along the equator activates the ‘tropical boiler’, the transfer of energy to the atmosphere and the transfer of this energy towards higher latitudes via the atmospheric Hadley Cell (figure 10). The consequences of El Niño are therefore not limited to the tropics: drought in Indonesia and Australia; abundant rainfall in Peru; drought in north-eastern Brazil; weakening of the Indian monsoon. The impact of El Niño also affects the temperate regions, especially in the North Pacific: warm, wet winters in the north-western part of North America. This occurred, in recent times, in 1972–73, 1977, 1982–83, 1986, 1992–95, 1997–98 and seems likely to occur also in 2002–03.

LA NIÑA: THE COOL PHASE OF ENSO

Figure 8 shows that the El Niño events are associated with minimal values of the SOI or, in other words, with the maximum positive sea-surface temperature anomalies in the equatorial Pacific. On the other hand, marked positive SOI anomalies (or negative surface temperatures) may also be seen. For reasons of symmetry, the name La Niña has been given to this situation, in which the Walker Cell and the associated oceanic circulation are at their maximal intensity: strong trade winds, maximum convection in the reservoir of warm water off Indonesia, minimum sea-surface temperature in the east, maximum sea-surface slope. Qualitatively, La Niña is therefore not different from the normal



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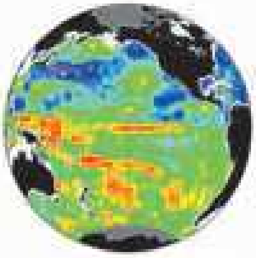
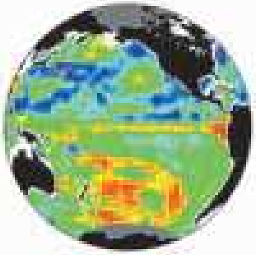
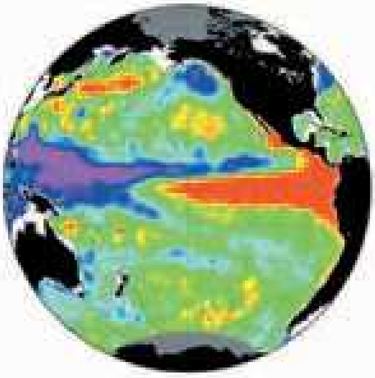


11 April 1997

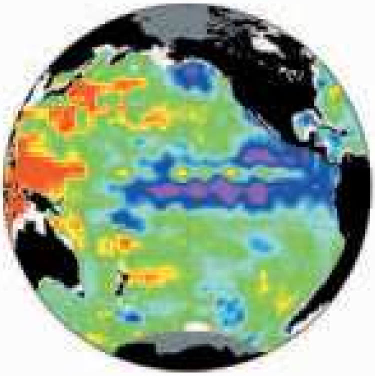


30 April 1997

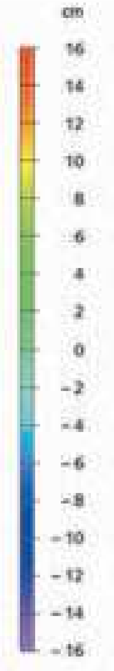
Figure 9
Propagation of a Kelvin wave along the equator, observed by the Topex/Poseidon satellite which measures the sea-surface height.
The anomalies of the sea-surface height, in centimetres, are shown here, with the relevant scale on the right-hand side of the image. A positive anomaly of 16 cm (in red) progresses from west to east along the equator. It was near the Indonesian coast on 22 March 1997, in the central Pacific on 11 April and at the coast of America on 30 April.



25 November 1997
El Niño



27 November 1998
La Niña



Sea-surface height anomalies in the Pacific, observed by the Topex/Poseidon satellite.
The positive anomalies (raised sea-surface height) are shown in red and the negative anomalies in blue-violet, following the colour scale on the right-hand side of the figure.
The contrast between the two situations is striking in the equatorial zone where the negative and positive anomalies are inverted, with a difference in sea-surface height greater than 30 cm, in the east as well as in the west.

Source: Images kindly provided by the Laboratoire d'Études en Géophysique et Océanographie Spatiale (Unité Mixte du Centre National d'Études Spatiales (CNES) du Centre National de Recherche Scientifique (CNRS) et de l'Université Paul-Sabatier de Toulouse).

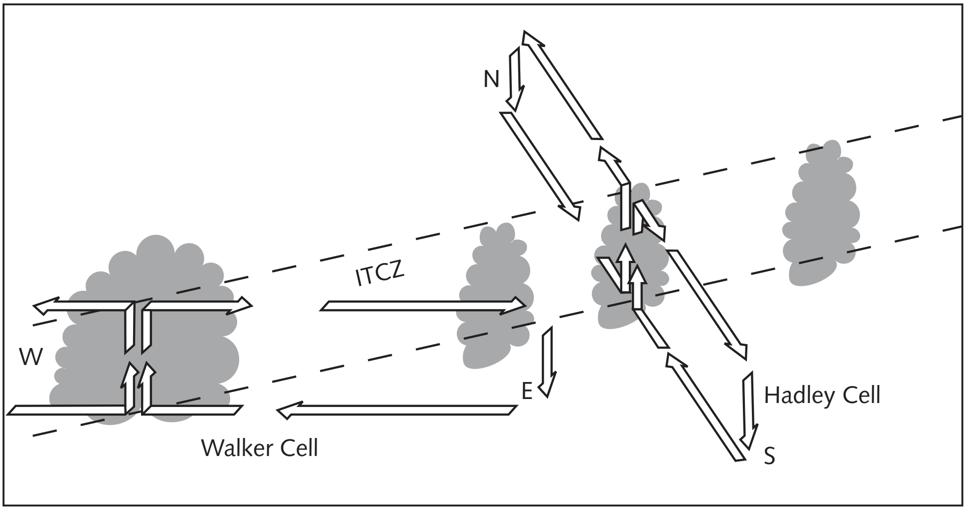


Figure 10

In the intertropical zone the atmospheric circulation may be decomposed into two components: (1) the Walker Cell, along the equator between the eastern and western sides of an ocean basin; (2) the Hadley Cell, on either side of the equator in a north–south direction, activated by the 'ocean boiler' in the Intertropical Convergence Zone (ITCZ) of which the descending branches are at the latitudes of the subtropical anticyclones. In an El Niño episode, the accumulation of warm water along the equator activates the Hadley Cell hence the transfer of heat to higher latitudes. In a La Niña episode, the maximal activation of the Walker Cell undermines the Hadley Cell.

situation: it reinforces dominant characteristics of the climate, unlike El Niño which, by dislocating the Walker Cell, inverts them. La Niña pushes the system to its limits; El Niño destroys it.

WHY EL NIÑO?

In such a closely knit system, it is difficult to assign responsibilities for the triggering of the phenomenon. It is in any case certain that, once triggered, it is the ocean that determines the rhythm of its evolution. Analysis of such events since 1975 shows that one El Niño follows another without ever being the same; there is no typical El Niño scenario, making it more difficult to answer this question. The mixed success of models for forecasting the phenomenon is doubtless a direct result of this diversity of scenarios and suggests that prudence is necessary. Analysis of the sequence observed during the 1997–98 episode shows that the atmospheric instability in the west could have been the triggering factor. In fact, in this region, bursts of westerly wind occur in a 40–60 day cycle (the Madden–Julian oscillation). These wind bursts may produce a westerly current, hence a convergence at the equator: the thermocline deepens, provoking a positive anomaly in sea-surface height. In certain circumstances, this perturbation will propagate eastwards in the form of a wave known as a Kelvin wave, just like the waves formed on a water surface when a stone is thrown into the water. The Kelvin wave will carry the convergence with it and deepen the thermocline. This convergence creates a demand for replacement water that is met by the warm surface water which is drawn eastwards as it follows the displacement of the Kelvin wave, which takes two to three months to traverse the whole Pacific from west to east. The result is that the sea-surface height decreases in the west and increases in the east. It was the propagation of such a characteristic wave in the sea-surface height that the Topex/Poseidon satellite tracked in March–April 1997 as an El Niño developed (figure 9). The Madden–Julian waves, when they occur, do not systematically provoke an El Niño; indeed, far from it. The state of the ocean must play a role here. It was perceived afterwards, as early as the autumn of 1996, but not understood at the time, that the deepening of the thermocline in the west had already produced a positive temperature anomaly of 2.5 °C between 100 m and 200 m depth. This was a warning sign that the ocean was ready to act if invited by the atmosphere, which it was, with westerly wind bursts that were observed at the beginning of 1997. It is doubtless illusory to seek the 'cause' of the El Niño phenomenon: it is not unique and can even be extratropical, outside the ENSO system, as we have just decribed, which is not an isolated system and interacts with the rest of the atmosphere and with the ocean. It would be better to look for the precursors in the ocean itself; they are assimilated in real time in the models and will reliably allow us to make a prediction six months in advance. This implies the need to ensure keeping up the observation systems established since 1985 in the framework of the Tropical Ocean and Global Atmosphere (TOGA) study of the El Niño phenomenon. And this leads us to operational oceanography (see Chapter 6).

DECADAL VARIATIONS: THE NAO

The ocean–atmosphere coupling through ENSO constitutes a comparatively simple system proper to the equatorial region where the ocean's inertia is relatively weak. For example, in the 1997 El Niño, from the oceanic precursors visible in the autumn of 1996, to the establishment of the phenomenon itself in the spring of 1997, to the reversal of the situation in the spring of 1998 and the shift to a La Niña situation, less than two years had elapsed. In this system, the SOI is physically representative of the coupling of the Walker Cell with the dynamics of the equatorial ocean. Other atmospheric indicators have been defined to characterize the state of the atmosphere and to analyse the development of the climate without our being able to relate so easily a coupling between the ocean and the atmosphere. This is the case for what is called the North Atlantic Oscillation (NAO) defined, by analogy with SOI, as the difference in atmospheric pressure between the Azores anticyclone and the low subpolar (Iceland) atmospheric pressure. Like the SOI, the NAO index also varies; that is, when the pressure off Iceland falls, the pressure of the Azores anticyclone tends to rise, and reciprocally. The climates of Europe, north-western Asia and the north-western coast of North America are closely linked, especially in winter, to the value of the NAO index, for reasons that are rather simple to understand. To a high value of this index there corresponds a very strong atmospheric-pressure gradient between the two systems and an acceleration of the west winds, with many low-pressure periods at mid-latitudes, which brings to Europe a significant flow of marine air; which is why mild, wet and stormy winters are experienced there. On the other side of the Atlantic, on the other hand, this situation favours the descent of cold continental air on the north-east coast of North America. The situation is inverted, with a low NAO index: attenuation of the westerly wind regime facilitates the descent of polar or continental air on north-western Europe causing colder and drier winters. Unlike the SOI, there is no cell analogous to the Walker Cell coupled with an oceanic current system and associated with the NAO: the connections are much more tortuous and the time-scale is much longer. It is also much more difficult to comprehend and represent the mechanisms that, in associating ocean and atmosphere, explain the observed variability.

We have available direct measurements of the NAO since the mid-nineteenth century, and it has been possible to reconstruct it back to the beginning of the eighteenth century by analysing the growth rings of trees, as the characteristics of these rings depend on such climatic parameters as temperature and humidity (figure 11). Analysis of the evolution of the NAO in time reveals several superposed periods of oscillation: every 2, 8, 24 and 70 years, although we do not have explanatory diagrams. This is because of the lack of oceanic measurements; even if the ocean imposes its rhythm on climate variations, oceanographic data are often lacking in trying to understand the mechanisms. This is especially true on a long time-scale because we cannot restrict ourselves to the exchanges between the sea surface and the atmosphere; the exchanges with the deep ocean which control the multidecadal time-scale also have to be taken into account.

On a short time-scale we know that, in the middle of winter, anomalies in the NAO generate wind anomalies and heat exchanges that produce temperature anomalies which the ocean can ‘remember’ and transfer to deep water as a result of winter mixing or variations in the intensity of convection. The thermohaline circulation of the Atlantic (see following section) is modified if the North Atlantic anomaly merely persists for several years. It has been possible to relate variations in the NAO with temperature and salinity fluctuations in the deep water west of Greenland, hence also to fluctuations in convection in the Labrador Current, to temperature anomalies on the western side of the subtropical anticyclonic gyre, to fluctuations in the Arctic sea ice, etc. We can also attribute to the strong negative anomalies of the NAO in the 1960s a curious phenomenon: the ‘great salinity anomaly’ which circulated in the subpolar part of the North Atlantic at the end of the 1960s up to the beginning of the 1980s. The weakening of the westerly winds concomitant with the negative anomalies of the NAO favoured northerly winds and an unusual advection of polar water, cold, of low salinity, and carrying ice towards Iceland and the Greenland coast. This low-density water, which could not mix easily with the underlying, denser water, formed a vast lens of low-salinity water at 700 m depth which flowed from Iceland to the North Cape (of Norway) via the Labrador Sea, west of the British Isles and the Norwegian Sea (figure 12). There was an inevitable corresponding weakening of the North Atlantic convection and of the thermohaline circulation for which it is difficult to evaluate the climatic impact.

Here we have the elements of a puzzle the pieces of which are far from being assembled. Taking into account the complexity of the system, the time-scales and the lack of observations, many years will be required to establish observing systems now within our grasp thanks to the development of *in situ* measurement technology and satellite tools, particularly altimetry, which allows us to follow and evaluate continually the fluctuations and meanders of the surface circulation.

LONG-TERM CLIMATE CHANGE: THE THERMOHALINE CIRCULATION

The formation of North Atlantic Deep Water (NADW) in the convection zone of the Norwegian Sea plays an essential role in climate dynamics on long time-scales. We have seen that the conjunction of the advection of salty water from the Gulf Stream, the winter cooling and the formation of ice led to the formation of very dense water in the Norwegian and

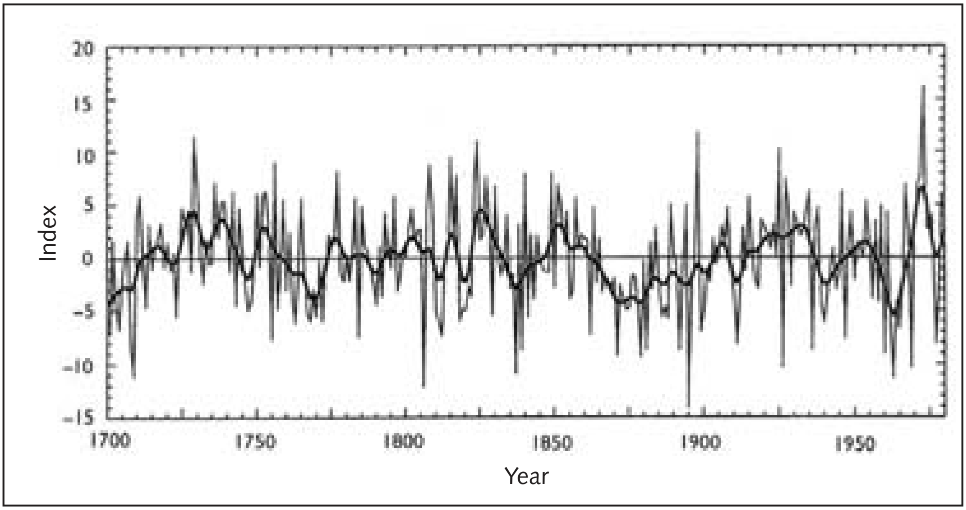


Figure 11
Variation of the North Atlantic Oscillation index in winter since 1700, reconstituted by means of dendrochronology, which allows the reconstitution and dating of climatic features expressed in tree growth rings.

Labrador Seas, which sinks to its level of hydrostatic equilibrium at about 3,000 m depth. This NADW then spreads throughout the ocean as far as the Antarctic and the Indian and Pacific Oceans, progressively losing its initial properties by mixing with other water masses. This convection does the job of a heat pump: it draws the still warm water of the Gulf Stream towards the high latitudes of the Norwegian Sea, giving Europe a less rigorous climate than that prevailing at the same latitude on the opposite side of the Atlantic. In 1985, Broecker proposed a diagram representing this thermohaline circulation as a kind of planetary conveyor belt (figure 3). Starting in the Norwegian Sea, the NADW reaches the northern limits of the Indian and Pacific Oceans at depth; there it reappears at the surface returning to its point of departure via the Indonesian straits, the equatorial current of the Indian Ocean, the Agulhas Current, rounding the Cape of Good Hope, the South Equatorial Current in the Atlantic and finally the Gulf Stream, ready to start a new cycle. This is, of course, a very schematic and simplified picture, but it gives an idea of the 'globality' of the oceanic circulation. Thanks to carbon-14, we can determine the age of a water mass; that is, the lapse of time since its last appearance at the ocean surface. For the water of the North Pacific, this age is 1,500 years; this is the duration of one cycle of the conveyor belt.

OCEAN CIRCULATION IN THE LAST ICE AGE

On such time-scales, we are clearly not in a position to detect significant variations in such a circulation. The only solution is to reconstitute, if we can, both the history of the climate and that of the corresponding oceanic circulation. Fortunately, we have available the archives stored in the polar ice caps of Greenland and of the Antarctic, and in the marine sediments, all of which, stratum by stratum, record indications of the conditions on Earth at the time they were being laid down. Recently, the Europeans, by drilling down to a depth of 2,860 m, in dome C in the Antarctic, have been able to trace back to 520,000 years ago. The isotopic composition of certain elements, such as oxygen and carbon, allows us to decipher these archives. Not only the oxygen from the air trapped in the ice, but also the carbon in the skeletons of Foraminifera (marine protozoans) found in the sediments, retain an 'isotopic signature' of the temperature of the water or the air of that time in which the Foraminifera lived. Thus, patiently, by analysing the drill core, layer by layer, the state of the atmosphere and of the ocean can be reconstituted. At the beginning of the 1970s, the international programme CLIMAP had the objective of thus reconstituting the sea-surface temperature at the time of the last Ice Age (18,000 years ago). These maps, one for the summer, and one for the winter, were published in 1981. Flushed by this success, the participants in the programme wanted, and were able, to go further, also reconstituting the deep circulation during the last Ice Age and the preceding interglacial period (120,000 years ago).

It seems that, in the preceding interglacial period, the oceanic circulation was quite similar to the present one. The conveyor belt and the heat pump of the Atlantic operated at the same speed as they do today. This is reassuring and gives us confidence in this sort of reconstitution, especially with respect to the circulation during the Ice Age which, nevertheless, was quite different from the present circulation. The Norwegian Sea, surrounded by the polar ice caps that covered the northern parts of the American and European continents, and the sea itself covered by ice most of the time, was not the end of the road for the warm waters of the Gulf Stream, which completed its cycle much further to the south. So the Norwegian Sea was not therefore the site of formation of the North Atlantic Deep Water, nor did it play a role as a heat pump, much to the displeasure of the Europeans of that time, as they had to put up with a much colder climate, with temperatures 10 °C lower than those of today. Even so, the conveyor belt did not come to a complete standstill. In the

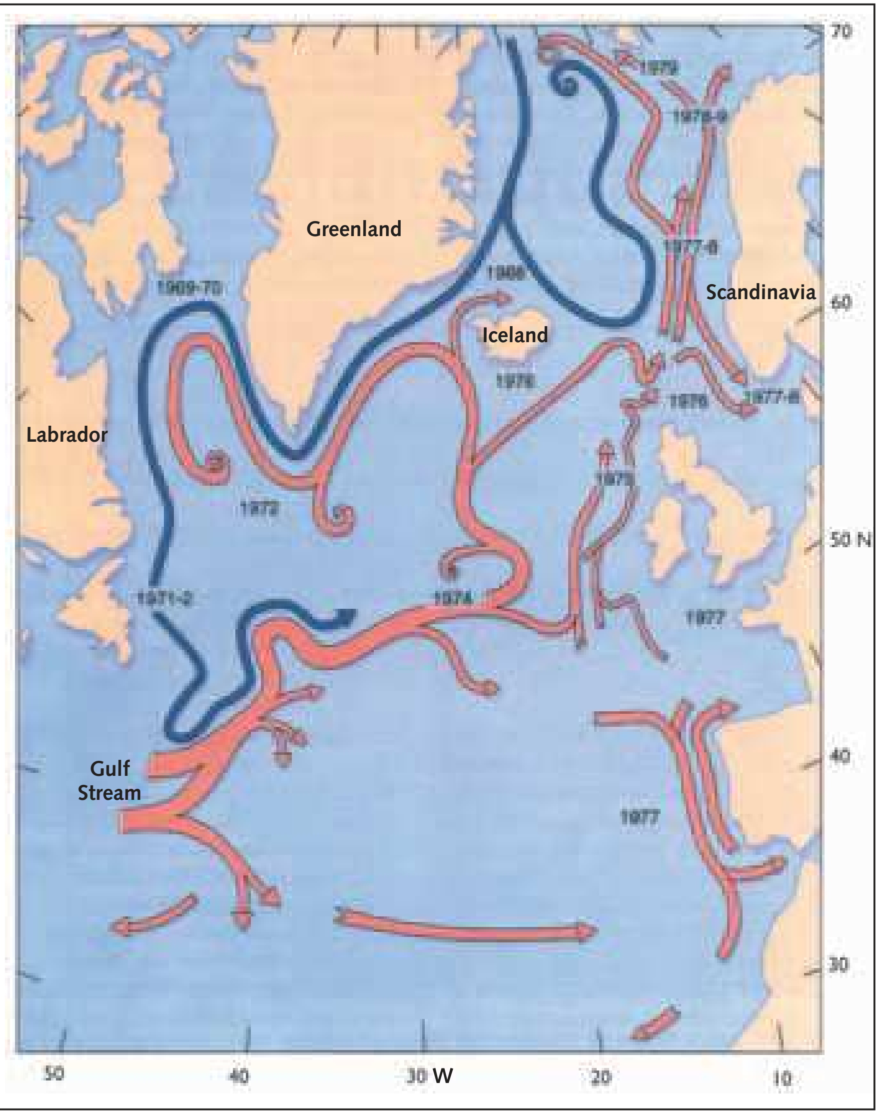


Figure 12

The great salinity anomaly of the North Atlantic Ocean between ~1970 and ~1980.

In 1968, sea ice from the Arctic Ocean brought an exceptional quantity of cold fresh water into the Atlantic Ocean. The dates of passage of this water are indicated on the figure. The cold current (in blue) descended from the Arctic between Iceland and Greenland, then along the coast of Labrador. At the beginning of the 1970s, it had reached the Gulf Stream which warmed the cold water which in turn flowed along the coast of Europe right up to Scandinavia.

Source: G. Reverdin, Les humeurs de l'océan, *off-series* Pour la Science, *No. 21, figure 4, p. 94. Copyright* Pour la Science, *October 1998.*

Atlantic, at the limits of the ice-covered area, the winter cooling was accentuated by violent and very cold catabatic winds which blew from the glaciers as they now do on the Antarctic continent. They also pushed the newly forming ice seawards, leaving on the spot the salt corresponding to the volume of ice thus formed. In this way, dense water was formed and sank to a depth (2,000 m) less than that of the NADW, representing a flux reduced by a good third. The conveyor belt was moving only very slowly; it is believed that it had a 2,000-year cycle instead of the estimated 1,500 years at present.

VARIABILITY OF THE ICE AGES: DANSGAARD–OESCHGER AND HEINRICH CYCLES

The oceanic circulation thus responds to the rhythm of the Ice Ages and interglacial periods. The ocean bears the perturbations but is not the cause of them. It is the astronomic cycle of Milankovitch, from the name of the Serbian scientist who proposed an astronomic theory of climate evolution, that plays the leading role. The underlying idea is that the energy the Earth receives from the Sun, and its distribution on the Earth's surface, depend on the parameters of the Earth's orbit around the Sun. This orbit is an ellipse, the more or less long form of which varies with a period of about 100,000 years. This produces a significant variation in the amount of energy received from the Sun. The precession of the equinoxes, with a period of 23,000 years, means that this ellipse turns in space, so that, whereas at present the Earth is at its closest point to the Sun in January, 11,000 years from now it will be at this point in June. Finally, the angle that the axis of the Earth's rotation makes with the plane of its orbit varies within about 3°, with a period of 41,000 years, thus modifying, at that speed, the distribution of the energy received as a function of latitude. By combining all these variation periods, Milankovitch demonstrated a very good correlation between the variations in energy received at 45 °N and long-term climate changes. The energy maxima correspond to the interglacial periods, and the minima to the Ice Ages.

However, progress in the more and more precise reconstitution of climate history has shown that, within the Ice Ages, there was a high level of climate variability, with warm peaks lasting from 1,000 to 3,000 years, or half the difference between the extremes of the Ice Ages and the interglacial periods. We have found twenty-five oscillations of this type between 75,000 and 10,000 years ago, which shows the extreme rapidity with which such fluctuations occur. These are called

Dansgaard–Oeschger cycles, from the names of their discoverers. These oscillations are marked by what is called Heinrich events, which themselves correspond to the coldest periods of the ice-age epochs. They recur at intervals of 7,000 to 10,000 years, and six have been found in the course of the last Ice Age. One thing is certain: all these fluctuations that modulate the glacial episodes cannot be linked to the astronomic cycle of Milankovitch.

It has been possible to establish a link between the Heinrich events and the instability of the ice caps. In 1988, Heinrich, analysing a core taken north of the Azores, noted that there were six exceptional sediment layers consisting of rock debris and not of clays rich in the usual Foraminifera. They were identified as debris transported by icebergs and released when the icebergs melted. The same layers have been found in all the cores from the Atlantic between 40° and 50° N, from Newfoundland to the Bay of Biscay. Such fall-out from the icebergs, corresponding to the melting of about 2% of the American and European ice caps, can be explained by the instability of the ice caps which, as they grow, encroach strongly on the sea, where they become unstable and break up, creating vast icebergs that are carried into the ocean where they melt. Each event is marked by a massive addition of fresh water to the ocean which slows considerably the circulation of the conveyor belt and diminishes further the already low efficacy of the heat pump of the North Atlantic: the temperatures reach their minimal values.

When the ice caps have been completely freed of their excess ice, the oceanic circulation restarts the conveyor belt which can therefore extend a little further towards the north, bringing relatively warm conditions during glacial periods. This is until the glaciers renew their growth in a new cycle that will be punctuated by Dansgaard–Oeschger oscillations, no doubt also depending on the ice–ocean coupling by mechanisms yet to be discovered. So we see that the perturbation initiated by the melting ice has been amplified by the response of the ocean to what, at the start, was only changes in sea-surface temperature and salinity.

A SAWTOOTH EXIT FROM THE LAST ICE AGE: THE RECENT DRYAS

The exit from the last Ice Age was not without a few jolts. About 12,500 years ago, when about half the ice of the northern hemisphere had already melted, when the ocean conveyor belt was restarting, when the most favourable part of the Milankovitch cycle (maximum insolation in the northern hemisphere) had been reached, suddenly, in a few decades, the cold returned, bringing almost glacial conditions into Europe for 1,000 years. This cooling did not correspond to any break-up of icebergs, as in the Heinrich events; nothing particular has been found in the sediment cores. It was, nevertheless, apparently due to an influx of fresh water which, as always, put a brake on the heat pump. Several hypotheses have been put forward to explain this. In the first phase of deglaciation, the water coming from the melting of the Laurentide (Canada) ice cap would have been discharged via the Mississippi River into the Caribbean Sea where it mixed with tropical water. Then, as it shrank, the glacier would have opened up access to the Saint Lawrence River so that the melt water, accumulated in a huge lake upstream, was discharged into the ocean, near convection zones. Similarly, it has also been suggested that, with the sea level rising, the Baltic, which until then had been a lake collecting the melt water from the European ice cap, became connected to the North Sea, there discharging its fresh water. And finally, we could blame the changes in the conditions in the Arctic. In fact, the Arctic Ocean has a vast continental plate along the coast of Siberia. This shelf was dry during the glacial period but became inundated owing to the sea-level rise. This was the time of the opening of the Bering Strait. This new area of shallow water is very favourable to the formation of sea ice which, with the Arctic circulation, would have been exported to the Greenland Sea and zones of convection, bringing to them huge quantities of fresh water.

All this shows that there is a coupling between the ocean and the cryosphere through the variable fluxes of fresh water which controls the formation of deep water, the intensity of the thermohaline circulation and the efficacy of the North Atlantic heat pump. This pump responds much more rapidly than we thought to the fluctuations in the amount of fresh water, producing within a few years significant climate variations.

A NEW FACTOR IN THE CLIMATE: HUMANITY. THE OCEAN AND CARBON DIOXIDE

It is only recently that we have been able to identify humanity as a new component of the climate system. For this, it has been necessary to measure systematically the concentration of carbon dioxide in the atmosphere at the observing station on Mona Loa (Hawaii) established by Keeling in 1958 for the International Geophysical Year. Thus we have seen that this concentration has increased year in, year out, at an annual rate of 0.5%. In parallel, the Earth's mean temperature has also increased, so we naturally look to see whether there is any relationship between the two phenomena, knowing that carbon dioxide has a strong greenhouse effect that could modify the radiation balance of the atmosphere. By using fossil fuels, we discharge huge amounts of carbon dioxide into the atmosphere: around 7 gigatonnes of carbon per year. We bear the responsibility for the increase in the concentration of carbon dioxide in the atmosphere. However, we only find in the atmosphere half of the gas produced. The other half can only be found in the continental vegetation or in the ocean. This raises two questions: What proportion does the ocean absorb? And does this absorption capacity have any limits?

