United Nations
Educational, Scientific and
Cultural Organization

The GULF STREAM

Bruno Voituriez

IOC Ocean Forum series

UNESCO Publishing

The Gulf Stream

In the same collection:
Coastal zone space: prelude to conflict?
El Niño. Fact and fiction
The changing ocean. Its effects on climate and living ressources
Understanding the Indian Ocean
Climate change

In Spanish:
El Niño. Realidad y ficción
Los caprichos del océano. Efectos sobre el clima y los recursos vivos
El cambio climático

In French:
El Niño. Réalité et fiction
Les Humeurs de l'océan. Effets sur le climat et les ressources vivantes
Le Changement climatique
Le Gulf Stream

The Gulf Stream

by Bruno Voituriez

IOC Ocean Forum Series

UNESCO Publishing

The designations employed and the presentation of material throughout this publication do not imply the expression of any opinion whatsoever on the part of UNESCO concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.
The authors are responsible for the choice and the presentation of the facts contained in this book and for the opinions expressed therein, which are not necessarily those of UNESCO and do not commit the Organization.

Published in 2006 by the United Nations Educational,
Scientific and Cultural Organization
7, place de Fontenoy, F-75352 Paris 07 SP, France

Typeset by Gérard Prosper
Printed by Policrom, Barcelona

ISBN-10: 92-3-103995-4
ISBN-13: 978-92-3-103995-9

© UNESCO 2006
All rights reserved

Printed in Spain

Acknowledgements

This volume represents the product of a fruitful dialogue between Erik Orsenna of the Académie française and the *Club des Argonautes* (see www.clubdesargonautes.org).

The latter, to which I have the honour of belonging, aims to draw the attention of the public to the evolution of the climate and the manner in which it functions.

Erik Orsenna – a lover of the sea and author of the book *Portrait du Gulf Stream*, a magnificent literary undertaking – visited us one day in order to pose some questions about the Gulf Stream in order to ensure the scientific quality of his work.

This book arose out of his questions and our answers.

My thanks go to Erik Orsenna for having posed these questions to us, as well as to my friends in the *Club des Argonautes*, without whom this meeting would not have taken place.

I would also like to express my gratitude to Annick Radenac of the library of the Center IFREMER in Nantes, who diligently provided me with all of the documentation that I required for writing this book.

Bruno Voituriez

The Economy, Science and Innovation Administration (EWI) of the Flemish government, Kingdom of Belgium, has chosen to support this book as a worthy activity in the area of public awareness, especially as concerns the Gulf Stream's impact on our planet's climate, thus on our environment and, essentially, our lives. Large parts of Northern Europe and North America are vitally dependent on this important Stream for the weather to which our societies and economies are adapted; furthermore the entire global climate system is likewise affected by this integral component in the delicate web of Earth's complex driving forces.

As part of its science information and dissemination policy, the Flemish government, Kingdom of Belgium, has contributed its support for this publication through the Flanders-UNESCO Science Trust funds (FUST). Credit is due to the author for providing the interesting and informative manuscript, and to UNESCO Publishing and the Intergovernmental Oceanographic Commission for producing and supporting the book.

Government of Flanders

Contents

THE GULF STREAM – ISBN 978-92-3-103995-9 – © UNESCO 2006

Preface

The role of the Gulf Stream in the dynamics of the planetary climate has recently received the attention of several researchers and even the general public. It was the underlying theme of a dramatic movie that portrayed the arrival of a new ice-age. Like its oriental counterpart, the Kuroshio off Japan, the Gulf Stream is a narrow and powerful current of surface ocean water that because of its intensity became known to mariners in the West as a 'fast lane' for sea voyages.

The present volume testifies to the importance that the Ocean (singular and not plural) has for our everyday life. This importance is insufficiently appreciated, even by the 'educated public', despite the fact that the huge thermal inertia of the Ocean makes this planet habitable in the first place. Bluntly and simply put: without the Ocean there would be no life on the Earth.

The heat stored in the surface layers of the ocean and the humidity carried with it through evaporation fuel the movements of air masses in the atmosphere. Over land, this heat exchange takes place largely on a diurnal cycle, following the seasons. In the Ocean, the movements of currents like the Gulf Stream displace large amounts of heat from their original sources to remote locations, affecting the climate of continents thousands of kilometres away. Mild or cool, rainy or dry, are climatic properties strongly influenced all over the world by the

THE GULF STREAM – ISBN 978-92-3-103995-9 – © UNESCO 2006

dynamics of the Ocean. The medium- to long-term forecasting of these properties depends on our acquiring a more complete knowledge of the vagaries of the surface layers of the Ocean.

The sources of these dynamics are mysterious and fascinating. Much of the movements of the Ocean and atmosphere, the 'fluid envelopes' of the earth, are controlled by the geometry of the planet and its intrinsic rotation. In a simplified rotating planet, with continents only around the North and South Poles, the mid-latitude tropical ocean would rotate unimpeded by the obstacles of continents in a series of symmetric, parallel, west-east circumpolar currents and countercurrents located north and south of the Equator. In addition to the rotation of the Earth, the motor of these movements would be the Sun's energy heating the water and the air at the Equator and cooling them close to the Poles. This, in turn, would produce the sinking of cold, hyper-saline water close to the polar continents and give rise to 'planetary' winds ascending at the Equator and falling to the surface at higher latitudes.

These forces are essentially what we meet with today. But we are also familiar with the evolutionary details of the planet and the origin and drift of the continents across the millennia, opening and closing passages between ocean basins and shaping the changing global circulation of the Ocean. The gyres at mid-latitudes in each ocean basin represent the more-or-less stable course of a series of currents running clockwise in the northern hemisphere and counter-clockwise in the Southern Hemisphere. The Gulf Stream and its counterpart, the Kuroshio in the North Pacific, close these gyres in the Western parts of the Ocean. These Western Boundary Currents are narrow with strong flow rates. They move significant volumes of sea water and greatly influence the marine productivity of their region. The great ocean currents, with their wealth of biological diversity, are crucial to supporting most of the world's marine life as well as maintaining the equilibrium of the global climate.

Bruno Voituriez has once more written a remarkable work, giving us this fascinating saga of the Gulf Stream and its counterparts. We in the Intergovernmental Oceanographic Commission are grateful for the efforts of this professor, colleague and friend in bringing closer to all of us, as citizens of the Earth, this wonderful knowledge of the Ocean as it affects our everyday lives.

Patricio Bernal
Executive Secretary of the Intergovernmental
Oceanographic Commission
Assistant Director-General of UNESCO

Introduction

The discovery of the Gulf Stream at the end of the eighteenth century marked the beginning of physical or dynamical oceanography. Thus, it is a recent science, which since the early nineteenth century has advanced the simple geographical description of the oceans with the study of ocean fluid dynamics.

There are two major challenges to the study and understanding of the ocean. First, while the ocean covers 71% of the Earth's surface, its average depth of 4 to 5 km renders it invisible to exploration by either the human eye or satellites. Previously, there were no alternative methods to explore the ocean other than sending down sophisticated sampling and measuring instruments, which required – and still require – significant strategic and economic input to enable their development.

The second challenge is that human beings cannot live in the ocean; they must leave their natural habitat to carry out these measurements. The incessant motion of the sea, including the waves, the tides and the currents, further complicates these oceanographic measurements. Thus, to assess this phenomenon and its dynamics, reference points are required. These are obvious on land as the diversity of landscapes provides geographers with a choice of sites to set up markers – except among the shifting dunes of the deserts, which in fact, resemble the ocean.

Geologists know precisely the spot where they drill a core and are sure to find the same spot if they come back months or even years later. The atmosphere is also in motion, but surveys can be made from the solid observation platforms of continents and islands. Nothing of this kind exists in the open sea. The first observation posts were navigators' ships, which were at the mercy of every movement of the sea, with only the Sun and the stars available as reference points. Yet despite the challenges this creates for oceanographers, it is precisely this absence that has given the ocean a reputation of freedom glorified by poets.

Beyond the realm of poetry, practical and material considerations governed the development of this science and guided oceanographic research. Historically, it was these practical issues that drove science to develop and implement appropriate observation tools.

The first driver for understanding the oceans was obviously navigation: for exploration, trade and even war. A very concrete navigation problem provided the impetus for scientific study of the Gulf Stream, and the first organized systematic measurements of oceanic parameters were ocean-surface temperatures taken by ships sailing across the North Atlantic. Also for navigation purposes, the first charts of the currents at ocean-basin scale were drawn up based on observations taken from ships' logs, to create pilot charts.

It was not until 1850, when difficulties were encountered in the installation of submarine telegraphic cables, that the deeper layers of the ocean became a subject of serious interest. These challenges played a significant role in the launching of deep-sea explorations; the British expedition on the *Challenger* was undoubtedly the best example. From December 1872 to May 1876, the *Challenger* sailed across the Atlantic, Pacific and Indian Oceans exploring their depths. It was the first expedition of world-ocean scale and marked the birth of oceanography.

Towards the end of the nineteenth century, significant fluctuations in fish catches compromised fishing industries. This caused both social and economic problems in the affected countries. Even at this early period in ocean science it was speculated that the catch fluctuations might be caused by overfishing or environmental changes. These issues fostered the foundation in Copenhagen, in 1902, of the first international organization dealing with oceanography: the International Council for the Exploration of the Sea (ICES). It coordinated and promoted marine research and the systematic measurement of physicochemical and biological parameters of the North Atlantic and adjacent seas with a clearly defined purpose: to predict, if possible, changes in exploited fish stocks.

Submarine warfare and the need to fully understand the conditions for the propagation of acoustic signals were powerful drivers of oceanographic research, particularly of the development of appropriate measuring instruments. The navy was the first to develop systematic oceanographic observation systems; and it is still at the forefront in the implementation of operational oceanographic forecasting systems.

In conclusion, as the oceans largely control the rhythm of climate change, questions surrounding the issues of climate variability and change, as well as their possible consequences for humanity, place ocean dynamics at the heart of the problem.

The 'scientific' discovery of the Gulf Stream at the end of the nineteenth century generated interest in the study of marine currents. Ever since, the Gulf Stream has occupied first place in popularity among ocean currents. Sometimes it is called 'king of the storms', other times, 'benefactor of Western Europe' – bestowing on it a mild climate. Painters have also praised the Gulf Stream. Figure 1 portrays a cataclysmic scene by Winslow Homer. In addition, a certain type of aircraft and an investment fund even carry its name. The Gulf Stream is also suspected of behaving like a Diva whose whims can have devastating consequences on our planet's climate. No other ocean current inspires such fascination and hyperbole, which is conveyed by the media with or without the complicity, if not the resignation, of scientists, who are unable to fight on equal terms with the power of these myths.

The Gulf Stream, however, is not the only one of its kind. It has an alter ego in the western North Pacific: the Kuroshio, a current known long before the Gulf Stream was discovered, yet one much less well known. The two are very similar both in the way that they are formed and in their dynamics. Thus, they can be described using more or less the same terms. But do they have the same effects? No, nor do their dynamics explain the difference. It is instead the morphology of the oceans in which they evolve that distinguishes them. The Gulf Stream is no more singular in terms of its dynamics than is the Kuroshio. The Atlantic Ocean, however, is indeed peculiar: for it is the only ocean connecting the polar oceans of the Antarctic and, what is more important, the Arctic. This connection changes the seascape, making the Atlantic paradigmatic for the problems brought about by ocean dynamics. These range from mid-scale eddies to large cyclonic and anti-cyclonic circulations – problems common to both polar oceans. In addition, the Atlantic displays the problem of deep-water formation in the Greenland Sea, which has no equivalent in the Pacific. The Greenland Sea is the main driver of deep oceanic circulation and the famous 'conveyor belt' that, it is feared, might one day stop – a victim of global warming, as it probably did at the peak of past glacial periods.

The Gulf Stream, like the Kuroshio, is an object of scientific study: and as is the case in science, the progress made in understanding these natural phenomenon challenges the mythology. Some say that science disenchants society, but in seeking to rationalize our vision of the world, science deprives some mythists if not of arms, at least – sometimes – of arguments. The world needs poetry, not mythology, and as has often been said the pursuit of science itself resembles the reverie of poets.

The Gulf Stream cannot escape its demythologization by science: it is not a river, nor merely a heat-conveyor for Europe, flowing from the Gulf of Mexico to Norway, as some have thought. The Gulf Stream will not stop, even if the 'conveyor belt' comes to a halt, any more than it did during the glacial periods. Importantly, this fact does not change in any way the possible climatic risks associated with this hypothesis. Like the Kuroshio, the Gulf Stream does not require deep-water formation to exist. On the other hand, and this is its singularity, it would not exist without the high salinity of the water it transports. But, once again, this condition is due more to the specific nature of the Atlantic Ocean, which is more saline than the Pacific, creating the unique dynamics of the Gulf Stream.

Scientific knowledge of a system usually begins by an analytical and 'reductionist' approach. The pejorative connotation attached to the word 'reductionist' will do nothing to change this. How can we globally understand the ocean and model it without the prior analysis, evaluation and appraisal of the processes controlling the diversity of currents that constitute its oceanic circulation? The Gulf Stream is a textbook case due to its dynamics and its location in an ocean with a peculiar configuration. To understand the ocean, it is essential to have understood the Gulf Stream, and the only good oceanographic models are those that take into account the complexity of this current. Of course, this also applies to other currents: the Equatorial Currents for instance, which, because of the relative strength of the forces operating on them, are situated in a very different dynamic context.

The Gulf Stream has the advantage of being close to the coast and easily accessible for oceanographic vessels, which were for a long time the only means of research. However, these vessels are slow and limited in use when compared to both the rate of marine current fluctuations and the immensity of the ocean.

Consequently, from 1850 onwards, the Gulf Stream became a real laboratory of dynamical oceanography, where measuring instruments and theoretical models were tested *in situ*, allowing knowledge of ocean dynamics to progress. This knowledge has now enabled the emergence of operational oceanography, which is similar to what was accomplished for the atmosphere to satisfy the requirements of weather forecasting.

This volume presents the history of the discovery of the Gulf Stream and its science. The text follows the history from the study of its peculiar dynamics, which seemed irreducible at the beginning of the nineteenth century, to its integration into the dynamics of a global ocean.

1 The Scientific History of the Gulf Stream

From Christopher Columbus to Benjamin Franklin

Christopher Columbus arrived in the Bahamas, the gateway to the Gulf Stream, in 1492. On 22 April 1513, after discovering Florida, the Spanish explorer Juan Ponce de León noticed the presence of a strong counter-current, which was later used by navigators and fishers and became known as the 'Gulf Stream'. Benjamin Franklin was the first to map the Gulf Stream, in 1769–1770.

From Benjamin Franklin to 1850: the first steps in physical oceanography

Following Benjamin Franklin's advice, ships systematically began measuring ocean temperature to determine the marine currents – in particular the Gulf Stream. During this period, ships' logs provided the only source of information on the Current.

The US Coast and Geodetic Survey: the first measurements of the Gulf Stream (1844–1900)

The Gulf Stream later became a scientific subject and purpose-built ships were made available for systematic exploration of the ocean's surface and depths. John Elliott Pillsbury made the first direct measurements of the current between 1885 and 1890, from a moored ship.

The first half of the twentieth century: the beginnings of systematic observation

Observations of ocean dynamics were intensified, and simultaneously theoretical and mathematical approaches to ocean dynamics began to develop. In 1955, Henry Stommel published the first summary report on the Gulf Stream.

The second half of the twentieth century: the space and technology revolution

In 1960, the study of the Gulf Stream reached the limits of traditional observational methods on board research vessels. A technological revolution then took place, thanks to satellites, which enabled direct measurements of the entire ocean through the deployment of in situ automated measuring stations in the ocean.

THE GULF STREAM – ISBN 978-92-3-103995-9 – © UNESCO 2006

FROM CHRISTOPHER COLUMBUS TO BENJAMIN FRANKLIN

The fall of the Mongol Empire in the fourteenth century severed, for a long time, the land route used by Marco Polo to travel to the Far East. As described by Daniel J. Boorstin in his work *The Discoverers*, an iron curtain had fallen between the West and the Far East – an area coveted for its spices. For Westerners, only unchartered maritime routes remained, with two options. The first was the maritime route around Africa and the perilous exploration of reputedly hostile, unknown lands down to the southernmost tip of the continent, where it was supposed – though only rumoured – that the Atlantic joined the Indian Ocean. This was the Portuguese route, which had been meticulously organized and planned over a period of fifty years in the fifteenth century, under the leadership of Henry the Navigator. The other solution was a westward passage through already explored lands, taking a direct maritime route without any idea of the distance involved. It was a gamble that tempted Christopher Columbus. In fact, he succeeded in selling his project to the Spanish monarchs, because he was convinced that there were islands between Europe and Cipango (Japan); and he dreamt of taking possession of them. It was not by chance that the agreement *Capitulaciones de Santa Fé* (Capitulations of Santa Fé), signed with the Spanish court, stipulated that he would become 'Viceroy and Governor of all the lands and islands that he shall discover and acquire in the said seas' on a hereditary basis. It was a clever deal, but his major discovery went well beyond anything he could have ever dreamed.

His dream to discover new islands was influenced, in part, by his discovery of wood debris on the banks of the island of Porto Santo (Madeira), where he had lived at the beginning of the 1480s; he believed that they could only have come from land farther to the west. Debris could also be found farther north, on the European coasts, brought by the currents – as if the Gulf Stream itself was sending signals inviting navigators to discover the New World. Luckily for Columbus and his fleet, not only the islands he had expected to discover but also the American continent were obstacles on his route to Cipango (Japan). He set sail from the Canary Islands on 6 September 1492 and reached the small island of Guanahani (San Salvador) in the Lucayes archipelago (Bahamas), at the entrance to the Gulf Stream, on

12 October. It was a minor achievement compared with the Portuguese expeditions and Magellan's forthcoming voyage, and he lost his gamble: the Bahamas was not Japan, but it nonetheless brought him glory.

Juan Ponce de León participated in Christopher Columbus's second voyage, in 1493. According to a persistent legend recounted by the historian Antonio de Herrera in *Historia General de los Hechos de los Castellanos en las Islas y Tierra Firme del Mar Océano* (General History of the Acts of the Castillians in the Islands and the Mainland of the Ocean Sea) published in 1601, an island named Bimini, the Island of the Fountain of Youth, existed and was supposed to ensure eternal youth to whoever drank its water. In 1513, Ponce de León equipped three ships at his own expense and set sail in search of Bimini. Although the Bimini Island was *mentioned* in the written instructions (*Capitulaciones*) granted by the King on 23 February 1512, these instructions did not assign objectives to Ponce de León other than to make new discoveries and to take possession of new lands. He set off from Porto Rico on 3 March 1513, sailed through the Bahamas – where he did not find Bimini, and perhaps he was not looking for it – and arrived on 2 April at the coast of a new land he named *La Florida* because it was the day of *La Pascua Florida* (Palm Sunday). While sailing along the coast of Florida, on 22 April, he and his fellow navigator Antón de Alaminos noted in the logbook the presence of a strong counter-current. The historian Antonio de Herrera, who had access to the logbook, describes it like this: '*It was such a current that, despite the strong wind, they did not advance but were seriously going backwards; finally, it was concluded that the current was stronger than the wind*.' This was undoubtedly the first reported observation of the Gulf Stream. On 8 May, when they rounded the southern tip of Florida, which they called *Cabo de Corrientes* (Cape of Currents), they provided further information on the current '*because water flowed so rapidly that it was stronger than the wind, and it did not allow ships to advance even when all their sails were hoisted*.'

Several years later (1519), Antón de Alaminos would draw a lesson from this experience. While he was returning to Spain from Veracruz, in Mexico, he took advantage of the current along the coast of Florida as he headed north before going eastwards towards Europe. Although the Gulf Stream had not yet been given a name, it had definitely been discovered, as navigators had incorporated the current into their navigation charts. Geographers and cartographers would soon include it in their representations of the New World. It semed to have appeared for the first time in 1678, on the map *Mundus Subterraneus*, a remarkable baroque work by Athanasius Kircher - a Jesuit who had never left Europe but had an encyclopedic mind, being familiar with every field of knowledge.

The navigators, from their accumulated observations at sea, created this work of science and in doing so became the only oceanographers of their time. Absorbed in their competitive trade or fishing industries the navigators were reluctant to pass on their knowledge to the academic world and guarded their understanding of the marine environment and currents. Nevertheless, 'scientific physical oceanography' would come into existence from the wealth of information in their logbooks. On their voyages from Louisiana to France, the French followed the Spaniards towards the Florida Current, but as they were also familiar with the North Atlantic thanks to their American colonies – the 'Nouvelle France' (New France) – they did not turn immediately towards Europe via Bermuda, but followed the current farther north, towards the banks of Newfoundland. One of them, Marc Lescarbot, describing his voyage to the New World in 1606–1607, was the first to observe the thermal contrast between the Gulf Stream water and the Labrador Current.

'I discovered something remarkable that a philosopher of nature should wonder about. On 18 June 1606 at 45° latitude and at a distance of one hundred and twenty leagues to the east of the banks of Newfoundland, we found ourselves surrounded by very warm water, although the air was cold. Yet on 21 June we were suddenly caught in such a cold fog that one would have thought oneself to be in January, and the sea was also extremely cold.'