THE OCEAN, A PHYSICO-CHEMICAL CARBON DIOXIDE PUMP

In the climate system, the ocean is the principal reservoir for carbon: 40,000 gigatonnes, compared with only 780 gigatonnes in the atmosphere (50 times less) and 2,000 gigatonnes in the continental biosphere (vegetation and soil). Most of the carbon in the ocean is in inorganic form: carbon dioxide gas, dissolved carbonates and bicarbonates, constituting a chemical system whose equilibrium point changes as a function of the exchange of carbon dioxide with the atmosphere. The increase or decrease in carbon dioxide in the sea-surface layer displaces this chemical equilibrium which, quite definitely, regulates the rate of absorption or resorption of the carbon dioxide. These exchanges depend on the relative concentrations of carbon dioxide in the atmosphere and in the sea-surface layer; they are characterized by what is called the partial pressure of the gas. If this is greater in the atmosphere than in the ocean, the gas will be absorbed by the ocean, which thus plays the part of a ‘sink’. If the opposite occurs, the ocean will release gas, thus becoming a ‘source’ of carbon dioxide for the atmosphere. Equilibrium is reached if the two partial pressures are equal, which is very rarely the case, because, on the one hand, the process of equilibration of the chemical system is slow and, on the other hand, the mixing processes continually renew the water at the air–sea interface.

So, depending on the conditions, the ocean can absorb carbon dioxide or release it. The solubility of the gas depends on the temperature of the sea water: the solubility is greater when the temperature is lower. The dynamic processes of oceanic warming will produce carbon dioxide; for example, in coastal or equatorial upwelling systems (see Chapter 4), the cold water at depth rises towards the sea surface and, in doing so, warms up, thus progressively giving up some of its carbon dioxide at the surface. Cooling processes lead to absorption of the carbon dioxide, as occurs in the zones of formation of North Atlantic Deep Water.

THE BIOLOGICAL CARBON DIOXIDE PUMP

Carbon dioxide is the source of carbon in the primary production (photosynthesis) of living matter. The biological production in the surface water of the ocean thus constitutes a carbon dioxide pump. Living organisms are carried towards the bottom when they die, undergoing decomposition and mineralization, enriching the deeper water in carbon dioxide. So the biological pump transfers carbon dioxide from the surface to the bottom, from where it will be returned when, finally, the deep water returns to the sea surface, whether as a result of upwelling or at the end of the long voyage at depth in the so-called conveyor belt. This voyage takes hundreds of years; only 0.4% of oceanic biological production actually enters the sediments on the sea floor.

THE OCEANIC FUTURE OF MAN-MADE CARBON DIOXIDE: LIMITS OF THE OCEANIC PUMP

An increase in the concentration of carbon dioxide in the atmosphere increases the partial-pressure difference between the atmosphere and the ocean. In other words, overall, the solubility of carbon dioxide increases as its atmospheric concentration grows. So it is not surprising, at first sight, that the ocean may have played, and continues to play, an important role by absorbing its share of man-made carbon dioxide. In the long run, this capability could be inhibited by the climate change induced. In fact, we expect that global warming will also warm the surface water of the ocean, thus diminishing the solubility of the carbon dioxide and the ocean's capacity to absorb it. For the pump to be efficient, the surplus carbon dioxide absorbed must be transferred to the deep water, so mixing and convection must not be lessened by climate change. But surface heating tends to stabilize the surface layer and limit vertical mixing with the deep water. Nor is a slowing-down of the conveyor belt to be excluded, according to the latest report of the Intergovernmental Panel on Climate Change (IPCC); this would attenuate the carbon dioxide pump, the zone of formation of North Atlantic Deep Water. And, moreover, this excess carbon dioxide transferred to deep water has only temporarily been removed from the atmosphere. The deep water, on returning to the sea surface, will sooner or later give up some of the carbon dioxide it had removed from the atmosphere several tens or hundreds of years in the past. As for the 0.4% of biological production that enters the sea-floor sediments, there is little hope that this sequestration will remove permanently from the system a significant proportion of the man-made carbon dioxide. The capacity of the ocean to absorb man-made carbon dioxide from the atmosphere is therefore apparently limited, and we should be better advised to concern ourselves with reducing its production than to expect the ocean to solve the problem.

Carbon dioxide is very abundant in the ocean and is never a limiting factor in primary production. So, in the first place, the biological pump is indifferent to any increase in carbon dioxide. It would not be indifferent, however, if climate change modified the functioning of marine ecosystems and their biological production. Globally, the stabilization of the surface-water layer (by an increase in its temperature), by limiting mixing with the deep water rich in the nutrient salts that are indispensable for photosynthesis, should diminish the intensity of the biological pump. We shall see later that the natural climate variability considerably modifies certain ecosystems. This can have a significant impact on the flux of carbon dioxide. For example, the El Niño phenomenon sufficiently perturbs the marine ecosystems to be detectable in the measurements of carbon dioxide at the Mona Loa station. The El Niño phenomenon manifests itself by completely hiding equatorial and coastal upwelling in South America (see Chapters 4 and 5), thus shutting off two important sources of oceanic carbon dioxide, which is manifested in a significant, but temporary, decrease in atmospheric carbon dioxide concentrations. This is but a short pause, however, in the ineluctable process of increasing carbon dioxide concentration. Global warming can modify the frequency and amplitude of El Niño and the North Atlantic Oscillation, with consequences for the ecosystems that will also interfere with the carbon dioxide biological pump.

REDUCING THE UNCERTAINTIES

WHAT CLIMATE CHANGES FOR THE NEXT CENTURY?

We can see that the unknowns and the doubts are still many. The possible climate impact due to the increase in greenhouse gases raises a double challenge: political and economic. This illustrates the difficulty experienced in achieving international understanding on the implementation of the Kyoto Protocol (1997) to reduce by 2008–12 the production of greenhouse gases by 5.2% relative to the 1990 level. This was, nevertheless, a Protocol drawn up in the context of the United Nations Framework Convention on Climate Change signed by 150 countries during the Rio de Janeiro Earth Summit in 1992. It is also a scientific challenge to propose reliable scenarios of climate change in the next century. In 1988, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) created the IPCC and charged it with evaluating the available scientific information and providing advice on the foreseeable impacts and the prevention/adaptation measures. The IPCC published its third report in 2001. It proposed several scenarios for the evolution of emissions of greenhouse gases, based on hypotheses of economic, demographic and technological development worldwide. These scenarios have been used to drive models simulating climate change during the next 100 years. Obviously, these simulations are only worth what the models are worth and it is difficult to calibrate them against past climate because, in the known past (to 500,000 years ago), there has never been such great variation in atmospheric greenhouse-gas concentrations. Newcomers to the climate system, we have already made our presence felt. During the last 500,000 years, between the extremes of ice-age cold and interglacial warmth, the carbon dioxide concentrations have varied between a minimum value of 180 ppm (parts per million) and a maximum of 280 ppm. We now have a level of 370 ppm, or 30% more than the natural maximum. So we are now outside the natural scheme of things and we have no historical reference. The reconstitution of palaeoclimates allows us to analyse or even quantify the natural processes in order to improve and validate the models in a natural situation, but that does not guarantee the quality of the model in the face of an extraordinary perturbation such as we are now causing. Nevertheless, we are not working completely without a safety-net: this man-made perturbation started detectably about 150 years ago and we know quite well the changes in the atmospheric concentration of carbon dioxide since then. Taking 1850 as the point of departure, we can apply the models in 'natural' mode without taking into account the increase in carbon dioxide, on the one hand, and in 'man-made' mode taking the increase into account, on the other hand. The comparison is eloquent: the two simulations are significantly different, especially since 1950; the 'man-made' simulation agrees far better with the observations than the 'natural' simulation. That obviously gives us confidence, for, if these models work well for the last century, why should they not work well for the next? And even if the perturbation increases, it remains qualitatively similar.

On the basis of the scenarios and the ten or so models available, the increase in mean temperature will be between 1.4 °C and 5.8 °C, the range of variability corresponding more to the emission scenarios than to the models themselves. The rise in sea level would be between 11 cm and 77 cm, due much more to the expansion of the sea water (between 11 cm and 43 cm) caused by the increase in sea temperature than to the melting of glaciers (between 1 cm and 23 cm).

The IPCC was not only concerned with a 100-year forecast, but was also interested in changes in climate variability that might arise on other time-scales.

The recent history of the El Niño phenomenon shows that its extent and frequency vary on a decadal time-scale. For example, if we refer to the values of the SOI, we see that negative anomalies predominated from 1975 to 1998, whereas the opposite was true before 1975, at least since 1945. The negative anomaly corresponded to the two strongest El Niños of the century: 1982–83 and 1997–98, and to an 'extended' El Niño which produced warm anomalies in sea-surface temperature in the central Pacific from 1991 to 1995. Is this situation the result of a natural climate variation or is it a sign of global change drawing ENSO towards its warm phase? This raises three questions:

1. Will the equatorial Pacific evolve towards a more favourable regime of the El Niño type (negative SOI anomalies, positive sea-surface temperature anomalies)?
2. Will the frequency and amplitude of the phenomenon be accentuated?
3. Will the climatic consequences be amplified?

The difficulty with taking climate variability into account on the scale of El Niño in the long-term models is illustrated by the difficulty we still have in making a forecast some months in advance of an El Niño. The prudent conclusion of the scientific experts on the IPCC is that, in fact, we should expect an evolution towards an El Niño-like situation (lower values of SOI) without such events being more frequent or their amplitude greater. The associated climatic perturbations would be strengthened: more abundant rainfall along the coast of Peru, increased drought in Indonesia.

In its report for political decision-makers, the IPCC says nothing about the evolution of climate variability on the decadal time-scale of the NAO. This is because there is insufficient agreement in the simulations produced by the different models. It is nevertheless clear from the scientific report that, even if the models do not agree, the trend is towards an increase in the mean value of the North Atlantic Oscillation index; in other words, mild, wet and changeable winters in western Europe.

The evolution of the thermohaline circulation is crucial if we are concerned with climate change on longer than decadal time-scales. It is mainly controlled in the North Atlantic, the zone of formation of the North Atlantic Deep Water, the driving force of the ocean conveyor belt and the heat pump, and by the fresh-water balance; that is, precipitation and ice formation (which, by increasing the sea-water salinity, increases its density). Global warming, by provoking a general retreat of the sea ice, with an increase in rainfall, could slow down the thermohaline circulation and therefore paradoxically, as in the recent Dryas, be the cause of a cooling rather than a warming in western Europe. The history of past climates has shown us that climate change caused by the slowing down of this circulation could be very rapid: a few years or decades. It is also important to pay attention to and reflect in the models the factors that control the genesis of this circulation; especially as this evolution may not be progressive and continuous – there are clearly thresholds that make the system flip irreversibly from one configuration to another. The Dansgaard–Oeschger cycle and the Heinrich events testify to sudden flips which, at first sight, seem periodic but which are only the manifestation of the thresholds that should not be crossed if a stable configuration is required. Do we then risk a complete shutdown of the heat pump? None of the models forecasts this for the next 100 years. All effectively forecast for this period a slow-down in the thermohaline circulation but insufficiently to doubt the warming of western Europe. But anything is possible if the measures taken to limit the production of greenhouse gases are insufficient. Some models foresee that, for an increase in global temperature between 3.7 °C and 7.4 °C, the situation could flip to one in which there was a shut-down of the thermohaline circulation, which would certainly refrigerate Europe, but would also have an impact on the rest of the world. If we recall that the 100-year forecast of the IPCC places the range of the mean-temperature increase between 1.4 °C and 5.8 °C, we have reason to worry.

THE RESEARCH PROGRAMMES

Incertitude, as we have seen, is not lacking. If it is now certain that the increase in man-made greenhouse gases has an effect on the planet's climate, that we have already detected the effects and that the trend to global warming will continue in the coming century, it is still difficult to evaluate its amplitude, the regional impacts and the consequences for climate variability. The scientific research backing the IPCC is also a major factor in making progress. It has been organized for the last twenty years around international multidisciplinary programmes under the aegis of international organizations.

The first of these, chronologically, was the World Climate Research Programme (WCRP) launched in 1980. It was organized jointly by ICSU (then the International Council of Scientific Unions, now the International Council for Science, emanating from national academies of science), the WMO and the IOC. The WCRP's objective was to establish the scientific basis needed to understand the physical phenomena governing the functioning of the climate system in order to evaluate its predictability and in what ways human activities would modify it. It had, therefore, to take into account all the compartments of the system: atmosphere, ocean, cryosphere, the Earth's surface, and the fluxes between them. Regarding the ocean, two pilot programmes were organized in the years 1980–90. The TOGA study between 1985 and 1995 of the interannual variability of the climate and, in particular, the El Niño phenomenon, was the opportunity to set up in the tropical Pacific Ocean the first quasi-operational ocean-observing system. The World Ocean Circulation Experiment (WOCE) between 1990 and 1997 was concerned with the whole global ocean in its three dimensions, with a view to evaluating currents, transport of heat and carbon, with the best possible resolution: the first-ever total-ocean experiment in terms of its overall objective, but also of the means employed (from research vessels to satellites). The two programmes have been extended through the ongoing Climate Variability and Predictability (CLIVAR) programme which includes all the compartments of the climate system and the principal time-scales relevant to climate variation: interannual (El Niño), decadal (NAO), centennial (thermohaline circulation), which, as we have seen, still conceal many unknowns.

Physics alone cannot solve the problem. The living world and humanity are actors in the climate system via the carbon cycle, which governs the atmospheric concentration of carbon dioxide. But they also suffer the consequences of climate change which can be dramatic for ecosystems and human societies. ICSU in 1986 adopted a vast programme to describe and understand the physical, chemical and biological interactions that regulate the functioning of the whole-Earth system, the changes it undergoes and the way in which they are modified by human activities. This was the International Geosphere–Biosphere Programme (IGBP). This vast programme is organized in projects and, for our present purposes, notably the JGOFS and GLOBEC projects. JGOFS (Joint Global Ocean Flux Study) was set up in 1987 with the objective of understanding and quantifying the carbon cycle in the ocean in order to evaluate the flux of carbon at the ocean's interfaces with the atmosphere and the ocean floor, and to forecast its evolution. It was a difficult programme to implement, bearing in mind the number of physical, chemical and biological parameters to be considered. Also, besides modelling and some measurements (temperatures, carbon dioxide concentrations and surface chlorophyll) that can be made more or less routinely from merchant ships and a few rare fixed measuring stations, most of the work is done from one or more research vessels in limited areas representative of typical situations that could be qualified as biogeochemical provinces. GLOBEC (Global Ocean Ecosystem Dynamics) started in 1991 and has, as its name indicates, the aim of understanding how global change could modify the functioning of marine ecosystems and affect the abundance, diversity and productivity of marine populations at the bottom of the food chain, from primary production to small pelagic species, especially fishes, and the juvenile stages of fishes, which are the determinant stages, especially for the future of exploited species.

All these research programmes are long-term and have allowed the IPCC to refine its forecasts, but there remains a great risk that, owing to political inertia in the application of real measures to diminish greenhouse gas emissions, the changes now taking place go much faster than progress in our capacity to forecast them.

4 Ecosystem dynamics

PRIMARY PRODUCTION

The living world of the Earth synthesizes organic matter from mineral elements. This synthesis is obviously not free of charge: energy is required. In the majority of cases, it is provided by the light of the Sun. Sometimes, in the absence of light, life finds the necessary resources in chemical reactions. This is the case, for example, in ecosystems established at the bottom of the ocean around hot hydrothermal sources in the absence of any light source. Even if there are good reasons to think that life was originally created on the basis of these chemosynthetic processes, there is no doubt that photosynthesis is the source of primary production that has predominated for billions of years and which, using solar radiation, has ensured the development of life on the Earth and in the sea.

The primary ingredients for the fabrication of organic matter are fairly simple: carbon dioxide (CO_2) and water (H_2O); using chlorophyll, which can fix light energy, the ingredients combine in accordance with the following simplified equation to produce the basic organic matter: $CO_2 + H_2O + \text{light} = (CH_2O) + O_2$

Living matter also requires other elements: nutrient salts that are the sources of nitrogen, phosphorus and silicon, as well as a whole range of the mineral elements that make a region more or less fertile. On land, a shortage of one or another of these elements can be remedied from external sources, by irrigation and the addition of fertilizer; with the necessary means we can even create golf courses in deserts. It is no doubt difficult to speak of a desert when referring to the ocean, where there is no shortage of water, but, as on land, there are very big differences in fertility from one region to another. In the sea, the vegetal plankton or phytoplankton, like the grass in a meadow, is responsible for the primary production that is the base of the marine food chain leading to the fish we eat. This plankton comprises microscopic monocellular algae of only a few microns across and whose abundance determines the fertility of a given ocean region. We can really speak of 'marine meadows', and there is a very big difference in yield amongst those at the centre of anticyclonic regions, which we may call ocean deserts, owing to their very low production, and others in certain coastal regions, as in Peru, where the production is nearly a hundred times greater.

MARINE MEADOWS

The colour of the ocean is an indicator of this fertility. But the eye of the observer can be deceived. If we fly over Brazil we can see with the naked eye the contrast of the luxuriant Amazonian forest with north-eastern Brazil not so far away yet dramatically arid. The differences are much more subtle in the ocean and, at first sight, an observer scanning the water surface will scarcely learn anything about the plant wealth under it, especially as, for the traveller or the sailor, most of the time, the colour of the sea is only the reflection of the sky: the blue of the Mediterranean turns gray when the sky is overcast. The true colour of the ocean, free from the artefact of reflection, is that seen by the swimmer looking downwards from the surface. It is the colour that can be obtained from outer space by certain types of radiometers on board satellites (see Chapter 6).

The colour of the ocean depends above all on the optical properties of the water, which is selective in its absorption of solar radiation: it lets through blue light much more easily than other colours; this is the blue of the open ocean that gave rise to the poetic term 'azure main'.

But this blue that poets may dream of can be altered by the 'impurities' that the ocean contains, whether it is, in the coastal zone, the sediment discharge carried by rivers and streams, or quite simply living organisms, especially the chlorophyll-rich phytoplankton which tends to colour the ocean green – the glaucous colour that was said to be the charm of the eyes of Athena. And the more phytoplankton, hence chlorophyll, there is in the ocean, the greener the ocean will seem. By analysing the light emitted by the ocean (its colour) and by comparing the light intensity of the wavelengths characteristic of chlorophyll (blue for

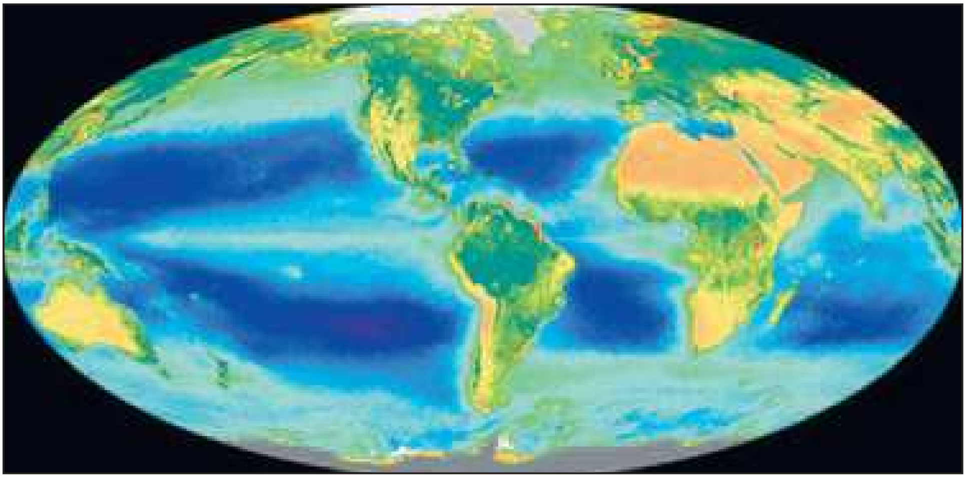


Figure 13
Map of the global chlorophyll distribution as seen by the SeaWiFS satellite between September 1997 and August 2000. In the ocean the concentration of chlorophyll increases from blue-violet (<0.1 mg/m^3) to red (>10 mg/m^3).
Source: SeaWiFS Project, US National Aeronautics and Space Administration (Goddard Space Flight Center) and ORBIMAGE.

maximal absorption, green for minimal absorption), we have a measure of the ocean chlorophyll concentration, hence its potential richness. This is what is done by remote sensing using radiometers on board satellites which measure the light intensity of the ocean at the wavelengths characteristic of chlorophyll.

Figure 13 shows the mean chlorophyll concentrations in the world ocean and on the continents between September 1997 and August 2000. It was based on measurements taken by the SeaWiFs satellite which makes it possible to draw up an inventory of terrestrial and marine vegetation. We can see that there are contrasts in the ocean analogous to those observed on the continents. To keep as close as possible to reality, the pallet of colours used for the terrestrial vegetation ranges from the colour of desert sand to the blue-green of the Amazonian forest, and that for the ocean, from the blue-violet of the poorest regions to the yellow, then red, of the richest regions, via green.

Immediately striking in figure 13 is the predominance of blue, hence the poorest regions, in the middle of the ocean basins – the Pacific, Atlantic, Indian – vast 'desert' areas that contrast with the relative richness we can see in the regions at higher latitudes and along the coasts.

Interpretation of the measurements is not always easy, and it seems that extreme values (in red) at the mouths of the major rivers (Amazon, Congo, Río de la Plata) correspond more to the sediment load these rivers carry to the sea and which bias the measurement of the chlorophyll. Equally remarkable are the green 'tongues' that extend along the equator in the Pacific and, to a lesser extent, in the Atlantic. And remarkable too are the zones of enrichment around the Earth at the edges of Antarctica, the south of South America, southern Africa and Australia.

FACTORS LIMITING PRIMARY PRODUCTION

In the ocean, there is obviously no lack of water, nor of carbon dioxide, the source of carbon: the ocean is saturated in it. The Sun, the exclusive source of light for primary production, bathes the water surface; but the water absorbs the solar radiation rapidly, so that this production will necessarily be limited to the surface layer of the ocean. The dark depths of the ocean below about 100 m depth are not favourable to the development of life. Only the oases centred on deep hydrothermal vents and dependent on other sources of energy escape this constraint. The other factor in ensuring the fertility of the oceans is the availability of nutrients. However, these are much more abundant at depth than at the surface, and that is easy to understand. Life is a renewable system that feeds ceaselessly on its own death: the decomposition of dead organic matter returns to the mineral world the elements that, alive, it had borrowed: water, carbon dioxide, nutrients, which become newly available to the living world. In this way ecosystems can be close to equilibrium in which life and death are quantitatively equal. But nothing escapes gravity, and marine organisms, deprived at their death of the capacity to swim, are inexorably drawn to the bottom, decomposing and mineralizing as they sink. In this way they restitute most of the inorganic components, not in the surface layer where conditions are suitable for photosynthesis, but at depth, without light, separated from the surface layer by the barrier erected by the thermocline, which is also a 'nutricline', separating the surface layer, poor in nutrients, from the deep water, where nutrients abound.

To ensure its fertility, the ocean must resolve this difficulty: bring the nutrients from the deep water to the well lit surface water. It does this by various enrichment mechanisms, and the map in figure 13 identifies the regions where such processes are operating. It is the movements of the ocean that, finally, control ocean productivity.

MARINE 'DESERTS' IN THE CENTRE OF MAJOR OCEANIC GYRES

The term 'desert', sometimes used to designate vast zones of low productivity in the middle of the oceans, is no doubt misapplied: certainly, they are not regions of intensive fisheries but, even so, you can find fish there that do not look as if they are threatened by death from starvation. It is doubtless better to be shipwrecked in such regions than to be lost in the middle of the Sahara. Nevertheless, they are the least productive regions of the ocean, and there must be a good reason for it, though not the lack of water as in the Sahara.

If we compare the chlorophyll distribution in figure 13 to the distribution of the surface currents (figure 1), we see that these oceanic pseudodeserts correspond to the vast anticyclonic gyres described in the preceding chapter, situated in the middle of the ocean basins in both hemispheres (except in the Indian Ocean whose maximum northward extension at 20° N makes it a semi-ocean with its own unique monsoon regime).

The constant accumulation of surface water inside the gyre leads to a relative deepening of the thermocline, hence of the water layer rich in nutrient salts which, far from the light, necessarily has a low productivity. The thermocline is clearly not impenetrable, of course, and the turbulence, even if reduced across the thermocline, always ensures a minimum flux of nutrient salts into the surface layer and adequate to maintain a sufficient level of photosynthesis to sustain the food chain. Nevertheless, it is too feeble to change significantly the natural colour of the ocean water.

COASTAL UPWELLING

A close-up of the colour of the sea in the Benguela Current along the west coast of South Africa (figure 14) in the latitudes of the anticyclonic circulation, with the same colour pallet as in figure 13, illustrates the contrast between the low chlorophyll concentration in the offshore water (about 0.1 mg/m^3) and the great richness of the coastal zone where the concentrations are a hundred times higher and which also contrasts with the extreme aridity on land. We are alongside the Namibian desert and it is difficult to impute this richness of the coastal waters to the handful of small rivers there which are dry most of the time. We find the same situation coupling marine luxuriance and terrestrial aridity on the eastern side of the other subtropical anticyclonic circulations of the Atlantic and Pacific Oceans: the Canaries Current alongside the Sahara, the Humboldt Current facing the Atacama Desert (Chile–Peru), and the California Current, with a dry inland climate, though not desert. This association is

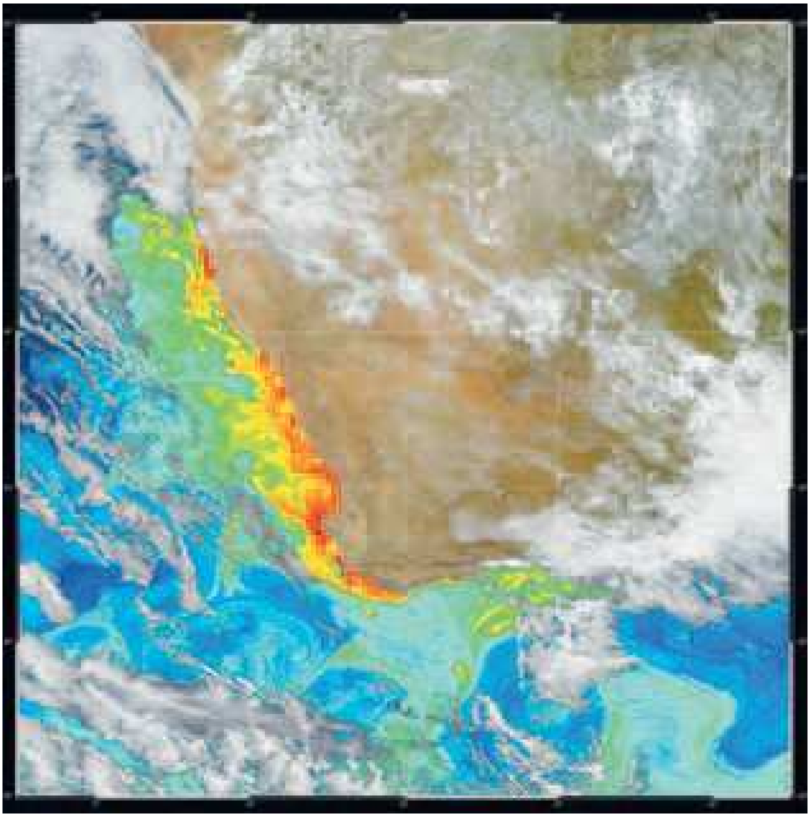


Figure 14
Chlorophyll in the upwelling of the Benguela Current off South Africa on 21 February 2000. The colour scale is the same as for figure 13.
Source: SeaWiFS Project, US National Aeronautics and Space Administration (Goddard Space Flight Center) and ORBIMAGE.

not found in the Indian Ocean, which is a half-ocean blocked to the north by the vast Asian continent, itself imposing a seasonal monsoon regime. So there is no permanent anticyclonic gyre as in the northern basins of the other two oceans. Corresponding to the summer monsoon, which blows from the ocean to the continent, there is along the Somali coast a highly productive zone analogous to the two mentioned above. We can easily infer a relationship between the current direction along these coasts, the wind, and the biological productivity observed there. All these regions owe their biological prosperity to the same phenomenon, the upwelling of deep water rich in nutrient elements towards the sea surface near the coast.