The first Gulf Stream experts were undoubtedly the American fishers – in particular the whalers, whose hunting grounds stretched from Newfoundland to the Bahamas and the Azores. They soon noticed that the whales they hunted did not like the relatively warm water at the centre of the Gulf Stream and that they remained at the edge. Crossing the Gulf Stream back and forth, the whalers acquired knowledge that they later transmitted orally to the captains of American ships, who often had been trained as whalers themselves. Encouraged by this information, they modified their route accordingly and thus saved almost two weeks on the Great Britain–America route. This did not go unnoticed. In 1769, the Customs Office in Boston complained to the British authorities (The Lords of the Treasury) that the British ships (packets) spent on average two weeks more than the American merchant ships on the England–New England route. Being questioned, the General Manager of the Post of New England, Benjamin Franklin, tried to obtain additional information from his cousin, Thomas Folger, a ship's captain and former whaler who was living in London. A certain sense of irony can be detected in Franklin's manner of recounting Folger's reply:

'Passing from one side to the other of the current, it was not unusual that we met with English ships in the middle of the current struggling against it and that we spoke to them. We informed them that they were fighting against a current of three knots and that it would be better to cross it, but they were too competent to accept advice from simple American fishers.'

Following Folger's indications, Franklin had a chart of the Gulf Stream engraved in London, in 1769–1770, and copies were sent to Falmouth for distribution among the English captains (Figure 2). These copies were accompanied by an explanatory note on how to avoid the Gulf Stream in order to cross the Atlantic in only twenty or thirty days. As an example, '*It is possible to know when one is in the Gulf Stream by the heat of the waters, which is higher than in the waters on either side. If we travel westwards, we must cross the current in order to get out from there as quickly as possible.*' The Admiralty and the English captains, faithful to the Euclidian principle that the shortest route is the fastest one, rejected Franklin's chart. In 1978, Philip Richardson found the oldest version of this chart at the National Library in Paris. The chart in Figure 2 is a French transcript from the same period, also kept at the National Library. Franklin, who had an inquiring mind and was a pragmatic scientist, took systematic measurements of sea-surface temperature during his voyages between America and Europe. He concluded that the thermometer could be a useful navigation instrument, as the currents running from north to south were apparently colder than those flowing in the opposite direction.

There is no certainty that the Folger/Franklin chart was really the first one of the Gulf Stream. Before Franklin made his enquiries into the Gulf Stream, William de Brahm, General Surveyor of the southern coast of North America on behalf of the British Crown, had gathered the elements of a chart, which could have been published in 1772 and in which a *Florida Gulf Stream* is mentioned. Nonetheless, since the Gulf Stream appears named for the first time in these charts, it is likely that the authorship belongs to neither of the two, but to those sailors who had learned how to use it or avoid it during navigation.

FROM BENJAMIN FRANKLIN TO 1850: THE FIRST STEPS IN PHYSICAL OCEANOGRAPHY

It is obvious that, thanks to Franklin, the Gulf Stream itself became a scientific subject, passing from the status of a common noun to that of a proper noun, and thus opening the way for the development of studies in ocean dynamics – physical oceanography – until then totally unknown. Franklin had emulators quite soon, including some belonging to the initially reticent British authorities, who instructed their ships to undertake observations of the Gulf Stream whenever possible. Thus, the study of marine currents actually started at the beginning of the nineteenth century using three instruments: the chronometer – sufficiently precise since the time of John Harrison in the middle of the eighteenth century – to determine longitude, the thermometer and bottles thrown into the sea, or other surface floats. These floats were tried out for the first time, in 1802, by the British ship *Rainbow*, which dropped a number of them in the North Atlantic. Prince Albert I of Monaco was a great advocate of the float technique: in 1885, he released 180 floats along a line of 170 miles across the Gulf Stream, northwest of the Azores. This method of following the currents with floats was further developed and expanded from the 1970s onwards, when satellite-positioning techniques made it possible to locate the floats in real time.

Logbooks onboard ships became an essential source of information about marine currents. The British geographer Sir James Rennell – the father of oceanography according to the

British – spent the last part of his life, from 1810 (he was then 68 years old) to his death in 1830, compiling them to draw up charts of the Atlantic currents, with particular interest in the Gulf Stream.

Rennell died before having accomplished his work, and his last publication, *Currents of the Atlantic Ocean*, appeared in 1832. It was, concerning the Gulf Stream, the first exhaustive scientific report describing the current, suggesting explanations and drawing attention to observations that anticipated forthcoming scientific issues. He was the first to clearly distinguish two types of currents: drift currents, pushed by the wind, and stream currents, produced by pressure differences (in fact, differences in sea level) in the direction of the current. In keeping with Franklin's idea, he believed that the Gulf Stream belonged to the second category. The Gulf Stream appeared as a direct and natural consequence of water accumulation on the American coasts carried westward by the Trade Winds. Consequently, Rennell considered that the Gulf Stream ended its course to the south, in the direction of the Azores, where it became diluted and eventually disappeared while, in his view, the water movements observed in the northeastern Atlantic and Europe corresponded to a drift current due to the strong prevailing winds from the west. It was an accurate analysis, but one which did not prevent the development of the theory that the Gulf Stream was directly responsible for the mild climate in northwest Europe; it is this idea which truly raised the Gulf Stream to the level of a myth.

The issue of the Gulf Stream's impact on climate in Western Europe was raised from the time of the first observations, at the beginning of the nineteenth century. In 1822, Colonel E. Sabine, on a voyage around the North Atlantic to determine the Earth's configuration, remarked on the presence of a mass of water in the eastern Atlantic that he judged to be abnormally warm. He credited it to an exceptional extension of the Gulf Stream towards Europe, due to a particularly high accumulation of water in the Gulf of Mexico and the Caribbean, and attributable to a strengthening of the Trade Winds. At the same time, the weather in France and in the south of Great Britain was unusually hot, humid and stormy. Sabine saw in this a relationship of cause and effect. In 1845–1846, England and Western Europe had a similar climatic anomaly. Sabine wished to know whether it was accompanied by a thermal anomaly in the ocean, as in 1822. He was quite disappointed, because none of the numerous ships navigating in the zone had carried out observations. He nevertheless thought it plausible that a particularly high speed of the Gulf Stream at its origin could correspond to an unusual extension towards the European coasts, which would thus benefit from particularly mild and rainy winters. He even proposed a forecasting system based on sea level monitoring in the Gulf of Mexico and the Straits of Florida. He expected it to anticipate fluctuations in the speed of the Gulf Stream and the arrival of warm water, with the climatic consequences experienced in the eastern Atlantic a few months later.

This theory was contested in 1836 by François Arago, who brought attention to the fact that a study of sea levels had revealed a difference of only 7.5 inches (19 cm) at 30°N, between the western coast of Florida, in the Gulf of Mexico, and the east coast, on the Atlantic side a difference he deemed insufficient to generate the Gulf Stream. Being a Cartesian, he put forward the idea that it was not necessary to find explanations for marine currents other than those that are taken into account for atmospheric currents, such as the Trade Winds, which arise from the density differences between the Equator and the Poles caused by the unequal distribution of solar energy.

He was wrong: this current does not require density differences to exist, even if they do have an influence on it. However, this theory did for a time discredit the idea that winds could generate large ocean currents of great scale, such as the Gulf Stream. Such is science, which, in order to progress, first seeks the principal, not the sole cause of a phenomenon before coming up against its complexity. This complexity is subsequently revealed by measurements and observations, which compels a reconsideration of causal mechanisms previously disregarded. In this case, the Gulf Stream, as with the majority of currents, is the result of the action of the wind and the Sun on the sea, both inextricably linked, and also of the Earth's rotation. Alexander von Humboldt, had already hinted at this influence of the Earth's rotation in 1814, when he wrote that currents flowing north were deflected eastwards, and vice versa.

Rennell checked certain observations which already called into question the simplistic image of the Gulf Stream as 'a river in the sea' (Figure 2), as suggested in the chart by Folger and Franklin. Indeed, he observed that there were variations in the position and width of the main stream: that these variations were independent of the seasons, that the presence of warm water did not necessarily mean an eastward current but sometimes a counter-current and, finally, that cold-water streams could be observed in the midst of warm water. These were the Gulf Stream's underlying meanders and eddies, structures that available data were unable to identify – much to Rennell's regret – owing to the lack of sufficiently dense and synoptic observations and measurements. This gap was one of the major difficulties encountered in physical oceanography until the end of the twentieth century: measurement of variations in the ocean dynamics was beyond the capability of methods available to oceanographic ships, which had limited autonomy and were too slow to provide a synoptic field. This continued to be the case until the advent, in the years 1960–1970, of space systems that enabled direct observations from satellites, covering in a few hours or days all the world's oceans, and the deployment in the entire ocean, both on the surface and at depth, of measuring instruments which were located by satellite and were also able to transmit the results to the satellites.

Matthew Fontaine Maury of the US Naval Observatory, considered by Americans to be the father of physical oceanography, took a first step towards 'synoptic oceanography'. By determining an average from the data collected, he drew wind and current charts specifically designed for navigation and thus created the first pilot charts. He was the instigator of the first international conference on meteorology, held in Brussels, in 1853, which set the foundation of international cooperation for the systematic organization of data collection onboard ships crossing the Atlantic.

THE US COAST AND GEODETIC SURVEY, THE FIRST MEASUREMENTS OF THE GULF STREAM (1844–1900)

Organized and systematic observation of the Gulf Stream began, in 1844, in the framework of the US Coast and Geodetic Survey, under the direction of Franklin's great-grandson, Professor Alexander Dallas Bache, Superintendent of the Survey from 1843 to 1865. He devised a strategy for systematic observation of the Gulf Stream based on temperature measurements taken at the surface and at depth, in cross-sections of the current, from the coastline to the open sea. The current speed was, at the time, only observed from the surface and inferred from the drift of the ships. The work began in spring 1845 on the brig *Washington*. Later, a steam-ship, the *Legare*, was used for the first time in 1848. Explorations continued year by year until 1860. From 1846 onwards, it had its victims: the *Washington*, commanded by Lieutenant George Mifflin Bache, ran into a cyclone in late summer. Ten members of the crew lost their lives, but the ship, practically a wreck, managed to return to port. The Gulf Stream earned the unfortunate reputation of being a storm-maker, well illustrated in a painting by Winslow Homer (Figure 1) at the Metropolitan Museum of Art in New York. In 1864, Louis Figuier wrote in *La Terre et les mers* (The Earth and the Seas):

'The temperature difference between the Gulf Stream and the waters it crosses inevitably produces storms and cyclones. Modern discoveries, which have helped to make known the itinerary of this warm-water current in the sea, have made it possible to considerably shorten navigation routes and avoid many dangers that in the past threatened and destroyed ships. In 1780, a terrible hurricane ravaged the West Indies and cost the lives of 20,000 people. The ocean left its bed and invaded the towns; the bark of the trees mixed with bloody debris swirled in the air: these are the too many catastrophes of this type that have earned the Gulf Stream the name of "King of the Storms".'

It was Bache who gave the name of 'Cold Wall' to the thermal front at which the temperature changes quickly, and which can be considered as the boundary of the Gulf Stream on its western side.

The exploration of the Gulf Stream was later interrupted and delayed until 1867 by the American Civil War. It resumed with particular efforts to try to determine the overall depth of the Gulf Stream, which implied that the capability of making velocity measurements at depth was available. Ships, also subjected to the currents, were not the best platforms for that type of measurement. Unfortunately, at the time there were no other options. While observations of the drift of ships enabled us to calculate surface currents, they gave no indication of what was happening at depth. It was only possible to carry out measurements at the surface. Professor Henry Mitchell of the US Coast and Geodetic Survey tried innovative measurements at depth, in 1867, in the Straits of Florida between Key West and Havana (Cuba). Two spheres of equal surface were attached to a rope, one on the surface and the other one at the depth at which the current was to be measured. The movement of the spheres was affected by the current speed at the surface and the depth at which the current was being measured. A third equivalent sphere drifted freely with the surface current. At the starting point, the two spheres on the surface were together and, after a certain lapse of time, the distance separating them measured the difference in current speed between the surface and the depth under study. Mitchell concluded that at a depth of six hundred fathoms (1 fathom = 1.83 m), the current speed at depth was less by only 10% than that at the surface, despite a strong temperature drop of 40°F (22°C). It was concluded that, to understand the Gulf Stream in depth, it was not possible to rely on temperature measurements only. This encouraged John Elliott Pillsbury (still within the framework of the US Coast and Geodetic Survey), to carry out, between 1885 and 1890, a series of direct and absolute measurements of the current from a moored ship, the *Blake's*.

This was a first in oceanography. Pillsbury developed, for this work, the first currentmeter, a transposition to the marine environment of the anemometer used to measure wind force. It was composed of a drift oriented in the direction of the current, a compass indicating the direction of the current and a rotor in which the number of revolutions in a given lapse of time is proportional to the velocity of flow.

Pillsbury completed six Gulf Stream profiles in a period of several years, from Cape Hatteras to the channel between Yucatan and Cuba. It was a thorough and meticulous work, which took a long time to complete, considering, in particular, the difficulty in maintaining anchor at great depth in such a strong current. For instance, it was necessary to undertake two studies (1885 and 1886) at the six stations of section A alone, with a width of only 43 miles (69 km) between the south of Florida (slightly south of Miami) and the Bahamas. In his report, dated 1890, Pillsbury noted down that the total time spent in measuring this section was 1,100 hours and that the longest uninterrupted period at anchor was 166 hours, that is, six and a half days. In this section, the maximum current speed measured on the surface was 3.5 knots (~6.5 km/h) and the flow rate was 90 billion tons/h, that is to say 25 million m^3/s – very close to today's estimates. At each station, measurements were taken at five levels, from the surface to 130 fathoms deep.

THE FIRST HALF OF THE TWENTIETH CENTURY: THE BEGINNINGS OF SYSTEMATIC OBSERVATION

In parallel with current measurements, Pillsbury also recorded temperatures. Thus, he created the first set of oceanographic data, which associated the measured current with the hydrographic parameters (temperature) characteristic of the water mass. This allowed George Wüst, in 1924, to validate the geostrophic hypothesis, which allowed the derivation of the currents from the seawater density field. This took a substantial weight off the oceanographers' shoulders. Paradoxically, they were able to make progress on the description and understanding of oceanic circulation without directly measuring the currents.

Indeed, Pillsbury's method, which was extremely difficult to put into practice and relatively imprecise, had hardly any impact, especially as it could not be envisaged for the great depths of the open sea. We can say that the knowledge acquired on marine currents up to the middle of the twentieth century was due less to direct measurement than to the analysis of hydrographic data – temperature and salinity – which allowed the determination of seawater density, and from which it was possible to trace the current field. In 1942, Harald U. Sverdrup, one of the founding fathers of dynamical oceanography and co-author, with Martin W. Johnson and Richard H. Fleming, of the first complete work on oceanography, *The Oceans, their Physics, Chemistry and General Biology*, used to say that the number of currentmeters surpassed the number of useful measurements. Meanwhile, the geostrophic method, which described an ocean in permanent (or stationary) equilibrium independently of the causes that kept it in motion, did not allow for the temporal variations in the current.

Priority was thus given to systematic observations by 'hydrographic' sections of the Gulf Stream. This was one of the first objectives of the Woods Hole Oceanographic Institution (WHOI), created in 1930 on the east coast of the United States (Massachusetts). Their research vessel the *Altantis* carried out detailed studies of the Gulf Stream, (the first led by Columbus Iselin), from 1931 to 1939, at the rate of four campaign per year. It took the *Atlantis* many weeks to carry out its measurements, and at the end of them, the Gulf Stream was no longer what it had been at the start of the campaign. It described a real Gulf Stream in terms of the structures in each section, but with no overall temporal context.

In 1950, the first synoptic exploration of the Gulf Stream – or more precisely of a small part of the Gulf Stream to the east of Cape Hatteras, in an area where, meanders and eddies form at a distance from the coast – was accomplished by the WHOI with seven ships operating simultaneously.

The period between measurements that can be considered synoptic in oceanography is large when compared to those of other synoptic fields. However, for synopticity the lapse of time between measurements only needs to be adequate to address the timescales of the variations in the factors of the environment being studied. Thus, in meteorology, taking into account the rapidity of atmospheric change, synoptic fields established every three hours imply exact simultaneity of the measurements taken by the meteorological stations. The ocean has a much greater inertia than the atmosphere, and the meanders and eddies that we try to identify in the Gulf Stream have a long enough life span that explorations covering about one week could be considered as synoptic. Indeed, for the first time, it was possible at this time to make a complete hydrographic description of a meander located at 61°W, 39°N in the Gulf Stream, and to identify an eddy formed by a meander detaching itself from the main stream. In the same zone, another synoptic campaign with four vessels was undertaken from April to June 1960, led by Fritz C. Fuglister. A meander was also observed in the same region and remained almost stationary until the end of the campaign, in June.

THE SECOND HALF OF THE TWENTIETH CENTURY: THE SPACE AND TECHNOLOGY REVOLUTION

By 1960, all traditional hydrographic resources and methods used to describe the Gulf Stream employing oceanographic vessels had been exhausted. Even if the Gulf Stream's complexity, with its meanders and eddies, had been qualitatively identified, a dual problem of scale in both time and space remained. The field of Earth science is completely dependent on available observation methods, which utilize time- and space-scales of phenomena that are accessible and can be analysed. Furthermore, these spatial and temporal measurement networks are dictated by technology, even as we adapt our concepts to our research means, which thus become our blinkers. It was impossible, even with several vessels, to obtain an overall synoptic description of the Gulf Stream from the south of Florida to the banks of Newfoundland. Moreover, this network of observation stations did not allow a correct description of the structure of eddies. The campaigns of 1950 and 1960 involved several vessels concerned only with a small part of the Gulf Stream. In addition – and this was the second difficulty – they provided a fixed image, a sort of snapshot that revealed nothing about the variation in the phenomenon. Considering the significant logistics required, it was impossible to repeat this type of operation regularly: hence the variation in the Gulf Stream and its structures was beyond reach. The third difficulty was direct measurement of the current. This was necessary for two reasons. First, the current fields derived from hydrographic data by the geostrophic method gave the relative currents; they were calculated based on a reference surface of zero motion. Lacking measurements, ignoring what the deep circulation might be, and starting from the hypothesis that current speed diminished with depth, it was considered satisfactory to take as reference the maximum measurable depth reached by the hydrographic stations. Then, the geostrophic method, which postulated a current in equilibrium, provided a 'smooth' image of the current field. However, this did not allow for the temporal variation in the current.

The difficulties highlighted here were not specific to the Gulf Stream: they represented a challenge to all physical oceanographers. To progress, it was vital to develop new instruments and methods, which would take into account the space-scale relevant to eddies, considered to be omnipresent in the oceans, and continuous measurements over longer periods make to access the variation in these structures and the ocean currents.

Nevertheless, the harvest was already sufficiently abundant that, parallel to the observations, progress could be made in understanding the mechanisms and their integration within a theoretical framework: that is to say, expressing the Gulf Stream in terms of hydrodynamic equations. In 1958, Henry Stommel, one of the most prolific oceanographers of the twentieth century, published *The Gulf Stream: A Physical and Dynamical Description*, a work that took stock of acquired knowledge of the Gulf Stream in terms of observation and theory. Beyond the Gulf Stream itself, which he integrated into the general problems of ocean dynamics, it was in fact a holistic work of physical oceanography integrating the Gulf Stream and its characteristics into a global conceptual framework. Consequently, because his work defined the Gulf Stream as an element of the general oceanic circulation – like any other current – his pioneering use of hydrodynamic equations became commonplace for currents other than the Gulf Stream. However, Stommel also went on to explain why it was sound to treat the Gulf Stream as a particular entity. Historically, we have seen that the Gulf Stream was easily identifiable. Initially considered as a warm-water stream, 'it' could be crossed in less than a day; the volume of water 'it' carried could be calculated; it was possible to determine 'its' boundaries, 'its' centre which is where 'its' maximum speed is; 'it' was also a current for which the current speed could be determined using indirect methods, such as the geostrophic method.

The Gulf Stream is just one of the components of the great North Atlantic anticyclonic circulation, but to comprehend its character, it is sufficient to attempt to describe the other currents constituting the gyre with the same criteria as those used to define the Gulf Stream. For instance, to the east, the Canaries Current, driven by the Trade Winds and known to navigators well before the Gulf Stream, is much weaker and indistinct. It is not possible to cross it in a few hours; there is no distinctive thermal sign, and it is not possible either to fix precise limits or identify a core velocity. It is therefore hardly surprising that, until the middle of the twentieth century, the physical oceanographers of the US Coast and Geodetic Survey focused on the Gulf Stream 'laboratory' and were less motivated by the apparently weaker dynamics of other ocean currents. Yet, it was necessary to legitimize the Gulf Stream's originality by developing a theory that took these observations into account. This is what Stommel did, explaining why, in the great anticyclonic circulations, currents were necessarily stronger on the western boundary than on the eastern boundary of the ocean. As we shall see later, this is the direct result of the rotation of the Earth; its effects vary in relation to the latitude, giving variable weight to the forces (in this case, the Coriolis force), which are taken into account in the hydrodynamic equations. Thus, the Kuroshio in the North Pacific and the Brazil Current joined the Gulf Stream in the aristocracy of the so-called 'western boundary' currents. Another category of currents, which was still unknown at the time Stommel published his work, challenged the above-mentioned currents in terms of originality or personality: the Equatorial undercurrents discovered by Townsend Cromwell in 1958. These are currents with intensity and flux comparable to those of the Gulf Stream, which cross the Atlantic and the Pacific along the Equator from west to east, at a depth of a few dozen metres. Again, the variations in the Coriolis force explain their originality; this force is zero at the Equator and increases with latitude, forcing these undercurrents to remain strictly along the Equator.