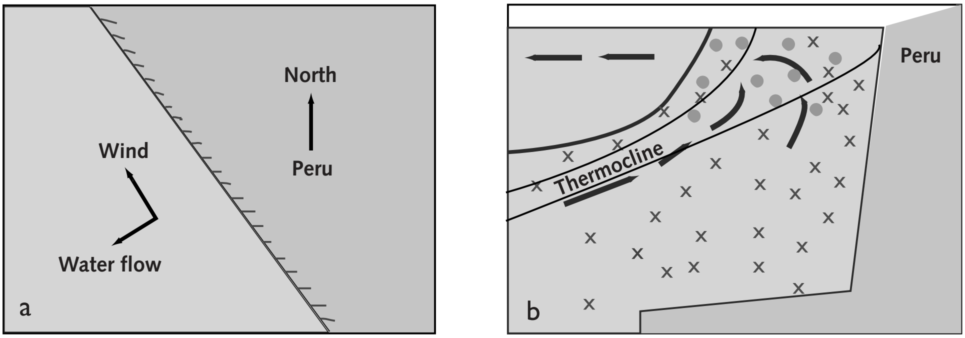


Figure 15
Diagram showing coastal upwelling (southern hemisphere).
(a) **A wind blowing parallel to the coast creates an average water flow to its left and at a right angle to the direction in which it is blowing.**
(b) **The surface water blown offshore is replaced along the coast by underlying cool water rich in nutrients (represented by crosses); the circles represent phytoplankton.**

We must return to the origin of the forces controlling the dynamics of the oceans to be able to understand the phenomenon; in the present case, once again, it is the wind and the Coriolis force. The California and Humboldt Currents in the Pacific Ocean, the Canaries and Benguela Currents in the Atlantic Ocean, driven by the trade winds, or the Somali Current, driven by the summer monsoon of the Indian Ocean, have, due to the Coriolis force and in conformity with Ekman's theory, a component driving them towards the middle of the anticyclonic gyres; that is, offshorewards. This offshoreward movement creates a 'demand' for replacement water at the coast which can only come from deeper cold water rich in nutrient salts. This coastal upwelling is shown in figure 15. Alexander von Humboldt, on his way to Trujillo on the coast of Peru in 1802, had the curiosity to measure the temperature of the atmosphere, which was quite ordinary, but also that of the ocean, which was much less so. He was surprised to find that, 'in the middle of the current', the temperature was 16 °C, whereas 'on the outside of the current' (that is, further offshore), it was between 26 °C and 28.5 °C, and moreover, that the temperature of the air, 17.8 °C, was higher than that of the sea. He could not help asking himself what was the origin of this cold water, as it could not have been cooled by the air over it. He was the first to observe this phenomenon (his name was given to this 'cold' current). He was also the first to propose an explanation: he suggested that this cold current flowing from the south towards the equator had a polar origin; it was the correct explanation. A few years later, Urbain Dortet de Tessan, a hydrographer of the French royal navy, who participated in the voyage around the world of the frigate *Venus* (1837–39) under the command of Admiral Abel Dupetit-Thouars, was the first to reach the conclusion that this cooling of the ocean was due to the upwelling of deep water: 'We must conclude that, in the Peru Current, the surface water is constantly renewed along the coast, being replaced by deeper, hence colder, water', he wrote in his logbook published in 1844. It is thanks to Ekman (1902), who mathematically formulated the action of the wind on the sea surface, that we have the solution, although this did not stop the Frenchman J. Thoulet from writing, as late as 1928, that the cooling of the coastal waters of Chile was due to the melting of the snow of the Andes Mountains.

This upwelling of deep water brings to the sea surface large quantities of nutrient salts, thus making the coastal zone extremely fertile, where fish are generally abundant. In the early 1970s, the catches of anchovy in the Peruvian upwelling area amounted to some 10 million tonnes per year; this was nearly a quarter of the world catch, by weight though not by value, as most of the catch was converted into fishmeal for animal feed (about 30% of world fish catches are used for animal feed). Peru and Chile together accounted for some 16 million tonnes of the 86 million tonnes of the world marine fish catch (1989), or 18% of the total. There are also several million tonnes of anchovies or sardines fished in the California, Canaries and Benguela Currents.

Of all these coastal upwelling systems, that of the Humboldt Current is the most famous, not only because it is the most productive, but also because it seems to be the most capricious, because of the El Niño phenomenon, for which it was the cradle (see Chapter 5).

THE EQUATORIAL SINGULARITY

In figure 13, the existence of the equator is attested to (if that were really necessary) by a band relatively rich in chlorophyll which extends all along the equator, clearly separating the northern and southern hemispheres of the Atlantic and the Pacific. Obviously, this is no accident: the equator is truly a singularity in the dynamics of the ocean. The Coriolis force is zero at the equator and is of different sign in one hemisphere from the other: the anticyclonic gyres turn clockwise in the northern hemisphere and anticlockwise in the southern hemisphere. So what happens along this equatorial dynamics frontier? Normally, the trade winds blow from east to west along the equator, driving westwards a strong current (the South Equatorial Current). Leaving the equator behind, the Coriolis force, which is zero at the equator, picks up strength and drives the surface water towards the right of the current (that is, northwards) in the northern hemisphere, and to the left of the current (that is, southwards) in the southern hemisphere (figure 16). The surface water 'diverges' and therefore creates a demand for replacement water along the equator, as we saw previously in coastal upwelling. This demand for water is met by the upwelling of deep cold water rich in nutrients which therefore fertilize the equatorial region of the Pacific and Atlantic Oceans. The equivalent process is not found in the 'half-size' Indian Ocean subject to the monsoon regime which, accordingly, does not have the same symmetry about the equator.

This situation can be perturbed, as the difference between the image for December–February 1998, which corresponded to an El Niño (the equatorial enrichment has disappeared), and that for June–August 1998 a few months later after El Niño, when equatorial upwelling was re-established (figure 17). During an El Niño, the trade winds weaken or disappear, the currents reverse along the equator and flow eastwards. The Coriolis force then induces the surface water to 'converge' (and no longer 'diverge') towards the equator where it accumulates, thus annulling the upwelling mechanism: the biological production is thus much reduced.

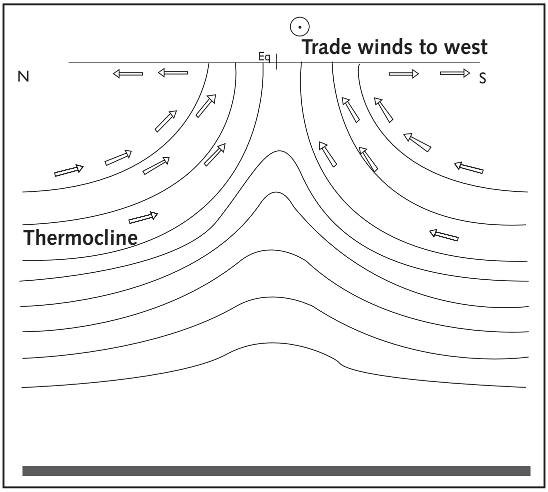


Figure 16
Diagram of equatorial upwelling.
The trade winds, which blow from east to west along the equator, drive the surface water, under the influence of the Coriolis force, towards the north in the northern hemisphere and towards the south in the southern hemisphere. There is a 'water demand' along the equator which leads to the upwelling of the deeper water.

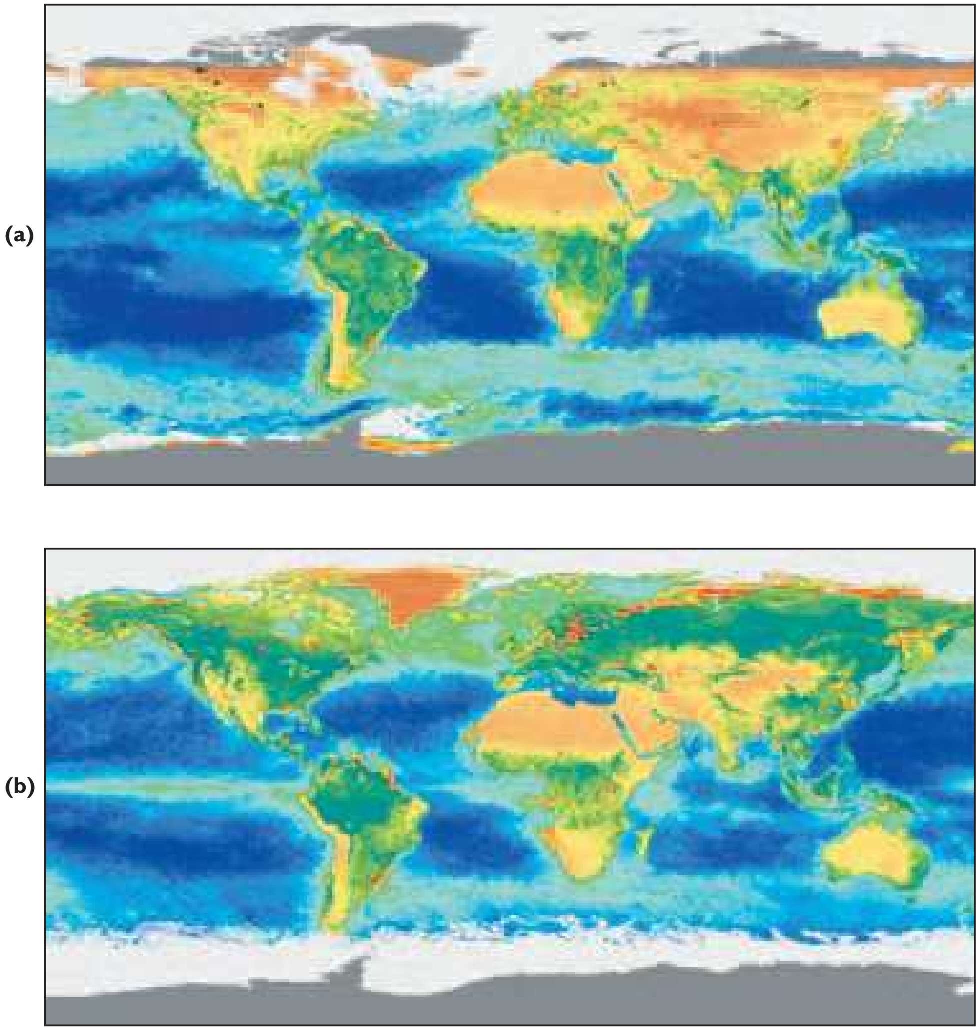


Figure 17

Chlorophyll along the equator in the Pacific Ocean as seen by SeaWiFS.

(a) **December 1997 to February 1998. An El Niño episode: the equatorial upwelling has disappeared and the chlorophyll concentration is low along the equator.**

(b) **June to August 1998. A La Niña episode: the equatorial upwelling is intense and chlorophyll concentration is high along the equator.**

Source: SeaWiFS Project, US National Aeronautics and Space Administration (Goddard Space Flight Center) and ORBIMAGE.

SPRING BLOOM: THE EXAMPLE OF THE NORTH ATLANTIC

In the tropics, the energy the ocean receives from the Sun is abundant and the seasonal variations are small. The tropics, in normal circumstances, are characterized by the permanence of a thermocline separating the warm, homogeneous surface layer from the deeper water of the ocean. As a density barrier, the thermocline blocks the passage of nutrient salts to the well lit surface layer, the euphotic layer, thus limiting productivity. Equatorial and coastal upwelling which, as a result of wind stress, cause the thermocline to rise towards the surface, are special features of the tropical world. In these tropical systems, the multiannual perturbations, such as El Niño, rather than the seasonal variations, are the main source of variability, as we have seen for the Pacific and Atlantic. The further from the tropics, towards the poles, the more the seasonal variations linked to the Sun's declination (height of the Sun in the sky, day length) will increase, reaching their maximum at the poles where there is a six-month-long day followed by a six-month-long night. These seasonal variations have a direct impact on two parameters that control primary production and can limit it: the availability of nutrient salts and the thickness of the euphotic layer.

The characteristic permanent-thermocline regime of the tropics is, at higher latitudes, replaced by that of a seasonal thermocline. In summer in temperate latitudes, with the help of the day length and the angle of the Sun, the solar energy is sufficient to create a quasi-tropical structure with a warm, homogeneous surface layer separated from the deep water by a strong thermocline. In autumn and winter, the surface layer cools, the vertical stratification weakens, and the wind increases vertical mixing: there is no more obstacle to the turbulence bringing the nutrient salts into the surface layer. Nevertheless, primary production decreases in winter in spite of this fertilization of the euphotic layer. We thought, with a certain logic, that it was the insufficience of the winter insolation that provoked this vegetal 'hibernation'. In fact, rather than the lack of light, it appears that the cause is the uncomfortable conditions for the phytoplankton created by the turbulence. The phytoplankton cells are passive and go where the water movements carry them. In the absence of a thermocline, the turbulent motion makes them migrate unhindered from the illuminated surface to the deep water away from the light where they no longer have sufficient energy resources for photosynthesis. The time spent outside the euphotic layer, and the difficulties of adaptation to these continually changing light conditions, combine to inhibit the productivity of the phytoplankton. In spring, the Sun regains its vigour: it rises earlier, mounts higher in the sky and sets later. The oceanic surface layer warms up, the thermocline becomes re-established. The phytoplankton above the thermocline finds stable lighting conditions again and benefits from the presence of the nutrient salts that the winter mixing brought and which the phytoplankton was not able to make use of; now it reproduces and grows. This is the spring bloom of the phytoplankton. Even if the spectacle is not as good as the blooming cherry trees or the buttercups in the meadows, the water surface grows greener all the same, and the colour of the ocean measured from space allows us to follow this development, as shown in figure 18 which illustrates the phenomenon in the North Atlantic. As time passes, the nutrients are consumed, the summer thermocline weakens the turbulent mixing, and the source of nutrient salts dries up; primary production decreases and the ocean returns to its winter lethargy to regenerate the supply of nutrient salts for a new bloom in the following spring. Thus it is the solar cycle that ensures at the opportune moment the availability of light energy, fertilization of the surface layer and its stability, all conditions necessary for the development of the marine meadows.

ANTARCTIC DIVERGENCE AND THE HNLC PARADOX

Around the Antarctic continent the ocean circulates unimpeded, except possibly in the narrow Drake's Passage between Cape Horn and the Antarctic Peninsula. Driven by the westerly winds whose reputation is very well established (the roaring 40s and the howling 50s), the huge Antarctic Circumpolar Current follows the Antarctic continent flowing from west to east between 65° S on the continental side and about 40° S, some 2,500 km equatorwards. Between this current and the Antarctic continent there is a counter-current (flowing westwards) which is very cold: the Antarctic Polar Current. This current is the result of a very special wind regime on the Antarctic continent: the catabatic winds, which are among the most violent on the planet. Over the peaks in the centre of the continent, where it is intensely cold all year round, a kind of cold-air dome forms which is therefore much denser than the surrounding air. Owing to its high density this air flows downslope and literally rushes towards the coast at speeds of up to 200 km/h. At the coast and forced to the left by the Coriolis force, the winds drive a current of very cold water in two directions. The first is horizontal, from east to west, all around the continent; the other is vertical, from the surface towards the bottom: the Coriolis force (to the left of the current in the southern hemisphere) will tend to make the water accumulate at the coast where, being cold, hence dense, it will have no other possibility than to sink towards the bottom along the continental slope, exactly like the catabatic winds mentioned earlier. The cold water that carpets the ocean floor is formed in this way. At the interface between this Polar Current (flowing from east to west) and the Antarctic Circumpolar Current (flowing from west to east), under the action of the Coriolis force, a very strong divergence zone is created: this Antarctic Divergence at about 65° S also encircles the continent. The water flux in this zone is considerable. In the Antarctic Circumpolar Current, the water from the Divergence is carried northwards all along its trajectory around the Antarctic continent until it sinks at the Antarctic Convergence, 20° further north, under the less-dense surface water, thus becoming what is known as the Antarctic Intermediate Water (see Chapter 2 and figure 2). The result is a heavy demand for deep water at the Divergence: in this case, the water does not move towards the surface from a depth of 100 m or 200 m, as in coastal upwelling, but from more than 2,000 metres depth. This rising water brings a significant flux of nutrient salts, and figure 19 clearly shows a large and rather heterogeneous zone relatively rich in chlorophyll in the Antarctic Circumpolar Current.

And yet there is a paradox here. The Antarctic Divergence brings to the surface a supply of nutrient salts greater than that of coastal upwelling: for example, we find in the richest and most productive coastal upwelling, that off Peru, a maximum nitrate concentration of 22 µmol/l, compared with 30 µmol/l in the Antarctic Divergence which is the oceanic zone that is the richest in nutrient salts. But whereas the water from coastal upwelling, under the effect of intense primary production, expends its nutrient salts within a few tens of kilometres, or within a few days of its movement offshorewards, the water of the Antarctic Circumpolar Current maintains its high level of nitrate till its arrival at the Antarctic Convergence 2,000 km to the north, or about 200 days later. Yet, the concentration of chlorophyll and the productivity measured in the Antarctic (1–1.5 mg/m^3 of chlorophyll and 60–165 gC/m^2 per year) are sufficiently high to be detected from outer space; even so, they are much lower than those measured in coastal upwelling where the values are up to ten times greater and where we would expect such enrichment. This is the paradox of the systems known as HNLC (high nutrient, low chlorophyll).

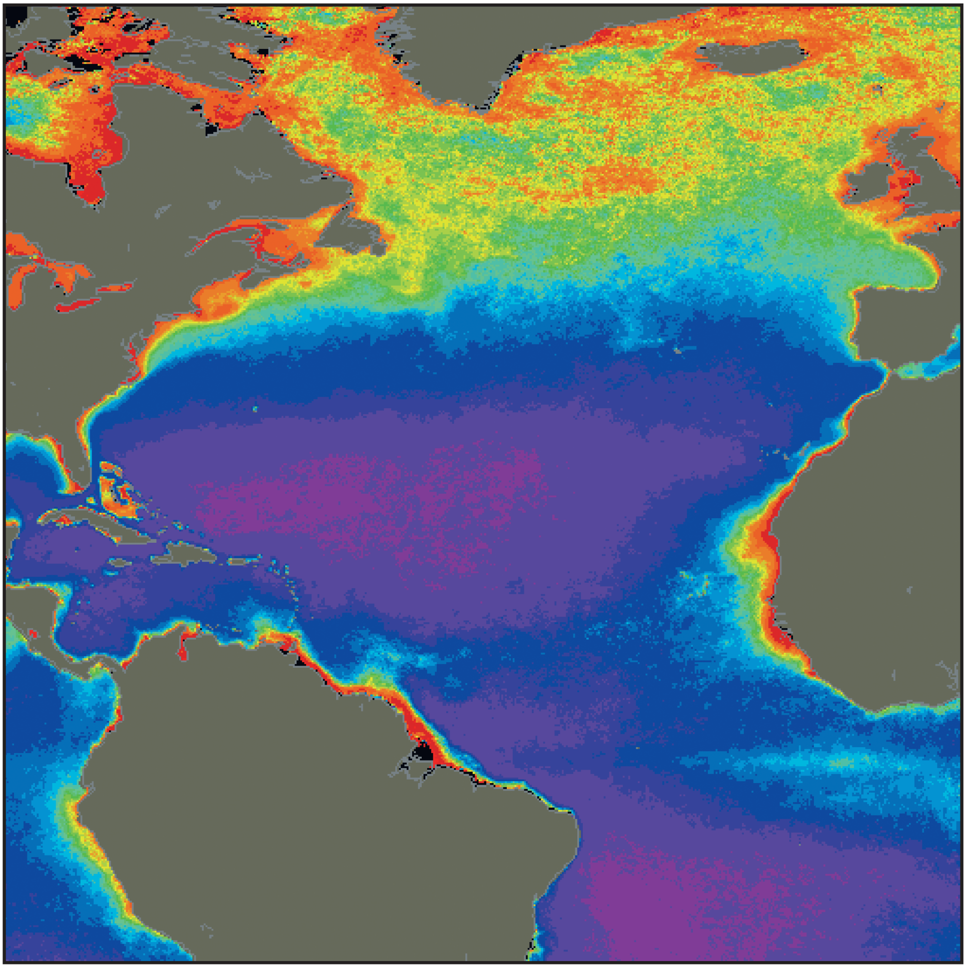


Figure 18

Distribution of chlorophyll in the North Atlantic as measured by CZCS between 1978 and 1986. The values increase from violet in the centre of the anticyclonic circulation to red in the West African coastal upwelling. The high values in the North Atlantic correspond to the spring bloom. Also to the east, along the equator, the signature of the equatorial upwelling can be seen and, a little further north, between the South American coast and Africa, there is a slight enrichment corresponding to the divergence between the South Equatorial Current and the Equatorial Counter-current.

Source: Coastal Zone Color Scanner Project, US National Aeronautics and Space Administration (Goddard Space Flight Center).

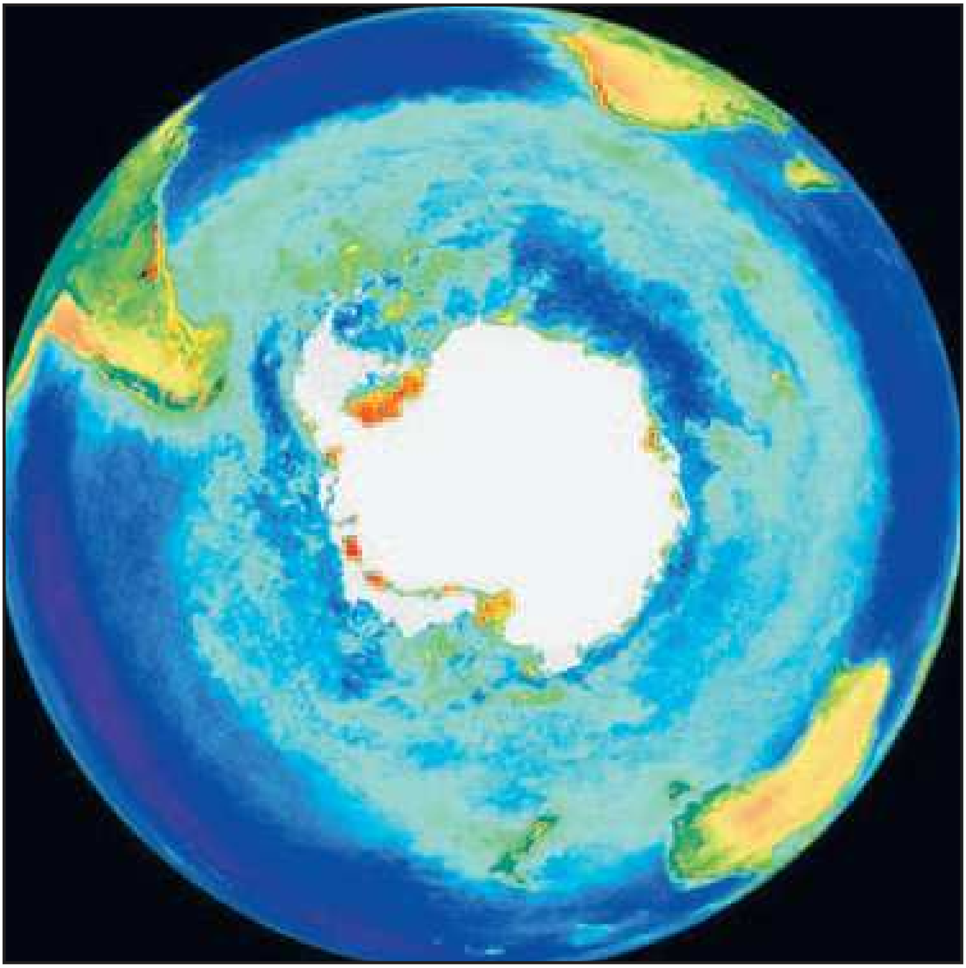


Figure 19
Chlorophyll in the Antarctic Circumpolar Current as seen by SeaWiFS, from September 1997 to August 1998.
Source: SeaWiFS Project, US National Aeronautics and Space Administration (Goddard Space Flight Center) and ORBIMAGE.

To speak broadly of nutrient salts without discriminating amongst them, and of the phytoplankton without caring about the different species composing it, as we have done so far, implies that we consider that the phytoplankton always utilizes the nutrient salts in the same way and in the same proportions, as if there were (as in chemistry) constant stoichiometric relations between the elements that take part in the creation of living matter. This is not the case and, as always in science, after having sought and found the 'laws' (that is, here, the supposedly constant relations amongst the constitutive elements of life, such as carbon, nitrogen, phosphorus, silicon), the reality obliges us to return to the awkward exceptions or anomalies, often rejected out of hand on the convenient basis of a presumed error of measurement. So do the HNLC systems call into question the currently accepted idea that nitrogen (in the form of ammonia, nitrite or nitrate) is the principal, if not the only, factor capable of limiting primary production and the development of phytoplankton? There was good reason for the currently accepted idea: measurements made in the ocean showed that, in the least productive zones such as the anticyclonic gyres, nitrogen was practically undetectable in the surface layer, whereas significant levels of phosphate or of silicate, for example, were found there. The conclusion was obvious: the lack of nitrogen limits the production. That was the case until the anomalies already noted here and there in coastal upwelling and even more so in the equatorial divergence could no longer be disregarded, given the size of the anomaly represented by the Antarctic Divergence with its shortfall in production, bearing in mind the high quantity of nutrient salts that it transfers to the surface and which rejects this role of quasi-exclusive 'controller' of production attributed to nitrogen.

So is silicate the arbiter? We might think so if we consider the evolution in the silicate concentration in the surface water from the Antarctic Divergence to the Antarctic Convergence 20° further north. Whereas nitrate starts at 30 µmol/l at the Divergence and is still at 20–25 µmol/l at the Convergence, the silicates, taking the same route, go from 60 µmol/l to only 5 µmol/l, with a rapid initial decrease, since at 55° S, the concentration has already dropped to below 10 µmol/l. There is a logical reason for this differential consumption of silicates and nitrates. In this cold water, the phytoplankton consists mainly of diatoms, which are species that develop inside a siliceous case called a frustule which they make themselves. So there is nothing surprising in the fact that these phytoplankton species consume more silicate than do species deprived of such frustules, like the dinoflagellates or the coccolithophores, which live in a self-made case of calcium carbonate.

There is another difficulty, however: even in the zone of rapid silicate decrease, between the Divergence and 55–60° S, the primary production and the quantity of chlorophyll remain low, as if there were an overconsumption of silicates relative to the production of living matter. Is something still missing that would explain this deficit in production and this excessive consumption of silicate which makes the Antarctic Divergence a veritable silicate pump? The answer is, it seems, iron. Even at this relatively elementary level of life, we cannot just take into account the so-called macronutrients – nitrates, phosphates and silicates. The development of phytoplankton also depends on oligoelements (or so-called micronutrients), such as iron, which may be lacking in oceanic surface water. This appears to be the case in the water of the Antarctic Divergence. The concentration of iron in the surface layer of the ocean is about one billionth of a gram (a nanogram) per litre. This indicates the difficulty of making such a measurement from a vessel itself made of iron. Even so, thanks to ultraclean techniques that avoid any possible contamination, we have been able to show that the concentration of iron in the Antarctic Circumpolar Current is exceptionally low: less than 1 ng/l. Iron enrichment in the ocean can have three sources: the upwelling of deep water; the inputs from the coast via runoff and rivers that discharge sediments which are always richer in iron than is ocean water; and aeolien inputs via the winds blowing in arid or desert regions and carrying dust far into the ocean from the coast. Satellite images show that such dust clouds can cross the Atlantic from the Sahara. The Antarctic Ocean benefits considerably from the upwelling of deep water at the Antarctic Divergence. But no river comes to feed it, and the wind that blows off the ice of the Antarctic continent and blows continually in a circle over the ocean without reaching the continents can hardly carry continental dust to the ocean. This could adequately explain the iron deficit in Antarctic sea water. The distribution of chlorophyll in the Antarctic Circumpolar Current is far from being homogeneous and measurements of ocean colour by satellite (figure 17) indicate that the highest values are found precisely in the regions where the current meets the land: on leaving Drake's Passage, a bottleneck between the Antarctic continent and South America dotted with islands (Falklands, Georgia and the South Sandwich Islands), or around isolated islands, such as the Kerguelen Islands in the Indian Ocean sector of the Antarctic Ocean. Uncontestably, proximity to the land fertilizes the Antarctic Ocean. So does the ocean recuperate a few nanograms of iron in passing? Without a doubt, but it still had to be demonstrated.

Conclusive experiments have first of all been carried out in the laboratory to test the iron hypothesis. But, to be convincing, nothing is as good as an experiment *in situ* and full-scale. This happened in February 1999; it was the Southern Ocean Iron Release Experiment (SOIREE), carried out in the Antarctic Circumpolar Current south of Tasmania

(61° S, 140° E). The region chosen was a typical HNLC region, with high values of nutrient salts (25 µmol/l of nitrate and more than 10 µmol/l of silicates, for very modest chlorophyll concentrations, 0.25 mg/m^3). Iron was added to the ocean so that the iron concentration increased from 1 nmol to about 4 nmol, approximately equivalent to an eightfold increase. It was possible to follow for several days the evolution of various parameters and to see that the chlorophyll concentration was multiplied by six, the primary production by four, and that the nutrient salts and the iron were rapidly consumed and, finally, that there was a notable diminution in carbon dioxide, hence an effective consumption of carbon. The latter point is important because the justification for so onerous an experiment was, of course, to resolve the HNLC paradox (this has now been done), but also and above all to evaluate the role of the Antarctic Ocean in the regulation of the atmospheric concentrations of the principal greenhouse gas produced by humanity: carbon dioxide.

THE ANTARCTIC OCEAN, MANAGER OF THE ATMOSPHERE'S CARBON DIOXIDE?