Coverage from space: drifting buoys

In 1957, an experiment by John C. Swallow and L. Valentine Worthington demonstrated that, under the Gulf Stream, there could be a current flowing in the opposite direction. This illustrated the difficulty in defining a reference level at which the current speed is zero, from which it would be possible to calculate the true current using the geostrophic method. This was one of the first, if not the first, times that floats were used to measure deep currents. Swallow developed floats that were ballasted to be able to maintain a constant depth, and fitted with an ultrasound transmitter. On the surface, a ship equipped with directional hydrophones was able to follow their trajectory in real time and thus determine the current speed and direction. Nine floats were deployed at 1,500 m to 3,000 m depth and followed during periods of 1-4 days. All the floats at a depth greater than 2,000 m took a south-southwest direction, opposite to the direction of the Gulf Stream, with a speed of up to 20 cm/ s. This is known as the Deep Western Boundary Current of the thermohaline circulation.

It was a conclusive experiment, which marked the beginning of the now massive deployment of drifting floats. Following progress in underwater acoustics and development of positioning systems and data transmission by satellite, the methods for tracking floats from a vessel on the surface were soon abandoned. One new method was the deployment of, for instance, the Rafos floats by Tom Rossby, which could receive sound signals from several moored acoustic transmitters. Analysis of the time differences required to receive the sound signals allowed 'triangulation' of the position of each float. At a predetermined time – after a few weeks or months – the float was released and it rose to the surface, where it sent the collected data via satellite to the researcher, thus enabling the reconstruction of its trajectory.

Later, it was possible to abandon anchored acoustic transmitters, which involved difficult operations, for autonomous floats programmed to come up to the surface at a determined frequency to transmit their data and position by satellite and afterwards return to their observing depth. Equipped with salinity and temperature sensors, they became, at each round trip to the surface, *de facto* hydrographic stations. These floats could function for months or years, thus enabling monitoring of almost the entire ocean.

Similarly, the drift bottles thrown into the sea by Prince Albert I of Monaco were replaced by surface floats, which could be located permanently by positioning systems placed on satellites such as Argos. It was generally by becoming stranded on the seashore or ultimately collected by a passing ship that their voyage – which could last several years – came to an end. One buoy launched in the Antarctic, close to Heard Island, on 17 March 1997, became stranded on a beach on Rodriguez Island, in the Indian Ocean, in September 2002, after five years and a complete tour of the Antarctic without ever failing to transmit.

Temporal continuity: currentmeter moorings

The measurement of current speed by floats left to float freely is called 'Lagrangian'. If the number of floats used is sufficiently great, a current field at the depth where the floats drift can be mapped. Each time the floats come to the surface, temperature and salinity profiles are obtained, allowing construction of an absolute geostrophic field. This can be determined because we have the current field at the depth of reference, which is, the depth at which the floats drift. This field must be confirmed by direct measurement, referred to as 'Eulerian', of real currents over periods sufficiently long to reveal their variation – as Pillsbury had done from an anchored vessel. Operating in this way, from a surface in perpetual motion, yields random results. It is easy to take soundings in the atmosphere: on the continents and islands there are stable platforms from which it is simple to take measurements. In the ocean, the *terra firma* is located at an average depth of 4,000 m, for a long time an insurmountable difficulty, which explains why fixed observation and measuring stations on moorings firmly anchored to the ocean floor appeared quite late in the 1970s. The logistics were challenging: a ship was required to deploy the moorings, which had to be picked up frequently to collect the data stored in the measuring apparutus.

Technological developments and the possibility of transferring the data via satellites as they arrived, without having to get them *in situ* from the mooring's surface buoy, considerably lightened the logistics and provided the opportunity to record measurements over long periods. Thus, measurements were taken at key points in the Gulf Stream during the international programme WOCE (World Ocean Climate Experiment, 1990–2000). The design of the currentmeters used was always based on the anemometer: a rotor turning in the current indicated the current speed, and the drift recorded by a compass indicated the direction of flow. The measurements were intermittent: the currentmeters were distributed along the mooring line at the levels selected for measurement. Real current 'profilers' have been developed recently, enabling continuous measurement of the current in relation to the depth. A submerged sound transmitter emits a sonar signal to the surface, which is reflected by the particles in the water moving at the speed of the current.

Variations in speed of the different water layers result in a varying Doppler effect from which the current speed in each layer can be derived.

The integration of time- and space-scales: measurements from space

Thanks to data localization and transmission systems, it has been possible to multiply the number of *in situ* automatic measuring stations throughout the oceans. The space revolution in oceanography does not end there: more impressively, the sensors positioned on satellites provide, in addition, spatial continuity and temporal variability. Combining measurements taken *in situ* and from space paves the way for synoptic and continuous observations of the entire ocean.

Exploration of the Gulf Stream and the entire ocean continues, based on all these technologies, and we shall see many examples in the following pages. It is time now to define Gulf Stream.

2 What is the Gulf Stream?

The drivers of the oceanic circulation

The Sun and the Moon are at the origin of the ocean's movement, which through their gravitational pull generate the tides. Solar energy sets the atmosphere in motion, which, in turn, through the wind, drives the ocean. Finally, the rotation of the Earth generates swirling atmospheric and oceanic movements at various temporal and spatial scales.

Oceanic gyres

The wind, which turns clockwise around the subtropical anticyclones, such as that of the Azores, drives ocean currents into vast basin-wide anticyclonic gyres; these gyres are to be distinguished from the omnipresent mid-scale eddies in the ocean, which have a dimension in the order of 100 km. There are also cyclonic gyres around major depression systems like those observed in Iceland and the Aleutian Islands in Alaska.

Western boundary currents

The Gulf Stream circulates on the western boundary of the anticyclonic gyre associated with the subtropical anticyclone of the Azores. Its driver is therefore the wind. It is not the only one of its kind: there are similar currents in the Southern Hemisphere and in other oceans. All these so-called 'western boundary' currents share the same *characteristic of being particularly strong, compared with the other currents that are elements of gyres. This is due to the rotation of the Earth and to the Coriolis force it generates.*

Anatomy of the Gulf Stream

From a dynamic point of view we can place the starting point of the Gulf Stream in the Florida Strait and its end in the North Atlantic, where it veers westwards beyond the banks of Newfoundland. However, the 'extensions' towards the east and the northeast, which are the North Atlantic and Norway Currents, do not depend on the dynamics created by the anticyclone of the Azores. Thus, it is a mistake to consider the Gulf Stream as a current flowing from the Gulf of Mexico to Norway.

THE DRIVERS OF OCEANIC CIRCULATION

When asked the question, 'What drives the ocean?' the simplest reply is energy from the Sun, the tides and the rotation of the Earth.

The Sun as the origin of marine currents

There is no motion without energy. Thus, on Earth it is possible to identify three independent sources of energy that affect the ocean movements. First, there is the Earth's internal energy: its radioactivity heats the Earth's core and keeps the continents like floating rafts on the surface of its mantle – animated by convective motion. It is the energy influencing plate tectonics, which shapes the continents and ocean basins at a geological scale, as well as the volcanoes, earthquakes and tsunamis. In spite of its occasionally violent manifestations, it has hardly any impact on marine currents and their variations at a timescale of centuries.

Second, there is the gravitational attraction of the Moon and the Sun, which generates the tides; these are more subtle, orderly and predictable. For a long time, it was considered that the influence of tides on general oceanic circulation of both surface and deep currents was negligible. We know today that this is not the case. Now that the three dimensions of global oceanic circulation are better understood, so that it is possible to make an energy balance, it has been established that the circulation known as *thermohaline* – the famous 'conveyor belt' of the Gulf Stream – cannot be sustained without a source of supplementary energy supplied to marine currents by the transfer of some of the energy dissipated by the tides.

Finally, there is the energy from the Sun irradiating the Earth's surface. It is the principal driver of the atmospheric and ocean currents. Transfer of radiant energy from the Sun to the atmosphere and the ocean in the form of mechanical and kinetic energy is not direct: an intermediary is necessary. The ocean plays this role for the atmosphere, and the atmosphere for the ocean.

The ocean: a reservoir of solar energy and a supplier of the atmosphere

Energy from the Sun is unequally distributed on the Earth's surface: it is minimal in the polar regions and maximal at the

Equator. In addition, because of the angle of the Earth's axis in relation to its plane of rotation around the Sun, the energy received at any given point on Earth varies according to the seasons. The Earth receives on average 340 W/m^2 of energy from the Sun. A third of this energy is directly reflected by the atmosphere, returned to space and thus lost to the climate system. The atmosphere, being largely transparent to solar radiation, absorbs only 20%. The remaining 50% reaches the Earth's surface, of which, 30% is absorbed by the oceans, and 18% by the continents. The ocean is thus the principal reservoir of solar energy. It restores part of it to the atmosphere, which finally receives 30% directly from the Sun, 25% from the continents and 45% from the oceans. Contrary to popular belief, the atmosphere is thus heated essentially from below and not directly from above by the Sun, and the ocean supplies 45% of its energy. This energy transfer from the ocean to the atmosphere takes place predominantly in the intertropical regions, which are the main beneficiaries of solar radiation and where ocean temperatures are at their highest. It is particularly the case in the Intertropical Convergence Zone (ITCZ), where the Trade Winds of the Northern and Southern Hemispheres converge. An intense convection movement can be observed; it is the famous doldrums (a zone of dead calm seas) where, by evaporation, the ocean transfers energy to the atmosphere - which mobilizes it when water vapor condenses at altitude creating the cumulonimbus clouds dreaded by sailors and the pioneers of air navigation. The Equatorial Oceans act as a boiler that starts motion in the atmosphere and thus generate the winds.

The ocean transfers energy to the atmosphere in three different ways. First by conduction: warmer fluid transfers to the colder one an amount of heat that is proportional to their temperature difference. It is the weakest of the components – an average of 10 W/m^2. It becomes significant – about 50 W/m^2 – when warm waters from the Gulf Stream meet with the polar air mass from Canada. Radiation comes next: the ocean, which absorbs solar radiation (mostly in the visible spectrum), releases in turn, in the infrared spectrum (depending on its temperature), an average radiation of 60 W/m^2 – which is then absorbed by the atmosphere. Finally, the most important one (70 W/m^2 on average) is evaporation, which can reach a peak of 200 W/m^2

in the tropical regions (the 'boiler' of the climate system) and in the Gulf Stream.

The wind as the driver of ocean surface currents

Wind created by energy inputs from the ocean to the atmosphere will, in turn, by friction on the ocean surface, transfer mechanical energy and generate surface currents. The wind is the main driver of the ocean surface currents. Thus, atmospheric and oceanic circulations are inextricably linked and can be said to be coupled. The climate system is a heat engine to convert and distribute the energy Earth receives from the Sun. The atmosphere and the ocean are its two fluids. They ensure the transport and distribution of thermal energy from the warm equatorial source to the cold polar source. Permanently in contact with one another, they continually exchange energy and are indissociable. Hence, the coupling they form controls our planet's climate. All the difficulty of physically interpreting this coupling stems from the fact that they have very different properties and rates of change.

Freshwater balance: salinity and density variations as drivers of the deep oceanic circulation

Weather forecasts on television have acquainted us with the relationship between atmospheric pressure and wind force: the lower the atmospheric pressure at the centre of a depression or a cyclone, the greater the wind force. We also know that atmospheric pressure differences on the ground correspond to differences in the weight of the air column above it. This also applies to the ocean, which is not homogenous. At a given reference level, the 'oceanic' pressure varies: it is equal to the weight of the water column above it and, therefore, depends on the density of the water layers making up the water column. Seawater density is largely determined by the water's temperature and salt content. Seawater acquires its properties at the surface, through exchanges between the ocean and the atmosphere.

We have seen that the principal means of exchange are evaporation, mainly in the tropical regions and from warm currents, such as the Gulf Stream. Evaporation constitutes a loss of water for the ocean and this corresponds to a rise in salinity and therefore in density. Energy transfer to the atmosphere takes place when the water vapor condenses in the atmosphere, and rainfall leads to a decrease in salinity and thus density. These evaporation zones do not necessarily coincide with those of rainfall, thus we say that there are density 'exchanges' between the oceanic regions through the freshwater cycle in the atmosphere. Highly dense surface waters will tend to sink to the depth at which they will be in hydrostatic equilibrium: the less dense water overlying the denser water. This is the driver of thermohaline circulation, from the Greek adjectives *thermos* (hot) and *halinos* (salty), which designates the mechanism at the origin of the circulation in the deeper layers of the ocean: density differences leading to exchange, at the surface, between the ocean and the atmosphere.

The climate heat engine: dissymmetry between the ocean and the atmosphere

If the climate system functions as a heat engine, this is due to the atmosphere and not to the ocean, even if they both contribute to heat transfer from the equatorial region to the polar regions. The atmosphere is a heat engine, not the ocean. Indeed, the atmosphere functions between a warm source – the Equatorial Oceans, which provide an input at its base – and a cold source – the polar regions; it is this thermal differential that sets the atmosphere in motion. It is not the same for the ocean, which has a relatively stable configuration. It receives thermal energy input at its surface and, as in a central heating system with the boiler placed above the installation and not below it – there is no spontaneous convection. The ocean has to be driven by the wind to create the unstable conditions that generate deep circulation. Therefore, contrary to what was suggested by Arago, the differential thermal energy received by the ocean does not induce its motion, but rather, initially, it is the mechanical action of the wind, which is fuelled by thermal energy. The movement is maintained at depth by energy dissipated by the tides, without which deep circulation would cease. In terms of the energy balance, it is interesting to note that oceanic circulation is maintained by a very small amount of energy (that of wind plus tide): only a thousandth of the thermal energy received by the ocean. Therefore, the thermohaline circulation and the famous oceanic conveyor belt, which will be fully discussed later, are not the drivers of oceanic circulation: they are the consequence of the forcing of this circulation by the atmosphere.

Pressure forces

The preceding thermodynamic and mechanical exchanges and forcing bring about, in the ocean, pressure differences, as in the atmosphere. Pressure at a given point represents the weight of the fluid column above it. In the ocean, hydrostatic pressure depends on the height of the water column and the density of its water layers. Currents driven by the wind create 'pile-ups' of water in certain regions (high pressure) and, necessarily, 'troughs' of water in others (low pressure). Thus, the sea level is higher by several tens of centimetres in the western parts of the Equatorial Pacific and Atlantic Oceans because of the accumulation of waters carried by the South Equatorial Currents, which are driven by the Trade Winds. The evaporation–rainfall equilibrium of the different water layers determines their density and, finally, the weight of the corresponding water columns. As in the atmosphere, differences in hydrostatic pressure between two points in the ocean create pressure forces that are proportional to the pressure differences. Hence, every ocean current is associated with a variation in the sea level.

The rotation of Earth and the Coriolis force

Logically, according to the principle of communicating vessels, in which a fluid is in hydrostatic equilibrium in such a way that, at any given level, when the pressure is equal, winds and currents under the action of the pressure force should flow from a high-pressure area to a low-pressure area at a velocity proportional to the pressure difference. However, all the charts presented in weather forecasts show the wind turning clockwise around high-pressure centres (anticyclone) and in the opposite direction around low-pressure centres (depressions). Yet geometry tells us that to go from one point to another, the shortest way is a straight line. Popular wisdom tells us that it is not necessarily the fastest route, but the ocean and the atmosphere came up with circular motion, which is the best way never to reach a destination. This is due to a complementary acceleration called the 'Coriolis force', caused by Earth's rotation. It applies to all bodies moving in a rotating system, be it a child's movement on a merry-go-round or a marine current on Earth.

The Earth is a sphere revolving around itself. Compared with an absolute reference system originating at the centre of the Earth with its axes directed towards fixed stars, each point on the Earth's surface is driven by a rotational movement at a velocity varying with latitude. A complete revolution is made in twenty-four hours everywhere, but the distance covered and thus the velocity are at a maximum on the Equator and decrease as the latitude increases. Compared with an absolute reference system, the velocity of a moving body is the velocity in relation to the Earth's surface (for instance a train relative to the rails) and the rotational velocity of the Earth for the position of that body on the Earth. Even if the velocity is constant in relation to the Earth's surface, as the body moves on Earth, its rotational velocity varies as it moves. Velocity variation implies acceleration – therefore force. In the absolute reference system, everything happens as if all moving bodies on Earth were subjected to a complementary force: the Coriolis force. It is not an ordinary force, in that it does not create movement, but it appears whenever there is movement and its intensity is proportional to the velocity of the moving body. It is directed towards the right of the movement and perpendicular to it in the Northern Hemisphere and towards the left in the Southern Hemisphere with nil affect on the Equator, as it increases with increasing latitude.

This can be illustrated as follows. Let us suppose we have a rocket going from the Equator towards the North Pole. It travels eastwards at Earth's speed of rotation, which is that of the Earth at the Equator. As the rocket moves up northwards, the rotational velocity of the Earth's surface diminishes so that the eastward movement of the rocket will be faster than that on the surface over which it flies. In other words, compared with the surface of the Earth, the trajectory of the rocket is deviated towards the east as if a force carried it towards the right of its direction of motion. Obviously, the opposite is true in the Southern Hemisphere. This force, when applied to the atmosphere and the ocean, ensures that their movements are not linear but always organized into swirling movements at various scales: anticyclones, depressions and cyclones.

The geostrophic equilibrium

We can describe atmosphere and ocean movements fairly well by putting forward the hypothesis that, at a particular point, the pressure force and the Coriolis force are in equilibrium. In a pressure field associated with, for example, high-pressure (raising the height of the ocean surface: Figure 3), the pressure force will be directed from the centre of high pressure towards the periphery and perpendicular to the isobars in the atmosphere or to the lines of equal value (isopleths) in the ocean. The Coriolis force, according to the hypothesis of equilibrium, will be equal to the pressure force and in the opposite direction. As the Coriolis force is perpendicular to the direction of the movement and towards the right in the Northern Hemisphere, the wind or the current will necessarily be at a tangent to the isobars and oriented clockwise, whereas it will be anti-clockwise around a depression. Starting from this hypothesis, turning the problem round, we can see that it is possible to establish the corresponding wind or current field from a simple atmospheric-pressure or sea-level chart. This approximation obviously does not take into account frictional and turbulent forces, and it also means that vertical movements are negligible and that the system is more or less in equilibrium. Nonetheless, such a method remains pertinent to the analysis of the average state of the atmosphere and the ocean at any given time.

This method, developed by Vilhelm Bjerknes for the atmosphere in 1898, was later adapted for the ocean by Björn Helland-Hansen and J. Sandström in 1909. Thanks to the geostrophic approach, it is possible to derive the average currents to which the differences in hydrostatic pressure correspond. Measuring the hydrostatic pressure of a given sea level is not an easy task. In fact, it is not measurable: it is calculated from the relevant temperature and salinity values (from which water density is also calculated), which are measured with the help of probes throughout the water column. It is thus possible to calculate, at a given point, the weight of the water column above the chosen level; that is to say, the hydrostatic pressure. The method is simple but cumbersome because it involves making measurements at sea and, therefore, using ships which are slow and have limited autonomy. It was thus impossible to determine synoptic oceanic pressure fields as the meteorologists do for weather forecasting, several times a day. This is the case even if, considering the very different time constants of the ocean and the atmosphere (the atmosphere varies faster than the ocean), the temporal scales required for 'synopticity' are very different: a few hours for the atmosphere, around ten days for the ocean. Satellites equipped with altimetric radars now allow access to these synoptic fields of 'oceanic pressure'. Indeed variations in the hydrostatic pressure result in actual sea level differences, which these satellites measure to a precision of one centimetre. Covering almost all the oceans, these satellites provide access, through the measurement of differences in the sea level, to variations in the oceanic pressure fields and, thus, in the framework of the geostrophic theory, to ocean currents.

Wind action on the sea: the Ekman spiral

We said that the wind is the principal driver of marine surface currents. Yet we explain general oceanic circulation, as it appears in Figure 4, by putting forward the hypothesis of geostrophic equilibrium between the pressure force and the Coriolis force; that is to say, precisely by disregarding the driving force of the wind! The paradox is only apparent if we remember that the geostrophic hypothesis explains the average currents in equilibrium and the fact that wind eventually generates hydrostatic-pressure differences – therefore, pressure forces and currents have a certain stability if the geographic structure of the wind field itself is sufficiently constant, as in the great anticyclones of the subtropical regions. The geostrophic equilibrium thus explains the phenomena of marine currents without too much concern for the original causes.

Fridtjof Nansen, the first person to cross the Greenland ice-cap from east to west, in 1888, and winner of the Nobel Peace Prize, in 1922, for his work with refugees at the Society of Nations also found time to study the wind action on the ocean. To investigate ice drift in the Arctic and hopefully reach the North Pole, he had a ship built, the *Fram*, specially designed to be caught in an ice floe and to drift with it. In the course of this memorable expedition – which was a success even if it did not reach the Pole – Nansen observed that ice drift, and therefore the current, did not follow the wind direction as common sense would have dictated, but that it made a 45° angle with the wind. Nansen presented this problem to Vilhelm Bjerknes, a physicist and meteorologist, who entrusted the study to a young student, Vagn Walfrid Ekman. The solution, published in 1902, considered the equilibrium between the carrying force of the wind and the Coriolis force in the absence of pressure forces. Ekman then demonstrated that, in accordance with Nansen's observations, due to the Coriolis force, the surface of the water is carried away towards the right forming an angle of 45° with the set of the wind. The superficial layer then carries away the underlying layer, which in turn deviates towards the right and so on (Figure 5). As depth increases, the current becomes weaker and always turns towards the right. There is thus a spiral and, globally speaking, the result is that in a water column of around 100 m in depth, called the Ekman layer, water is carried away perpendicularly to the direction of the wind, to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.