The ice that accumulates year after year on the Antarctic continent is a precious record that allows us to reconstitute the history of the Earth's climate and the composition of the atmosphere over the centuries. Looking into this record is no simple matter, as we have to drill through kilometres of ice to take out some cores, and the longer the core, the further we can go back in time. Then the ice core must be analysed to see what it contains: the particles and air bubbles enclosed in it are witnesses to the composition of the atmosphere at the time and allow us to reconstitute the evolution of temperature, the concentration of carbon dioxide in the atmosphere and the abundance of minerals carried to the ice by the atmosphere. The most recent drillings in the Antarctic allow us to go back 520,000 years, thus covering several very cold Ice Ages, like the one our cave-painter ancestors experienced some 20,000 years ago, and interglacial periods that were much more clement, like the one we are now passing through. Throughout this long period there was a very good correlation between the temperature of the air and the atmospheric concentrations of carbon dioxide and methane, both greenhouse gases that we now fear will seriously and rapidly modify the Earth's climate. In the Ice Ages and interglacial periods, the atmospheric concentrations of carbon dioxide have ranged between minimal values around 180 ppm and maximal values of about 280 ppm. At the present level of about 360 ppm we have largely exceeded the maximal value measured in the last 520,000 years; and therein lies problem, for this rapid exit from the norm is certainly the result of human activities. The natural variation in the carbon dioxide concentration in the atmosphere is itself not surprising: it would have been astonishing if the warmest periods had corresponded to the weakest greenhouse effect, and vice versa. One thing is certain, humanity had nothing to do with it: the fires that took so much trouble to keep going did not present a risk of perturbing the composition of the atmosphere! These variations can be explained only by variations in the biosphere on a planetary scale, and here too the ice cores have shown the way. It was seen that the mineral deposits on the Antarctic continent were far greater during the Ice Ages than in the warmer interglacial periods. When we mention mineral deposits, we perforce think of iron. Hence the attractive hypothesis that, in an Ice Age, the Antarctic Ocean, enriched by the aeolien inputs, is no longer limited in iron; so biological production increases vigorously and pumps much greater quantities of carbon dioxide, thus bringing down its concentration in the atmosphere and increasing cooling by diminishing the greenhouse effect. But we still have to explain the abundance of mineral dust in the atmosphere during an Ice Age. This is easy enough: a large quantity of water is stocked in the ice caps, the ocean water is colder, and evaporation and precipitation diminish, as does the terrestrial vegetation, thus exposing dry soil to wind erosion. This leads to great quantities of mineral particles in the atmosphere which will be deposited all over the globe and particularly in the Antarctic, where the ice records the information, thus giving substance to the scenario. Inversely, in the interglacial periods, abundant precipitation and terrestrial vegetation protect the soil. The Antarctic Ocean is thus deprived of its source of iron, biological production falls, the carbon dioxide pump loses its efficacy and the atmospheric concentration of carbon dioxide returns to a high level, thus amplifying the greenhouse effect and planetary warming. That is, until the next Ice Age, unless in the meantime, as the great producers of greenhouse gases, we have provoked a perturbation such that this climatic alternation is interrupted, leading to a warming of which we do not know the limits.

THE ANTARCTIC OCEAN, A CARBON SINK?

This is a possible, if not probable, catastrophe scenario if we fail to put a brake on his production of greenhouse gases. Some hope to escape this dilemma and are searching for potential carbon sinks; that is, reservoirs capable of storing for a very long time the atmospheric carbon dioxide. The way of taking into account (or not taking into account) the forests and reforestation in the application of the Kyoto Protocol on the reduction of greenhouse gas emissions has been the subject of much discussion. If the subject has not been officially addressed so far, the question has already been raised in a rather provocative manner: could the Antarctic Ocean, where the main nutrients are underexploited, be exploited as a carbon dioxide sink by enriching it artificially in iron, as has been done already on a small scale in the SOIREE experiment? That was in fact the real point of this experiment. If the result confirmed that iron limitation affects biological production in the Antarctic Ocean, nothing can be affirmed regarding future production. Yet that is the point: in order to fight the increase of carbon dioxide in the atmosphere in the long term, a significant proportion of this production artificially induced by the addition of iron must be removed from the system by sequestration in the sediments. The current estimate of the present total oceanic production of carbon is 50 gigatonnes/year, of which 0.2 gigatonnes, or only 0.4% of the total production, is definitively retained in the sediments. The rest, 99.6%, becomes remineralized in the water column between the surface and the bottom. The promoters of the SOIREE project estimate that, with 300,000 tonnes of iron, the oceanic production of 2 gigatonnes could be increased, which is no small matter given the fact that the man-made annual production of carbon dioxide is 7 gigatonnes. But, if these 2 gigatonnes removed from the atmosphere are also 99.6% remineralized in the water column, they will serve principally to enrich the ocean in carbon dioxide which, inevitably, sooner or later, will be returned to the atmosphere because, as we have seen schematically in the conveyor belt, even the deepest water finally reappears at the surface and will there release this excess of carbon dioxide that it has stored only provisionally: potentially a new carbon dioxide time bomb! It is doubtless wiser to seek the means of reducing our production than to dream of this new Promethean utopia.

It is also iron, or rather the lack of it, that explains the over-consumption of silicate in water from the Antarctic Divergence. Observations have shown that, in the HNLC systems deficient in iron and in which the silicates and nitrates are consumed by phytoplankton, the Si:N ratio is multiplied by three relative to its value in regions where iron is not limiting. So we can say that iron deficiency multiplies by three the consumption of silicates by diatoms. Thus, from the Antarctic Divergence to the Subtropical

Convergence, production would first of all be limited by iron with, nevertheless, a high consumption of silicates which, with a concentration falling to less than 5 µmol/l, would in turn become limiting further north, thus leaving the nitrates under-utilized.

UNDULATIONS OF THE THERMOCLINE–NUTRICLINE IN THE TROPICAL ENVIRONMENT

Coastal upwelling and equatorial divergence are ‘anomalies’ of the tropical ocean, normally characterized by a stable stratification maintained thanks to a permanent thermocline separating a warm homogeneous surface layer from the cold deep water. The thermocline is also a ‘nutricline’ in the sense that, as a density barrier, it opposes vertical mixing and limits considerably the transfer towards the surface layer of the abundant nutrient salts in the deep water. The thermocline–nutricline is thus also a separation between the surface layer, where biological production is limited by the lack of nutrients, and the deep water, where they are abundant but where the light becomes rapidly limiting. This is what is called the ‘typical tropical situation’. The depth of the thermocline–nutricline is evidently not the same everywhere: it ranges from more than 100 m in the middle of the anticyclonic gyres to less than 20 m in some places. We have seen that the topography of the thermocline is a signature of the variation in the currents in the surface layer which alternate convergence and divergence. Its depth also determines the quantity of light energy available at the ‘nutricline’, where the nutrient salts are not limiting, and where we can observe in the water column maximal values of chlorophyll and primary production. The typical tropical situation therefore differs from upwelling areas in which the most productive layer is found at depth, in the thermocline–nutricline and not in the surface layer. To a first approximation, it has been possible to show that, in the typical tropical situation, primary production is inversely proportional to the depth of the thermocline–nutricline. This corresponds to the fact that, quite logically, at depth the light becomes the limiting factor in biological production, so that the deeper the ‘nutricline’ the less light there is and the lower the production. The depth of the thermocline–nutricline is, if not a measure of biological production, at least a qualitative indicator of it. But the variations in production and chlorophyll concentration as a function of the depth of the thermocline do not necessarily have a signature at the surface, as they are nearly always at depth at the level of the ‘nutricline’; they do not affect the colour of the ocean surface except in areas where the 'nutricline' is the shallowest, as can be seen, on close inspection, in the divergence zone in the Atlantic Ocean that separates the North Equatorial Current and the Equatorial Counter-current, where the thermocline–nutricline is close to the surface and, with favourable light, there is high production based on high chlorophyll concentrations that are detectable by observing satellites that integrate the first few metres of surface water in their measurements (figure 18).

MESO-SCALE PERTURBATIONS: EDDIES, NUTRIENT PUMPS

The meso-scale eddies (~100 km in diameter) have, like the major subtropical gyres, an influence on the hydrological structure. In the tropics in particular, they act on the depth of the thermocline. This depth decreases in the cyclonic eddies which form veritable thermocline domes in which the summit is several tens of metres above the surrounding thermocline, depending on the intensity of the eddy. The 'nutricline' and the productive layer associated with it follow the movement of the thermocline and this uplift leads them to a more favourable level of illumination which will stimulate biological production. These cyclonic eddies are thus nutrient-salt pumps, a kind of episodic oasis that brings bursts of plankton to the least productive tropical areas, such as the Sargasso Sea, where they have been observed. These oases are not exceptional in an ocean in which turbulence on this scale is predominant and they ensure that, even in regions where the thermocline is deepest, production is maintained at a level that is sufficient to ensure that fish never die of starvation. Thanks to the fertilization they provoke, there are no true biological deserts in the ocean. These oases can be seen at the surface, as a result of vertical mixing, by a slight reduction in the sea-surface temperature and an increase in chlorophyll concentration which are detectable from space, as was shown by the eddy Loretta which was observed for eight months in 1999 in the vicinity of Hawaii (figure 20).

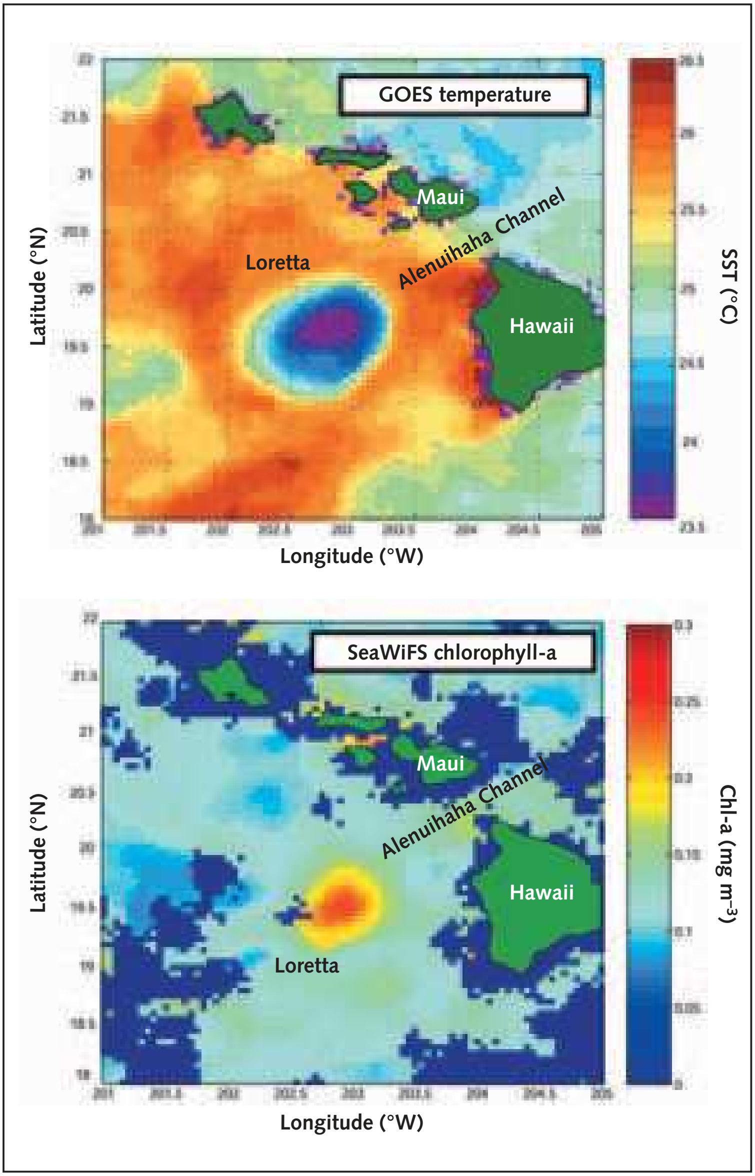


Figure 20

The eddy Loretta in September 1999 in the vicinity of Hawaii.

Top: the eddy is seen in blue as a result of a sea-surface temperature drop (geostationary satellite GOES).

Bottom: the eddy is seen in red as a result of a rather high chlorophyll concentration (SeaWiFS).

Source: SeaWiFS Project, US National Aeronautics and Space Administration (Goddard Space Flight Center) and ORBIMAGE.

5 Climate variation and fish

From the marine meadows of the preceding chapter to the fish they support, the road, trophically speaking, may be more or less long. If the planktonivores are bound rather tightly to these meadows, the carnivores and highly migratory species, such as the tunas, display quite considerable independence of them. Nevertheless, they are no less dependent on the marine environment which varies on various time-scales; they must adapt to these variations, just like the fishermen who live by exploiting them. Overall, the higher up the food chain, the more the factors and the processes that affect fish behaviour diversify. In spite of their evident real complexity, ocean dynamics seem to be child's play compared with the living world that depends on them. For biologists and fishery experts, it must be rather irritating to find that ocean dynamics are self-sufficient: the physical oceanographers have nothing to do with living organisms, which have no effect on ocean dynamics, whereas the opposite is not true. From primary production to the most evolved fish, the biologist cannot avoid ocean physics and dynamics. Hence the sometimes conflicting relationship between the two communities, one of which feels that it has nothing to gain from possible co-operation with the other. On the one hand, there is a medium of only one phase entirely governed by hydrodynamical equations which, with the help of computers, we can resolve numerically better and better, and a limited number of parameters (temperature, salinity, velocity) which we can measure objectively. On the other hand, there is all the diversity and complexity of life which cannot be factored into an equation as easily as the ocean in which it develops.

Marine fisheries are perhaps an anachronism in the sense that they constitute the last large-scale industrial exploitation of wild-animal resources. Perhaps one day, aquaculture will relegate fishing to a simple leisure; but we have not yet reached that point. According to the Food and Agriculture Organization (FAO) of the United Nations, in 1996 marine fishery production was 87 million tonnes (about a third of which was used for the production of fishmeal and oil). Marine aquaculture represented 11 million tonnes. If capture fisheries appear to have stagnated over the last few years while aquaculture production has increased significantly, we are still far from the day when aquaculture will have replaced capture fisheries. Again according to FAO, 70% of fished species are at a maximum level of exploitation or even overfished. There is nothing really surprising about that if we think about the growth in catches, which were only 17 million tonnes in 1950 (five times less than now)! This spectacular increase is mainly due to the opening up of new fisheries, such as the Peruvian anchovy fishery, in which the catches rose from a few thousand tonnes in 1950 to 12 million tonnes in 1971; it is also partly due to the exploitation of new species. This overall growth should not hide the fact that many fisheries have collapsed, however, or have undergone major fluctuations as a result of overfishing or of the natural variability of the resource.

For a very long time and much to their own cost, fishermen have had to endure the variability of catches. The dramatic economic consequences of these sudden changes and the demands of the fishermen, which they began to express bitterly in the nineteenth century, led governments anxious for social peace, and therefore a minimum of prosperity, to determine the reasons for these devastating fluctuations. The fishermen, well before the scientists, were not short of a whole range of explanations. The Norwegian cod fishermen, who had been fishing for centuries under especially difficult conditions around the Lofoten Islands and saw their catches vary by a factor of one to two from one decade to another, blamed the migratory fantasies of the fish. The Breton sardine fishermen underwent a serious crisis at the beginning of the twentieth century. The catches were extremely variable from one year to the next: at the end of the 1890s, each sardine cannery produced about 1 million tins of sardines per year; in 1901, the production was ten times less; and in 1907, there was almost no fishery at all. The fishermen blamed the dolphins and porpoises, which they claimed were now coming in schools to decimate the stocks, not only for this shortage but also for damaging their fishing nets. Climate changes and the currents were also blamed, and subsequent studies showed that they were indeed the root cause of the 'Breton sardine crisis'. But it is often more satisfying to identify the enemy or, at any rate, the scapegoat. Other explanations even more fantastic, such as the disturbance of the marine environment by steamships, were also put forward. The overfishing hypothesis, that is, the concept that the growth of the fishery itself was responsible for the decreased yields, and which is now the main problem, was first formulated by J. Cleghorn in 1854 with respect to the herring fishery in the British Isles. Cleghorn showed that the ratio of the herring catch to the number of fishing vessels continually decreased and concluded that this was the result of overfishing, primarily on the most accessible species. No one is a prophet in his own land: the fishermen did not at all appreciate the implication that they were the primary culprit in the drop in catches. They had the 'support' of the famous British biologist Thomas Huxley (see Chapter 1) who was impressed by the enormous number of fish eggs, and when opening the Great International Fisheries Exhibition in London in 1883 affirmed that 'probably, all the great marine fisheries were inexhaustible' and consequently 'any attempt to regulate them seemed pointless'. To which, E. R. Lansker, another reputed British biologist, replied when closing the Exhibition, that 'it was an error to think that the ocean was a vast warehouse of inexhaustible resources.' The idea of overfishing was only welcomed if, in a moment of protectionism, it allowed an 'outsider' to be blamed, either a foreigner or anyone who introduced other, rival fishing methods. Hence the Anglo–Iceland cod wars, which lasted for centuries, and the European–Canadian war over the Newfoundland fishing grounds, which ended not for lack of combatants but rather for lack of the very object of the conflict: the cod itself. Finally, there were the internal conflicts between the diverse fishing communities exploiting the same resource, which the politicians were forced to arbitrate. More so then than now, of course, they lacked knowledge; it was this need that gave rise to fishery oceanography or fishery research. Norway, which was then a rather poor country and highly dependent on fisheries, provided the impetus.

AMBIGUITIES OF FISHERY RESEARCH: CREATION OF THE INTERNATIONAL COUNCIL FOR THE EXPLORATION OF THE SEA

In the face of the difficulties confronting fishermen and the wide range of explanations they put forward, the Norwegian Government, in 1864, commissioned G. O. Sars to undertake a study aimed at understanding the reasons for the large fluctuations in cod catches in the Lofoten Islands. He could not give a precise reply to 'this difficult hence obscure question: what are the causes of the irregularities that have always been observed in the catches?' Nevertheless, he affirmed that 'this phenomenon, like everything else in nature, must have its own natural causes which can only be discovered through scientific study.' Today, such an affirmation might seem like a 'truism', but it is not, because of the ambiguous status of fishery research, which is why this issue is always in the news. On the other hand, it is caught between the urgent demands of politicians charged with fisheries management and who are preoccupied with short-term forecasting, and on the other hand, the scientific concern to know the stocks and the ecological mechanisms that regulate their fluctuations, which takes a long time. It is hardly a caricature to say that the result is often a double system of research. The first system, tied to the concerns of the political, economic and social management of fisheries, only deals with the demography of the exploited species, with a view to evaluating the state of the stocks and their evolution. This is 'population dynamics' in which the only perturbing element is the fisherman who increases the fish mortality. The fish, literally 'removed' from their ecosystem, and the fisherman are brought face to face. The management models are simple demographic models into which we introduce the mortality due to fishing. The second component of this parallel research system is dedicated to marine biology in the traditional academic framework, which does not take into account the fisherman-predator as an actor in the ecosystem. This irrational separation was prejudicial to a full understanding of the impact of the variations in the environment on the resources and, at the same time, of the fishery itself on the ecosystem.

This harmful duality was clearly evident in the birth of the International Council for the Exploration of the Sea (ICES), the first international oceanographic organization, created on the initiative of Scandinavian scientists. They were in no doubt that there was a strong relationship between the presence of fish, on the one hand, and the physical and biological conditions of the marine environment, on the other. They therefore proposed a plan for undertaking systematic oceanographic cruises in the Baltic and North Seas and in the North Atlantic Ocean which would be the object of an international agreement to share the work. The plan was presented by the Swede O. Pettersson at the International Congress of Geography in London in 1895 (the one to which Alfonso Pezet presented his communication on El Niño), which adopted a resolution underlining the scientific and economic importance of such a plan and, given the interest in fisheries, the necessity of international co-operation. The plan stressed the fluctuations of the environment hence the need for systematic observations. This was an 'ecological' conception, even if the word was not used at that time, and it upset quite a few people who believed that such research was of no interest with respect to fishery problems. Nevertheless, with strong backing from the congress in London, and with the support of the Swedish Royal Academy of Sciences, Pettersson undertook to convince the coastal countries which Sweden invited to a conference in Stockholm in June 1899. Participants were Sweden, Norway, Denmark, Germany, Russia and, surprisingly, the United Kingdom which had, nevertheless, let it be known that the proposed research was only secondary relative to the all-important objective (for that country) of determining whether or not the fishery had an adverse effect on the fish stocks in the seas in question (the confrontation fish–fisherman) so that adequate steps could be taken. To counter this British wish to limit the scope of the conference to the fish–fisherman relationship, Pettersson, in his declaration, explained the need for purely scientific research to precede that concerned with fishing methods and the related legislation. Thus the stage was set for many years, opposing two types of research that should have been complementary.

The Stockholm conference adopted a number of recommendations directed to governments, proposing a programme of systematic seasonal measurements of the physico-chemical and biological environmental parameters and an organization to run it, with a central office and a shared laboratory, under the aegis of the International Council for the Exploration of the Sea (ICES). The conference also proposed to initiate the programme on 1 May 1901 for a period of at least five years. Through these proposals the conference therefore laid the foundation of an organization permanently dedicated to oceanographic research in the North Sea and its adjacent waters. This choice of the long term was naturally backed by the scientists' logical certitude that fluctuations in the fish catches inevitably corresponded to fluctuations in the physical and trophic conditions in the marine environment and, if we were to understand them, there was no other solution than to observe them by way of systematic measurements. In response to these recommendations, the United Kingdom persisted in its mistrust and showed its reticence by only committing itself for two years. Lord Salisbury (Prime Minister) again stressed the desirability of the work being directed 'to promoting a scheme of investigations, which would result in the acquisition of information of practical advantage to the fishing interests of this country as apart from information of a purely scientific value.'

It was in July 1902 in Copenhagen that ICES was officially created, the first international oceanographic research organization. This landmark achievement was reflected in a conference organized by the FAO some hundred years later in Reykjavik in October 2001 on the theme of 'Responsible Fishing in the Marine Ecosystem'. The Conference adopted a declaration aimed at including ecosystem considerations in the management of fisheries. To reach that point had required acceptance of the fact that half the resources were already fully exploited and a quarter of them were overexploited, as well as the recognition of the total failure to forecast the collapses. In 1978, an FAO technical report (*Expert Consultation on the Management of Multispecies Fisheries*, Rome, Italy, 20–23 September 1977. FAO Fish.Tech. Pap. 181, 42 pp) had already noted: 'Fishery biologists were particularly unfortunate in the scientific advice they provided in the prediction of the collapses. The history of the California sardine fishery, the Atlantic–Scandinavian and the North Sea herring fisheries, or the Peruvian anchovy fishery are among the worst setbacks with which fisheries science has been associated.' And it added: 'The analysis of the population dynamics of the stocks using classical monospecific evaluation methods has not taught us much [about these collapses].' This was an indefensible condamnation of monospecific population-dynamics models. Yet twenty-five years later, in 1992, the cod stock off the Newfoundland and Labrador coasts collapsed, contrary to all forecasts. This was an exemplary case that illustrated the difficulty for fishery science and the limits to knowledge imposed by the means of observation.

LESSONS OF THE COLLAPSE OF THE NEWFOUNDLAND COD STOCK

The cod stock off the coasts of Newfoundland and Labrador declined spectacularly in 1992 to the point at which a moratorium was placed on the fishery in the hope that the stock would recover. Yet it was one of the best, if not the best, monitored and regulated fisheries in the world: fishermen, managers and researchers were constantly watching over it. Every year since 1981, systematic scientific trawling campaigns had been carried out in the autumn to evaluate and monitor the stock abundance. Until 1991, however, these campaigns did not allow detection of the decrease in the biomass, thus giving the fishermen and the fishery managers confidence; so, thus reassured or wishing to be so, they saw no reason for alarm. This was a set-back for the scientists, which was to open a much-needed discussion of the possible causes. It was also a set-back for the fishery managers, who were forced to revise their management methods with a view to reducing the likelihood of such collapses recurring. The researcher was obviously in a much more comfortable position than the fisherman. The researcher overcame the humiliation of the set-back quickly; it was even a stimulus that opened up a new period of scientific inquiry. The researcher would certainly find the explanation, albeit retrospectively, and would integrate it into new models and theories that other fishermen could benefit from, later and elsewhere. On the other hand, the fisherman could only acknowledge his failure and hope that the stock would recover, which it did not.

The question was put in these terms: Was the collapse of the stock due to excessive fishing pressure *or* to a modification of the so-called environmental conditions? The 'or' is important, because it shows that, by separating population dynamics from ecosystem dynamics, we still take a simplistic black-and-white view of things that prolongs the duality discussed above. Because the scientific fishing surveys did not indicate anything and the biomass appeared to be stable, an implicit hypothesis was made: that the fishery system (prey–fisherman) was, if not in equilibrium, at least stationary and that an environmental perturbation, such as a temperature change causing a southward migration or a change in the ecosystem and an abundance of prey, was necessary to destabilize it. An uncontestable reasoning if we are certain of the validity of the methods of evaluating the stocks and their demography. But in most cases the only information we have available on a stock and its age structure is provided by the fishery itself. We adopt the hypothesis that the catch per unit of fishing effort is a measure of the state of the stock, but we are a long way from the sampling strategy used in opinion polls. Luckily for them, the fishermen's strategies are anything but random. Also, the models have serious weaknesses: fish have no civil status and we cannot measure either their natural mortality or their natural natality. Obviously, these are essential parameters if we want to forecast the evolution of a stock. If we may make the reasonable assumption that the mortality rate of a given stock is constant, the same is not true for what is called the recruitment, which can be defined as the youngest fraction of the stock that for the first time enters the group of accessible fish (i.e. catchable fish).

This somewhat self-serving definition takes into account the fact that, as the only source of information is the fishery itself, the fish only really 'exist' if they are fishable, just as in the army the 'soldier' only exists when he has been recruited. We know almost nothing about the life of the fish prior to this official 'birth', the date of 'recruitment' which makes the fish catchable by the fishing gear. But the initial phases – the so-called 'prerecruitment' phase – have nothing to do with the life of the adult fish. They include, in particular, the larvae which are far more sensitive to environmental conditions than are the adults. The survival rate in the larval stage depends on the physical parameters – temperature, currents, turbulence – on the biological production which determines the larval food supply and on the abundance of the larvae's predators, which may even include their own parents. There are so many unknowns, which makes forecasts of the recruitment unreliable. We were also forced to admit that the rate of recruitment was independent of the parent stock – which is plausible so long as the biomass of the parents exceeds a certain threshold value – and that the environmental variations remain within reasonable limits so that on average, from one year to the next, variations in recruitment cancel out. This means that these models are only applicable if the fish stocks are in equilibrium or in a stationary state, which ceases to be the case when fishing pressure becomes excessive or environmental variations become large. In other words, the models are intrinsically incapable of forecasting collapses such as that of the Newfoundland cod stock of 1992. In this specific case, there was even less reason to doubt that the systematic trawling campaigns to assess the abundance went in the same direction as the models. We were in the ideal situation for the experimental method dear to the scientists: the theory (the model) verified by the experiment (the trawl-fishing campaigns).

Is the primary question no longer one of excessive fishing or environmental perturbation, but one of methodological error in the evaluation of abundance or environmental perturbation? It certainly seems that the first term in the choice should not be disregarded and that effectively there has been a constant and consistent underestimation of the effects of fishing. The sampling strategies of the stock-evaluation campaigns and the techniques for treating data could not detect, and therefore take into account, the growth in the fishing-mortality rate which was masked by a change in the distribution of fish density caused by the decrease in stock and which increased its catchability. In other words, as the biomass decreased, the spatial organization of the fish aggregations rendered them more vulnerable to fisheries and increased the catch rate, giving the illusion of a steady abundance until the day when, owing to the weakness of the stock, as a result of not ensuring an adequate level of recruitment, the catches collapsed suddenly and lastingly.

Everyone involved would have liked to blame the environment, but nothing in the analysis of environmental conditions during the preceding century could give weight to this idea. The cod stock had already experienced the same conditions as those that prevailed in the 1980s, with catches just as big at the end of the nineteenth century in an environment that was much colder, hence less favourable to recruitment, without compromising the stock. To accept this comparison, so as to be able to set aside the role of the environment in the collapse of the cod stock, suffers from the same bias as before, which consisted in admittting that the catches provide a reliable picture of the abundance which, as we have just seen, was not the case. Also, even if the catches were at a level in the 1980s similar to that at the end of the nineteenth century, it is almost sure that the levels of abundance were radically different between these two periods, as were the responses of the recruitment to environmental variations. This renders the comparison inoperative. In an overfished stock, as soon as there is a divergence from the equilibrium point at which – in a good or a bad year – the fluctuations in recruitment and mortality are in balance, recruitment becomes the crucial parameter in the population dynamics. And especially so, given that we cannot forecast the level of recruitment, because we evaluate it retroactively from the catches and because it is very responsive both to variations in the parental biomass when this decreases and to variations in the environment which determine the survival of the larvae.

From the standpoint of recruitment the over-simplistic black-and-white approach of the initial question – excessive fishing pressure or environmental variation? – to explain the collapse of the stock is nonsensical, for the two elements are linked: the overfishing, through the randomness of the recruitment, makes recruitment all the more sensitive to environmental variations as overfishing increases.

THE ECOSYSTEM APPROACH

It is evidently rather easy, retrospectively, to carry out a critical analysis of the research carried out on fisheries during the last 100 years. The scientific unanimity reached at the Reykjavik conference, reconciling population dynamics and ecosystem dynamics using an approach qualified as ecosystemic, does not however resolve the problem of the management of fisheries or marine ecosystems. Scientifically, this is a return to square one.

And the conference declaration also sent the problem back to the managers for immediate action, and to the so-called precautionary approach, which is nothing more than a principle of action based on an avowal of ignorance. In the long term, it comes down to scientific research to fill as well as possible the gaps in our knowledge and to establish the scientific basis of 'management strategies that incorporate ecosystem considerations and which will ensure sustainable yields while conserving stocks and maintaining the integrity of ecosystems and habitats on which they depend.' For this, the conference declaration continued, it is necessary 'to identify and describe the structure, components and functioning of relevant marine ecosystems, diet composition and food webs, species interactions and predator–prey relationships, the role of habitat and the biological, physical and oceanographic factors affecting ecosystem stability and resilience.' It is also necessary to 'build or enhance systematic monitoring of natural variability and its relations to ecosystem productivity', which is none other than the programme proposed in 1895 by Pettersson.