OCEANIC GYRES

The Hadley Cell and the formation of subtropical anticyclones

If the Earth did not revolve around itself, it would be possible to think that cells of atmospheric circulation would form between the Equator and the Poles and they would function as follows. Air heated by the Equatorial oceanic boiler would rise in altitude creating an Equatorial belt of low atmospheric pressure. At altitude, the circulation would be directed towards the Pole, where cold and dense air would descend to the ground generating a zone of high atmospheric pressure. At ground level, the return would be made from the high polar pressures towards low equatorial pressures. The rotation of the Earth and the Coriolis force modify this simple pattern, and we note the result, without concern for the underlying processes responsible for the pattern.

To describe this, let us begin with one of the drivers: the equatorial oceanic boiler. Along the Intertropical Convergence Zone (ITCZ), the meeting of the North and South Trade Winds, carrying oceanic moisture, results in a large upward movements of air masses powered by energy from the ocean.

Trade Winds transform their horizontal kinetic energy into vertical kinetic energy so that, at sea level, winds are light in these regions of ascendance – to the great displeasure of sailors – and the atmospheric pressure there is low. At altitude, this flux diverges north and southwards, and dry air re-descends in the subtropical regions around 30° latitude, where high-pressure zones form: for example, the subtropical anticyclones of the Azores and of Saint Helena in the Atlantic. The Hadley Cell is the name given to the meridianal circulation cycle that is established between the meteorological Equator – or doldrums, a zone of dead calm – a low-pressure zone and the heart of the anticyclones in the north and in the south (Figure 6).

Anticyclonic atmospheric circulation

Around the anticyclonic high-pressure zones produced by the Hadley Cells, and in accordance with the geostrophic pattern, the atmospheric surface circulation is organized in a great clockwise circuit – westerly winds on the northern side in temperate regions and easterly Trade Winds on the southern side, in tropical regions. An identical symmetrical pattern is found with regard to the Equator in the Pacific. The Indian Ocean is a partial ocean, closed off at 20°N. Therefore, the Asian continental mass controls atmospheric circulation in the Northern Hemisphere and imposes an alternative regime of monsoons; hence there are no permanent anticyclonic systems in the northern Indian Ocean. On the other hand, in the Southern Hemisphere, the situation is 'normal', with an anticyclone similar to those found in the Atlantic and the Pacific.

The subtropical oceanic gyres

The vast anticyclonic atmospheric circulation systems drive the oceans along a circular path. The wind action can be felt in the top one hundred metres of the ocean, following the pattern of the Ekman spiral. All along the anticyclonic circuit, the wind drives the water 90° to the right of the wind in the Northern Hemisphere and likewise to the left in the Southern Hemisphere as in Figure 7; that is, in all cases, the water moves towards the centre of the anticyclone, where it converges and accumulates. This produces a sea level rise of 1 m above the surface at the periphery of the anticyclone and therefore a significant increase in hydrostatic pressure and hence a pressure force from the centre towards the periphery. The Coriolis force is opposite to the geostrophic equilibrium and the corresponding geostrophic current flows perpendicularly to these two forces and tangentially to the 'isohydrobars' (lines of equal hydrostatic pressure); in other words, roughly the contour line around the centre of the anticyclone and clockwise (Figure 7, corresponding to the Northern Hemisphere). Water cannot continually accumulate at the centre of the gyre: it sinks (convergence) causing a deepening of the thermocline. The thermocline is a layer of very rapid vertical temperature change which separates the homogenous warm surface layer from the deep cold layers of the ocean.

Ekman's theory on the driving of the ocean surface layer is based on the equilibrium between the wind frictional force and the Coriolis force, neglecting the pressure force. This implies that the movement of surface water thus produced is not in geostrophic equilibrium – which, in fact, stipulates the equilibrium between the Coriolis force and the pressure force, neglecting the wind. It may therefore seem paradoxical that, starting from the wind and Ekman's theory, we finally end up with an anticyclonic geostrophic circulation. This is because, to explain this circulation, it has been necessary to establish a chronology and find a starting point: wind action, in this case on a motionless ocean at the initial time. Wind action only affects a thin layer of the ocean surface, whereas the pressure force that it induces concerns a depth of several hundred metres in the water column, so that, in the end, the driving force of the wind becomes weak relative to the pressure force and to the Coriolis force. Hence, a geostrophic equilibrium is possible, independently of the original mechanism creating the current. Moreover, these calculations of currents based on sea temperature and salinity measurements (from which the hydrostatic pressure is derived) with the application of the geostrophic hypothesis explain the average currents observed and provide the proof that anticyclonic gyres are close to equilibrium.

Beginning with the Sun and Earth's rotation, and following the transformation of the solar energy and the exchanges between the ocean and the atmosphere, we have arrived at this coupled system by which the subtropical anticyclonic circulation generates its double or mirror-image in the ocean. This is a first step towards the Gulf Stream, which is an element of the North Atlantic subtropical gyre. The next step will take us to a peculiarity: the currents bordering the western side of these anticyclonic circulations.

The subpolar cyclonic gyres

Energy transfer from tropical to polar regions is not limited to the subtropical anticyclonic cells. Symmetrically, in the North Pacific and North Atlantic oceans there are atmospheric and oceanic subpolar cyclonic circulation cells associated with the areas of low pressure in the Aleutian Islands and Iceland. The cold currents flowing towards the south on the western side of these oceans – the Oyashio in the Pacific and the Labrador Current in the Atlantic – are on the western boundaries of these cyclonic circulations (Figure 4). The atmospheric and oceanic subpolar anticyclonic cells are tangent to one another: in the atmosphere, they have in common the westerly winds in the temperate latitudes; in the ocean, the North Atlantic Current and its equivalent in the Pacific, which extends into the the Gulf Stream and with the Kuroshio, link the two. These two types of circulation are not independent, and thus they interact with one another. For example, a reinforcement of westerly winds necessarily corresponds to a reinforcement of both the subtropical anticyclone and the subpolar low-pressure area. A high-pressure area is also found beyond the subpolar gyres at the heart of the Arctic, around the North Pole.

WESTERN BOUNDARY CURRENTS

The chart in Figure 8 represents the so-called 'dynamic topography' of the oceans. It relates the sea level to what would be the surface of no motion: an ocean without currents. The raised levels (high pressures) appear in white and the low pressures, in dark blue. The maximum height exceeds the mean level by 1.10 m. This chart was obtained from the Topex/Poseidon altimetry satellite launched in 1992. It illustrates the power of satellite tools: it is actually a synoptic representation of the complete hydrostatic field of the ocean, which was impossible to obtain with traditional means of oceanographic observation. It is for the oceans what atmospheric pressure charts are for weather forecasting.

The chart highlights the reliefs in the three oceans, associated with oceanic anticyclonic circulations. We can see that the highest points of the ocean surface are not at the centre of the oceans: they are clearly shifted to the west and do not coincide with the centres of atmospheric circulation, which themselves are not displaced. We owe this characteristic to the continents, which put up barriers to ocean currents; however, the continents and mountain ranges are not insurmountable obstacles for atmospheric movements. It is also due to the rotation of the Earth, which, through the variations in the Coriolis force, creates a lack of symmetry in the dynamics of ocean currents between the eastern and western boundaries. This narrowing of the 'isohydrobars' to the west corresponds to an increase in the slope of the sea surface, and therefore to a velocity increase in the corresponding current: in all the oceans, it is possible to note a reinforcement of currents on the western boundary of the subtropical anticyclones. This peculiarity earned rapid recognition and fame for these 'western boundary' currents. In the Northern Hemisphere, they are the Gulf Stream in the Atlantic and the Kuroshio in the Pacific, in the Southern Hemisphere, the Brazil Current in the Atlantic and the Agulhas Current in the Indian Ocean and, finally, in the Pacific, the East Australian Current. There is one absentee from this list: the North Indian Ocean, subjected, as we have mentioned, to a particular monsoon regime, whose dynamics are not associated with an established anticyclonic circulation.

Vorticity conservation

Obviously, oceans obey the physical laws of conservation: of mass and energy, but also of momentum, which is less intuitive since it entails mass, velocity and direction of motion. For example, let us imagine that two cars collide at a crossing. Before the shock, it is possible to represent each vehicle by a vector; the length of the vector is the product of the vehicle's mass and its velocity. The two vectors make an angle of 90° to each other. After the shock, each vehicle will bounce back, obviously with its original mass, but with a modified velocity and direction: it will be represented by a new vector with a length and direction that will have changed. However, one thing remains unchanged, the sum of the two vectors, which must remain the same before and after the shock. Let us now imagine clumsy tennis players on two adjacent courts. It may happen that the two balls collide. If the balls have topspin, they spin at different velocity and, in this case, not only the linear momentum of the balls is conserved, as in the case of the cars, but also the momentum corresponding to their rotation: it is said that there is conservation of the angular momentum before and after the shock. This conservation of the angular momentum has significant consequences in oceanography, because any element on Earth's surface is subjected to a rotation that varies with latitude owing to the fact that Earth rotates. This rotation is called 'planetary vorticity'.

Planetary vorticity

On the Earth's surface, we have the impression of living on a plane: the tangent plane to the Earth's surface where we are standing. In this plane, a movement around the vertical at this point results from the rotation of the Earth, and the rotational velocity depends on the latitude. Let us imagine that we are at the North Pole, with an ice cap over the Arctic region, for which there is no need to use one's imagination. There, the vertical and the rotational axis of the Earth become one; therefore, on our plane, we move at the Earth's speed of rotation, that is, $\Omega = 360^\circ$ in twenty-four hours. Let us now go down to the Equator; our plane is now tangent to the Equator and the vertical is perpendicular to the rotational axis of the Earth. Here, as everywhere, we turn around the rotational axis of the Earth in twenty-four hours, but we do not feel any rotational movement around the vertical. Mathematically, it may be said that our rotational velocity is zero or that it would take an infinitely long time to complete one revolution. This rotation around the vertical, brought about by the rotation of the Earth, and which varies according to the latitude, is called planetary vorticity: its velocity is maximal at the Pole and zero at the Equator. It varies as sine φ, where φ is the latitude (in degrees). Planetary vorticity is called f and $f = 2\ \Omega$ sine φ.

It is possible to 'see' this planetary vorticity by means of Foucault's experiment. In 1851, to demonstrate experimentally the rotation of the Earth, Léon Foucault attached to a wire 67 m long, suspended from the dome of the Pantheon, in Paris, a pendulum weighing 28 kg, which he set in motion from side to side. Everyone could observe that the plane of oscillation of the pendulum, to which a stylet was attached to record its trajectory directly on a bed of sand, completed a clockwise revolution in thirty-two hours. This experiment can also be seen today, though with a smaller pendulum, at the Conservatoire National des Arts et Métiers, in Paris and it is reproduced in many science and technology museums around the world. The rotation of the Earth was thus demonstrated, as well as the reality of planetary vorticity. It is the axis of the pendulum at rest that represents the vertical, and the rotation of the plane of oscillation around the vertical that provides proof of the rotation of the Earth. At the Poles, the plane of rotation of the pendulum makes a complete revolution in twenty-four hours, while on the Equator it takes an infinitely long time.

Relative or local vorticity

Imagine that Foucault, happy with the result of his experiment, began to dance, turning around the pendulum – which perhaps he did. He would have thus created under the dome of the Pantheon a local whirl (core ring), which will be called local vorticity. The conservation of angular momentum means that in relation to a fixed landmark (the origin of the coordinates at the centre of the Earth and the three axes directed towards faraway motionless stars), the sum of local vorticity and planetary vorticity, all things being equal, must remain constant if by any chance the whole 'system' moved on the Earth's surface. The term vorticity is more commonly employed, which does not obligatorily imply a circular movement. When we are in a car and we approach a bend, it creates a local vorticity; of course, we pay attention so as not to miss the bend and we could not care less about the planetary vorticity; nonetheless, vorticity conservation is still applicable in this case. In a car, the bend represents a change of direction: in the Northern Hemisphere, a bend towards the right is anticyclonic while a bend towards the left is cyclonic, and vorticity, a tendency towards rotation, represents the velocity at which the change of direction takes place. In a system of horizontal coordinates where velocity is broken down into two components, on the x-axis and on the y-axis, vorticity is represented by a magnitude: the curl. It conveys the velocity of the directional changes by comparing the velocity change of the two components of velocity: curl equals velocity change of component x minus velocity change of component y. We can see that the greater the difference (positively or negatively), the tighter the bend and the greater the local vorticity. Relative vorticity is represented by $\zeta = \delta u/\delta x - \delta v/\delta y$. This also applies to ocean currents.

Vorticity conservation: the western boundary currents

Vorticity conservation implies an equation: $f + \zeta$ = constant. Strictly speaking, the constant is the quantity $(f + \zeta)/h$ where h is the depth conserved; this does not, however, changed the ensuing reasoning. Planetary vorticity f is linked to the rotation of the Earth and is determined by the latitude: it is completely independent of the currents. What, on the contrary, can make relative vorticity vary? Firstly, the wind, which is subject to the same law of vorticity conservation and has its own local vortex ring. In the case of anticyclonic circulations, a rise in the anticyclonic circulation of the wind corresponds to a rise in the intensity of the vortex in the subtropical currents. Then there is the friction between a current and the neighbouring mass of water at the bottom or at the edge of the basin, which slows down the currents and always diminishes the absolute value of the vortex. Friction always creates a vorticity opposite to the direction of the current. A crucial point for ocean dynamics is that the frictional effect becomes greater as the velocity of the current increases.

In the anticyclonic circulation of the Azores, the wind tends to increase the intensity of the anticyclonic vortex of the water. This, of course, cannot continue forever and, at equilibrium in a stationary regime, a mechanism is required to stabilize oceanic vorticity. By virtue of vorticity conservation, this tendency towards an increase in local vorticity under the action of the wind has to be compensated by an equivalent decrease in planetary vorticity and thus by an average water displacement towards the Equator (a decrease in the Coriolis force and, therefore, in the planetary vorticity). We are in a stationary regime, so this water movement towards the Equator must, in turn, be compensated by an equivalent movement northwards. In 1948, Henry Stommel demonstrated that this return necessarily takes place on the western boundary, taking into consideration the dissipation of energy transferred to the currents by the wind and the frictional effect. In the present case of anticyclonic circulation, the frictional effect is necessarily cyclonic. On the western boundary of the basin, the current is directed towards the north: planetary vorticity, which is always anticyclonic, increases and joins the local core-ring, which is also anticyclonic. For the requirements of vorticity conservation, friction opposing the current introduces, by way of compensation, a cyclonic effect. On the eastern side of the basin, the current proceeds southwards: the planetary effect decreases and naturally counterbalances the tendency towards an increase in relative vorticity under the action of the wind. The current being weak, friction, which is proportional to its velocity, thus plays a marginal role. However, on the western side, friction, which is the sole force acting to compensate the accumulated joint effects of local vorticity and planetary vorticity, must be, on the contrary, very strong and the current necessarily of great intensity.

The reasoning developed by Stommel to explain the Gulf Stream in the North Atlantic also applies in the same way to anticyclonic circulations in other ocean basins. It is thus possible to explain this characteristic of all the oceans: the intensification of currents on the western boundary of the oceanic anticyclonic circulations and the observed westward displacement of the centres of the oceanic anticyclonic gyres relative to those of the atmospheric anticyclones, which remain much more symmetrical. The reasoning developed here for anticyclonic circulations also applies, but in the opposite sense, to cyclonic and subpolar circulations. Currents such as the Oyashio and the Labrador, on the western side of the cyclonic subpolar circulations associated with atmospheric low-pressure areas, are accelerated in the same way as the Kuroshio and the Gulf Stream. Therefore, the Gulf Stream is not, despite the myth, a unique phenomenon in the ocean: the Kuroshio, the Agulhas, Brazil and East Australian Currents are of the same type.

These currents are of the same type but are not identical. In the Olympic Games of the Currents, the Gulf Stream stands out and outstrips its fellows by the magnitude of its rate of flow. However, it deserves a silver medal, the gold medal incontestably going to the Antarctic Circumpolar Current, which, driven by the westerly winds – like the Roaring Forties – ciculates without constraint and unobstructed around our planet.

Current flow rate is measured in one million cubic metres per second, or sverdrup (Sv), from the name of the famous oceanographer Harald Sverdrup. No river attains such a flow rate: the Amazon, the biggest of them all, reaches 300,000 m^3/s at its maximum. The total flow rate of all the rivers on our planet is around 1 Sv, while the Gulf Stream already attains thirty times this value at the entrance to the Straits of Florida. The average flow rate of the Antarctic Circumpolar Current is about 140 Sv. The Gulf Stream almost achieves the same value towards the end of its course, near the Grand Banks off Newfoundland. Thus, it may be said that the Gulf Stream can only match the Antarctic Circumpolar Current in the home straight. The Agulhas Current is not far behind, with a maximum flow rate varying between 90 Sv – 135 Sv. The Kuroshio and the Brazil Current follow with 60 Sv – 70 Sv. Finally, the East Australian Current is the poor relative, with an average flow rate of only 15 Sv.

This pre-eminence of the Gulf Stream is due to three things. First, the Atlantic Ocean on its western boundary is completely bordered by the American continent. The separation between the Atlantic and the Pacific is waterproof: the waters brought to the west by the equatorial currents have no escape route and are forced to flow northwards or southwards. The boundary between the Pacific and Indian Oceans is, on the contrary, porous, and part of the waters from the Equatorial Currents flows into the Indian Ocean through the many straits in the Indonesian archipelago, from New Guinea to Borneo and to the Philippines. This is particularly true for the Southern Equatorial Current and it is much the same for the East Australian Current, which is reduced to a minimum flow. Moreover, the Atlantic Ocean is not symmetrical with respect to the Equator – more precisely, the meteorological Equator, also called the thermal Equator, does not coincide with the geographic Equator. The meteorological Equator is the convergence zone for the Trade Winds at the ITCZ that separates the subtropical anticyclones of the Azores in the North Atlantic from that of Saint Helena in the Southern Hemisphere. The Equator's position oscillates, depending on the seasons, but it is always situated in the Northern Hemisphere between

10°N in summer and 5°N in winter. It is the zone where the Equatorial Counter-Current flows from west to east, separating the North and the South Equatorial Currents. This north—south dissymmetry means that the South Equatorial Current straddles the Equator and stretches from 8°S to almost 5°N (Figure 4).

Of course, arriving at the eastern extremity of the South American coast, the flow splits into two parts. The southern part feeds the Brazil Current, a western boundary current of the South Atlantic anticyclonic circulation. The northern part joins the North Equatorial Current reinforcing the Gulf Stream, which thus benefits from two sources: one that can be qualified as legitimate and the other diverted from the South Atlantic anticyclonic circulation. Considerably larger than the Atlantic Ocean, the Pacific Ocean is less asymmetrical, particularly in the west: the northward flow of the South Equatorial Current is all the more negligible since, as we have seen, its northern part hardly encounters any obstacles in pursuing its course towards the Indian Ocean through the Indonesian straits.

Last but not least, the Gulf Stream is reinforced by thermohaline circulation – for which it is partly responsible. We could say that it is a return on investment. However, we will investigate this point later in this book. In short, the Gulf Stream transports warm and above all saline waters northwards via the North Atlantic Current and the Norway Current, which are its extensions, reaching the seas of Norway and Greenland, where they are cooled down in the winter and, due also to their high salinity, they will become denser than the underlying water. They therefore sink (a process known as convection), and feed the thermohaline circulation and the oceanic 'conveyor belt'. Thus, a water demand is created, which will increase the Gulf Stream flow accordingly. This is called the Atlantic Overturning Circulation. We shall see that this phenomenon has no equivalent in the Pacific Ocean.

ANATOMY OF THE GULF STREAM

'There is a river in the ocean. In the severest droughts, it never fails, and in the mightiest floods, it never overflows. Its banks and its bottoms are of cold water, while its currents are warm. The Gulf of Mexico is its fountain and its mouth is in the Arctic Seas. It is the Gulf Stream. There is in the world no other such majestic flow of waters. Its current is more rapid than the Mississippi or the Amazon.'

More than describing it, M. F. Maury reverently celebrated the Gulf Stream in his famous work *The Physical Geography of the Sea.* The success of this publication and its religious tone reflect at the origin of the Gulf Stream's mythologization. The predominant myths were that the Gulf Stream was the *deus ex machina* of the European climate at the time and now for the entire planet. The new myth is that its weakening could plunge the Northern Hemisphere into a new ice age, in spite of the proven global warming of our planet.

Maury's vision was supported by the explanation given by Jacques Arago. At the beginning of the nineteenth century, the debate was heated between those who considered marine currents were due to the driving force of the wind and those who, like Arago, thought that light and aerial winds could not drive such a mass of water. Many agreed to make the water accumulated in the Gulf of Mexico the starting point of the Gulf Stream. Some believed that its origin was to be found in the water discharge of the Mississippi River in the Gulf of Mexico. James Rennell was the first to make the distinction between the Gulf Stream, as such, and the North Atlantic Drift, explaining the latter by the action of the prevailing westerly winds. It was a correct idea, which was, for a while, swept aside by Maury's enthusiasm for a Gulf Stream as a continuous river flowing from the Caribbean to the Arctic, and which preferred Arago's partially correct thermohaline approach. Arago had a rather simple and Cartesian argument: why look for another explanation for oceanic circulation than the one applied to the atmosphere? It was admitted that atmospheric circulation was the result of the thermal adjustment between a warm region (the Equator) and a cold region (the Poles). It is also the same for the ocean: cold and dense waters sink in the polar region, flow towards the Equator, where they rise to the surface; there, the Gulf Stream completes its circuit by returning water towards the Arctic. Arago had thus described the mechanism of the thermohaline circulation, essential for climate. However, his concern for simplicity and clarity meant that he overlooked the importance of the 'mechanical' coupling between the ocean and the atmosphere, as well as wind as the driving force for the currents – by taking only thermodynamical exchange into account. He thus emphasized only the fluid dynamics internal to each of the fluids, based on the same processes of density variation (thermal variations for the atmosphere and thermohaline variations for the ocean). We should pay tribute to Rennell, who understood that such Manichaeistic thinking was not appropriate in any attempt to explain ocean currents. As we said, Arago was wrong: the driving force behind the Gulf Stream is the wind action in the subtropical anticyclonic circulation. Even if it reinforces the Gulf Stream, the thermohaline circulation is not its cause, but rather its consequence.

Therefore, here we have the Gulf Stream, a western boundary current of the North Atlantic anticyclonic circulation, with few characteristics distinguishing it from its fellow currents to explain its exceptional mythologization and media coverage, which nowadays reach an audience well beyond its historical connections to the Euro-American world.

Where does the Gulf Stream begin?

With just the description of the western boundary currents involved in the subtropical anticyclonic oceanic circulations, it is not an easy task to determine their beginning and end because they are all part of a continuum. The Gulf Stream is an exception due to the morphology of the continents, which reduce the Caribbean Sea and the Gulf of Mexico to a *cul-de-sac* into which pour a part of the North Equatorial Current and the Guyana Current, forming an extension to the north of the South Equatorial Current. An exit cannot be found, except to the north, in the direction of the anticyclonic circulation; the only possible way out is the strait separating Florida and Cuba. This overflow – let us forget the Mississippi – marks the origin of the Gulf Stream. In Florida, the sea level is higher on the Gulf of Mexico side than on the Atlantic side by about 70 cm: enough to supply the considerable flow measured in the Strait – 30 Sv, on average being fed by the North Equatorial Current and the South Equatorial Current besides the water diverted from the South. The Gulf Stream, therefore, benefits from particular initial conditions that are not found in the other currents.

Where does the Gulf Stream end?

The question is dificult to determine and has been the subject of great controversy. Besides, it is not merely scientific, as a response to this question comes up against the force of a well-entrenched myth, which we owe to Maury and the public's acceptance of the myths surrounding this phenomena as sacred. Thus, the myth dictates that the Gulf Stream conveys heat from the Gulf of Mexico to the Arctic. Hence, to be understood, particularly by the media, scientists are compelled to compromise and call the Gulf Stream what is really not the Gulf Stream. For example, in response to a question often asked by journalists: 'What would happen if the Gulf Stream stopped?' a scientist would hardly be able to give a lesson on the necessary distinction between the Gulf Stream *sensu stricto* and its extensions – the North Atlantic Current and the Norway Current – which in the mind of both the journalist and the public are the same, when in fact the question actually focuses on the extensions. The Norway Current undoubtedly disappeared during glacial periods without necessarily entailing the disappearance of the Gulf Stream itself, which is an element of the North Atlantic anticyclonic circulation. However, a scientist will be practically compelled to answer by using the name Gulf Stream, which would be convenient for the journalist. Thus, the Gulf Stream myth endures.

Among the topical issues concerning the climate, there is another one competing with the Gulf Stream: El Niño, which, with such a name, was obviously destined for a great future. El Niño – the Infant Jesus – was the name initially given by Peruvian fishers to a warm current that appears along their coasts around Christmas bringing to them tropical species that improve their fish-dependent existence.

To get back to the question 'Where does the Gulf Stream end?' let us return to the causes previously analysed and the resulting definition: the Gulf Stream is the western boundary current of the North Atlantic anticyclonic circulation. Its dynamic feature is due, on the one hand, to its proximity to the coast (frictional force) and, on the other hand, to the increase in planetary vorticity, both of them disappearing when the current, following the anticyclonic movement, flows away from the continental slope and turns eastwards, which is the direction in which planetary vorticity does not vary. Therefore, we can say that, in terms of dynamics, the Gulf Stream ends its course at around 40°N and 50°W. Obviously, this does not mean that the current stops and that the velocity falls to zero at this point. There is continuity of flow, and the warm and saline waters transported by the dynamic Gulf Stream pursue their course: northwards to the North Atlantic Current and the Norway Current (as we will see later when examining the role played by the Gulf Stream in climate dynamics) and southwards to the anticyclonic circulation through the Azores Current.

The Gulf Stream flow

The Gulf Stream at its origin in the Straits of Florida remains close against the continental slope up to Cape Hatteras (North Carolina) where, following the anticyclonic circulation, it moves away from the coast and towards the open sea, creating, on its left flank, a space between its boundary on the port side and the American continental slope, called the 'Slope Sea'. Some call the Florida Current the area between the Straits of Florida and Cape Hatteras, reserving the name of Gulf Stream to the current beyond Cape Hatteras. Qualitatively, there are reasons behind this difference and the satellite images of surface temperature (Figure 9) are convincing: the Florida Current looks like a kind of jet, whereas beyond Cape Hatteras the current appears much more turbulent and swirling. This difference is due more to the morphology of the continent than to the dynamics of the current. The Florida Current is channeled by the continental slope; however, moving towards the open sea beyond Cape Hatteras, the current no longer has this physical constraint and instabilities can develop without restraint. In the Straits of Florida, the Gulf Stream flow rate is around 30 Sv, at Cape Hatteras it rises to 80 Sv–90 Sv and, finally, it reaches its maximum, close to 140 Sv, before the Grand Banks of Newfoundland (Figure 10). After that, it declines until it becomes incorporated into the North Atlantic Current.

On the continental land mass, small streams can make great rivers; the Amazon from its source until its maximum flow is continually fed from both right and left by numerous rivers – draining an entire hydrological basin, then flowing into the Atlantic. In the ocean, it is hardly possible to talk about 'tributaries' as is done on land. The Gulf Stream certainly receives an input from the West Indies Current, a branch of the North Equatorial Current that remains on the eastern side of the West Indies Antilles, joining its flow to that of the Gulf Stream as it leaves the Straits of Florida. However, it is not sufficient to justify the threefold increase in flow rate at Cape Hatteras – nor the doubling beyond that point. Nevertheless, it is possible to talk about the Gulf Stream basin, as is done for the Amazonian basin: and this is called the recirculation of the Gulf Stream.

A source of energy: potential energy

This recirculation is shown, simplified, by two circulation circuits in Figure 11, one to the north in the cyclonic direction and the other to the south in the anticyclonic direction. In both cases, these circuits bring water, which will feed and reinforce the Gulf Stream upstream. This recirculation mobilizes an energy source that has not yet been mentioned: the potential energy related to gravity, or universal attraction. It is a well-known fact that under the effect of gravity, bodies fall and, by so doing, they liberate energy. A waterfall, for example, provides more electricity as the height of the fall is greater. In other words, the available or potential energy of water in a lake increases with its altitude. Water in the ocean, also subject to gravity, contains potential energy in the same way. In a stratified motionless ocean (where density increases with increasing depth), the lines of equal density (isopycnals) are almost horizontal: all the water particles of the same density are at the same depth and, therefore, have the same potential energy. However, the ocean is not motionless: driven by the wind, it generates currents. The result is that the isopycnals are not horizontal but sloping, and their slope is steeper as the associated force is stronger. This creates important differences of potential energy between the high and low points in the layers of equal density. The potential energy of the ocean is one hundred times greater than its kinetic energy. Let us suppose then, that we could stop the currents: the isopycnals under the force of gravity would return to their corresponding horizontal surface, leading to vast water displacements and liberating potential energy created by the currents, as in a hydroelectric dam. The potential energy thus accumulated in the ocean is about 10^6 joules/m^2. Therefore, if the winds stopped blowing it would take more than ten years for the ocean to become motionless. It is through the recuperation of part of this energy and its transformation into kinetic energy that eddies create the Gulf Stream recirculation cells.

General oceanic circulation – for example the anticyclonic gyre – is an average circulation, which does not reflect the 'everyday' reality of the currents composing it. Currents are unstable and form meanders and eddies at a scale of hundreds of kilometres. We can say that the average circulation represents the ocean's 'climate', while the meanders and eddies represent the ocean's 'weather', as the fronts and depressions or cyclones do for the atmosphere. The contrasting viscosities of the ocean and the atmosphere also make the dimensions and the lifespans of these phenomena different in the two fluids: at hundreds of kilometres and several months for the ocean, and at thousands of kilometres and a few days for the atmosphere. In both cases, these 'disturbances' result from instabilities in regions of strong velocity variation in a horizontal or a vertical direction.

Eddies as agents of energy transfer

A stratified motionless ocean is stable; it means that a disturbance is spontaneously reabsorbed without affecting the state of the system, which returns to its initial state. On the contrary, we talk of instability when, once started, the disturbance intensifies spontaneously. It is movement that creates instability in the ocean. At geostrophic equilibrium, which represents the average state of oceanic circulation, the current intensity between two points is proportional to the hydrostatic pressure difference between these two points – thus as the isopycnal slope is greater the current is faster, and vice-versa. In the Gulf Stream, the world speed champion (2 m/s in the Florida Current), the isopycnal of value 27 (the unit is not relevant) goes from a depth of 800 m (high pressure) in the south to one of only 200 m (low pressure) 100 km farther north – which is significant in the ocean (Figure 12).

We intuitively see, the further the ocean moves away from the stable state (horizontal isopycnals), the greater the risk of instability. When the slope is very steep, small displacements easily bring less-dense water into more-dense water, and vice-versa. Instead of being reduced, the movement is going to increase because, being in a denser environment, light water will necessarily tend to rise, while, conversely, heavy water in a less dense environment can only sink. A tendency of the isopycnal slope to decrease and the recovery of potential energy to maintain motion will follow. Eddies originate from these instabilities, drawing their energy from the ocean's stock of potential energy. We can say that they recover potential energy and transform it into kinetic energy. Contrary to what one might think *a priori*, eddies associated with the Gulf Stream, as seen in Figures 34 and 36, do not correspond to dissipation of current energy through friction. On the contrary, far from drawing their energy from it, eddies will give energy back freely, via the Gulf Stream recirculation that they feed. The instability at the origin of the eddies is initiated by the Gulf Stream's meanders, which will end up pinching themselves off (Figure 13). The eddy is warm and anticyclonic when it is formed on the north side of the main current. Conversely, it is cold and cyclonic when it is formed on the south side. Generally speaking, eddies associated with the Gulf Stream are called warm- and cold-core rings.

Eddies can be found in all the oceans and their energy is ten times greater than the energy in the average currents of the general oceanic circulation, like the North Atlantic anticyclonic circulation. They are very active agents in the transfer of momentum and heat in the oceans. Associated with current instability, they are particularly developed in zones with strong velocity gradients, as found in western boundary currents, such as the Gulf Stream, the Kuroshio or the Agulhas Current. Eddies were discovered relatively recently in oceanography. The existence of such phenomena was suspected for quite a long time: suggested by the drift of ships and the observation of the trajectories of drifting objects. However, traditional oceanographic campaigns with only one vessel could not identify these small, mobile and ephemeral structures. It was necessary to wait until the 1970s when the Mid-Ocean Dynamics Experiment (MODE) and POLYMODE experiments were conducted between 1972 and 1977. They provided an exceptional concentration of means (six ships, moorings, floats) in a limited area of the Sargasso Sea to simultaneously evaluate the impact of these eddies on energy transfer. The experiment also demonstrated the challenge of sampling eddies using classical methods. The elucidation of eddies would have been practically impossible without the space revolution of the 1980s, which provided almost synoptic access to the entire ocean. Thus, it is now possible, with altimetric satellites, to categorize and monitor the evolution of eddies associated with the western boundary currents (Figure 14).

Eddies must be taken into account in simulation models of ocean dynamics, if we wish them to be realistic. This calls for the development of models with very high spatial resolution (less than a dozen kilometers), which demand a very high processing power. The development of these models has long been hindered by the challenges of both adequate spatial resolution and computational power.

The Gulf Stream recirculation

The warm anticyclonic eddies (warm-core rings) to the north and the cold cyclonic eddies (cold-core rings) to the south move southeastwards, the former via the 'Slope Sea', which separates the Gulf Stream from the continental slope, and the latter via the Sargasso Sea. They all rejoin the main course of the Gulf Stream to which they provide additional energy and flow, thus explaining the increase in the Gulf Stream's flow rate. It was with surprise that scientists discovered these eddies did not represent a loss of energy for the currents but a recovery of potential energy, and thus it has often been named 'negative' viscosity. Eddies do not structurally appear at the scales of general circulation, which is a 'climatic' average of the 'weather' represented by eddies. Their contribution is integrated into the general circulation.

The two recirculation circuits in Figure 11 represent the average circulation brought about by eddies on either side of the Gulf Stream. The northern circuit is trapped in the 'Slope Sea' where eddies have little space to evolve; their life span is relatively short – an average of a few months. On the other hand, there is much more space to the south, where eddies can last up to two years. The southern recirculation circuit creates a small anticyclonic gyre, a short circuit inside the big North Atlantic anticyclonic circuit. It is responsible for tightly enclosing the Sargasso Sea and giving this shoreless sea its peculiar ecological characteristics.

The Gulf Stream extensions

The Gulf Stream, at 50°W, loses its dynamic characteristics and its flow decreases. The water it carries does not come to a halt, and although it changes trains, it continues along the same route. This new train is called the North Atlantic Current. It constitutes both the northern boundary of the subtropical anticyclonic circulation previously described, and the southern boundary of the North Atlantic subpolar cyclonic gyre. The latter is associated with low atmospheric pressures more or less centred on Iceland, of which the Labrador Current (Figure 4) constitutes the corresponding western boundary of the Gulf Stream that it will come to meet, and does, at the level of the Grand Banks of Newfoundland. This current soon splits in two: the southern branch follows on the eastern side of the subtropical anticyclonic circulation to form the Azores Current and later the Canaries Current; the northern branch, still often called the North Atlantic Current and also designated as the North Atlantic Drift, flows northwards as far as the Norway Current under the double action of the wind and the thermohaline pump of the Arctic, which here plays an essential role.

The thermohaline pump

When describing or explaining the Gulf Stream, little attention has been given to the process favoured by Arago and Maury: the creation of a north–south oceanic cell initiated by the sinking of cold and dense water in the polar regions, 'pumping' warm equatorial water towards the north via the Gulf Stream, with a deep return current towards the Equator, where the water would close the circuit by rising to the surface. There is indeed no need for this mechanism to explain the anticyclonic surface circulation driven by the wind and the existence of the Gulf Stream on the western side. However, this thermohaline circuit does exist. It is even greater than what Arago probably thought, since it is to this thermohaline mechanism of dense water plunging below relatively light surface water that we owe oceanic circulation below the few hundred metres of surface water governed by wind action.

The water in the Gulf Stream is originally warm and saline. During its course northwards, its properties change due to mixing with neighbouring water and exchange with the atmosphere (evaporation, rainfall). On coming into contact with cold air of polar origin at the northern end of its course, the warm water of the Gulf Stream transfers to the atmosphere a considerable amount of energy through evaporation, up to 350 W/m^2. This is equivalent to the average amount sent from the Sun to the Earth, and earns the absolute record for transfer from the ocean to the atmosphere – the Kuroshio and the tropical regions being less effective. This strong evaporation cools down the ocean surface and increases its salinity and therefore its density. The balance on arrival in the Norway and Greenland Seas (which will be called GIN Seas, for Greenland, Iceland and Norway), beyond the sill between Greenland and Scotland via Iceland and the Faeroe Islands, is still very saline water – 35.2 PSU (Figure 23) – and relatively warm. There, the water is suddenly cooled, which further increases its density, already high due to its salinity. It is sufficient to make this water sink. In winter, the formation of ice (which consists only of fresh water) further increases the salinity and accelerates the phenomenon. Sinking water accumulates in the Norway basin, which periodically empties out across the sill between depths of 800 m and 600 m, on both sides of Iceland via the Denmark Strait to the west and the Faeroes Channel to the east. This is the North Atlantic Deep Water (NADW), which flows in the Atlantic between the depths of 2,000 m and 3,500 m and is characterized by its maximum salinity.

The GIN Seas are not the only regions of NADW formation. Such regions are also found in the Labrador Sea, between Greenland and Labrador and in the Baffin Basin. The process here is different: it is not salinity that ensures relatively high density, but cold wind, which, blowing over the water, cools it and homogenizes it by convection down to depths as great as 2,500 m. The deepest layers of the mass of water thus formed mix with the deep water coming from the GIN Seas. The appearance of this deep water of the Labrador Sea is therefore independent of the transport of saline water northwards by the

Gulf Stream and its extensions. It is related to the variations in the subpolar cyclonic gyre. As for the Gulf Stream, but in the opposite direction, the southward flow of the NADW will be accelerated on the western boundary of the ocean. There is, therefore, below the Gulf Stream, a Deep Western Boundary Current of around 15 Sv flowing southwards, which continues its course farther southwards below the Brazil Current. It is the current anticipated by Stommel and first revealed by J. C. Swallow and L. V. Worthington in 1957. These are the 15 Sv, which, added to the Gulf Stream at the surface, provide a quantitative advantage over the Kuroshio. The peri-antarctic circulation afterwards distributes this deep water in the Indian and Pacific Oceans. Thanks to the dissipation of tidal energy, water rises progressively to the surface and returns either: by a warm route via the Indonesian Straits, the Agulhas Current, around southern Africa via the Benguela Current, the South Equatorial Current and the Gulf Stream and its extensions, to return to the starting point in the Norway Sea, before leaving again for another tour; or by a cold route directly from the Pacific to the Atlantic through the Drake Passage. It is the outline of the conveyor belt proposed by Broecker in 1991 (Figure 15).

The reality is, of course, much more complex, but it remains an outline that well illustrates the functioning of the thermohaline pump, which plays such an important role in the climate system. The NADW movement is very slow: although it may reach 10 cm/s in the 'deep undercurrent of the western boundary' of the Atlantic; elsewhere, its velocity is in the range of millimetres per second. Therefore, it takes on average almost 1,500 years to complete a full cycle. This outline of the thermohaline circulation is an extension of Arago's for the North Atlantic to that of the global ocean.

3 The Gulf Stream and Earth's climate

The climate system

The climate system is an engine to convert and distribute energy received by the Earth from the Sun. The atmosphere and the ocean are its dynamic agents: they ensure the transfer of heat from the tropics towards the high latitudes. The ocean, which has a much greater heat capacity than the atmosphere and a longer 'memory', controls the climate. Thus, at timescales of several decades and centuries, the entire oceanic circulation has to be taken into account in climatic processes.

The Gulf Stream and the Western European climate

The Gulf Stream and its extensions transport heat towards the high latitudes of the Atlantic and play a vital role in our planet's climate, particularly in the high latitudes of the Northern Hemisphere, which would be much colder without their contribution. Nevertheless, the mild winters of Western Europe are not the direct result of the warm water transported by the Gulf Stream, which would warm up Europe like a central-heating system. Western Europe, like the Pacific coast of North America, simply benefits from a marine climate.

The Gulf Stream and the North Atlantic Oscillation (NAO)

On a decennial timescale, the North Atlantic has climatic variations related to atmospheric pressure differences between the anticyclone of the Azores and the low-pressure area over Iceland: this is the North Atlantic Oscillation (NAO). The position and movement, more or less north of the Gulf Stream, evolve according to the NAO. It is a sign of a possible coupling between the ocean and the atmosphere at these timescales, which also involves deep-water formation and Arctic ice dynamics.

The Gulf Stream and the thermohaline circulation

The thermohaline circulation is the result of transport, by the Gulf Stream and its extensions, of highly saline water to the Greenland Sea where, cooling down, it sinks to its depth of hydrostatic equilibrium at around 3,500 m depth. There it begins a long journey, finally rising to the surface to return to its starting point. This is the famous conveyor belt; its smooth functioning ensures heat transport to the high latitudes of the North Atlantic. During the glacial periods, the conveyor belt slowed down and even stopped altogether. In spite of that, the Gulf Stream did not stop: the subtropical gyre of the Azores remains stable and thus so does the Gulf Stream. Its northward extension is simply limited. The Gulf Stream is a necessary, but not sufficient, condition for the thermohaline circulation: if the latter stops, the Gulf Stream flow would decrease but it would continue its southward flow.

The future of the thermohaline circulation

According to certain climate scenarios, global warming due to increasing greenhouse gas concentrations in the atmosphere could result in the slowing down or a rapid halt in the thermohaline circulation and a significant cooling of the temperate regions in the Northern Hemisphere. This is not the most likely scenario, but it is not an impossible one, if we consider the uncertainties and possible threshold effects. As we lack a sufficiently long historical data record, it is impossible at this stage to say whether the observed deep-circulation variations are a consequence of global change. Should this be the case, the Gulf Stream will not come to a standstill, just as it did not during the glacial periods.