On the scale of the world ocean, the task is enormous and the road is likely to be long before it yields strategies for the management of these complex marine ecosystems, which are so variable and so difficult to penetrate and observe. The complexity of the coupling between the physical medium and the biological medium and the complexity of the trophic interactions render illusory any search for predictive models of the evolution of ecosystems analogous to the models developed for climate forecasting, which fortunately can be kept amongst physicists. Here, the objectives will be to identify key points in the functioning of the ecosystems and to elaborate as simple as possible indicators of the good health of the system as a sound basis for a management strategy.

THE ANCHOVY, THE SARDINE AND EL NIÑO

In 1970, the catches of the Peruvian anchovy (*Engraulis ringens*) reached a record level of more than 12 million tonnes, or a quarter of the world marine fish catches (in tonnage, but not in value, as these landings were destined for animal feed after transformation into fishmeal). Between 1962 and 1971, the average catch level had been 9 million tonnes. In 1972, it fell to 4 million tonnes and to only 1.5 million tonnes in 1973, or six times less than two years earlier. Why this fall? A culprit was at hand: El Niño, which made its presence strongly felt precisely in 1972–73, and immediately earned itself the reputation of anchovy-killer.

And not without reason, as along the Peruvian coast El Niño expressed itself as an occultation of the upwelling and as an invasion of the coasts by water of tropical origin that was warm and poor in nutrient elements. This cut the anchovy from its food supply, forcing it to look elsewhere for more-favourable conditions, either further south or at greater depth; either way, they escaped the fishing gear. The stock did not recover in subsequent years: the catches only exceeded 4 million tonnes twenty years later, thus reinforcing the contention that El Niño had durably ravaged the stock. Nevertheless, certain questions should have been raised at once.

The El Niño phenomenon was not born in 1972 and the previous events (1965, 1969) had had almost no impact on catches, as they never dropped below 7 million tonnes between 1964 and 1971. Would not the same causes have had the same effects then? It might also have been thought that the record catch in 1970 (12 million tonnes) was a guilty party to the decimation of the stock. No, it was more comfortable for the fishermen, as for the scientists, to stick with the idea of the El Niño scapegoat. This way, the fishermen were able to dismiss the question of possible overfishing and their possible blame for it. For their part, the scientists had a ready-made subject of research that was all the more saleable as the economic consequences were financially palpable. But natural systems do not operate in a binary black-and-white mode: events are rarely attributable to a single cause. No more than for the cod of Canada could we incriminate exclusively the fishery or the environment; we cannot blame El Niño alone for the disappearance of the anchovy. Starting in 1993, the catches regained their pre-1972 levels and the El Niño of 1997–98, in spite of its reputation as the El Niño of the century, only appears as a minor 'blip' in the catch curve. Nor can we accuse overfishing alone. The anchovy reproduces very rapidly, reaches maturity in a few months, and has a high reproduction rate, which means that normally, after an El Niño, the stock is reconstituted very quickly. For example, in 1998, corresponding to the 1997–98 El Niño, the catches were only 1.2 million tonnes and, from the following year on, they rose to nearly 7 million tonnes.

This did not happen after 1973. Why? In Peruvian waters, even if the anchovy is normally predominant, it is not alone. There are other pelagic species, notably the sardine. Clearly, the less we fish the anchovy, the more we fish the sardine and vice versa, as if the sardine had taken the place of the anchovy between 1975 and 1992 (figure 21). The sardine appears to be insensitive to the El Niño phenomenon, since in 1984 following the El Niño of 1982–83, when catches of anchovy were at their

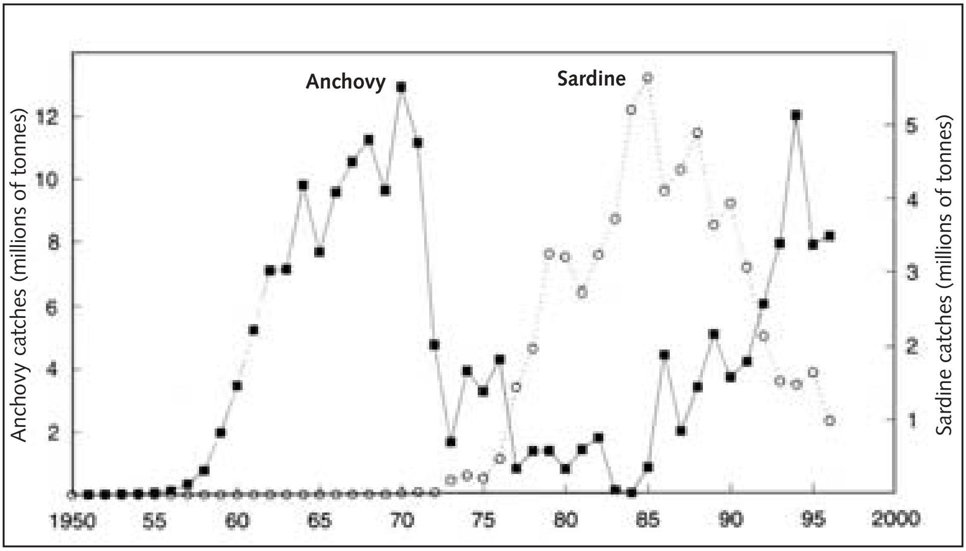


Figure 21
Variation in the catches of sardine and anchovy in the Humboldt Current from 1950 to 1996.
Source: Schwartloze et al., Worldwide large-scale fluctuations of sardine and anchovy populations, S. Afr. J. Mar. Sci., 1999, pp. 289–347.

lowest, those of the sardine doubled, reaching 5 million tonnes. They were completely indifferent to the perturbation. So what happened that, in the twenty years following the 1972–73 event, the anchovy relinquished its place to the sardine?

FROM GUANO TO FISHMEAL: THE CALIFORNIA SARDINE, A VICTIM OF THE WAR?

The fishery for anchovy in Peru owed its growth to the collapse of the California sardine fishery which was flourishing greatly between the two world wars of the twentieth century. It made the fortune of the port of Monterey, as illustrated by John Steinbeck in his novel *Cannery Row.* His next novel, *Sweet Thursday,* opens on the collapse of the sardine fishery between 1945 and 1950. ‘The canneries themselves fought the war by getting the limit taken off fish and catching them all. It was done for patriotic reasons, but that didn’t bring the fish back.’ As a result, it became necessary to find other resources, and eyes turned towards Peru whose riches were in the hands of the powerful guano lobby led by the public company created by the Peruvian Government in 1909 to exploit the guano.

The anchovy fishery was very strictly limited, for the anchovy was at that time reserved for the millions of sea birds which nested on the coast or the nearby islands and produced with their faeces the precious guano that was rich in nitrate and used as a fertilizer the world over. Via a very short food chain – plankton, anchovy, bird, guano – Peru possessed a machine for extracting from the sea the nitrate brought by the upwelling, concentrating it and depositing it on land where it only had to be collected. Guano was for a long time an important source of foreign currency for Peru. So guano-producing birds had to be protected and their food, the anchovy, had to be safeguarded. That is, until the guano met competition from other resources and industrial fertilizers and so lost its value, and the anchovy fishery, stimulated by the collapse of the California sardine fishery, gained in value. The Peruvian Government then raised the restrictions imposed on the fishery, and that was the start of the 'gold rush'. From a few tens of thousands of tonnes at the beginning of the 1950s, the catches exceeded 10 million tonnes at the beginning of the 1970s. But, contrary to what Steinbeck supposed, the patriotism of the Monterey canneries doubtless had little to do with the collapse of the sardine stock, which was more likely due to a change in the oceanographic regime on the scale of the Pacific Ocean, as the next part of the story will show.

SYNCHRONY OF CATCHES IN THE PACIFIC

If the collapse of the California sardine fishery heralded the heyday of the Peruvian anchovy fishery, there was no reason *a priori*, in spite of some coincidences, to think that there was any relationship between the two fisheries. Yet examination of the sardine catches in the Pacific since 1920 shows that, in areas as far apart as Peru, California and Japan, there is a remarkable synchrony in the evolution of the catches: they increase and decrease together. Reaching their peak between 1930 and 1940, the Japanese and California catches declined together between 1945 and 1950 (there was no sardine fishery in Peru then). Around 1975, when the Peruvian sardine fishery replaced the anchovy fishery, the sardine fishery in Japan increased strongly, as did the California sardine fishery, though to a lesser degree and with some lag (figure 22). It also seems that this alternation between the sardine and the anchovy is not limited to Peru, but is also found to different degrees in the other two systems, even if the anchovy catches in Japan and California never come near to the record

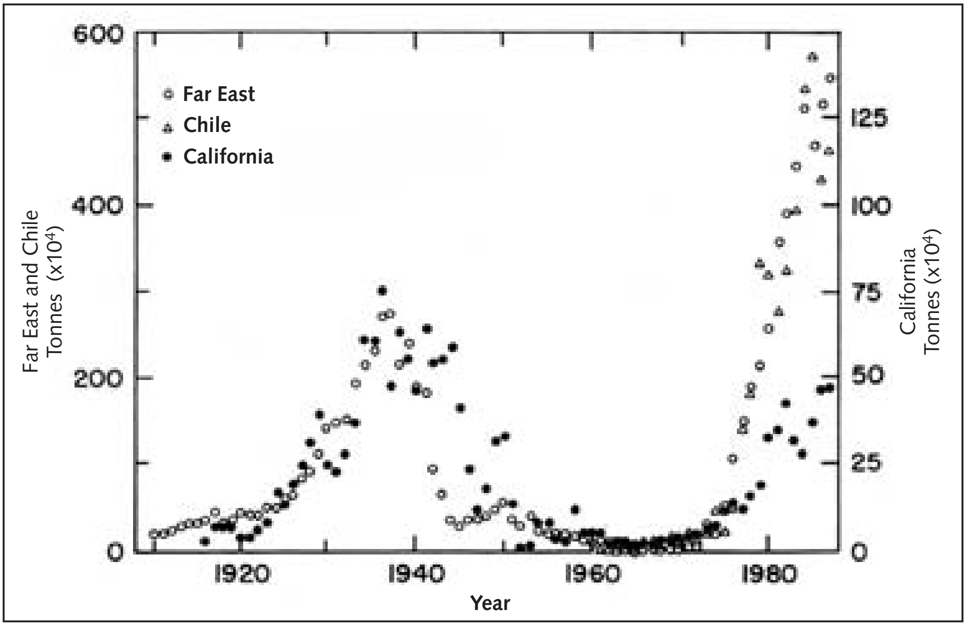


Figure 22

Variation in the catches of sardine in the Pacific Ocean: Far East, Chile and California fisheries.

Source: Tsuyoshi Kawasaki, in Climate Variability, Climate Change and Fisheries, *M. H. Glantz (ed.), Cambridge, Cambridge University Press, 1992.*

levels of the Peruvian fishery (in Japan, only 500,000 tonnes in the best years and, in California, only 300,000 tonnes, compared with 10 million tonnes in Peru before the collapse of 1972).

The available fishery data since 1920 cover a period that is far too short to allow us to determine whether the out-of-phase oscillation observed between the 1930s and the 1990s of the sardine, on the one hand, and the anchovy, on the other, is an isolated phenomenon or corresponds to a real cycle, to an oscillation with a period of between fifty and sixty years (see figure 21). Fortunately, the anchovy like the sardine leaves in the sediments traces of its presence and abundance: its scales, which fall to the bottom of the ocean where, deprived of oxygen, they are preserved. This has made it possible to reconstitute the more or less alternating 'history' (off the coast of California) of the anchovy and the sardine from the year 270 to 1970, which reveals that the cycle observed in the twentieth century is not unique and recurs fairly regularly, with a period of about sixty years. The sardine fishery has a long history in Japan and analysis of historical data since the seventeenth century shows that there too the catches evolve continually, with peaks in the catches more or less regularly spaced, with a periodicity similar to the one observed in California: around 1650, 1710, 1820, 1875, 1935 and 1985.

THE ALASKA SALMON

It would be astonishing if this remarkable synchrony and alternation sardine/anchovy on either side of the Pacific Ocean, north and south, were a simple coincidence. Unless the fish have some unsuspected means of telecommunication, the explanation can only come from a cyclical variation in the marine environment on the scale of the whole Pacific. It is from analysis of fluctuations in the Alaska salmon, and not from those of the sardine and the anchovy, that a possible explanation will come. There is nothing unusual in that. First of all, the salmon has a quite different market value from that of the anchovy or the sardine; the fisheries of Alaska (pink and sockeye salmon) are among the most lucrative in the United States. So it makes sense to pay close attention to the pereniality of their exploitation. These salmon are certainly more at risk of over-exploitation than either the anchovy or the sardine, both of which reach maturity in a few months and reproduce very rapidly at a very high rate, which allows them to recover after events as spectacular as an El Niño. The same is not true for long-lived species such as the salmon that reach maturity only after several years. And finally, if there really is a perturbation on the scale of the whole Pacific, there is no reason why the salmon would not be sensitive to it as well.

We have available data on the landings of salmon in Alaska (Bristol Bay) since 1920 (see figure 23). The fishery flourished between 1930 and 1945; more than 120 million individual salmon were landed in 1935. It then declined, reaching its rock-bottom level around 1975 at about 20 million individual salmon, five to six times less than when the fishery was at its peak. The catches rose very rapidly after 1975, a decidedly crucial period because, as we have seen, it corresponded to the collapse of the Peruvian anchovy stock and the rapid rise in the sardine stocks off Peru, California and Japan. Moreover, the catch curve for these sardines (see figure 21) bears a striking resemblance to that for the Alaska salmon. This is another disconcerting coincidence that makes us think that something really took place in the Pacific in 1975, that it was not the first time, and that similar events had occurred in the past.

PACIFIC DECADAL OSCILLATION

To assess the impacts that variations in the physical medium might have on biological production in the ocean, we always start by analysing the sea-surface temperature. It is an easily accessible parameter and we have measurements of it for the whole of the ocean for relatively long periods. Thus, in looking for the reasons for fluctuations in the salmon fishery since 1920 and wishing to know whether they corresponded to a recurrent oscillation, we discovered what is now called the 'Pacific decadal oscillation' or PDO. It is a reflection (see figure 24) of the fact that the sea-surface temperature varies out of phase with, on the one hand, the central North Pacific Ocean and, on the other hand, its eastern side and the eastern part of the intertropical zone. In other words, whenever we observe warm anomalies on one side of the Pacific Ocean, we also have cold anomalies on the other side. We now call the situation corresponding to the warm anomalies on the eastern side and the cold ones of the central North Pacific Ocean, the warm phase; and the inverse situation, the cold phase. The evolution of this PDO (illustrated in figure 24) has

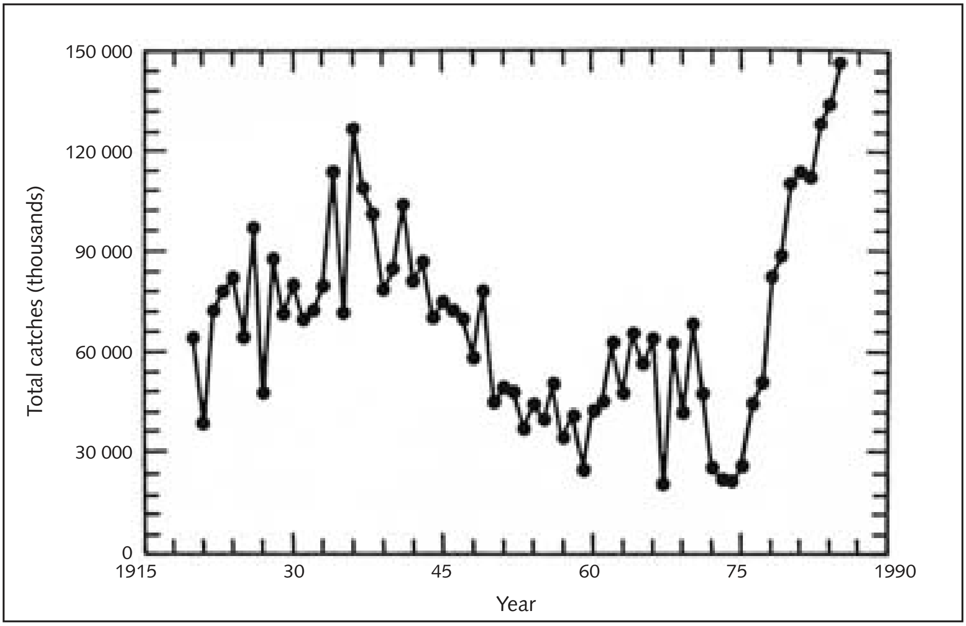


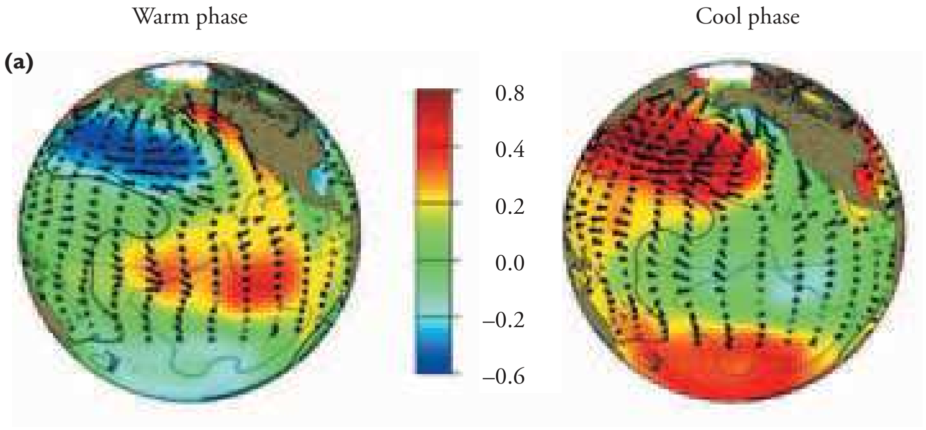
Figure 23

Variation in the catches of Alaska salmon.

Source: K. A. Miller and D. L. Fluharty, in Climate Variability, Climate Change and Fisheries, *M. H. Glantz (ed.), Cambridge, Cambridge University Press, 1992.*

the following phases: warm from 1920–25 to 1945 and from 1975 to 1999; cold from 1945 to 1975. That is to say, exactly the same major cycles of fifty to sixty years described above. The warm phase is favourable to the Alaska salmon and the sardine of California, Peru and Japan; the cool phase favours the anchovy and not at all the Alaska salmon or, to be precise, those who fish it.

Pacific decadal oscillation



Variation in the PDO index anomaly between 1900 and 2000.

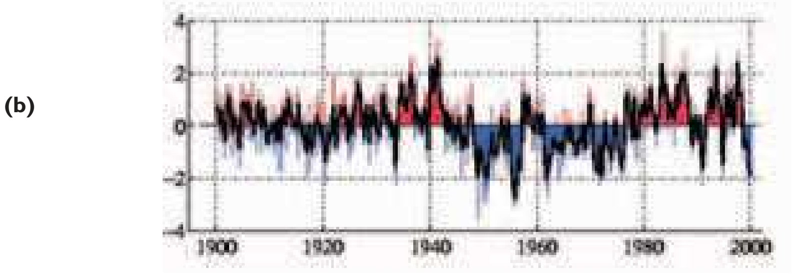


Figure 24

Pacific decadal oscillation (PDO).

(a) Sea-surface temperature anomalies in winter. In blue, the cool anomalies and, in yellow-red, the warm anomalies. The wind anomalies are indicated by arrows. On the left: the warm phase of the PDO; on the right, the cool phase. (b) Variation in the PDO index anomaly between 1900 and 2000.

Source: The Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle.

Apparently, the PDO is not a phenomenon confined to the ocean; in the atmosphere, there are corresponding pressure variations, hence winds, which in turn influence ocean currents and biological production, by the mechanisms described earlier. As a signature of a major climate oscillation in the Pacific, a kind of El Niño on a decadal scale, the PDO is still only a bare fact and we still do not have an explanation analogous to that proposed for El Niño, mainly because we only have a relatively short time-series of observations relative to the nearly sixty-year period of the phenomenon. In sixty years, for one complete cycle of the PDO, we can observe a dozen complete El Niño cycles. Also, to understand the relationships between the PDO and the various fisheries of the Pacific, we must adopt a reductionist approach and fall back on the ecosystems to which the fisheries are linked.

CYCLONIC CIRCULATION OF THE GULF OF ALASKA

The Gulf of Alaska is characterized by a zone of low atmospheric pressure to which there corresponds a cyclonic (anticlockwise) oceanic circulation (see figure 25). In the central part of this cyclonic gyre there is quite normally (see Chapter 2) a corresponding 'divergence', an uplift in the thermocline, hence of water rich in nutrients, and consequently a relatively high biological production. In fact, the plankton is abundant there and this abundance is all the more marked as the divergence intensifies when the cyclonic circulation accelerates. This is what was observed just after 1975 when the PDO went into its warm phase and the salmon catches grew spectacularly. This was the explanation proposed to link the abundance of the salmon in the Gulf of Alaska to the PDO by way of the more or less high fertility of the water in the gulf, itself dependent on the decadal fluctuations of the cyclonic circulation.

In the warm phase of the PDO, there is active divergence and abundant food for the salmon; in the cool phase, inversely, the divergence is weak and food scarce. When we think of the complexity of the salmon's life-cycle, during which it returns to reproduce and die in the lake in which it was born, and the many obstacles it has to overcome during its life, the explanation may seem simplistic. And yet analysis of the sedimentary record allows us, as in the case of the sardine and the anchovy, to reconstitute the history of the salmon for the last three centuries. In the case of the salmon, we are talking about the sediments in the lake where it reproduces and dies. The tracer of its history is not the scales it leaves on the bottom, but the nitrogen-15 isotope. In the several years of its oceanic life, during which it gains 99% of its adult weight, it feeds on plankton and small fish which enrich it in nitrogen-15, a very stable isotope, which we find in the lake sediments in an amount related to the number of salmon that have returned there to die. Thus, by determining the nitrogen-15 concentration in a sediment core, we have an indicator of changes in the abundance of the salmon. A clear pattern emerges: the number of Alaska salmon tends to decrease when the temperature of the ocean falls (the cool phase of the PDO) and to increase when the ocean temperature rises (the warm phase of the PDO), with a periodicity of some fifty years. This is therefore yet another indicator of the reality of the PDO and of its impact on pelagic fishery resources.

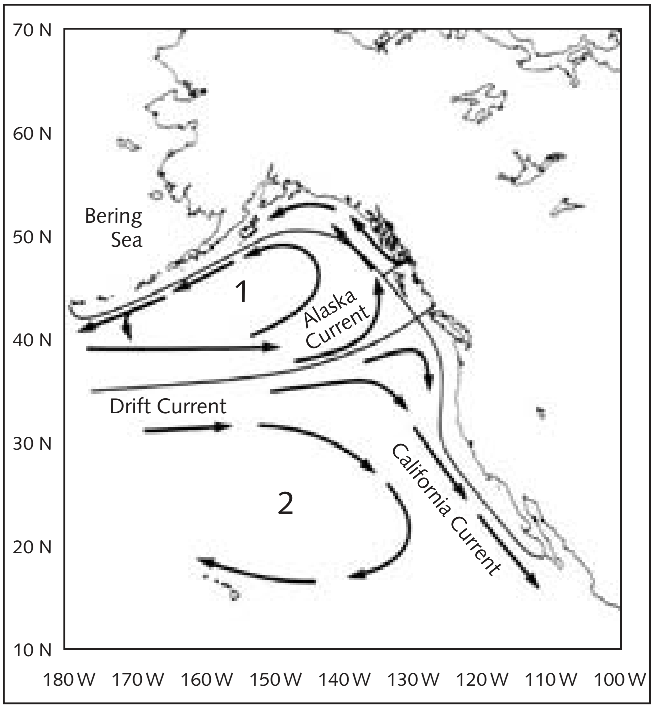


Figure 25
The surface currents in the north-eastern Pacific Ocean.
(1) Cyclonic circulation in the Gulf of Alaska
(2) Subtropical anticyclonic circulation
The North Pacific Drift Current driven by the westerly winds in the northern part of the subtropical gyre splits into two streams on arrival at the coast: the Alaska Current towards the north and the California Current towards the south. The respective intensities of these two currents are modulated by the PDO.
Source: D. M. Ware and G. A. McFarlane, Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models, Can. Spec. Publ. Fish. Aquat. Sci., 108, 1989.

THE ANCHOVY, THE SARDINE AND COASTAL UPWELLING

In California and Peru, the exploitation of the sardine and the anchovy is linked to the particular ecosystem based on coastal upwelling, described in Chapter 4**.** The warm phase of the PDO corresponds to a warm anomaly of the sea-surface temperature off California as well as off Peru and to a 'sardine' period in the respective ecosystems which are thus in phase. This anomaly is the sign of a lowered capacity of the upwelling to bring from depth to the surface the cold water rich in nutrients, resulting in the lower productivity of these ecosystems. Either the flux of the upwelled water is effectively lower because of a less intense wind field, or the greater stratification of the water column due to warming impedes this upwelling (in which case more energy would be needed to achieve the same flux). In the years following the major event of 1975 and when during this same period the sea-surface temperature increased, the abundance of zooplankton in the California Current decreased by about 70%, which was proof of reduced fertility. From the standpoint of their productivity, the Gulf of Alaska gyre and the California upwelling vary out of phase.

The link between the two systems may be sought in the North Pacific Drift Current (the northern part of the subtropical anticyclonic circulation) which is driven by the westerly winds and which, on approaching the coast of North America, divides into two branches: the northern branch is the Alaska Current, which generates the cyclonic gyre, and the southern branch is the California Current, which drives the coastal upwelling. In the warm phase of the PDO, the northern branch (the Alaska Current), which controls the intensity of the divergence in the heart of the cyclonic gyre, is strengthened at the expense of the southern branch (the California Current), thus causing the upwelling. The situation is, of course, inverse in the cool phase. The link to the Peruvian upwelling in the southern hemisphere is less easy to establish. Nevertheless, after 1975, the Peruvian upwelling underwent a regime change analogous to that of California and with the same consequences: a positive thermal anomaly and a sharp decrease in the anchovy to the advantage of the sardine. Analysis of the variation in the SOI (difference in atmospheric pressure between Tahiti and Darwin) shows that there is a corresponding weakening in atmospheric pressure in the south-east Pacific anticyclone hence in the south-easterly winds which on its eastern side drive the Humboldt Current and cause the upwelling along the coast of Peru. These decadal fluctuations in the upwelling have nothing to do with the extent of the El Niño phenomenon which in Peru is manifested in the virtual suppression of the upwelling, whereas the warm phase of the PDO only attenuates the effects, but just enough that, ecologically, we pass from a regime favourable to the anchovy to one more favourable to other species, especially the sardine. Consequently, along the coast of Peru during an El Niño, the sea-surface temperature may increase by nearly 10 °C, whereas the decadal anomaly linked to the PDO is always less than 1 °C.

As a result, intensification of the upwelling creates a regime favourable to the anchovy, whereas its relaxation creates conditions favourable to a greater variety of pelagic species, particularly the sardine. At first sight, this is a surprising result, for if both species are planktonivorous the diet of the sardine appears to be richer in phytoplankton than that of the anchovy. We might therefore expect that the increase in the production of phytoplankton when upwelling is at its maximum would favour the more herbivorous of the two: the sardine. But this is not so, as the sardine develops best when the upwelling is less intense. Rather than in the diet of the adults, an explanation may be found in the conditions of development of the larval stages which, although they last no more than about ten days, are crucial, as they influence recruitment. To reach the end of their development, the larvae, even more so than the adults, need sufficiently stable environmental conditions. During upwelling the great abundance of phytoplankton is not enough; two dangers await the larvae. They can be rapidly carried offshore by the surface current and be removed from their coastal habitat. Or excessive water turbulence may scatter their food and make it all the more difficult to capture, just as they are also perpetually shaken up by this same turbulence. Both risks increase as wind speed increases; that is, as the intensity of the upwelling increases: the stronger the wind, the stronger the offshoreward displacement and the more the turbulence creates instability.

We can see that above a certain threshold the intensification of the upwelling by the wind becomes a handicap in spite of increased primary production. This threshold corresponds to what we call the ‘optimal environmental window’ for recruitment: as long as we are below it, recruitment increases as the wind speed increases; above it, larval survival and recruitment decrease and may be compromised. This optimal window is not necessarily the same for all species, and the passage from a ‘sardine’ regime to an ‘anchovy’ regime when upwelling becomes more active may be explained by an optimal window corresponding to a higher wind speed for the anchovy than for the sardine. After eclosion (emergence of the larva from the egg), the sardine has a growth rate (1 mm/day) much higher than that of the anchovy (between 0.2 and 0.5 mm/day). We can deduce from this that to maintain its growth rate the sardine needs a sustained diet, hence a stable moderate upwelling, whereas the anchovy, in less of a hurry, can apparently adapt better to the erratic conditions of a more intense upwelling.