THE CLIMATE SYSTEM

The climate system behaves like an engine for the Earth by converting and distributing energy it receives from the Sun. The Sun is not an absolutely constant source of energy. Its 22-year cycle brings, every 11 years, a period of maximum intensity, as observed during the International Geophysical Year in 1957–1958. It may also have relatively weak bouts, as in the seventeenth century (the Maunder Cycle), when the solar cycle seemed to dwindle to its minimum radiation level. The parameters of the Earth's orbit around the Sun vary. In addition, energy received from the Sun and its distribution over Earth fluctuates at timescales of 10,000 to 100,000 years; this explains the sequence of glacial and interglacial periods. The part of solar energy absorbed by the continents and subsequently returned to the atmosphere depends on the properties of the land surface and the vegetation. The cryosphere (ice-caps of Greenland and the Antarctic, and the pack-ice) reflects back into space a certain proportion of the incoming energy, which is therefore lost to the climate system, which depends on the state of the ice and the area covered by ice. Finally, oceanic and atmospheric movements change according to all these variations in the planetary energy balance. Therefore, all these elements of the climate system evolve, each at their own very different pace. Any variation or disturbance in any one of them has repercussions on the others – at each elements respective pace of reaction. The climate system is seeking an equilibrium that it can never attain. It varies constantly at every timescale. The essential thing for human beings is for the climate to be sufficiently stable, and remain within an acceptable range of variation and speed of change. This may be jeopardized in the near future by the increase of greenhouse gases in the atmosphere due to human activities.

The dynamic agents of the climate: the atmosphere and the ocean

The atmosphere and the ocean are the two fluids of the planetary heat engine. They are interactive dynamic agents that ensure energy transfer and distribution. Permanently in contact with each other, they do not stop exchanging energy and are indissociable.

The atmosphere has a very short memory and a very low heat capacity. It has a very short reaction time when subjected to a disturbance; it dissipates the energy it receives quickly and evolves rapidly. This creates challenges for weather forecasting. Nowadays, specialized services make forecasts up to seven days in advance. In spite of progress in atmospheric modeling, it seems unlikely that weather forecasts beyond fifteen days ahead will be possible.

Weather forecasting, in practice, starts from a given state of the atmosphere and, with the application of models based on the laws of physics governing atmosphere dynamics, calculates what is likely to occur one, three or seven days later. It is almost certain that there is a limit to this forecasting capability; that is, beyond a given time, the state of the atmosphere will be completely independent of its initial state. Regardless of the quality of the models and the observations, it is very difficult to forecast the weather. As the limit is probably fifteen days it may therefore seem paradoxical to talk about climate forecasting at a timescale of seasons and years. Climate forecasts are statistical; they do not tell us what the weather will be at a given date and place, but the probability of this or that kind of weather, as shown by the average values of climatic parameters: temperature, rainfall, insolation, wind and so on.

The ocean has a greater heat capacity than the atmosphere: the heat-storage capacity of the first three metres of the ocean equals that of the entire atmosphere; and thus as mentioned the ocean is a tremendous reservoir of solar energy. It also has a much longer memory than that of the atmosphere, and its characteristic time variations are on an altogether different scale from those of the atmosphere. The ocean plays a double role: it supplies a fraction of its energy to the atmosphere and, through the currents, it directly distributes the other fraction at a planetary scale. Both the atmosphere and the ocean transport heat from the equatorial regions to the Poles. At a given place, the amount of energy exchanged with the atmosphere depends on the temperature of the ocean surface water – which in turn depends on the amount of heat previously transported there by the ocean.

The part of the ocean to be considered in climate processes depends on the chosen timescale. If we care about weather forecasting less than two weeks in advance, the models only need to have available the surface temperature of the ocean to determine the energy exchange between the ocean and the atmosphere. During this forecasting period, the evolution of ocean surface temperatures is too small to have a significant impact on this exchange; it would be useless to complicate the models by introducing ocean dynamics. Weather-prediction models are essentially atmospheric models. On the other hand, at climatic scales, it is necessary to consider these dynamics: as it is the slower partner, the ocean that imposes its rhythm on climatic variation. For year-to-year changes (for example, El Niño), it is the first hundred metres of the Equatorial Ocean that are the most important. Beyond that, it is necessary to consider the entire oceanic circulation from the surface to the ocean floor – which has a cycle spanning several centuries.

The ocean remembers the 'signature' of past climatic events for hundreds of years. To a certain extent, present-day climate depends on the cooling down of the Earth during the short glacial period between the sixteenth and the nineteenth centuries. If the ocean moderates climatic variations, it expresses their effects only decades or even centuries later. Climate forecasting models, whatever the timescale considered, must couple the oceanic and the atmospheric dynamics. They must also take into account the other components of the system: continental surfaces and, particularly, ice and the pack-ice – which reflect significant amounts of solar energy. A decrease in the extent of the pack-ice, which would increase the absorption of solar energy by the ocean, is a factor increasing and accelerating global warming.

The Gulf Stream is an important actor in the Earth's climate system. It has been put forward in a mythical way to explain the relative mildness of the Western European climate – an idea contested by today's scientists. Now, as we are confronted with the eventual consequences of the increase in the greenhouse effect, the Gulf Stream is being made a kind of conductor, no less mythical, of possible climate change. To fully understand the role the Gulf Stream plays, we have to refer to the timescale appropriate to the phenomena. Firstly, the short timescale relevant to the relationship between the Gulf Stream and the European climate. Then the multi-decennial variations in the North Atlantic, in relation to the North Atlantic Oscillation

(NAO) and, finally, the long timescale corresponding to the variations in the thermohaline circulation, as well as past and future climatic fluctuations in relation to global change.

To be consistent with the preceding chapters, and avoid any ambiguity, the term 'Gulf Stream' refers to the western boundary current of the North Atlantic subtropical anticyclonic circulation, and the term 'extensions' refers to the North Atlantic and the Norway Currents.

THE GULF STREAM AND THE WESTERN EUROPEAN CLIMATE

The chart of annual average values of temperature anomalies relative to their average value at the same latitude (Figure 16) shows a strong positive anomaly of 10°C over Western Europe, from the north of France to the whole of Scandinavia. This anomaly is accentuated in winter and Maury puts forward a bold theory in *The Physical Geography of the Sea and its Meteorology* for the difference between Western Europe's winter temperatures and those on the east coast of North America at the same latitudes:

'Modern ingenuity has invented a beautiful method of warming houses in winter using hot water. The furnace and the boiler are sometimes placed at a distance from the rooms to be warmed, as is done in our Observatory. In this case, pipes are used to conduct the heated water from the boiler-room some thirty metres from the Director's dwelling […] Now, returning from this miniature system to the oceanic reality, we have, in the warm water, confined in the Gulf of Mexico, just such a 'boiler' for Great Britain, the North Atlantic and Western Europe. The furnace is the thermal-maximum zone; the Gulf of Mexico and the Caribbean Sea constitute the 'boiler'; the Gulf Stream is the conducting pipe. From the Grand Bank of Newfoundland to the shores of Europe is the hot-air room, in which the pipes are flared so as to present a large cooling surface. Here the atmospheric circulation is organized by nature: it is from west to east; consequently, it is such that the warmth thus conveyed into this mid-ocean hot-air room is carried by the beneficial westerly winds and distributed throughout Great Britain and Western Europe. Every west wind blowing towards Europe crosses the Stream on its way to Europe, where it tempers the sharpness of the northern winds during winter. It is the influence of this current that gives Ireland the name 'Emerald of the Seas", and that clothes the shores of Albion in

evergreen robes, while, at the same latitude, on the opposite side, the coast of Labrador is fettered by its belt of ice. In a valuable paper on currents, Mr. Redfield states that, in 1831, the harbour of St. John's, Newfoundland, was closed by ice as late as the month of June; yet whoever heard of the port of Liverpool, on the other side, though 2° farther north, being closed by ice, even in the depth of winter?

Maury was not the inventor of the idea of a Gulf Stream central-heating system; Saby and Humboldt had already suggested it, but Maury was able to express it with force and lyricism, which practically speaking made the idea dogma. Pupils at school in Brittany, in the westernmost part of France, learn that, thanks to the Gulf Stream, they live under the mildest possible climate. In the seaside resorts of the northern coast of Brittany, on the Channel coast, there are several 'Gulf Stream' Hotels, probably named so to convince holidaymakers that the seawater, which rarely exceeds a maximum of 17°C in summer, is tropical. In Iceland they thank the Gulf Stream for its generosity, as they believe it is responsible for the abundance of cod in their seas. These generally accepted ideas were called into question in 2002 in a scientific publication with a deliberately provoking title: *Is the Gulf Stream Responsible for Europe's Mild Winters?* To this question, the authors reply with a resounding 'no'. What does this mean, exactly?

The mild winters on the eastern side of the oceans

The French youngsters from Brittany also learn the difference between cold continental climates in winter and marine climates, which experience milder winters. They know that Western Europe, being subject to a westerly wind regime laden with oceanic moisture, benefits from a marine climate. At the same latitude on the other side of the Atlantic, in winter, with a continental climate, the Saint Laurence River freezes over and Newfoundland is covered with snow and remains cold for several months of the year. It goes without saying that there is no need for the Gulf Stream to explain this difference. For example, in the Pacific, at the same latitude as Newfoundland and Brest, no one is surprised that it is clearly less cold in winter in Vancouver (Canada) than on Sakhalin Island, off eastern Siberia, and that the Okhotsk Sea is closed by ice in winter, while 10° further north, the Gulf of Alaska is ice-free throughout the year. The same causes sometimes produce the same effects and the answer is simple: the west coast of North America, thanks to the Pacific Ocean, benefits from a marine climate, while Siberia, on the other side, suffers a continental climate. Have we ever heard the Canadians of Nanaimo thank the Kuroshio for its benevolence? If so, it has remained very confidential. Unfortunately, the Indian Ocean is out of the race to support the argument, since the Asian continent blocks its northward extent.

We can therefore say that the east coasts of the Atlantic and the North Pacific both benefit from a marine influence, ensuring them a temperate marine climate. We may add that this situation is also due to the configuration of the oceans and continents, as well as to the rotation of the Earth. Due to this rotation and the Coriolis force, the atmosphere cannot transport heat from the tropics to the Poles in a straight line. Instead, it becomes organized into vast gyres, of which one of the elements has been described in detail: the subtropical oceanic anticyclones, which are at the origin of the Gulf Stream and its fellow currents. To the north of the anticyclones, there are, in the North Atlantic and the Pacific, subpolar low-pressure centres around which the wind and the associated oceanic circulation turn anti-clockwise: the low pressures of Iceland in the Atlantic and the Aleutians in the Pacific. The Labrador and the Oyashio, which flow southwards, are the western boundary currents of these circulations. At middle latitudes between the high pressures of the south and the low pressures of the north, a regime of westerly winds develops which, going around the Pacific and Atlantic Oceans, brings mildness and humidity to the coasts of Europe and North America. On the contrary, on the western side of the Atlantic, the northwesterly winds of the Icelandic low-pressure zone bring a polar cold to the American coast. This also applies to the coasts of Asia, on the western side of the Pacific.

The atmospheric properties – temperature, rainfall and wind – enable the climate to be defined. The energy balance of the atmosphere makes it possible to undertake a quantitative analysis of climatic differences on Earth. This is what R. Seager and his collaborators did on the North Atlantic, in their attempt to demythify the Gulf Stream's role in the climate of Western Europe. They examined the three processes that influence the winter east–west dissymmetry of the North Atlantic climate: heat transport by the ocean, heat transport by the atmosphere and the processes of storage and release of the heat received locally from the Sun. The latter certainly deserves an explanation. At the latitudes considered, the seasonal variations in solar energy received by the ocean are considerable. In summer, when the Sun is high in the sky, the energy received is at its maximum: the surface layers of the ocean warm up, and a seasonal thermocline is established, which also plays an important role in biological processes (see below). The ocean thus stocks thermal (heat) energy. In winter, the energy received by the Earth is lower, the westerly winds become stronger, the thermocline is destroyed and the ocean transfers to the atmosphere some or all the energy it stored during the summer. What Seager et al. showed is that, in winter, the energy released and recuperated by the atmosphere along the path of the westerly winds over the ocean is enough to explain the temperature differences observed between the two sides of the Atlantic and that there is hardly any need to look for an additional source of energy – for example, heat transport by the currents and, therefore, the Gulf Stream or its extensions. In other words, the climatic east–west dissymmetry in winter can be explained almost exclusively by the local solar energy input during the summer. Except in the north of Norway, where high sea-surface temperature in the Norway Current prevents ice from forming.

Is this sufficient to discount the effect of heat transfer by the oceans on climate in Western Europe? Obviously not, but we have to acknowledge that Western Europe no longer benefits from a kind of exclusivity ensuring direct transfer, via the Gulf Stream and its extensions, of warm water from the Gulf of Mexico to Norway. All the higher latitudes benefit from the heat transport from south to north by the Gulf Stream and its extensions. Without it, the climate would be considerably colder on both sides of the Atlantic.

In a complex and interactive system, such as the climate system, it is practically impossible to isolate one of the components in order to analyse step-by-step, in a deterministic and linear way, the effect of its variations on one or another region of the world. The expression 'all things being otherwise equal' does not apply here, except for elements external to the system. We can, for example, 'all things being otherwise equal', wonder about the consequences of a change in the amount of solar energy reaching Earth, but it would be futile to question, in the same terms, the direct impact of a slowing-down of the Gulf Stream on the climate in Great Britain. At the beginning of the nineteenth century Saby had hoped to do just this, by measuring the variations in the Gulf Stream flow from its starting point at the tip of Florida. It is not possible to test this kind of theory in a simple way because, if heat transport by the Gulf Stream changed, things would not be 'otherwise equal', if only because there is a close coupling between the ocean and the atmosphere, and it is not possible to change with impunity the circulation of one without modifying the other. The only way to carry out climate experiments is to use numerical simulation models: we put all the components of the climate system, their interactions, the physical laws or the empirical relations governing them into 'equations' that cannot be solved analytically but only 'numerically', that is to say, by successive iterations. Starting from a known initial state, we apply the model, which will tell us how the climate will evolve under particular constraints. Simulation models are like experimental laboratories for climatologists, who can thus test the hypothesis and propose various development scenarios. With such models, it is therefore possible to test the hypothesis of a decrease in the northward heat transport by the Gulf Stream and discover that the impact will not be limited to the temperature in Great Britain or Norway, but will also concern the entire climate in the North Atlantic on both the east and the west of the Atlantic. This is achieved even without being able to follow step-by-step, phenomenon-by-phenomenon, the determinist causal chain leading to this result. Paradoxically, we can say that the better the simulation, the closer it is to reality and the less we understand the details of the mechanisms responsible for the phenomena. Following Maury's line of thought and at the risk of reviving the myth, we can say that the Gulf Stream, through complex interactions between the ocean and the atmosphere, on one hand, and the anticyclonic subtropical circulation of the Azores or the subpolar cyclonic circulation of Iceland, on the other hand, has an effect on both the climate in Great Britain and in Labrador.

To conclude, heat transport northwards by the Gulf Stream is not unrelated to the climate in Great Britain. It is warmer

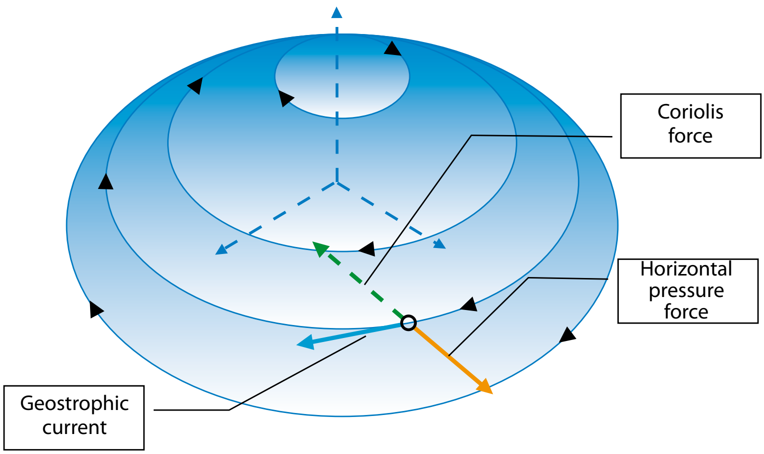


Figure 3.
Geostrophic equilibrium around a sea level (high pressure) maximum. The pressure force (*red*) moves from the centre towards the periphery. The Coriolis force (*green dashes*) is equal and opposite. The current (*blue*) is tangent to the clockwise sea-height contour line, so that the Coriolis force is perpendicular to it and towards the right in the Northern Hemisphere.
CLS–Satellite Oceanography Division

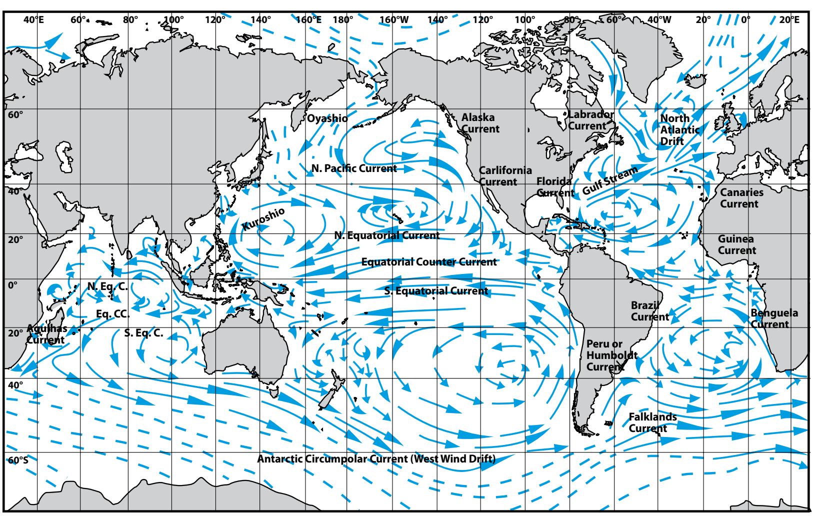


Figure 4.
The general ocean surface circulation.
***Ocean circulation*. The Open University, Pergamon Press, 1989**

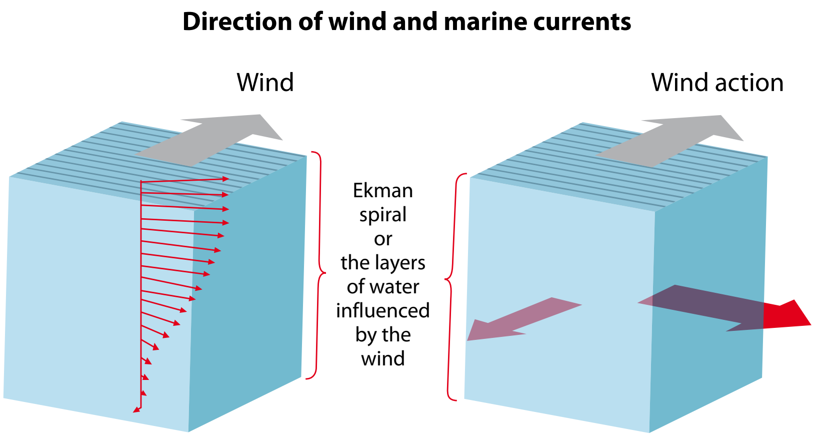


Figure 5.
The Ekman spiral. The wind drives the surface layer towards the right. This, in turn, entrains the underlying layer towards the right and so on, in a descending spiral, with the current speed diminishing with depth. Finally, the equilibrium between the driving force of the wind and the Coriolis force results in an overall transport at 90° to the right in the Northern Hemisphere.