THE ANCHOVY AND THE SARDINE OF THE KUROSHIO

The evolution of the sardine catches in Japan poses a problem. The Japanese sardine fishery is very ancient and study of historical data has shown that there are more or less periodic variations (60 to 70 years) with marked peaks in abundance around 1650, 1710, 1820, 1875, 1935 and 1985 which seem to indicate that the large fluctuation observed in the twentieth century and which has been associated with the PDO is no accident but is recurrent, as in California or Peru. However, we have seen that the PDO is characterized, in the North Pacific, by an out-of-phase evolution of the sea-surface temperature between the eastern and western sides. So, two populations of the same species of sardine, that of Japan and that of California, which vary in parallel, react in opposite ways to the sea-surface temperature fluctuations. A warming of the ocean favours the sardine in California, whereas the opposite is true in Japan. This is an apparent paradox that simply confirms that temperature is not by itself a determining factor and we must analyse the sea-surface temperature as a simple indicator of the state or of the mode of functioning of the ecosystem concerned. There is nothing against the idea that, in Japanese waters, colder water may correspond to trophic conditions that are more favourable to the sardine. There, we are not dealing with a case of coastal upwelling as in California or Peru. The situation in Japanese waters is more complicated.

The Pacific Ocean side of Japan is influenced by two opposing currents: the Kuroshio and the Oyashio. The Kuroshio is a warm current analogous to the Gulf Stream in the Atlantic Ocean and flows from the tropics towards the north-east. The Oyashio is a cold current from the Arctic Ocean. The sardine lives between the coast and these two currents, encountering highly variable conditions depending on the meanders the two currents create and their relative positions (more or less to the south or to the north, more or less close to the coast). The sardine adapts to the conditions by migration that takes it to its spawning areas which are more or less extensive and more or less suitable for the development of the larvae. Just like the California Current, on the eastern side of the anticyclonic circulation in the central Pacific Ocean, the Kuroshio, on its western side, is under the influence of the PDO which causes the atmospheric pressure of the anticyclone to vary. The way in which this dependence affects recruitment of the sardine in Japan is not yet clear, but given the complexity of the system there is no objective reason for judging the observed association contradictory; it is indeed clear-cut between the warm phase of the PDO (cold anomaly in the western Pacific Ocean) and the abundance of the sardine.

THE HERRING OF THE NORTH ATLANTIC: THE COLLAPSE OF THE 1960s–1970s

The principal stocks of North Atlantic herring (Norway, the North Sea and Iceland), strictly speaking, collapsed in the 1960s–1970s. In the words of J. Jakobsson, speaking in 1983 at an international symposium on herring, in Nanaimo, British Colombia (Canada), this was 'the outstanding phenomenon in the history of European fisheries'. In every case, the scenario was the same: a big increase in catches in the years preceding the collapse followed by a rapid decline leading, as a result of the failure to take appropriate management measures, to a complete ban on fishing until the stock recovered. That was twenty years before the breakdown of the cod fishery discussed earlier. Fishery science lacked maturity then and had not yet been confronted with nor strengthened by the test of refutation in the sense proposed by Karl Popper. In the natural sciences, the experimental method is hardly applicable inasmuch as it is difficult to design and monitor an experiment in nature as one can in a classical physics or chemistry laboratory. This is particularly true of fisheries in which the object of the research, the fish, is mobile and swims about in an opaque medium.

John Sheperd said that counting fish is as easy as counting trees except that you cannot see them and they are constantly on the move. In fact, we get to see them, but only after they have been caught and hauled out of the water! Fishery biologists can then easily count them, weigh them, measure them and determine their age, but they have no control over the sampling, which is imposed by the fisherman who decides the fishing strategy or tactics by criteria of his own and which may be biological, meteorological, economic or even social: a funny kind of science in which the researcher is forced to accept someone else's sampling plan and sampling techniques! I doubt that there is anything like it in any other domain of science.

The fish is like a quantum particle: it does not exist as a fish and is only located when the observer (the fisherman) catches it. In the water, we might almost be able to describe it as a probability function of the ocean it is hidden in. The only solution, as we have seen, was for fishery scientists to construct, from fishery data, models and scenarios/hypotheses which for a long time, and this was the case at the time of the herring-fishery collapse, could not be confronted with reality, as unlike physics, experimental data independent of those that had been used to create the scenario/hypothesis were not available. We were biting our own tail. It was clearly a scientific heresy that could only find an epistemological outcome in the collapse of the stocks. It was the only way open to refute the scenario/model and thus advance fishery science. So, we could say somewhat provocatively that fishery science as it had been built up (via population dynamics) could not, by definition, be of use in forecasting the collapses, but that the collapses were indispensable for its progress. It is through them that the fishery scientist meets Popper's scientific criterion of refutability.

Paradoxically, then, having been built up under pressure from the managers, fishery science, conceived in this way, could not meet their demands. So were fishery scientists unconsciously scientific swindlers? Not really, because the managers are rarely buyers of foretold catastrophes that would compel them to take, in uncertain circumstances, decisions that could prove unpopular, only to be forced to anticipate sudden decisions imposed on them. As it happened, for the herring, banning fishing was a decision that was all the easier to take because there was nothing left to fish! The shock was sharp but beneficial from the standpoint of science as well as of management. The catches in the Norwegian Sea reached a peak of 1.7 million tonnes in 1966 only to fall to a mere 270,000 tonnes in 1968 and barely 20,000 tonnes in 1970! The traditional methods of stock assessment based on fishery data (whose limitations we have seen) allowed us, *a posteriori*, to reconstitute the evolution of the stock. The catch would thus have been 11 million tons in 1956 and only 9,000 tonnes in 1972. The scenario for the North Sea would have been similar, the catches passing from a strong maximum in 1965 (1.5 million tonnes) to the total closure of the fishery in 1977. Off the coasts of Iceland the catches, which were modest prior to the 1960s (between 20,000 and 30,000 tonnes), grew considerably thereafter as a result of the modernization of the fleet; for only a meagre profit, however, as, after a peak of 125,000 tonnes in 1963, the landings subsequently declined to practically zero in 1970. This repetitive scenario strongly suggests that, in the absence of any regulation, the growth in the fishing effort would have led to the collapse of the stocks. The increase in fishing-mortality rate apparently went well beyond the capacity of the stock to recover. If there was no regulation, it was in part because the scientists argued among themselves over the impact of the fishing on the stock, so they were not in a position to give clear advice. Some of them still thought that the herring, being at the base of the food chain, should be so abundant that fisheries could only have a minor influence on the stock. Others, in contrast, tried to show that fishing mortality could compromise the survival of the stock. Hence the endless discussions that only the final outcome could decide, as neither side had objective data on the stock that would have allowed one or the other hypothesis to be rejected. The successive collapses settled the argument They had, scientifically speaking, two consequences.

First, it had become obvious that 'objective' data – obtained from a source other than the fishermen – were required. This led to the development of exploratory fishing campaigns using research vessels and following a scientific plan to evaluate stock abundance, to try to quantify recruitment and even to evaluate the abundance of larvae and their spatial distribution. There was also the development of acoustic detection methods (sounders, sonars) to measure the abundance directly, to determine the organization of stocks in space and time and even to study the behaviour of the fish. Moreover, there was the use of fish-marking techniques that made it possible to follow a fish's tracks for several hours, days or even months.

The second consequence was the need to better understand the parameters that determine recruitment, the veritable Achilles heel of fishery science. The question may be put as follows: Is recruitment independent of fishing mortality, as the preferred hypothesis had been for a long time; in which case, should not the fluctuations in abundance be primarily ascribed to environmental variations? To put the question in such black-and-white terms is clearly oversimplifying, which nature generally refuses to do. But is there a way to differentiate, during the rapid decline of a stock and a drop in recruitment, between the part corresponding to excessive catches and that corresponding to the caprices of the environment to which fish larvae are, undeniably, very sensitive?

Not always, for if the natural fluctuations in recruitment are large and if the fishing effort increases steadily, as was the case with herring, it is inevitable that the increase in fishing mortality will combine with periods of weak or very weak natural recruitment to have a fatal impact on the exploited stock. In other words, if in certain cases the analysis of sufficiently long time-series of data allows us to identify the environmental factor and its preponderance (anchovy, sardine in the Pacific Ocean), in other cases the fishing pressure completely masks the influence of the environment even if it plays a part in the evolution of the stock. Apparently this is what happened in the virtual disappearance of the herring in the North Atlantic in the 1960s–1970s. The managers also learned from the collapse: following the total ban on fishing, the restoration of stocks was monitored by systematic stock-evaluation campaigns using the above-mentioned fishery-independent methods. The fishery could only be reopened once the criteria of abundance had been satisfied. In the early 1980s, this was the case of most of the North Atlantic herring stocks. Regulations were imposed, including the establishment of quotas, minimum size of fish taken and limitation of the fishing periods and areas.

THE HERRING, THE SARDINE AND CLIMATE OSCILLATION IN THE NORTH ATLANTIC

The European herring fishery in the North Atlantic is very ancient. All stocks taken together, it reached nearly 5 million tonnes per year in the 1960s, prior to the collapses. That was then 11.5% of world fish catches. Only the Peruvian anchovy, with more than 10 million tonnes in the early 1970s, exceeded it in amount. This long history was not without incident and in certain cases, notably that of the Norwegian Sea stock, the boom periods for the fishery alternated with other periods in which the herring almost completely disappeared. One particular fishery has allowed us to establish a kind of reference time-scale of the variations in the North Atlantic herring fishery: this was the coastal fishery in the region of Bohuslän in Sweden, in the Skagerrak between the Baltic and the North Seas. Periodically, huge quantities of herring gather in autumn and winter in the fjords and around the rocky islands along this very irregular coast. These migrations occur over periods of several decades and provide the opportunity for heavy fishing. Two hundred thousand tonnes were landed in 1895–96. Over the last 1,000 years, nine such periods, known as ‘Bohuslän periods’, have been observed; in recent centuries they were 1556–90, 1660–80, 1747–1809, and 1877–1906. The herring must come from somewhere, and it has been fairly well established that they come from the North Sea. Whatever the fishes' capacity for adaptation, it is unimaginable that the North Sea fishermen cause the herring to flee to the illusory refuge of the Swedish fjords where they are much easier to catch than offshore in the North Sea. Instead, there is a climatic reason and these Bohuslän episodes are the indicator of the perturbations which, beyond the Skagerrak, concern the whole of the North Atlantic and have an impact on the fishery, not only that of the herring, though by far the most important, but also that of the sardine.

The herring and the sardine do not swim in the same water. The sardine, which is rather more sensitive to cold than the herring, is generally fished in lower latitudes than the herring, which is considered to be an arctico-boreal species. In the north-eastern Atlantic Ocean, the line of demarcation where individual fish of the two species may meet is at the latitude of the English Channel. In this region, cold periods correspond to good herring fishing, whereas a more clement temperature favours the sardine fishery. Taking the Bohuslän time-scale as a reference, it was seen that certain fisheries could be classified into two groups operating out of phase with each other. The first comprised the Bohuslän fishery and the English Channel herring fishery, and even the Bay of Biscay fishery. The second group comprised the Norwegian Sea herring fishery and the sardine fishery of the Channel and south-western England. Until its collapse in the mid-1970s, the herring fishery in the North Sea was more stable, which may be explained by its central position in the area of distribution of the herring, far from the cold boundary to the north in the Norwegian Sea and far from the warm boundary to the south in the English Channel. To put it simply, we call 'cold fisheries' those in the first group (the Bohuslän group), since they flourish in cold periods, and 'warm fisheries', those in the second group (the Norwegian Sea group) which prefer a more temperate climate.

It has proved possible to link this alternation between cold and warm periods, indicated by the Bohuslän fisheries, to the North Atlantic Oscillation (NAO). Because the positive anomaly of the NAO favours western winds, it also facilitates the spread of Gulf Stream water towards the north-eastern Atlantic, inducing a positive sea-surface temperature anomaly in the region of interest to us. The cold and/or warm boundaries for the herring and the sardine move northwards: the herring becomes more abundant in the northern part of the region (the Norwegian Sea stock), disappears from the southern part (English Channel) in favour of the sardine, and varies little in the intermediate zone (North Sea). Conversely, in a cold period, the herring surges southwards: the catches in the Norwegian Sea decrease noticeably, to the benefit of the Bohuslän region, and even of the English Channel, where the sardine disappears.

The NAO fluctuates on various time-scales and the positive and negative anomalies may extend over several years, even decades. Thus, in recent history, the positive anomalies (warm periods) have clearly predominated between 1900 and 1930 and since 1975, whereas, between 1950 and 1975, the reverse was true (figure 11). We do not have direct measurements of the NAO prior to the mid-nineteenth century, but we can nevertheless reconstitute its history indirectly from the length of the season in which the coasts of Iceland are ice-bound; this is possible from the analysis of tree growth rings or even from the cores of the Greenland ice cap which shows us the annual abundance of the snowfall in Greenland. This all confirms the preceding scenario linking the so-called Bohuslän episodes to the negative anomalies of the NAO (cold periods).

The last recorded Bohuslän episode dates back to 1877–1906. The NAO did not cease to oscillate then and another should have occurred in the 1960s when the negative anomaly of the NAO was at its maximum. But it did not. Why? Probably because the considerable increase in the fishing effort which led to the collapse of all the stocks in the 1960s–1970s made the climatic signal quite secondary and insignificant.

BLUEFIN TUNA IN THE MEDITERRANEAN

The bluefin tuna (*Thunnus thynnus*) fished in the Mediterranean is of interest to us because we have reliable catch data since the sixteenth century, owing to the fishing method: tunny traps. The bluefin migrates each year from the North Atlantic into the Mediterranean to spawn in the western part around the Balearic Islands and Sicily. Swimming along the coasts, they are caught in the traps, which are large barriers blocking their way. As fixed gear that remains unaltered for decades, if not for centuries, we may assume that each trap represents a constant fishing effort. The traps are also well monitored, by the fiscal authorities, by collectors of the ecclesiastical tithe, by the customs officers, who note carefully their takings, and by the investment bankers who keep account of the catches: all are reliable samplers. We may, without difficulty, consider the catches as being representative of the biomass. The analysis of time-series data on the catches, some of which (as in Sicily) are virtually continuous since

1600, show that, from Portugal to Sicily and from Tunisia to Sardinia, the variations are synchronous, with a clear-cut periodicity of 100 to 120 years (figure 26). Maximal abundance occurred around 1640, 1760 and 1880, and the minimal around 1700, 1800 and 1920. The amplitude of the variations from one extreme to the other is highly significant, the high:low ratio ranging from 2 to 7 depending on the case. We could attribute these variations to societal or economic events (war, revolution, epidemics) which have no reason to be simultaneous so far apart in time and which, moreover, do not generally occur on this time-scale. Nor can we really speak of overfishing, as the fishing effort has remained constant. So, what about climatic fluctuation, which would modify the bluefin's migratory path? Or the conditions for larval survival? Or even the fluctuations linked strictly to the biological dynamics proper to this species, which would amplify by resonance the random variability in recruitment? We do not at present have an answer, but we do have a clear demonstration that the stocks vary widely and independently of the fishery.

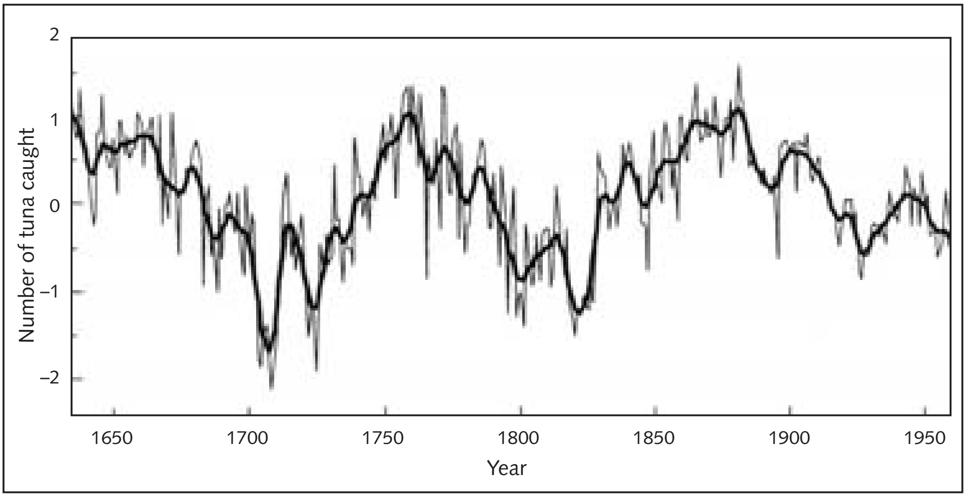


Figure 26

Variation in the bluefin tuna catches of the various tunny trap *(madrague)* fisheries in the western Mediterranean.

The vertical scale (number of tuna caught) has been normalized and may be interpreted as 'catch anomalies' in the sense this term is used for temperature, for example.

Source: C. Ravier and J.-M. Fromentin, Long-term fluctuations in the eastern Atlantic and Mediterranean bluefin tune population, ICES J. Mar. Sci., *58, 2001.*

REGIME CHANGES

We have mentioned several times the climatic break that occurred around 1975. This is the period when we passed from the ‘classical scenario’ of El Niño to a more peculiar regime, with a predominance of negative anomalies in the Southern Oscillation Index. It was also the period in which the PDO switched from the cold phase to the warm phase, with the consequences we saw for the fisheries for salmon, sardine and anchovy. It was the time at which the NAO inverted, passing from a negative anomaly (cold) to a positive anomaly (warm). As climate dynamics are a planetary phenomenon, it is not surprising that all these oscillations are not independent of each other. Their discovery and their utilization are only reductionist conveniences for analysing climate fluctuations and to give some reference points to comprehend the functioning of so complex a system. The problem posed by the possible global warming of the planet due to the increased concentrations of greenhouse gases stimulates research on climate variability on various time-scales. We need to be able to determine the part attributable to the natural variation in the climate so as to be able to determine what might be effectively attributable to the greenhouse gases that we inject into the atmosphere. Hence the multiplication of those oscillations characteristic of the various space–time scales of climatic variability. Using air-temperature data from the Intergovernmental Panel on Climate Change, the Americans M. E. Schlesinger and Navin Ramankutty were able to show that there was for the whole of the northern hemisphere an oscillation with a period of 65 to 70 years, which is close to and in phase with that of the PDO. The extremes of this oscillation, in 1910 and 1975 for the negative temperature anomalies, and in 1940 for the positive anomalies, correspond to the inversions of the PDO. Less markedly, perhaps, we find the same conjunctions in the NAO. We may conclude that the NAO and the PDO agree in this frequency of oscillation, which they have in common and which must be taken into account if we are to evaluate correctly the climatic signal due to the increase in the greenhouse effect since the beginning of the twentieth century. We may also conclude that ruptures analogous to that of 1975 have occurred in the past.

Returning to our fish, if this link between the NAO (in the Atlantic) and the PDO (in the Pacific) is confirmed, we should be able to deduce that the fluctuations in the North Atlantic herring fishery are not independent of those in the fisheries for salmon, sardine and anchovy in the Pacific. To describe this oscillation with a 65 to 70-year periodicity, the Russian L. B.

Klyashtorin has defined an index of atmospheric circulation in the northern hemisphere: the ACI (atmospheric circulation index) deduced from the atmospheric pressure field over the Atlantic and the Eurasian region. Globally, this index allows us to measure the relative importance of the atmospheric circulation meridionally (north–south) or zonally (east–west). The zonal periods correspond to the positive temperature anomalies and the meridional periods to the negative anomalies. With this tool, Klyashtorin then analysed the evolution of catches worldwide for the last 100 years and showed that the variations in this index, whose period is close to sixty years, closely reflected fluctuations in the catches of the species mentioned above: the sardines of Japan and California, the anchovy of Peru, the salmon of the North Pacific, and the herring of the North Atlantic. This synchrony on a world scale, which appears to link the fish to the movements of the atmosphere, may seem very surprising, or even artificial, but it should be borne in mind that the connection is via the ocean dynamics, as we saw with the oceanic cyclonic circulation in Alaska and the variations in coastal upwelling. It is much easier to evaluate climatic fluctuations by way of atmospheric parameters, which are easily accessible and which we have been measuring for a long time on a global scale, than by way of the properties of an opaque ocean in which it is much more difficult to set up stable observatories. This difficulty of observation and this lesser knowledge of the ocean should not be allowed to hide the fact that on these time-scales it is the ocean dynamics that impose their rhythm on the coupled ocean–atmosphere system. So there is nothing surprising in the fact that we can find in the atmospheric parameters we use to characterize climate the signature of variations in the marine ecosystems linked to the dynamics of the ocean (and consequently to the fish that live in it). Concerned by the need for integration, Klyashtorin went even further. The speed of the Earth's rotation is not constant, but varies slightly as a function of the distribution of masses and the movement of the fluids composing it (atmosphere, ocean, crust, core). The climate variations which modify the exchange of water between the ocean, the atmosphere and the continents and which cause the marine and atmospheric currents to vary have an impact on the Earth's speed of rotation. This was clearly shown by the El Niños of 1982–83 and 1997–98 which caused an increase in the day length of nearly 1 ms. Klyashtorin has shown that there was good correlation between his ACI, characteristic of the fluctuation in the climate every sixty years, and the Earth's speed of rotation. Could this speed of rotation become an index of the evolution of marine ecosystems?

6

See, observe, measure and model, to understand and forecast

MODELLING: EXPERIMENTATION AND FORECAST

Whether we are talking about climate, ecosystems or fishery resources, beyond the simple comprehension of phenomena, we are seeking above all to develop a capacity to forecast their evolution. The physical and chemical sciences have compelled us, not without reason, to adopt the paradigm of the experimental method which is inevitably linked to the idea of a laboratory in which an experimental apparatus is set up that is well controlled so as to verify a hypothesis or establish by measurement the relation between one parameter and another of a particular system. In this way, in the nineteenth century, a number of ill-named 'laws' were enunciated, although they were nothing more than empirical relations derived from laboratory experiments. Ohm's Law is an example which everyone knows and which simply defines the ratio of the electrical voltage to the current intensity in a circuit observed in an experiment. But how can we experiment on natural media over which we have almost no control (which does not stop us from modifying them profoundly but, precisely, in an uncontrolled way)? It would be difficult to put the whole of nature in a laboratory. We can only carry out very partial experiments to study this or that phenomenon: the phytoplankton production, for example, in enclosures where we can play with the parameters (e.g. nutrient fluxes, light level) that control it. We can also try to isolate parts of systems *in situ*. This is done in agronomy, in which we can compare parcels of land treated differently. It is also done in aquatic media, by isolating parts of an ecosystem in the hope that they remain representative of the whole, in which case we speak of a 'mesocosm'. Each time, we are talking about very partial experiments that allow us to better understand and quantify certain processes, but no case is a simulation of the real functioning of an ecosystem as a whole. Especially in the open sea, which is constantly in motion, and which we are quite incapable of controlling or simulating physically. The experiments are more a means of study and quantification of processes to improve the quality of the models than tools for simulation and forecasting. For there is not, in this case, any other experimental solution than the model: the most complete conceptual representation possible of the system studied with which the 'experimenter-modeller' can play, modifying the value of this or that parameter with a view to studying its impact on the functioning of the system and its evolution and, in the end, having in hand a forecasting tool. It is in this way that the simulations of the climate changes proposed by the Intergovernmental Panel on Climate Change were developed to evaluate the potential impact of the increase in greenhouse gases on the climate. Based on economic and political scenarios (application of the Kyoto Protocol, evolution of energy needs, etc.), projections are made of changes in the concentration of man-made greenhouse gases. Projections are also taken into account in climate models as representative as possible of the whole system, in order to simulate, for example, the changes in temperature and rainfall over the next 100 years. The results of these numerical experiments are obviously only as good as the models themselves. Which brings us back to the harsh reality which we could, somewhat provocatively, formulate in the following way, inverting the roles: Does reality simulate the models correctly? There is no other way available to validate a model than to confront its predictions with reality. In rapidly evolving systems, such as meteorological phenomena, the reality judges the quality of the prediction within a few hours or days. Errors can thus be analysed and interpreted in near-real time. We can consider this still to be the case on the scale of the El Niño phenomenon, the occurrence or non-occurrence of which follows the forecast by a few months.

The repeated errors in the forecasts of El Niño provided moreover a powerful stimulus to research on the climate system and a real factor in the improvement of coupled ocean–atmosphere models. El Niño therefore remains an irreplaceable experimental laboratory. But beyond that, in the longer term, how can we trust the forecasts of the models knowing that, in spite of the considerable increase in computer power, the models will never be able to take into account all the phenomena in play on an appropriate scale? Also, knowing that in a non-linear system as all natural systems are, an approximation, an error, an uncertainty can be amplified exponentially as a function of time. The reconstitution of palaeoclimates and palaeoenvironnements, based on fossil data, allows us to test the models up to a certain point: by setting the starting point at a given situation, we can verify whether they simulate correctly the changes that actually took place. We can see that numerical experiments using models, in spite of their sophistication, are full of uncertainties that can only be dissipated by confrontation with the reality. There is no alternative to observation and measurement *in situ*. Unfortunately, in the case of the growing greenhouse effect, we cannot await the results of this confrontation before taking the necessary steps to limit it.

MODELLING OF OCEAN DYNAMICS

Ocean dynamics are governed by the laws of hydrodynamics based on the fundamental principle of mechanics, which postulates that the inertia of a particle in motion (the product of its mass and its acceleration) balances the sum of the forces that set it in motion. This principle is expressed by a differential equation known as the Navier–Stokes equation, which is basic to the modelling of ocean dynamics. The Ekman model and the geostrophic hypothesis are only simplified versions of this equation. In a dynamical system, the differential equation poses the problem, and the solving of the equation provides the answer to it. Unfortunately, there is no known analytical solution for the Navier–Stokes equation from a simple mathematical point of view and independently of any physical consideration. It can only be solved numerically, that is, by iteration, which is what all the models used are doing. This requires considerable calculating capacity, and for a long time the limited power of computers was the main obstacle to the development of global ocean models with sufficient spatial resolution (of about 10 km) so as to be able to take into account, realistically, the essential elements of ocean dynamics: the eddies. But that is not the only difficulty with ocean modelling. It is necessary to define analytically the applied forces and to know what are the thermodynamic ‘drivers’ or ‘forcings’ at the interface between the ocean and the atmosphere which are not always expressed through relationships – ‘laws’ – as reliable and robust as Ohm’s Law, for example. The example of turbulence is especially illustrative.

The Navier–Stokes equation applied to viscous fluids, to express the dissipation of the energy of friction between the layers, introduces a coefficient of viscosity that is a physical property characteristic of the fluid, just as the density is. In a fluid, we find that the internal frictional force is proportional to the differences in the speed of flow within the fluid, and this factor of proportionality is what we call the coefficient of viscosity, just as we call it the resistance in Ohm's Law. This magnitude is thus treated in the equation as an independent flow constant; that is, in time and place. This holds true as long as the fluid is not turbulent, that is, when all the fluid elements in a layer flow at the same speed; in this case, we speak of laminar flow. This is what we usually see in highly viscous fluids, such as oil, that appear to have a steady flow. Under certain conditions which depend on the fluid's average flow speed, its viscosity and the dimension of the flow channel, the system becomes turbulent, that is, the elements of the fluid are in continuous agitation so that, instead of following the mean flow, they continuously move in all directions. This turbulence diminishes considerably the internal frictional forces and increases correspondingly the mixing within the fluid. In this case, the coefficient of viscosity is no more a relevant parameter of the frictional forces in the Navier–Stokes equation. Nevertheless, the formalism of the equation is maintained by substituting the coefficient of viscosity by a coefficient of turbulence, with the following fundamental difference: whereas the coefficient of viscosity is an intrinsic physical property of the fluid, the coefficient of turbulence itself is not a constant. It depends on the flow conditions and varies continuously as a function of time and place. Strictly speaking, the Navier–Stokes equation in which the coefficient of turbulence is assumed to be constant is not applicable to turbulent systems, and therefore not to the ocean which is always turbulent. Hence the obligation to 'parameterize' the coefficient of turbulence; that is, to attribute to it the best possible value in the context of the current under study. This is a purely empirical step that can make this parameter an adjustable variable that allows the model to be tuned so that it corresponds as well as possible to reality; just as, when listening to a radio broadcast, we adjust the tuner knob to get the best quality of reception.

Wind stress, like the thermodynamic exchanges between the ocean and the atmosphere, cannot be expressed in a simple way by a law that could be applicable in all cases. Wind stress is taken to be proportional to the square of wind speed, but in fact it depends greatly on the turbulence in the lower layers of the atmosphere. Thermodynamic exchanges are even less well known: they are difficult to measure, highly variable, dependent on the temperature of the water surface and of the lower layers of the atmosphere, on the humidity of the air, on the wind speed, and on the turbulence of the ocean and the atmosphere. But they have to be taken into account in the models and to operate over global fields of magnitudes corresponding to the ocean. Measurements from space combined with traditional measurements of meteorological and oceanic observatories now provide wind fields and sea-surface-temperature fields from which we can calculate at best, and empirically, wind stress and thermodynamic exchanges between the ocean and the atmosphere. Even so, these exchanges remain one of the weak points of oceanography. There is no shortage of weak points and, unless they are properly taken into account, they can transform the modeller into 'manipulator': does the modeller have available, with all these uncertainties, a console (a tuner) on which each poorly known parameter is a kind of knob for fine-tuning the parameter's value so that the model can be adjusted to say what the modeller wants to hear? Is it not significant that the verb 'to simulate', in English, and the verb 'simuler' in French, both mean 'reproduce faithfully' as well as 'feign'?

OBSERVATION OF THE OCEAN IN SITU

Be forewarned, there is only one solution: observe and measure. Measurement in oceanography, properly speaking, began with the *Challenger* between 1872 and 1876. It was truly revolutionary, based on some 400 measurement stations across the planet requiring more than three years of work to complete. Between 1925 and 1927, Germany, with its *Meteor*, carried out a series of expeditions in the South Atlantic Ocean. This was the first complete description of an ocean basin ever made. The *Meteor*, between 20° N and 65° S, made fourteen transoceanic sections from east to west, along each of which it carried out a large number of measurements from the surface to the bottom. It was therefore possible to undertake a complete analysis of the Atlantic Ocean water masses. It took two years to achieve this result: each hydrographic station took several hours or even days. The idea was not to detect variations in the oceanic circulation. It was, in fact, done in the framework of a constant ocean. The International Geophysical Year of 1957–58, which was a kind of *Meteor* super-expedition, conformed to the same concept. How indeed to conceive the variability of a medium if the means of measurement available could not provide access to it? The mind, including that of the researcher, adapts to the available means of observation and, to use the language of social sciences, it ‘constructs’ the object of its research to the time–space scales imposed on it by the instruments of measurement. So progress in oceanography did not come from conceptual revolutions: fluid dynamics was not born with the study of the oceans, but has been adapted to it by way of meteorology which was, in this respect, a long way ahead. It came from technological advances that overcame the ocean’s opacity and gave access to unsuspected scales of variability. The stake is to have measurements available that allow us to ‘resolve’ the various scales of ocean variability, from the eddy to the general ocean circulation, and from a few days to 100 years, God or the Devil willing.

OCEANIC ‘SOUNDINGS’

The first basic tools of oceanographic observation were bottles for taking samples of water from different depths, which were analysed on board the research ship, truly a floating laboratory, and the thermometers which were usually attached to the sampling bottles. Current measurements made with instruments adapted from the anemometers of meteorology from a platform as unstable as a ship, even when at anchor, provide qualitative information that is not very reliable and is no longer used. Developments in electronics have, since the end of the 1960s, made probes available that are still deployed from vessels and which measure a continuous vertical profile, from the surface to the bottom, of the hydrographic (temperature and salinity) or chemical (nutrient salts, dissolved oxygen) parameters, and even biological ones (chlorophyll). There are also versions, developed initially for military purposes, that are cheap (at least for the measurement of temperature) and expendable and which can be launched from any commercial vessel and even, in certain cases, from aircraft. Observations of temperature in the upper 500 m of the ocean have thus been carried out regularly for the last twenty years, as for meteorological observations, from selected merchant vessels along transequatorial routes for the study of the El Niño phenomenon. This was the first civil quasi-operational ocean-observing system that allowed, and continues to allow, us to track the dynamics of the surface layer of the equatorial ocean, the driver of the El Niño phenomenon in the Pacific. Measurements of this type are now made routinely in the whole ocean.

TEMPORAL CONTINUITY: MOORINGS

The kinds of observation just mentioned allow good spatial coverage in the case of oceanographic campaigns, but they do not ensure the sampling rate we need, even in the case of commercial vessels whose routes are well spaced and, moreover, irregular. Meteorologists, who still provide some inspiration to oceanographers, have established a synoptic-observation network that reports from stations worldwide on the global atmospheric conditions every six hours and which they use to adjust their forecasting models which are thus continually being refined. The response time of the ocean obviously does not impose so rigorous a synchrony, but it is clear that the adaptation of such a system to the ocean is necessary. To scrutinize the atmosphere, the continents and islands provide stable platforms on which it is easy to construct observation and measurement stations. In the ocean, there is no similar terra firma, except the bottom, at a mean depth of 4,000 m; but there is no one to set up and maintain such observation stations. Which brings us inexorably back to the surface where are again obliged to work with its chronic instability. This explains why, besides their very high cost in equipment and maintenance (which requires a vessel for setting and hauling), fixed observing stations based on moorings anchored to the sea bed were late in appearing. They have become operational, because of the interest in El Niño once again. The TOGA (Tropical Ocean and Global Atmosphere) study was carried out between 1985 and 1995 in the framework of the World Climate Research Programme to study, on seasonal and multi-annual time-scales, the dynamics of the climate, controlled by the dynamics of the equatorial currents, mainly in the Pacific, as we have already seen. El Niño was the core of the subject. This was an opportunity to set up from one end of the equatorial Pacific Ocean to the other, between 5° N and 5° S, an observing network (called TAO, Tropical Atmosphere–Ocean) comprising seventy moorings fitted, subsurface, with thermistor chains down to a depth of 500 metres, some current-meters and salinometers and, in the air, on the surface buoy, meteorological stations (figure 27). In what is called the equatorial wave guide, nothing (water-mass transfer, Kelvin wave, current inversion) can escape such an observation system which was made precisely to catch the El Niño. This network has been maintained and even extended to the equatorial Atlantic Ocean with the programme PIRATA (Pilot Research Moored Array in the Tropical Atlantic) which comprises, more modestly, twelve moorings but still appropriate to the scale of the Atlantic.

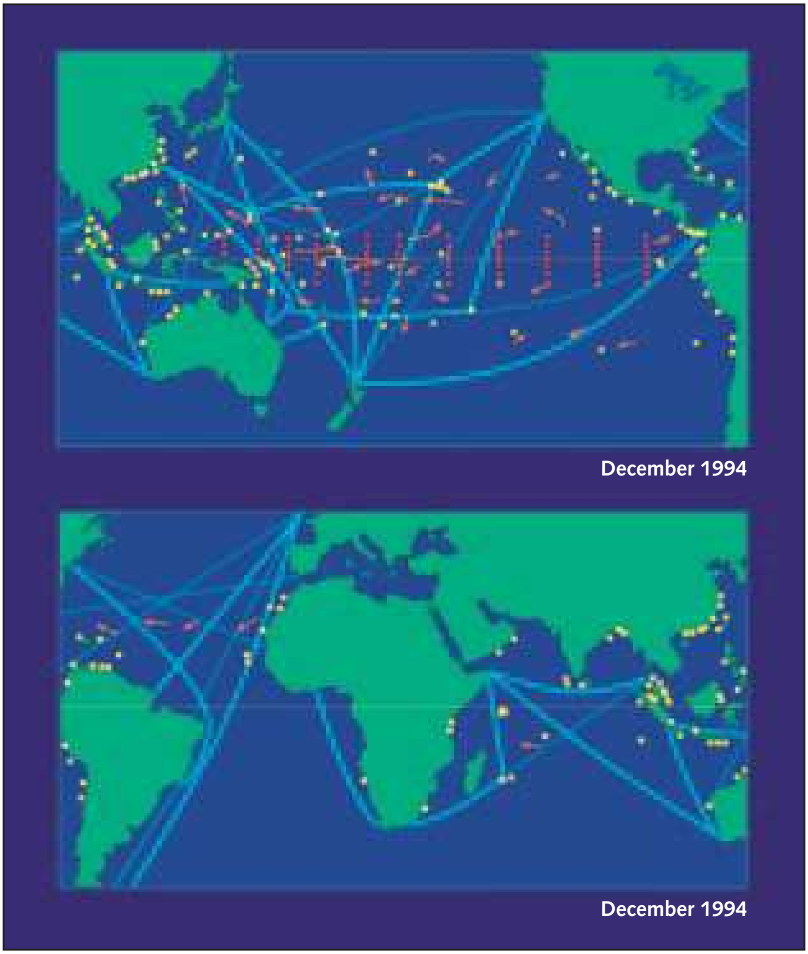


Figure 27

System of *in situ* observations of the tropical oceans during the TOGA (Tropical Ocean and Global Atmosphere) study.

Red diamonds: moored buoys
Yellow dots: sea-level measuring stations on islands and continents
Red arrows: surface drifting buoys
Blue lines: routes of merchant vessels (ships-of-opportunity) taking systematic temperature and salinity measurements.

All the data are transmitted by satellite, which thus constitute a powerful means of measuring the principal meteorological and oceanographic parameters, as well as the sea level. The observations are especially dense in the part of the Pacific of main interest, with the ENSO as the 'mastermind' of multi-annual climate variability.

Source: Images kindly provided by the NOAA/PMEL/TAO Project Office, Michael J. McPhaden, Director.

Oceanography in copying meteorology systematically leads us to ask why the principle of the atmospheric sounding balloon has not found an application in the ocean. Nevertheless, there is a project called EMMA (Environmental Monitoring Moored Array) aimed at establishing stations on the sea floor that release periodically and automatically, at a predetermined time, probes fitted with sensors which, on arriving at the surface, transmit by satellite the measurements made during their ascent.

SPATIAL CONTINUITY: DRIFTING FLOATS

The quickest way to measure a current is doubtless to let an object float in it and follow its path. Thus, the first currentmeters were the ships themselves; not that they were left to float, but the currents made them drift relative to their route or, conversely, with acquired experience, the ships anticipated the drift and adjusted their heading so as to maintain their track. The bottle thrown into the sea, carrying the hope of the shipwrecked, was also a way, if not to measure the currents, at least to provide information on them. And, in a more recent, more comfortable and more fashionable version, during some pleasure cruises the passengers were invited to throw handfuls of little plastic squares into the sea, and those who recovered any were requested to send them to a particular address. Even so, that only gives a rather poor idea of the currents and illustrates the difficulty of the method: how to follow a float wherever it goes. For the surface floats, the solution came from space: position-fixing by satellite with the Argos system mounted on the meteorological satellites of NOAA (US National Oceanic and Atmospheric Administration) and which, since 1978, tracks moving objects on the Earth's surface, whether they are deer, marine turtles, sailors or buoys, so long as they are fitted with some kind of an emitter; the emitters are becoming more and more compact. The trajectories of these floats sometimes resemble Brownian movement which illustrates the swirling character of the ocean (figure 28).

Paradoxically, the floats drifting in the deep layers of the ocean, which nevertheless rely on a more sophisticated technology, were in use before the more common-place surface floats. This was thanks to the military which, for the purpose of anti-submarine warfare, had acquired an understanding of marine acoustics, for which they kept the monopoly for a long time. An Englishman, John Swallow, in 1955 carried out the first experiment with floats designed and ballasted so as to remain at a depth of 1,000 m. Fitted with an acoustic emitter, they were followed by the research vessel which 'listened' to them. The necessity of mobilizing or, rather, immobilizing a

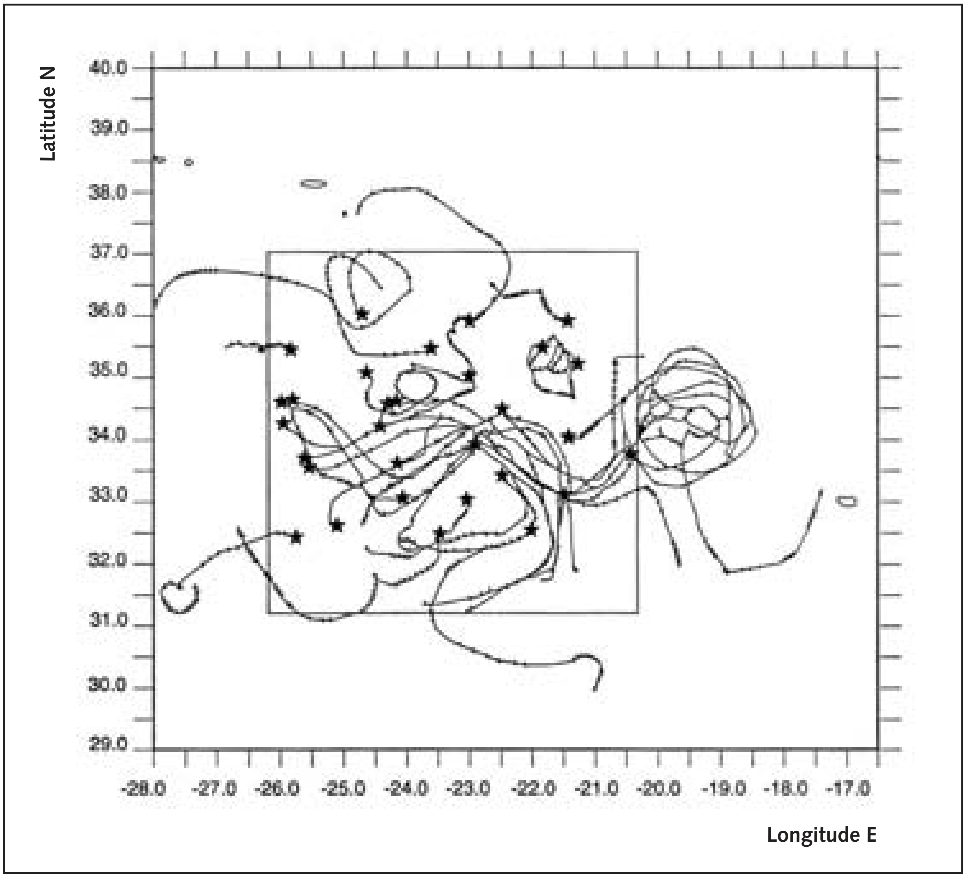


Figure 28
Trajectories during one month of twenty-seven drifting surface buoys in the central North Atlantic Ocean.
The positions of the buoys are provided by the Argos system.
Source: J.-F. Minster, La machine océan, *Paris, Flammarion, 1997.*

vessel to carry out the operation significantly limited its utilization. The technique was subsequently perfected by deployment in the sea (on a mooring) or alongside listening stations, allowing us to determine by triangulation the position of the floats over great distances. There is an inverse solution in which the fixed stations emit and the floats listen and transmit their data by satellite when they return to the surface.

For WOCE (World Ocean Circulation Experiment), the second part of the World Climate Research Programme which was carried out from 1990 to 1997, a new type of float was developed. It was a kind of yo-yo which, following a period that can range from a few days to several months, returns to the surface, making hydrographical measurements throughout the water column, transmits its position and its data by satellite, then redescends to its assigned depth. About a thousand of these different types of deep floats were deployed during the WOCE.

The oceanographic programmes of the International Geophysical Year were qualified above as a *Meteor* super-expedition. Now we can say that WOCE was a super-IGY, at least for oceanography. Some twenty countries participated in it. Its ambition, which was achieved, was to provide a definitive description of the whole of the world ocean from the surface to the bottom, from the North Pole to the South Pole, from mesoscale eddies (100 km) to the major subtropical gyres and the thermohaline circulation, with a view to elaborating the global ocean circulation models that were indispensable for the development of models for medium- and long-term climate forecasting. To attain this objective, all possible means of observation were mobilized: hydrographical experiments, moorings, surface and deep floats, and satellites. It was specifically for this programme that the finest example of space oceanography technology was designed and launched in 1992: the Topex/Poseidon satellite, which is still operating.

THE SPACE REVOLUTION: THE OCEAN IN ALL ITS MOODS

The arrival of the space age was for oceanography a revolution no doubt comparable to that produced by the *Challenger* expedition in 1872. Oceanography utilizes satellites in three ways. Positioning systems, such as Argos which is mounted on the meteorological satellites of NOAA, are demultipliers of measurement points: they allow us to deploy and track all over the ocean the movements of measuring platforms, such as drifting floats whether on the surface or, if they drift at depth, whenever they come up to the surface. In April 2002, the Argos system thus tracked 1,850 surface floats and 830 subsurface floats. While indispensable for positioning, satellites also offer the possibility of transmitting in real time data (position co-ordinates, measurements of parameters) emitted from any fixed or mobile platform anywhere in the world. Thanks to this capability, the way is open to the establishment, at last, of a truly operational *in situ* ocean-observing system. Thirdly, and the most remarkable, is the possibility of the observation from space of the whole world ocean in near-real time, if we are concerned with the scale of oceanic variations and the measurement of the parameters that control ocean dynamics. By combining *in situ* measurements and remote-sensing measurements, we have access to the synoptic observation of the whole of the ocean. The observation and measurement of parameters from space utilize two types of sensors mounted on satellites. Those known as passive, such as radiometers, measure the radiation emitted from the ocean surface at a given wavelength. Thus we can determine the sea-surface temperature and what is called the 'colour of the ocean' from which we can derive the chlorophyll concentration and the biological production. The so-called active sensors are radars; they emit a signal that is reflected or backscattered from the ocean surface and is detected by a receiver associated with the emitter. In this way, the effect of the sea surface can be measured and certain characteristic properties can be derived, such as the wind speed and the height and direction of the surface waves.

SURFACE TEMPERATURE

The sea-surface temperature is itself an indicator of the ocean dynamics and of the currents that are the thermal signatures detectable from space. The surface temperature is also one of the principal parameters controlling heat exchange between the ocean and the atmosphere, hence the climate dynamics. The meteorological satellites launched in the 1960s ushered oceanography into the space age by determining the sea-surface temperature simply by measuring the infrared radiation emitted from the sea surface. The physical oceanographers thus discovered on sea-surface-temperature charts the thermal signature of certain components of the ocean dynamics, such as upwelling, eddies and currents, which afforded them a global view (figures 6 and 20). Physicists and climatologists, having available the sea-surface temperature field, had one of the key parameters controlling the exchanges between the atmosphere and the ocean. Biologists were able to define the contours of, and follow the changes in, specific ecosystems, such as those associated with coastal and equatorial upwelling. And finally, fishermen, and especially tuna fishermen, being able to see structures such as thermal fronts, which were known to be favourable to fish, utilized these temperature charts in their fishing strategy.

COLOUR OF THE OCEAN: CHLOROPHYLL, PRIMARY PRODUCTION

We speak here of 'ocean colour' because the radiometers used operate in the familiar part of the electromagnetic spectrum: the visible. The colour of the ocean is modulated by the particles it contains: the phytoplankton, which is responsible for primary production, or the sedimentary particles in suspension or of terrigenous origin brought by rivers or coastal runoff from the land. By carefully choosing the wavelengths, we can differentiate between the different types of particle. So we can evaluate, in each case, the concentration of chlorophyll, hence infer the fertility of the marine ecosystems, or the sediment load in the water, hence the sediment transport in the coastal zone. We saw in Chapter 3 the interest of this measurement for the dynamics of productive ecosystems (figures 13, 14, 17, 18 and 19). Knowledge of the overall oceanic primary production also allows us to evaluate the consumption of carbon dioxide by the oceanic biosphere; this is an important component of the carbon cycle which we need to know to be able to evaluate the reality of the increase in greenhouse gases in the atmosphere. The first instrument of this type, the CZCS (Coastal-Zone Color Scanner), was launched by NASA (US National Aeronautics and Space Administration) in 1978 and remained operational till 1986. We had to wait till 1997 for a replacement, the SeaWiFS satellite, also from NASA; it was still operational in March 2002, at which date the European Space Agency launched its ENVISAT (Environmental Satellite) which also carried an instrument (MERIS, Medium-Resolution Imaging Spectrometer) for the measurement of ocean colour.

‘MICROWAVE’ RADIOMETERS

These are instruments that operate in a part of the electromagnetic spectrum far from the visible or the infrared wavebands, that is, in the centimetric waveband, also used in microwave ovens. We can use these instruments to follow the sea ice. And, owing to their very high sensitivity to water molecules (which is moreover the principle of the microwave oven: the agitation/heating of water molecules by this radiation), we can deduce the water vapour and the liquid water content of the atmosphere; both these parameters are very important in the heat exchange between the ocean and the atmosphere, hence in the ‘forcing’ of the ocean. These instruments are mounted on nearly all satellites because their sensitivity to water vapour makes them indispensable for correcting the signals received from the radars which are affected by the water vapour content of the atmosphere.

MEASUREMENT OF THE WIND BY SCATTEROMETER

We now look at the active sensors: the radars. Scatterometers emit an electromagnetic wave towards the sea surface with an angle of incidence of a few tens of degrees. The scattering of the wave (its intensity in a given direction) depends on the state of agitation of the sea surface, hence the wind that produces it. Analysis of the scattered signal received back by the radar allows us to evaluate the wind speed and direction at the sea surface. In this way, we have for the whole ocean a measurement of one of its principal drivers: the wind. The first measurement of this type was made in 1978 by Seasat (Sea Satellite) which, unfortunately, only worked for a few months. The European Space Agency ERS (European Remote Sensing Satellites) which were first launched in 1991, are equipped with such scatterometers.

SEA-SURFACE HEIGHT: SATELLITE ALTIMETRY

Altimetric satellites are of especial interest for ocean dynamics: they alone can measure the changes in sea height to a precision of less than a centimetre, thus giving direct access to ocean dynamics. We saw earlier that the differences in the sea-surface topography induce ocean currents and the greater these differences are, the more intense are the corresponding currents. Inversely, by measuring the sea-surface height all along a satellite's 'footprint' on the ocean surface, we can calculate the currents associated with the sea-surface height variations and, if the satellite retraces rather rapidly the same 'footprint', we can also find the variations themselves. This is valid for the mesoscale in the major anticyclonic gyres and for the equatorial currents and counter-currents.

The principle is simple: the altimeter radar emits vertically downwards from the satellite a microwave that is reflected from the sea surface. The measurement of the time taken by the wave to complete the return trip, and knowing the speed of the wave, allows us to calculate the distance between the satellite and the sea surface. This is, however, easier said than done and is very complicated, as may be imagined when we are trying to measure differences of 1 cm in the round trip from a satellite at an altitude of 1,200 km! The trajectory of the satellite must be very precisely known, so the satellite must be fitted with a special positioning instrument that allows us to calculate this trajectory continuously. When, in ocean dynamics, we speak of sea-surface height, we are not thinking of it in relation to a geometric surface as, for example, the ellipsoid, which is our best representation of the shape of the Earth. The Earth is far from being homogeneous, and the field of gravity varies from one point to another as a function of the distribution of the mass inside the planet. Also, even without motion, without any dynamics, the sea-surface height relative to a geometric reference varies as a function of the gravity field, and the differences between the extremes can be several tens of metres.

The reference surface, in relation to which we establish the topography of the ocean surface, should therefore be an equipotential surface; that is, a surface of equal gravity (geoid). It is a kind of ellipsoid with bumps on it, and which we might call 'potatoid'. To know this equipotential surface, we obviously need to know very well the field of gravity. The last difficulty is that we must introduce a whole range of corrections that take into account the state of the atmosphere on which the speed of propagation of the electromagnetic wave depends. In spite of all these difficulties, it all works, and even very well, as we saw with the detection of the El Niño signal (figure 9). We see it also in the study of the eddies or of the Gulf Stream. Some instruments were used in the 1970s, but the objective of centimetre precision was first attained with the Franco-American satellite launched in 1992: Topex/Poseidon, which is expected to remain operational until 2003. Its successor, Jason 1, was launched in December 2001. The European satellites ERS-2 and ENVISAT are also fitted with altimeter radars, as is the American Geosat (Geodetic Satellite); which makes five in all in operation as of March 2002: an exceptionally rich data harvest.

Under the heading satellite remote sensing one data type is missing: salinity. We know that, at certain wavelengths, the radiation emitted by the sea surface varies slightly with salinity. So it is envisageable to measure salinity from space. Studies indicate that we do not yet have sufficient sensitivity and spatial resolution to justify the experiment, but its time will come one day.

TOWARDS OPERATIONAL OCEANOGRAPHY. A CRUCIAL EXPERIMENT: GODAE (2003–05)

When we speak of 'operationality', we generally think of a service to be provided to a client which necessitates the systematic and continuous collection of information. Here too, the reference is the meteorology born of a need for a forecast that we can date symbolically from the Crimean War, when the Anglo-French fleet which participated in the siege of Sebastopol was badly damaged on 14 November 1854, not by the Russian adversary but by a violent storm that, according to Urbain Le Verrier, Director of the Paris Observatory, could have been foreseen if an observing system with telegraphic transmission of data had been in place to issue the warning. With some difficulties, the first International Meteorological Committee, predecessor of the present WMO, was created in Rome in 1879, eighty years before the IOC in 1960 which, under the aegis of UNESCO, now has the ambitious project of setting up an operational ocean-observing system, GOOS (Global Ocean Observing System). To carry out such a project, and in contrast to meteorology, oceanography was until now short of clients. Even sailors, the primary clients for meteorological services, cared little for oceanography. Except the military, that is.

Given the development of submarine warfare which depends on the propagation of acoustic waves under conditions imposed by the local hydrography, the military were the first to take an interest in it and to test the feasibility of forecasting the changes in the mesoscale ocean features of most interest to them. They were the first to run, in real time and in an operational mode, ocean-forecasting models incorporating *in situ* data and remote-sensing data, especially altimetric. In 'civil society', the first client for ocean-observing systems was, and still is, scientific research, which maintains as far as is feasible the systems it needs and which (apart from meteorological forecasting systems) for budgetary reasons do not have the guarantee of continuity and reliability that is characteristic of operational services, largely because scientific research has failed to convince 'solvent' clients. Except, perhaps fishermen, who use such systems to guide their fishing fleets to potentially favourable fishing areas; this involves the analysis of charts of oceanographic structures at the sea surface based on hydrographical data and satellite remote-sensing data (temperature, wind, colour, altimetry). Some simple models afford a forecast of several days. They only deal with the water right at the surface and, for this simple purpose, there is no need for global modelling of the ocean or for complicated *in situ* ocean-observing systems.

Other than that of the military, the real need that justifies operational oceanography and the establishment of global ocean-observing systems is that of climate forecasting. And even this has to be proven to be convincing. This is the objective of GODAE (Global Ocean Data Assimilation Experiment) which will be conducted between 2003 and 2005. It will attempt to demonstrate the feasibility of setting up a global-ocean forecasting system with a high resolution (of about a quarter of a degree) and in real time, in the same way as is done in meteorology. From this, we shall be able to elaborate a realistic climate-change prediction model valid on time-scales ranging from that of the El Niño to that of the global change expected in response to the increase in atmospheric concentrations of greenhouse gases. GODAE is thus not a research programme, but rather a test of the oceanographer's capacity to provide useful real-time data products. The ‘real time’ of the ocean is clearly not that of the atmosphere. It varies from a week to several months, depending on the time-horizon chosen. The experiment will be aimed at the complete chain of activities: the *in situ* observing system, data transmission, assimilation of the *in situ* and remote-sensing data into models designed to routinely produce descriptions and forecasts of the entire ocean circulation. The observing networks set up in the framework of the WCRP (World Climate Research Programme), such as TOGA and WOCE, will be completed by the deployment of several thousand floats in the ARGO programme. These floats, which have a working life of three to four years, will float at a depth of 2,000 m and will be programmed to float to the sea surface at regular intervals (about every ten days) measuring the temperature and the salinity in the water column. Some 300,000 measurements will be made in the world ocean during the programme. We may say that, in a way, oceanography is laying its credibility, hence its future, on the line in this experiment.

GODAE is an initiative of the IOC through its GOOS project and through the World Climate Research Programme organized twenty years ago by WMO, ICSU and IOC. As a programme of international co-operation, GODAE is also a competition: a technological competition in the development of the best floats; a competition also in the development of the model because if the data belong to all the participants, the use made of them and the quality of the data products provided will depend very much on the model, and there will be several at the finishing line.

Conclusion

The growing 'humanization' of our planet is not, contrary to what is often said, a mortal menace for Earth and the life on it which has seen worse and is certainly capable of resisting even a nuclear winter, with or without mankind. This 'humanization' is above all a menace to mankind itself, thus exposed to grave difficulties that are generators of deadly conflicts, if it does not take care. We can no longer say, as the scientists of the nineteenth century might have said: if it does not master its own evolution. The fact is, we do not master anything, and we know that in our stochastic world, our capacity for prediction will always have limits whatever may be our efforts to reduce the uncertainties, as has been attempted for fisheries, for example, by the adoption of the 'precautionary principle' recommended by the FAO and taken up by the Reykjavik Conference as 'responsible fishing in the marine ecosystem' in October 2001. Far from providing a methodology for decision-making, this approach is only a principle of action based on admission of ignorance, albeit a recognized and no longer a camouflaged ignorance. The objective of scientific research is to reduce this ignorance. The problem is now planetary and scientists are being called on to simulate the functioning of the planet Earth, by going back through their archives so as to know Earth's history better, by multiplying the observation networks in order to make an inventory and to understand Earth's present functioning better, and by modelling it in order to propose future scenarios. Given the results of research, the scenarios the research proposes and the uncertainties that they hide, two extreme extrapolations are possible. First of all, to deny a phenomenon on the pretext that it has not been formally proved. For example, even if there are strong and convergent indications relating the currently observed increase in the surface temperature of the Earth to a man-made increase in the greenhouse effect, we cannot consider this cause-and-effect relationship as being strictly proven experimentally and the scenarios may therefore be simply conjectures. Based on this uncertainty, some people argue that what has not been proven makes no sense scientifically and they deny categorically the existence of this relationship. This, we may say, is itself not a very scientific attitude, as the production of greenhouse gases by human activities and the increase in their atmospheric concentrations have been verified, so it is difficult to see why anyone should think that this change should have no impact at all. This does, however, allow us to dismiss out of hand any conservation measure based on the optimistic wager that, with progress in technology, we shall have the answers between now and later. A second possible attitude is the precautionary approach, in the strongest sense of the term, or more precisely the negation of this approach as a principle of action, thus turning it into a principle of reaction opposing any management and development plan in the name of a more obscure ecology that makes humanity the enemy of the planet and a kind of outlaw on Earth. This attitude joins the pessimism of Arthur Koestler who, having lost faith in humanity, ended up considering the human species a mistake of evolution. Even if 'all is for the best in the best of all possible worlds', let us guard against thinking that all goes wrong in the worst of all possible worlds. We are the future of the human race and we have only the resources offered by the planet on which we live and our intelligence to make the best of it. If there is anything that can be labelled 'Common World Heritage', it is precisely the Earth, which we must bequeath to future generations and which we are (and they will be) obliged to manage together. A limited and unexpandable Heritage which the French poet Jules Supervielle, inveighing against Earth for its meanness, treated it as follows:

'la tenancière des quatre saisons
l'avare ficelée dans ses longitudes'
['Proprietress of the four seasons
the miser tied up in her longitudes']

There is no other solution than a common and joint management, than a global view of this so definitely finite world. Scientific research, if unable to provide certainty, remains the only means of acceding to it, of giving humanity a common understanding of the world and a common language that transcends cultural differences in which to express it.