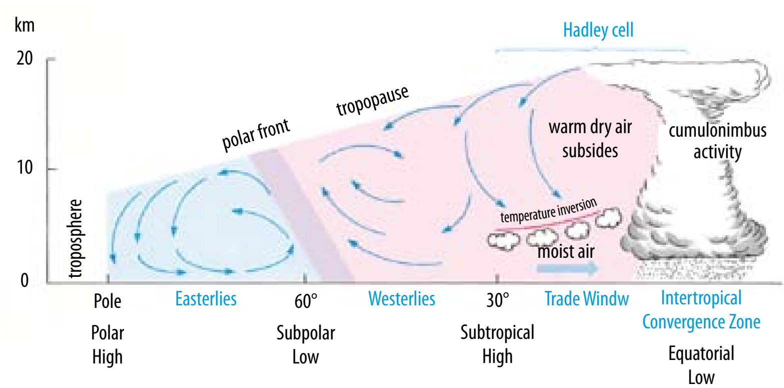


Figure 6.
Hadley Cell. Profile of the atmosphere from the Equator to the Pole. In the intertropical convergence zone of the Trade Winds, the air ascends (creating low pressure) and later descends around 30°N (creating high pressure: an anticyclone). At ground level, on the southern side of the anticyclonic gyre, the easterly Trade Winds blow over the sea surface, and, on the northern side, the westerly winds prevail.
Ocean circulation. The Open University, Pergamon Press, 1989

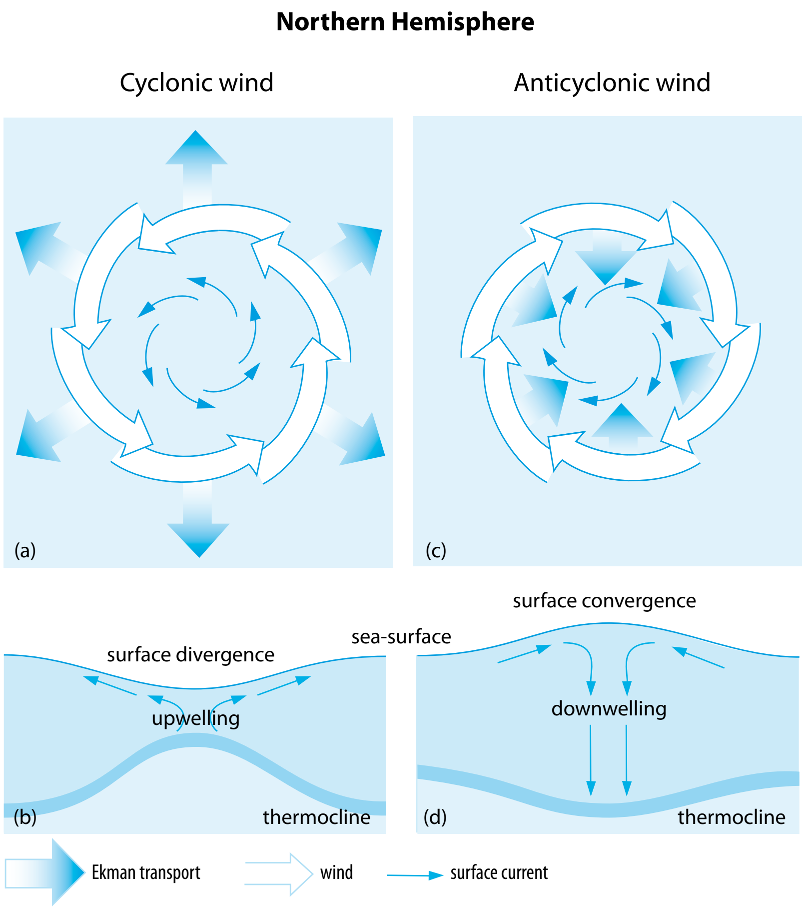


Figure 7.
The currents driven by the cyclonic wind to the left and by the anticyclonic winds to the right. In the anticyclone, the wind-driven Ekman transport drives water towards the centre of the gyre, creating an elevation of the sea surface and a convergence (deepening of the thermocline). The geostrophic current resulting from the pressure field thus created turns clockwise. It is the opposite in cyclonic conditions.
Ocean circulation. The Open University, Pergamon Press, 1989

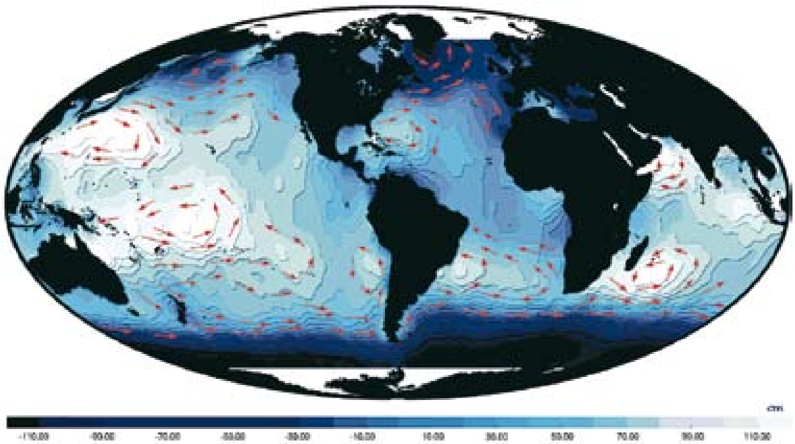


Figure 8.
Topography of the ocean surface derived from satellite altimetric measurements (TOPEX/Poseidon). This chart represents the 'anomalies' of the sea level compared to what it would be in the absence of the current. The positive anomalies increase in value from *medium blue* to *white;* the negative anomalies from *medium blue* to *dark blue*. In the North Atlantic, the subtropical anticyclonic circulation is visible, and, in the north, the cyclonic circulation associated with the Icelandic depression.
CLS–Satellite Oceanography Division

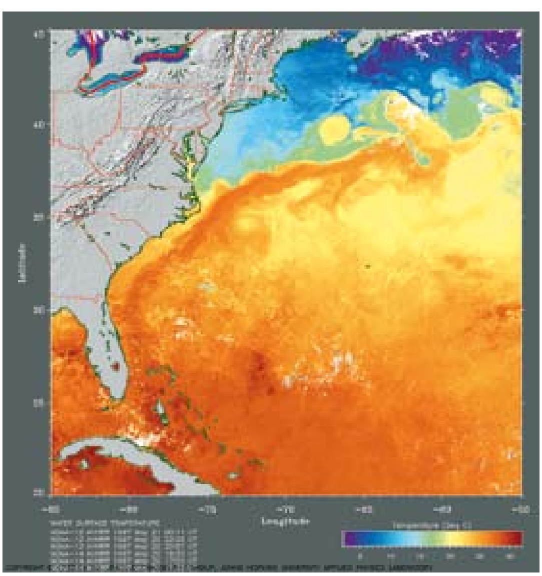


Figure 9.
The sea-surface temperature of the western Atlantic obtained by satellite remote sensing on 21 May 1997. The Gulf Stream eddies are formed after the current flows away from the coast beyond Cape Hatteras, just above 35°N.
The Space Oceanography Group, Applied Physics Laboratory, Johns Hopkins University

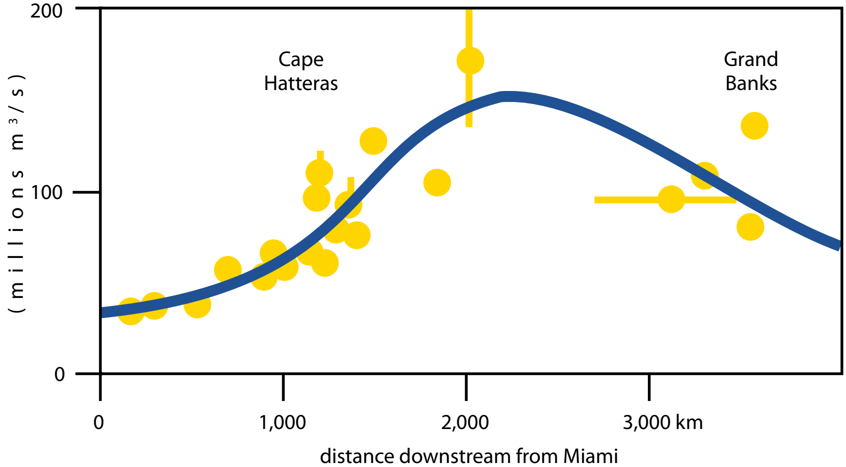


Figure 10.
Variation in the Gulf Stream flow, from Miami to the banks of Newfoundland.
***Regional oceanography: an introduction*, by M. Tomczak and J. S. Godfrey. Pergamon Press, 1994**

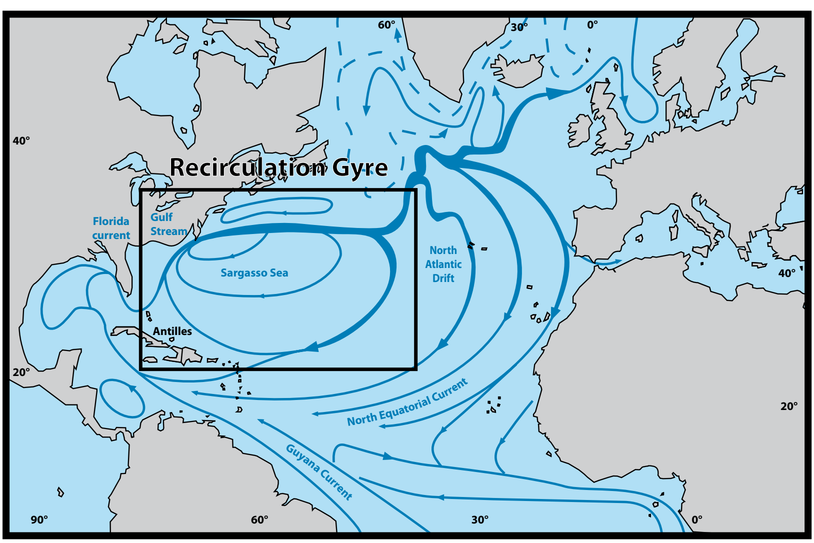


Figure 11.
The Gulf Stream recirculation. To the north, a cyclonic loop between the current and the continental slope; to the south, the anticyclonic loop bordering the Sargasso Sea.
***Ocean circulation*. The Open University, Pergamon Press, 1989**

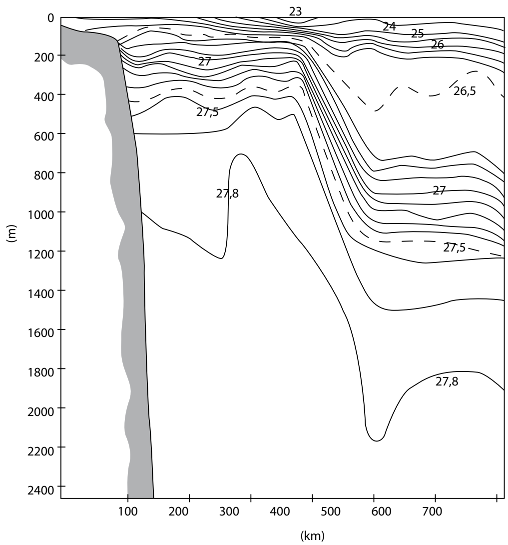


Figure 12.
A water-density profile of the Gulf Stream. The isopycnal 27 passes from a depth of 800 m in the Sargasso Sea to 200 m within a distance of only 100 km, by crossing the Gulf Stream. This is the dynamical result of the intensity of the Gulf Stream.

***Introduction to physical oceanography*, by J. Knauss. Prentice Hall, 1978**

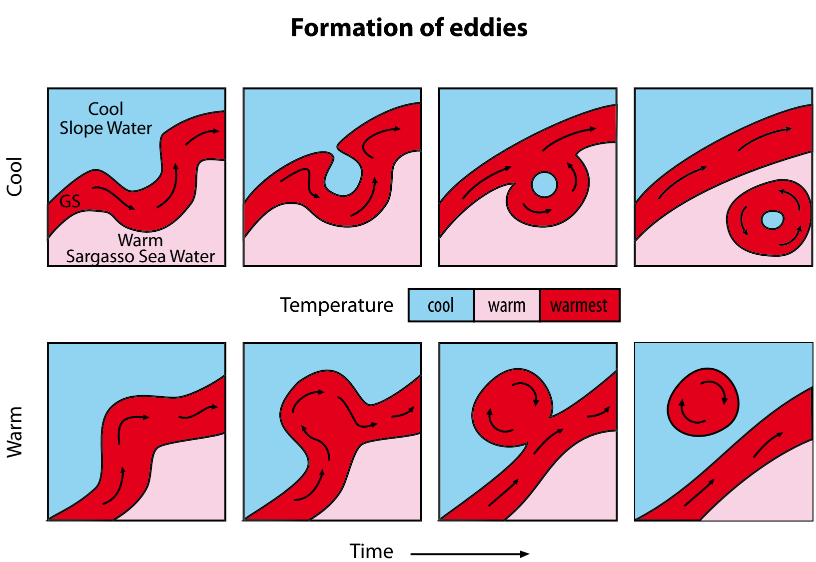


Figure 13.
Formation of eddies. Each meander starts as an instability that continues to increase until they pinch themselves off from the main flow. A meander towards the right creates a cold-water eddy to the south, in the warm water of the Sargasso Sea. A meander towards the left ends up as a warm-water eddy in the cold water of the 'Slope Sea'.

The Space Oceanography Group, Applied Physics Laboratory, Johns Hopkins University

Another view of the Gulf Stream: altimetry

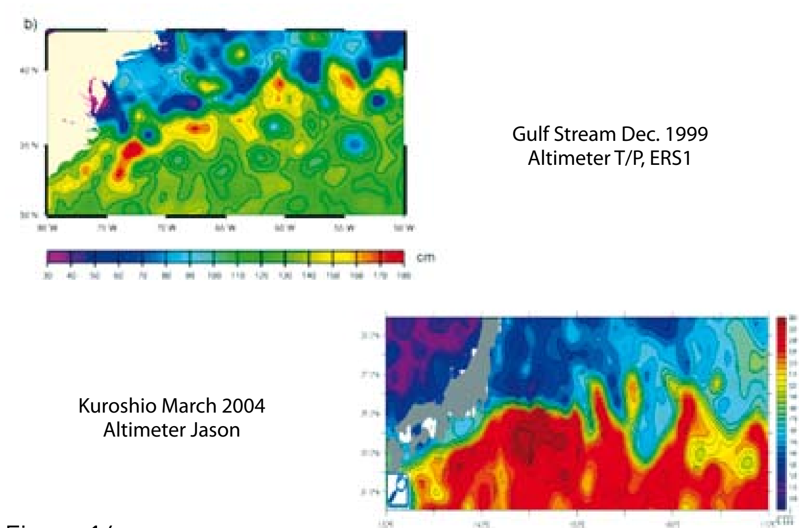


Figure 14.
Gulf Stream and Kuroshio eddies as seen by a satellite-borne altimeter.
CLS–Satellite Oceanography Division and Aviso

Thermohaline circulation of the Atlantic

Adapted by Maier-Reimer after Broeker

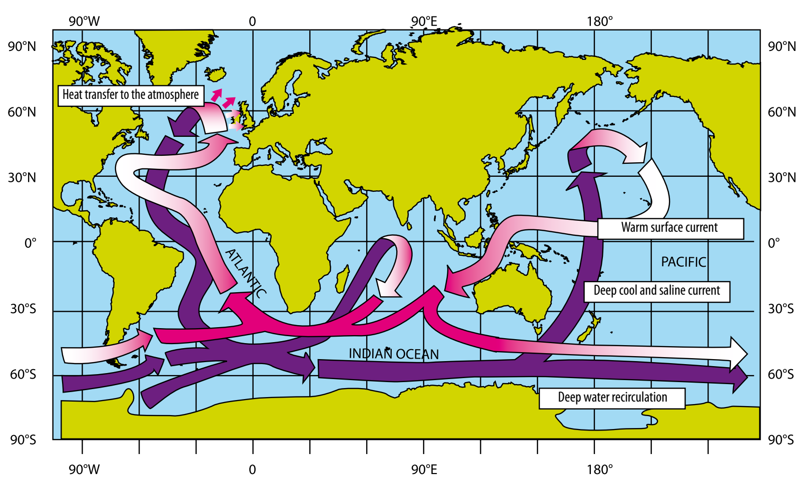


Figure 15.
The 'conveyor belt' of the thermohaline circulation. In *blue*, the deep circulation. In *pink* and *mauve*, the return at the surface via the cold route through the Drake Passage, between South America and the Antarctic; and the warm route from the North Pacific through the Indonesian Straits.

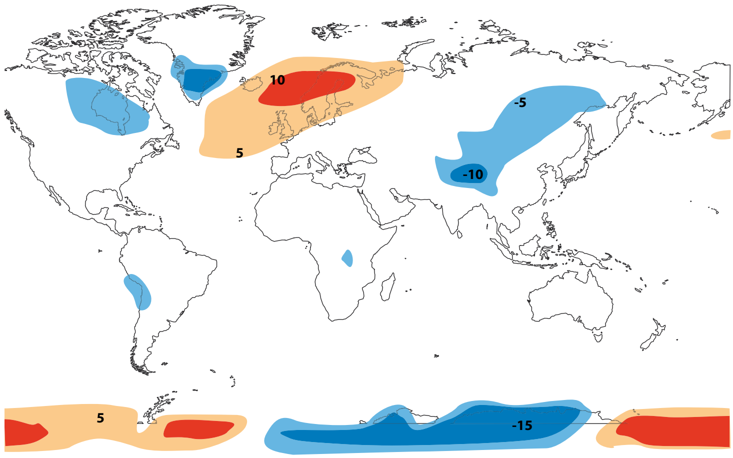


Figure 16.
Air-temperature anomalies, by latitudinal bands: the anomalies are relative to the average temperature at a given latitude.
***Ocean circulation and climate*, by Gerold Siedler, John Church, John Gould (editors), according to Rahmstorf and Ganoposki (1999), *International Geophysics Series*, Vol. 7.7 (2001)**

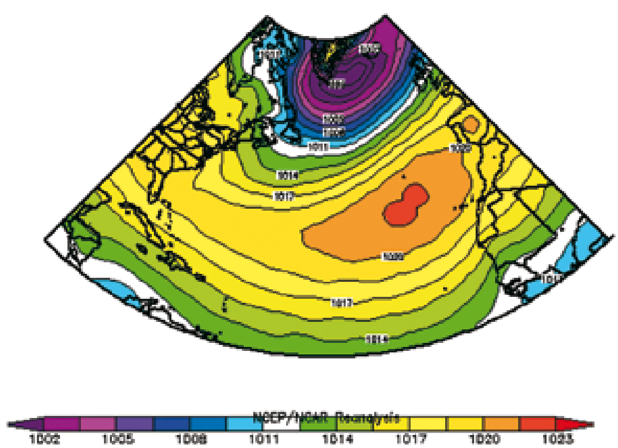


Figure 17.
The mean atmospheric pressure field in the North Atlantic in winter. The NAO Index shows the pressure differences between the high-pressure zone of the Azores anticyclone (in *red*) and the low-pressure zone of the Icelandic depression (in *violet*).
NOAA–Cires/Climate Diagnostic Center

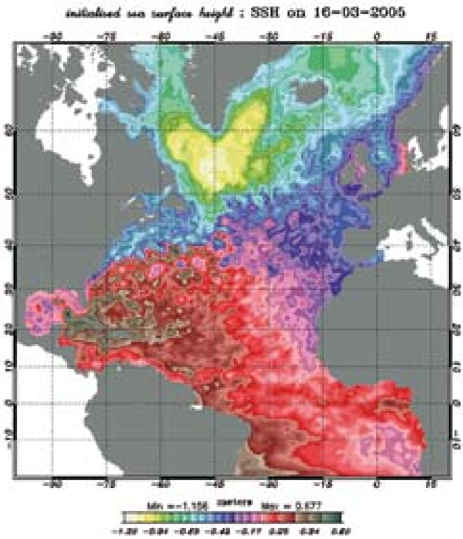


Figure 18.
Topography of the North Atlantic ocean surface. There is a level difference of nearly 1.8 m between the maximum in the anticyclonic circulation (in *brown*) near Bermuda and the minimum in the cyclonic circulation in the north (in *yellow*). This level difference can be used to estimate (by analogy with the NAO) the Gulf Stream flow, which circulates between the maximum and the minimum.
***Mercator Oceans*: www.mercator-ocean.fr**

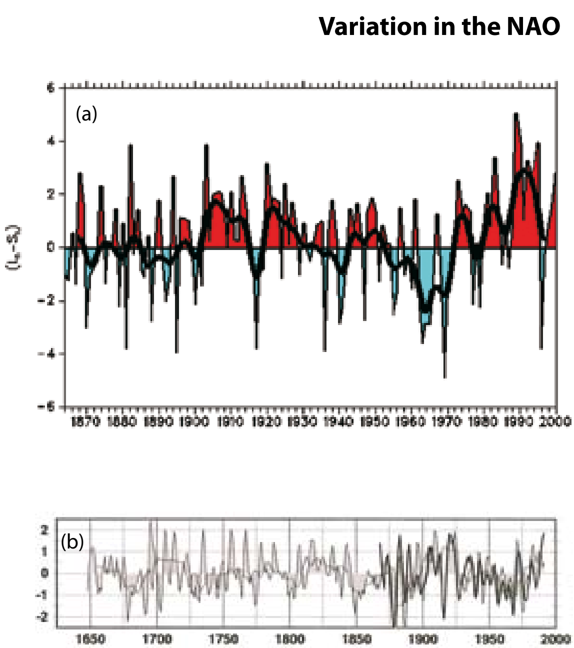
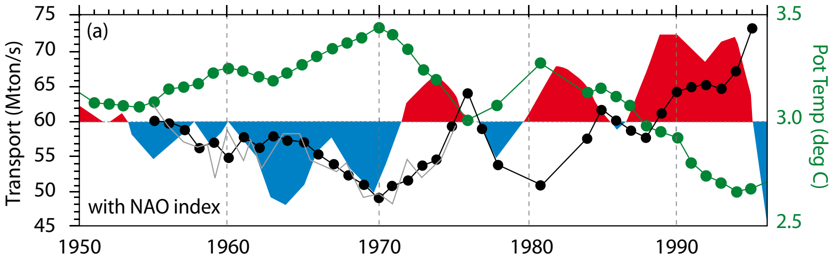


Figure 19.
Variation in the NAO: a. since 1860, from instrumental measurements;
b. since 1650, as reconstructed from ice cores in Greenland.
a: The North Atlantic Oscillation, by Hurrel et al. (2001), *Science*, Vol. 291, pp. 603–605;
b: North Atlantic Oscillation dynamics recorded in Greenland ice cores, by Appenzeller et al. (1998), *Science*, Vol. 282, pp. 446–448