Glossary*

AADW

Antarctic Deep Water; a water mass formed in the Antarctic *convection* zones and which covers the bottom of the world ocean.

AAIW

Antarctic Intermediate Water; a water mass formed by the *subduction* of the Antarctic circumpolar water at the Antarctic *Convergence*.

ACI

Atmospheric circulation index; an index of the relative *meridional* (north–south) and zonal (east–west) transport of air masses in the Eurasian and Atlantic regions.

Advection

In the oceanographic context, the entry of water into a region from outside it, usually to compensate for loss of water through, for example, wind action; *upwelling* is a special form of [vertical] advection.

Altimetry

Measurement by satellite-born radar of the distance between the satellite and the sea surface; the *sea-surface topography* and the related geostrophic currents can be deduced from the measurements.

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*Terms in *italic* also appear elsewhere in this glossary, either as their acronyms or in full.

Anomaly

The difference between the value of a parameter at a given moment and its long-term mean value.

Antarctic Circumpolar Current

The current that is driven by westerly winds and circulates around the Antarctic continent; it lies between latitudes 65° S and 45° S.

Anticyclonic (circulation)

Horizontal gyral motion that is clockwise in the northern hemisphere and anticlockwise in the southern hemisphere, around zones of high pressure in the ocean or in the atmosphere.

Argo

Experiment within the Global Ocean Data Assimilation Experiment (*GODAE*) on the deployment of thousands of drifting [Argo] floats at a depth of 2,000 m all over the ocean; these floats ascend to the sea surface at regular intervals, measuring hydrographical *parameters* (temperature, *salinity*) in the water column during their ascent and descent, and transmit their data.

Argos

Satellite-based positioning and data-transmission system mounted on the meteorological satellites of *NOAA*; it has been operational since 1978.

Bathymetry

In the present context, the measurement of the depth of the sea floor relative to the sea surface; the production of [bathymetric] maps displaying the *sea-bed topography.*

Biogeochemical processes

Biological, geological and chemical processes, separately or in combination, that determine the distribution of chemical elements in the Earth's environmental compartments (e.g. biosphere, geosphere, hydrosphere).

Biomass

The amount (usually weight) of living matter in a specified environmental space.

Biosphere

A notional concept signifying the totality of living matter on Earth.

BP

Before present; dating of past events (usually geological, palaeontological) from the present.

Brownian motion/movement

The incessant random movement of the components (molecules or groups of molecules) of a liquid.

Catabatic

'Downward movement'; referring particularly to winds that, because of the heavy density of the air and the local topography, blow downslope, often at great speed.

Chlorinity

Concentration of chlorine in sea water; for a long time sea-water *salinity* was estimated by measuring its chlorinity by chemical methods, based on the hypothesis (verified to high precision) that there is a constant ratio between *salinity* and chlorinity.

CLIMAP

Climatic Long-range Investigation, Mapping and Prediction; a project in the 1970s–1980s on the reconstitution of ocean conditions during the preceding Ice Ages and interglacial periods.

CLIVAR

Climate Variability and Predictability; a *World Climate Research Programme* component launched in 1993 for a period of fifteen years, dedicated to the study of climate variation on all relevant time-scales, including that relative to the response of the climate system to the increase in the concentration of *greenhouse gases*; hence CLIVAR is an extension of *TOGA* and *WOCE*.

Coccolithophores

Microscopic organisms of the order Coccolithophorida of the class Flagellata; they are often important members of the phytoplankton, are usually very small and roundish, have one or two flagella (whips), contain photosynthetic pigments, and are typified by an exoskeletal case composed of calcareous plates (coccoliths) or rods (rhabdoliths).

Coefficient of viscosity

Essentially a measure of the difference in speed of flow between notional layers in a liquid relative to the layer in contact with the surface over which the liquid moves, hence of the tangential force between two adjacent layers not in contact with this surface; expressed as the tangential force per unit area; the coefficient depends on the nature of the liquid and its temperature.

Convection

Process by which surface water has acquired a high density due to cooling and/or increase in *salinity*, and by which the ocean's deep *water masses* are formed and become the *driver* of the *thermohaline circulation*.

Convergence

A zone within a current or more often at the interface between two currents, towards which surface water flows, causing a deepening of the *thermocline*.

Conveyor belt

Diagrammatic representation of the *thermohaline circulation* initiated by *convection* in the North Atlantic Ocean and which transports, at depth, the Atlantic water to the Indian and Pacific Oceans and where it returns to the surface.

Coriolis force

The force due to the Earth's rotation about its own axis that acts on any body in motion on the Earth's surface; its strength increases from zero at the equator to a maximum at the poles, and it causes a deviation of ocean currents to the right in the northern hemisphere and to the left in the southern hemisphere; named after the French mathematician Gaspard Coriolis.

Cryosphere

A notional concept signifying the totality of the solid (frozen) water on Earth; comprising mainly the principal ice caps of the Antarctic and of Greenland, the glaciers and the sea ice.

Cyclonic (circulation)

Horizontal gyral motion that is anticlockwise in the northern hemisphere and clockwise in the southern hemisphere, around zones of low pressure in the ocean or in the atmosphere.

CZCS

Coastal Zone Color Scanner; an instrument for measuring the colour of the sea from (originally) the *NOAA* Nimbus-7 satellite operating between 1978 and 1986.

Dansgaard–Oeschger (cycles)

Climate oscillations during the last Ice Age, as revealed by glacier ice cores; the cycles correspond to warm peaks of one to 3,000 years' duration.

Diatoms

A large group of microscopic organisms, relatives of *coccolithophores*, though somewhat bigger in size and non-flagellate; they are often predominant members of the *phytoplankton* (especially of the spring bloom), are typified by a siliceous shell (frustule) in the form of a 'pill-box' and often comprising many successive compartments due to rapid fission; some frustules bear spines, and some diatom colonies are gelatinous aggregations of individuals.

Dinoflagellates

Microscopic organisms of the order Dinoflagellida of the class Flagellata; they are often predominant members of the *phytoplankton*; they have two flagella (usually set in grooves in the exoskeletal case) and are usually typified by an armour of cellulose plates; upon repeated fission some species develop long chains of individuals; most species carry photosynthetic pigments.

Divergence

A zone within a current or more often at the interface between two currents, towards which subsurface water flows, causing a shoaling of the *thermocline*.

Dynamics

The branch of mechanics dealing specifically with the motion of bodies (here, also water masses, as in ocean dynamics and, more generally and more abstractly, hydrodynamics); notionally, also applied to the exchanges and losses or gains of energy and mass in a specified system: hence ocean dynamics, ecosystem dynamics.

Eddy

The term used in *oceanography* to designate 'whirlpool' structures characteristic of oceanic mesoscale (~100 km) *turbulence*; on the bigger, ocean-basin scale of the major *anticyclonic circulation*, the term *gyre* is preferred.

Ekman's theory

A theory stipulating an equilibrium between the wind stress on the sea surface and the *Coriolis force* which explains the angle between the direction of the wind and that of the surface currents; Ekman transport is the movement of the water resulting from the interplay of these two forces at a given time and place.

El Niño

Originally, a warm sea-surface current flowing southwards, usually off the western coast of South America (Ecuador–Peru); now signifying the 'warm' phase of *ENSO* characterized by a negative value of the *SOI* and by abnormally warm ocean temperature at the equator and in the eastern Pacific, as well as collapse of the *Walker Cell*.

ENSO

El Niño–Southern Oscillation; an oscillation of the coupled system formed by the equatorial Pacific Ocean and the atmosphere, such that the system alternates between an *El Niño* situation and a *La Niña* situation, characterized by the *SOI*.

ENVISAT

Environmental Satellite; a satellite of the *European Space Agency* for the observation of Earth, launched on 1 March 2002.

Equatorial Counter-current

An ocean-surface current running eastwards between (and contrary to) the westward-flowing *North* and *South Equatorial Currents* in the Pacific and Atlantic Oceans (but not in the Indian Ocean which has an incomplete northern hemisphere part); the strength of the Equatorial Counter-current is very variable and may practically disappear at times.

Equipotential surface

A notional surface on which the value (strength) of a force, gravity or an electrical field, for example, is the same at all points on the surface.

ERS-1 and ERS-2

European Remote Sensing Satellite; Earth (and ocean) observing satellites of the *European Space Agency*, launched in 1991 and 1995, respectively.

ESA

European Space Agency (HQ in Paris).

Euphotic layer

Etymologically the ‘well lit layer’, it is the layer of water between the sea surface and the depth at which there remains only 1% of the incident solar radiation at the sea surface.

FAO

Food and Agriculture Organization of the United Nations; a Specialized Agency for food production, agriculture, forestry, fisheries and aquaculture.

Foraminifera

An order of microscopic planktonic organisms (Protozoa) with, usually, a calcareous or siliceous (or other materials in some species) shell which may be single- or multi-chambered; analysis of the isotopic composition of the carbon of the shell in oceanic sediments allows the reconstitution of sea-surface temperature when the organisms were alive.

Forcing/driver

Terms designating the external factors that play a role (forcing) in oceanic circulation, such as the wind and heat exchange with the atmosphere.

Geoid

An *equipotential surface* of the Earth's field of gravity; if the ocean were immobile, its surface would constitute a geoid, so the differences from place to place relative to the geoid represent the dynamical topography of the currents.

Geosat

Geodetic Satellite; altimetric satellite series of the US Navy, the first of which operated from 1986 to 1990, and the present one was launched in 1998.

Geostrophic equilibrium

A hypothesis stipulating an equilibrium between the horizontal pressure force and the *Coriolis force*; the ocean circulation can be deduced from it (geostrophic method) to a good approximation.

Gigatonne

A billion tonnes.

GLOBEC

Global Ocean Ecosystem Dynamics; a component of the *International Geosphere–Biosphere Programme* dedicated to the study of marine ecosystem dynamics and their variability.

GODAE

Global Ocean Data Assimilation Experiment; the first 'operational *oceanography*' project; to be carried out from 2003 to 2005 to test the feasibility of operational ocean forecasting.

GOOS

Global Ocean Observing System; a system for the routine observation of the ocean, now being developed under the auspices of *IOC*.

Greenhouse gases

Gaseous compounds that have the property of absorbing infrared radiation emitted by the Earth, hence of causing atmospheric warming; the most abundant of them is water vapour which ensures that the Earth's surface has an average temperature of 15 °C which is liveable for human beings, who in turn produce other greenhouse gases (carbon dioxide, methane, chlorofluorocarbons) thus risking introducing into the climate system a detrimental perturbation.

Guano

A natural fertilizer rich in nitrate, produced along the coasts of Peru and Chile by bird droppings; the birds feed on small anchovies that abound in the highly productive water in the areas of coastal *upwelling*.

Gyre

Usually designates the major loops of the oceanic circulation associated with the major subtropical *anticyclonic circulations* of the Atlantic and Pacific Oceans.

Hadley Cell

Meridional atmospheric circulation typified by the ascent of warm, humid air (*convection*) over the *Intertropical Convergence Zone* and its descent over the high-pressure areas in the centre of the subtropical *anticyclonic*.

Heat pump

The term designating here the role of the deep *convection* of the North Atlantic Ocean in the northward extension of the warm water of the Gulf Stream.

Heinrich cycles

Climate oscillations during the last Ice Age and recurring at intervals of 7,000 to 10,000 years; these cycles were detected through the rock debris carried by icebergs and found in marine sediments, and correspond to the coldest episodes of the Ice Age.

HNLC

High *nutrients,* low chlorophyll; a term designating regions where, in spite of the abundance of macro*nutrients*, the chlorophyll concentration and the *primary production* are relatively low.

Hydrography

The formal description of the principal physical characteristics of a water body, including the bottom topography; applicable to fresh- as well as salt-water bodies (unlike hydrology, which has become more or less restricted to the occurrence and distribution of water over the land).

Hydrostatic equilibrium

The balance between the gravitational force acting on a body (including a ‘parcel’ of water) in a liquid and the buoyancy of that body; the depth of the hydrostatic equilibrium is the depth in the water column relative to the surface at which the two forces (gravitation and buoyancy) are equal.

ICES

International Council for the Exploration of the Sea; ICES was created in 1902 and was the first international oceanographic organization, with the objective of preserving the ecosystems of the North Atlantic Ocean, its adjacent seas and their resources.

ICSU

International Council for Science (formerly International Council of Scientific Unions); a non-governmental organization drawn from national academies of science or national research councils.

IGBP

International Geosphere–Biosphere Programme; an international programme of research on the environment, organized by *ICSU*.

International Geophysical Year

An international programme of co-ordinated studies of the various physical compartments of the planet (geosphere, atmosphere, oceans, cryosphere), carried out in 1957–58; this was the first-ever co-operative international programme in oceanography.

Intertropical Convergence Zone (ITCZ)

The zone in which the *trade winds* meet, in both hemispheres; it is the meteorological equator; it does not coincide with the geographical equator, being displaced a few degrees northwards; it corresponds to the zone of intense atmospheric *convection* that activates the *Hadley Cell*, and is known to sailors as the doldrums.

IOC

Intergovernmental Oceanographic Commission (of UNESCO); it is charged with developing and co-ordinating international co-operative research programmes on the ocean and its resources.

IPCC

Intergovernmental Panel on Climate Change established in 1988 to evaluate, using the available scientific information, the evolution of the climate, its impacts and the corresponding desirable adaptive measures.

Jason 1

Franco-American altimetric satellite launched in December 2001.

JGOFS

Joint Global Ocean Flux Study; a component of the *International Geosphere–Biosphere Programme* dedicated to the study of the oceanic carbon cycle.

Kelvin waves

Internal oceanic waves generated by atmospheric perturbations; Kelvin waves propagate from west to east along the equator.

La Niña

The ‘cool’ phase of *ENSO* during which the *SOI* is strongly positive, accompanied by activation of the *Walker Cell* in the Pacific and by a marked cooling of the ocean surface in the eastern Pacific and near the equator, which corresponds to a reactivation of coastal *upwelling* and of the equatorial *divergence*.

Madden–Julian oscillation

Bursts of strong westerly winds occurring in a 40- to 60-day cycle in the tropical Pacific Ocean; they produce a *convergence* at the equator and cause the *thermocline* to deepen, producing a positive sea-surface height anomaly that may (under certain circumstances) propagate eastwards as a *Kelvin wave*.

Maunder cycle

This is a 'sub-cycle' of the solar cycle (which lasts some 22 years and is marked every 11 years by a period of maximal intensity); each Maunder cycle is marked by a relatively short period of minimal intensity, as occurred in the seventeenth century at the coldest time of the 'Little Ice Age'.

Meander

In the present context, an ocean current or part of one that departs laterally from the mean direction of flow or from the main stream, tracing a generally slower and more erratic path without, however, any meandering part cutting itself off to form an *eddy*.

Meridional

Following the meridians; a north–south direction; meridional component of a current; or a north–south component.

MERIS

Medium-Resolution Imaging Spectrometer; an instrument for the measurement of ocean colour, mounted on *ENVISAT*.

Milankovitch (cycle)

Cycle of the variation in the parameters of the Earth's orbit around the Sun that accounts for the Ice Ages and the interglacial periods; it is the astronomical theory of climate change developed by Milankovitch.

Mixed layer

The ocean's surface layer homogenized by the wind, which overlies the *thermocline*.

MODE

Mid-Ocean Dynamics Experiment; an international programme dedicated in the 1970s to the study of the ocean eddies. (See *POLYMODE*)

Mooring

A line, anchored to the sea bed, to which are attached measuring instruments which are, usually, buoyant in the water column or at the sea surface.

Mortality

The proportion of a population that dies (from whatever cause) in a specified period of time; specific types are natural mortality and fishing mortality; not synonymous with death, however; strictly speaking the terms ‘mortality’ and ‘mortality rate’ are synonymous, once the relevant time period has been defined.

NADW

North Atlantic Deep Water; a *water mass* formed in the *convection* zone of the North Atlantic and which flows at a depth of about 3,000 m; it drives the *thermohaline circulation* and the *conveyor belt*.

NAO

North Atlantic Oscillation; an oscillation opposing the atmospheric-pressure variations of the Azores anticyclone and the sub-polar low-pressure areas (Iceland); it is characterized by an index: the atmospheric-pressure difference between the Azores and Iceland; the higher the index, the more intense is the westerly atmospheric circulation over Europe.

NASA

National Aeronautics and Space Administration; a US governmental agency concerned with space exploration.

NOAA

National Oceanic and Atmospheric Administration; a US governmental agency concerned with meteorology and *oceanography*.

North and South Equatorial Currents

The currents driven by the *trade winds* and which traverse the Atlantic and Pacific Oceans from east to west to the north and to the south, respectively, of the *Intertropical Convergence Zone* which, itself, is generally north of the equator, so that the South Equatorial Current flows along the equator.

Nutricline

A water layer, associated with the *pycnocline*, in which there is a rapid increase in the concentration of *nutrients* with increasing depth due to the *pycnocline* which limits the transfer of *nutrients* upwards into the mixed layer, thus also limiting *primary production*.

Nutrients

A term designating the set of chemical elements (other than carbon and hydrogen) necessary for the production of living matter; the term is commonly reserved for nitrates, phosphates and silicates, or nutrient salts, which are sometimes qualified as macro*nutrients* in contrast to others, such as iron, which are needed in much smaller quantities and are therefore called micro*nutrients*. (See also *nutricline*)

Ocean colour

The spectrum of the light backscattered by the sea surface-water layer, which depends on the particles and substances in the sea water, notably the chlorophyll of the *phytoplankton*; this backscattered radiation can be measured from satellites and the marine *phytoplankton* concentration can be deduced from it. (See also *scatterometer*)

Oceanography

The scientific study of the oceans; often subdivided into physical, chemical, biological and geological branches; specific study of the motion of the water and the currents, including their variation, is often called dynamical oceanography. (See also *hydrography*)

Overfishing

An excessive level of fishing such that *recruitment* to the stock becomes insufficient to maintain the fished stock.

Palaeoclimate

A climate inferred from climate signatures, such as specific isotope ratios, growth rings in trees, etc., in fossil structures or in other ancient, preserved structures such as fish scales, ice caps, etc. (See also *Palaeoenvironment*)

Palaeoenvironment

An environment inferred from environmental signatures, such as specific isotope ratios, organic debris in fossils or other ancient, preserved structures. (See also *Palaeoclimate*)

Paradigm

An example or reference by which to judge a given fact, situation or system.

Parameter

A measurable characteristic of a system; temperature and *salinity* are parameters of sea water, for example.

Partial pressure

In a mixture of gases, the partial pressure of one of them is equivalent to its concentration in the mixture; for a dissolved gas with a certain concentration, the partial pressure is the same as that of the gas in an atmosphere in equilibrium with the solution; hence the partial pressure is closely related to the concentration, so that when the partial pressures in the air and in the water are equal, there is no exchange, whereas, if the partial pressure is greater in the atmosphere, the gas enters into solution in the water, and vice versa.

PDO

Pacific decadal oscillation; out-of-phase oscillations in the sea-surface temperature of the central North Pacific Ocean, on the one hand, and of the eastern boundary and the eastern part of the intertropical Pacific, on the other hand.

Pelagic

Qualifies the open sea and the organisms that live there (in contrast to the demersal species which live on or close to the sea bed); *plankton* is pelagic, as are tuna, salmon, anchovy, sardine and herring, and cod are demersal.

Photosynthesis

The process in green algae and plants by which the pigment chlorophyll captures visible solar energy for use in the biochemical reactions that convert carbon (basically as carbon dioxide) and hydrogen (basically as water) into simple organic sugar-like compounds that can be used to create living tissue. (See also *primary production*)

Phytoplankton

Vegetal plankton; it is the principal agent of *primary production* by *photosynthesis.*

Plankton

Literally 'floaters'; the ensemble of aquatic organisms in a body of water, usually unicellular and microscopic, that are incapable of displacement independently of the movements of the aquatic medium. (See also *phytoplankton* and *zooplankton*)

Planktonivores

Organisms that feed primarily, if not exclusively, on *plankton*; also sometimes called planktivores.

Plate tectonics

The movements of the Earth's crustal plates with respect to one another over the Earth's mantle; these movements lead to, among other things, the *subduction* of one plate beneath another and the uplifting of mountain ranges in the *subduction* zone.

POLYMODE

International programme dedicated in the 1970s to the study of the ocean eddies. (See also *MODE*)

Population dynamics

The sum of changes continuously occurring in a population of organisms due to natural natality (birth rate), natural mortality (death rate due to natural causes) and fishing mortality (death rate due to fishing, usually by human beings); individual growth and *recruitment* are also important factors; also, by implication, the study of these dynamics.

Primary production

Production of living matter from inorganic elements using light as the energy source; this is *photosynthesis*; primary production is usually measured in weight of carbon (or something equivalent) per cubic metre of water, and primary productivity is the rate of production usually expressed as the weight of carbon (or equivalent) per square metre (standing as the column of water beneath a square metre of water surface in which production is possible) per unit time.

PSU

Practical *salinity* unit; see *salinity*.

Pycnocline

A layer of water in the ocean in which the density increases rapidly with increasing depth; generally, the pycnocline coincides with the *thermocline* and is a layer of high stability that limits vertical mixing between the surface mixed layer and the deeper water.

Radiometer

An instrument for measuring (electromagnetic) radiation of a specified wavelength emitted from a body (of sea water, usually, in *oceanography*); commonly used in satellite remote sensing of the ocean.

Recent Dryas

A geophysical period corresponding to an abrupt cooling some 12,000 years ago in the middle of a period of ice-cap melting.

Recruitment

In fisheries, this term refers to the fish that, for the first time, enter the stock of fish accessible to the fishery; the new recruits are therefore the youngest fish catchable by the fishery.

Salinity

Originally, the mass of salts contained in a kilogram of sea water; now measured as the ratio of the electrical conductivity of a given sample of sea water to that of standard artificial sea water; although this ratio is, by definition, dimensionless, the unit is called a practical salinity unit or *PSU*; the salinity of sea water is, on average, about 35 PSU (about 35 g/kg).

Scatterometer

A radar mounted on a satellite to evaluate wind speed and direction at the sea surface by analysis of the backscattered signal, the intensity of which depends mostly on the agitation of the sea surface by the wind.

Scenario

A reasoned but imaginary representation of a future state of a given system as a basis for planning such activities as scientific research, environmental management, environmental protection.

Sea-bed (or sea-floor) topography

The description of the sea-bed relief (usually in the form of a chart bearing values of sea-bed depth relative to the sea surface with or without the corresponding depth contours).

Sea-surface topography

A chart of the sea-surface height relative to an *equipotential surface* used as a reference (i.e. here, a surface on each point of which the force of gravity has the same value); the *Topex/Poseidon* altimeter allows the elaboration of such charts, from which the geostrophic currents can be deduced.

SeaWiFS

Sea-viewing Wide Field-of-view Sensor; a *NASA* satellite for measuring *ocean colour*.

Section

In *oceanography*, the representation (typically by lines of equal value of a parameter, such as the 20 °C isotherm), normally in the vertical dimension, of the principal properties of the ocean along a line on which hydrographic/oceanographic stations have been carried out to make the measurements; a transoceanic section crosses a whole ocean, usually from east to west or north to south. (See also *vertical profile*)

SOI

Southern Oscillation Index; an index based on the atmospheric pressure difference at sea level between Tahiti and Darwin (Australia) and characterizing *ENSO*.

Subduction

The process by which, when two [fluid] masses (water masses in the oceanographic context) meet, the denser of the two sinks beneath the other (which is less dense). (See also *plate tectonics*)

Subtropical Convergence

A prominent oceanographic feature of the major oceans; a relatively narrow zone at about 40° S at which the permanent *thermocline* intersects the sea surface, essentially separating the Southern (Antarctic) Ocean (including the Antarctic Circumpolar Current) from the Atlantic, Indian and Pacific Oceans.

Subtropics

The latitudinal zones (N and S) between the tropics (~20° N–20° S) and 40° latitude (N and S); these zones correspond approximately to those of the subtropical *gyres*.

Thermocline

A layer of water in the ocean in which the temperature decreases rapidly with increasing depth; generally, the thermocline coincides with the *pycnocline* and is a layer of high stability that limits vertical mixing between the surface mixed layer and the deeper water.

Thermodynamic

Referring particularly to the exchange of energy, especially heat, among entities acting on each other in a given system; notably, in *oceanography*, the heat exchanges between the ocean and the atmosphere.

Thermohaline

The predominant combined property of sea water based on the two main determinants of sea-water density: temperature and *salinity*. (See *thermohaline circulation*)

Thermohaline circulation

The deep circulation of the oceans driven by the sinking of surface water that has acquired a very high density, owing to its cooling and/or increase in *salinity*.

TOGA

Tropical Ocean and Global Atmosphere; an international study of the processes linking the tropical ocean, particularly in the Pacific, to the planetary climate on a multi-annual time-scale; the study was carried out between 1985 and 1995 in the framework of the *WCRP*.

Topex/Poseidon

A Franco-American altimetric satellite launched in 1992 to measure the variations in sea-surface height (with centimetric precision), hence to determine the topography of the sea surface and thence to deduce the geostrophic currents.

Trade winds

Easterly winds along the eastern and equatorial edges of the major *anticyclonic* subtropical *gyre*s of the atmosphere; they drive the *North* and *South Equatorial Currents*.

Trophic (level, web, chain)

Referring to food supply; the trophic chain goes from the *phytoplankton* which is grazed by the *zooplankton* which itself is consumed by small fish, etc., up to the large predators and humans at the top of the food chain; the term trophic web is used to express the notion that the system is non-linear, and the trophic level of an organism is determined by what it eats and what eats it.

Turbulence

This term designates movement of the components of a fluid in all directions relative to the average direction of movement; turbulence favours mixing.

UNEP

United Nations Environment Programme; a UN agency responsible for global environmental assessment and the organization and co-ordination of intergovernmental programmes of environmental protection and pollution abatement.

UNESCO

United Nations Educational, Scientific and Cultural Organization, a Specialized Agency, based in Paris.

Upwelling

The movement of subsurface water towards the surface under the action of *wind stress* on the sea surface, in accordance with *Ekman's theory*. Coastal zone and equatorial *upwelling* are mechanisms of *nutrient* enrichment which make *upwelling* areas particularly productive.

Vertical profile

In *oceanography*, the representation (typically by a line) of the value of a parameter (e.g. temperature) at specific successive depths in the water column, at a specific hydrographic/oceanographic station carried out to make the measurements; several vertical profiles may be represented simultaneously in one diagram for comparison of several stations.
(See also *section*)

Walker Cell

Atmospheric circulation in the equatorial region typified by the ascent of warm, humid air *convection* over the low-pressure zone on the western side of an ocean in the intertropical zone and its descent over the arid high-pressure areas on the eastern side of the ocean.

Water mass

In *oceanography*, a major body of water with a specific (and strongly conservative) temperature–*salinity* relationship with respect to depth (or pressure) which allows it to be distinguished from other water masses; with the erosion of this specific relationship (as a result of such processes as mixing, evaporation, heating, etc.), its 'evolution' may be followed, from which the oceanographic processes at work may be inferred or deduced.

WCRP

World Climate Research Programme; an international programme organized jointly by the *World Meteorological Organization*, the *International Council for Science*, and the *Intergovernmental Oceanographic Commission of UNESCO*.

Wind stress

The frictional force applied to a surface due to the wind blowing over it (notably, in *oceanography*, the sea surface), hence a transfer of mechanical energy from the atmosphere to the ocean; this frictional force is modified by the sea-surface roughness it generates.

WMO

World Meteorological Organization; a Specialized Agency that co-ordinates actions taken with a view to improving weather and climate forecasting.

WOCE

World Ocean Circulation Experiment; an international programme under the *WCRP*, which carried out the first global description of ocean circulation from 1990 to 1997.

Zonal

Refers to a latitude band in an east–west direction; a zonal or east–west component of a current.

Zooplankton

Animal plankton; it feeds on *phytoplankton* and other tiny particles.

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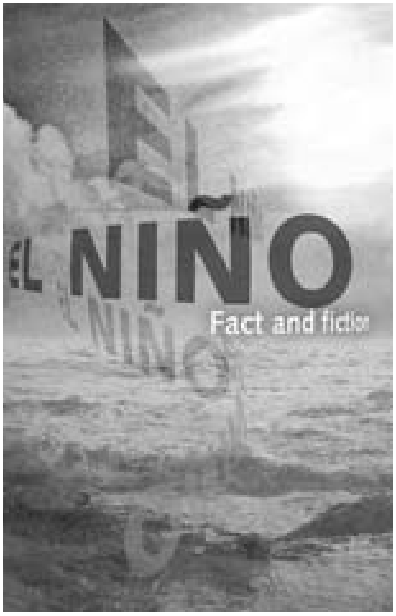

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