Gulf Stream NW index (annual) and Winter NAO

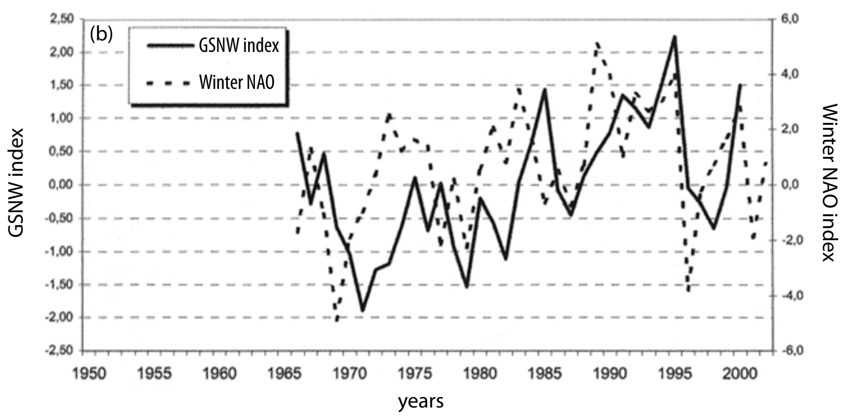


Figure 20.
a: Variation in: the NAO Index (low values in *blue* and high values in *red*); temperature in the Labrador Sea (*green line*); Gulf Stream transport (*black line*) derived from the difference in potential energy between Bermuda (high point) and the Labrador Sea (low point). Salinity in the Labrador Sea and the Gulf Stream transport are out of phase, but both parallel the variation in the NAO.
b: Comparison of the variations in the NAO and the Gulf Stream North Wall Indexes.
Ocean gyre circulation changes associated with the North Atlantic Oscillation, Curry and McCartney (2001), ***Journal of Physical Oceanography*****, Vol. 31, No. 12, pp. 3374–3400**

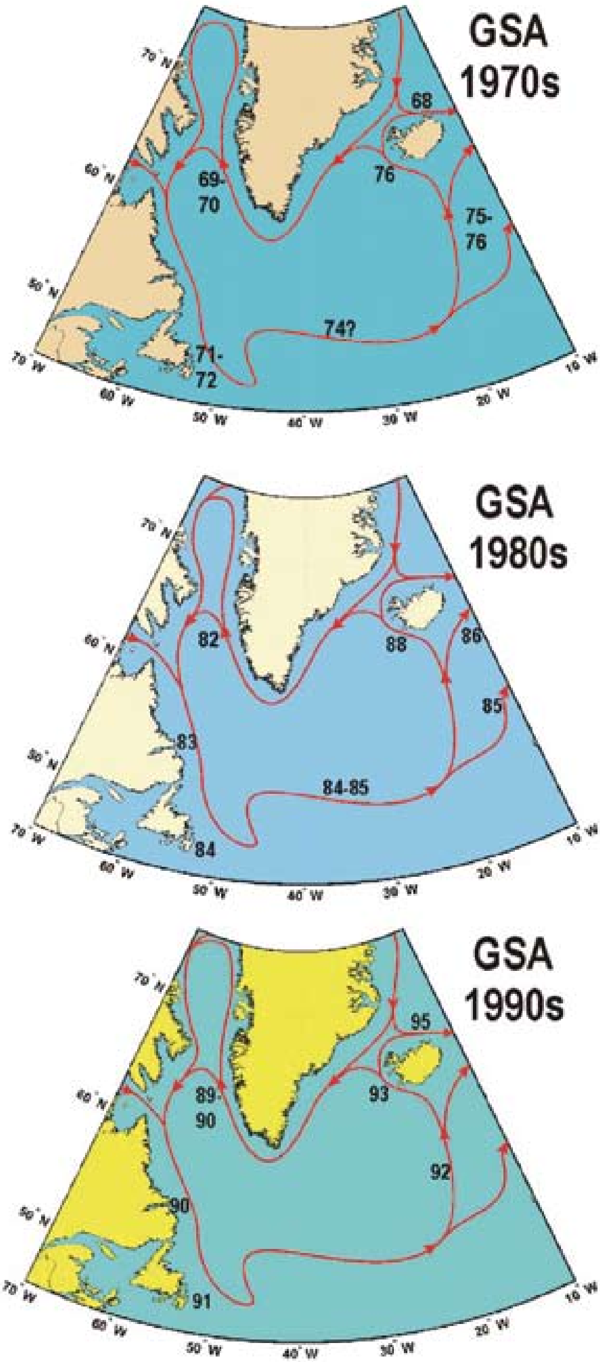


Figure 21.
The three great salinity anomalies (GSA).
Igor Belkin, personal communication

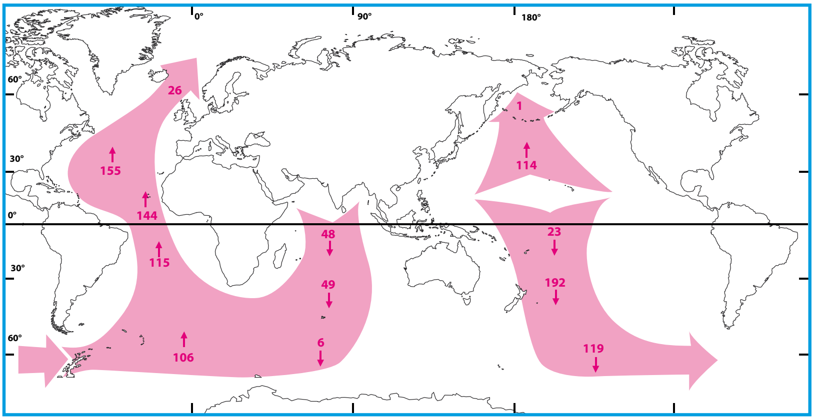


Figure 22.
The heat flux in the ocean. (10^{13} watts).
Ocean circulation. The Open University, Pergamon Press, 1989

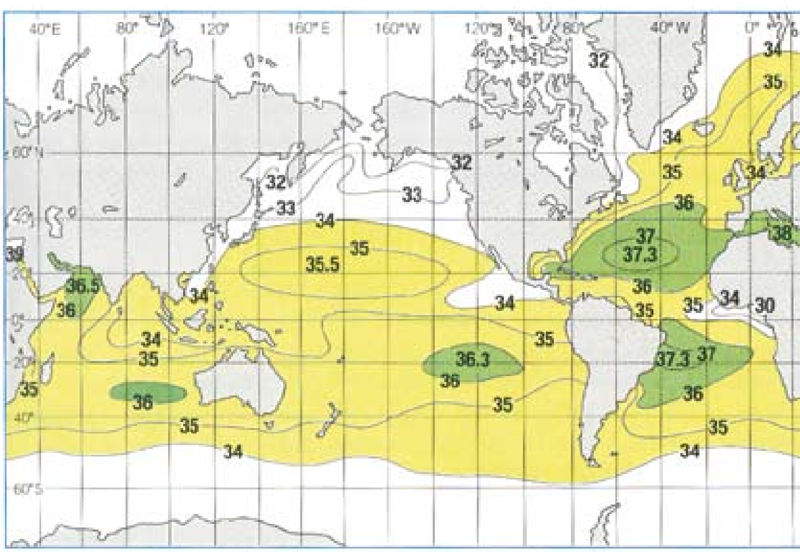


Figure 23.
Surface salinity of the ocean. The salinity values are much higher in the Atlantic than in the Pacific. The development of high salinity values in the North Atlantic via the Gulf Stream and its extensions is remarkable.
Ocean circulation. The Open University, Pergamon Press, 1989

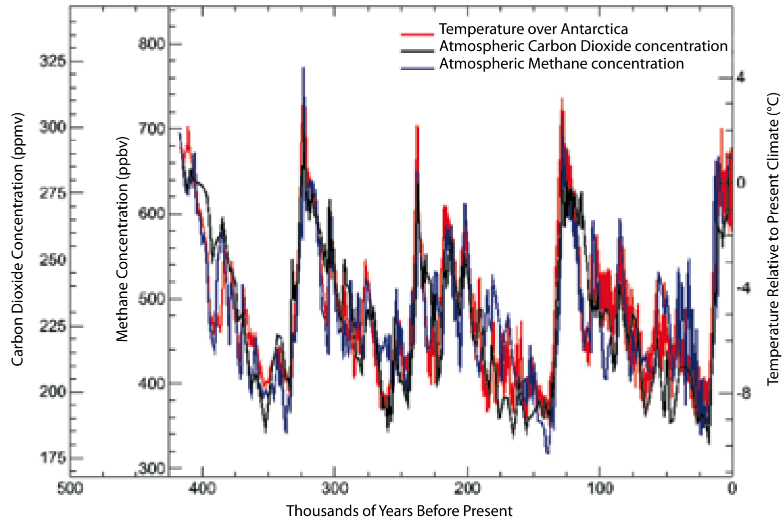


Figure 24.
Evolution of temperature and concentration of greenhouse gases (carbon dioxide, methane) in the atmosphere in the last four glacial/interglacial cycles.
Laboratoire de Glaciologie et Géophysique de l'Environnement, LGGE: www.lgge.uif-grenoble.fr

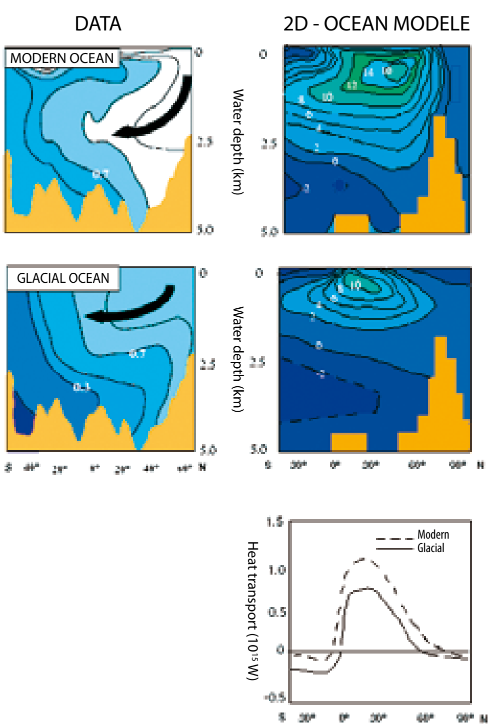


Figure 25.
On the *left*, C_{13} in a North–South section of the Atlantic. *Above*, the actual ocean based on ocean measurements. *Below*, the ocean at the height of the last glacial period, reconstructed from measurements of benthic Foraminifera. The deep layers of the actual ocean are richer in C_{13} and thus better ventilated (water recently formed at the surface) than the ocean during the last glacial period.
***Quand ocean se fâche*, by Jean-Claude Duplessy. Odile Jacob, 1996**

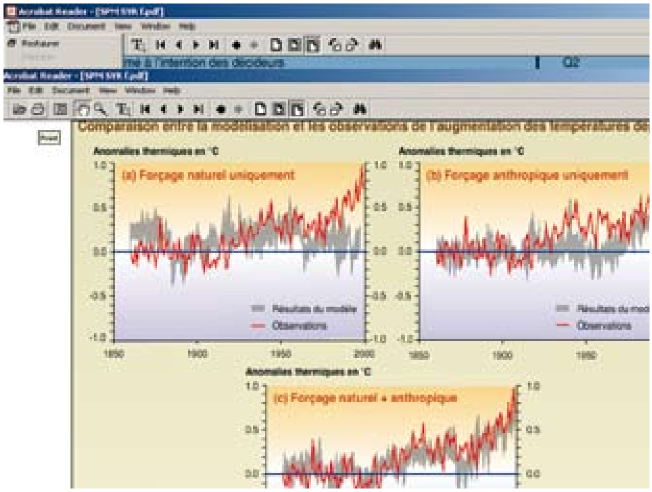


Figure 26.
Temperature changes since 1860. In *red*: observations; in *grey*: variation simulations based on models initialized from 1860. According to the data, the 'great salinity anomaly' (GSA) could be held responsible for the drop in temperature recorded between 1960 and 1970. The most accurate simulation of the variations observed takes into account both natural and anthropic forcing.
***Climate change: the scientific basis.* Third Assessment Report of IPCC, Cambridge University Press, 2001**

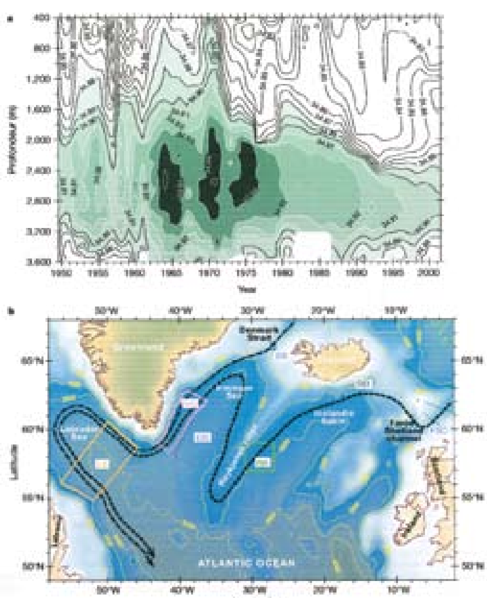


Figure 27.
Below, the course of the North Atlantic Deep Water from the sills between Greenland and Scotland (Denmark Strait and the Faeroe Islands Channel) to the Labrador Sea. *Above*, the salinity change in the Labrador Sea; the maximum salinity between 1960 and 1980, in the North Atlantic Deep Water, and a decline since 1980, are notable. The salinity maximum corresponds to a low NAO Index.
Rapid freshening of the deep North Atlantic Ocean over the past four decades, by Bob Dickson et al. (2002), *Nature*, Vol. 416

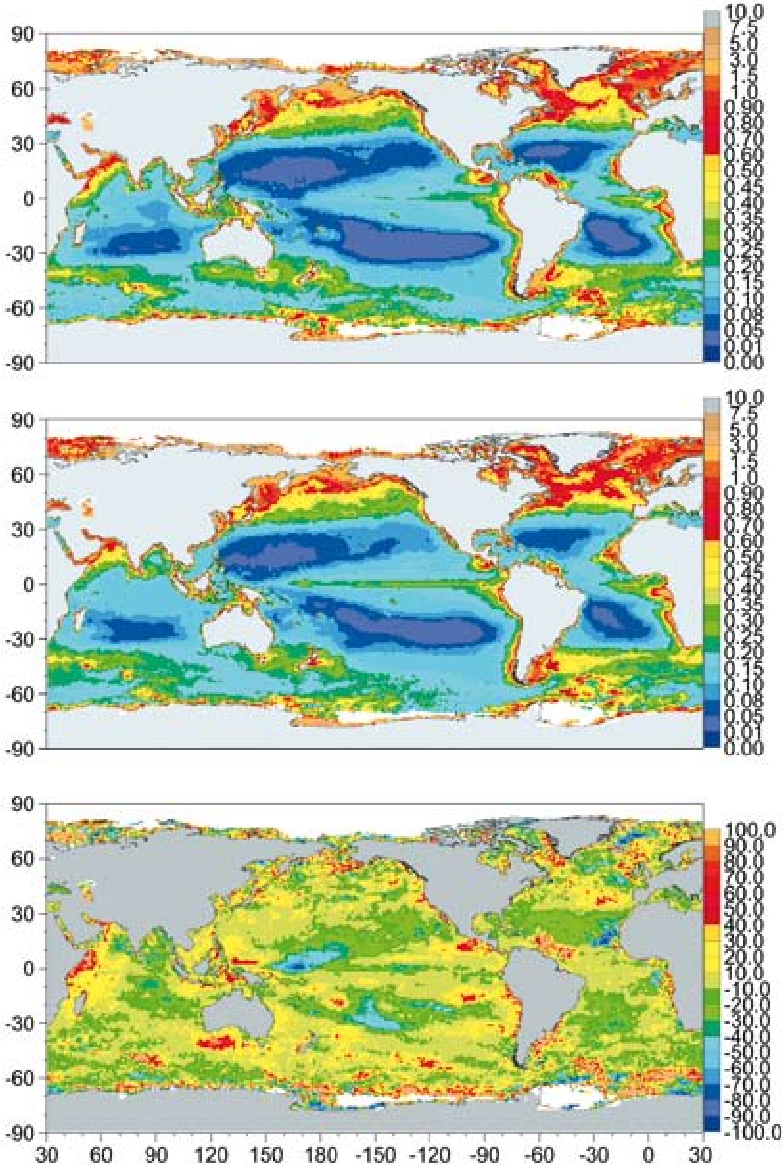


Figure 28.
Ocean chlorophyll, as seen with the SeaWiFS satellite. *Above*, the situation in 2003; in the *middle*, in 1998; and *below*, the difference between the two. Values change from *blue* to *red* via *green* and *yellow*. Chlorophyll concentration has increased in the coastal zone, while tending to decrease in the open ocean, particularly in the anticyclonic regions.
Watson Gregg and NASA

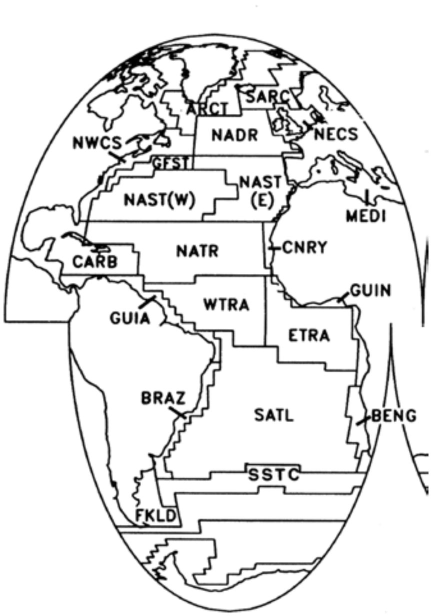
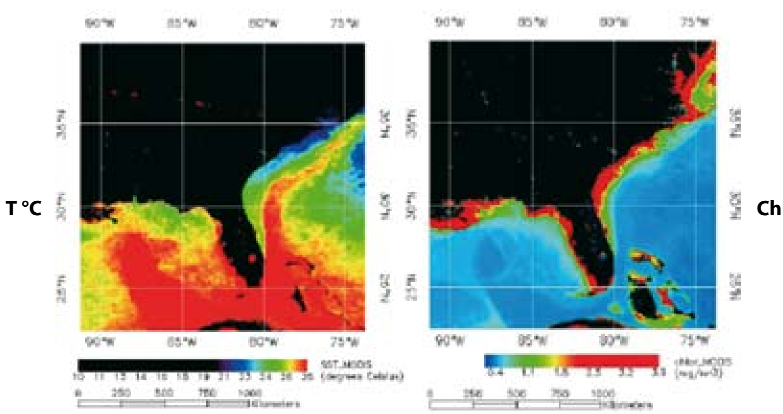


Figure 29.
Ocean biomes. Trade-wind biome – *CARB*: Caribbean Province; *NATR*: North Atlantic Tropical Gyral Province. Westerly-wind biome – *GFST*: Gulf Stream Province; *NAST*: North Atlantic Subtropical Gyral Province; *NADR*: North Atlantic Drift Province.
Coastal biome – *NWCS*: Northwest Atlantic Shelves Province. The Florida Current is not included in any of the provinces; it should be considered as an extension of the *CARB* and *NATR* provinces of the trade-wind biome towards the westerly-wind biome.
Ecological geography of the sea,
by A. R. Longhurst, Academic Press, 1998

The extension of the tropical region by the Florida Current



Southern tip of Florida and Cape Hatteras

Figure 30.
The Florida Current seen by MODIS in May 2003. *Left*, the sea-surface temperature; *right*, chlorophyll concentration.
Spectral recognition of marine bio-chemical provinces with MODIS, **by Karl-Heinz Szekielda (2004), EARSel Proceedings 3**

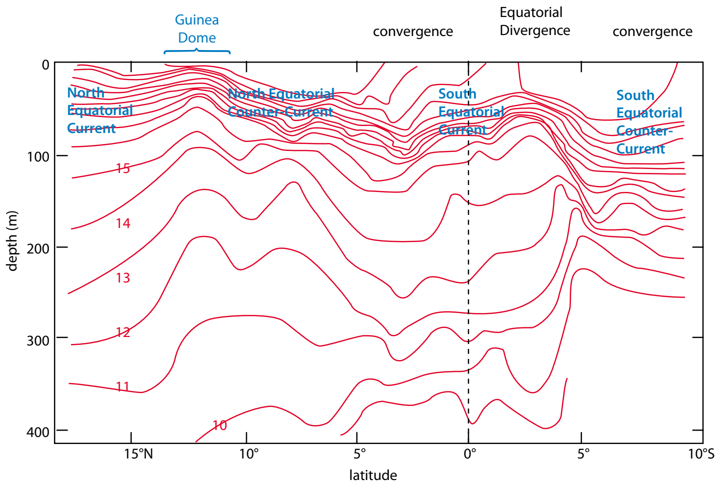


Figure 31.
North-South temperature profile across the Equator in the Atlantic.
Ocean circulation. The Open University, Pergamon Press, 1989

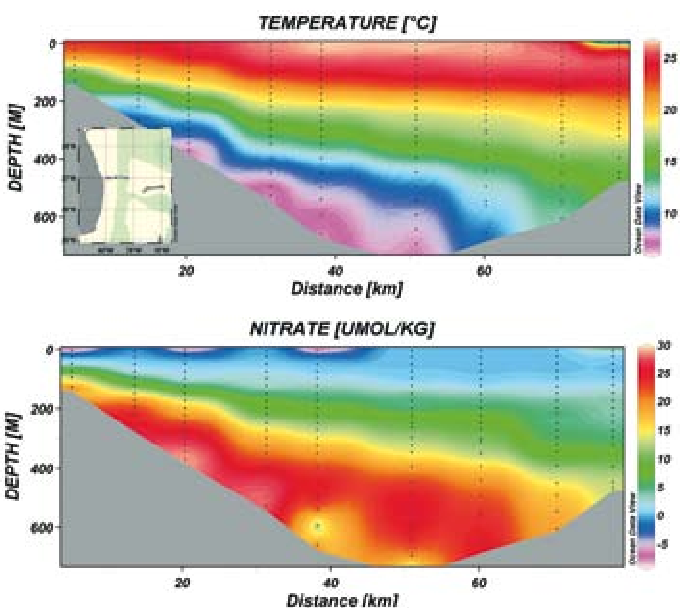
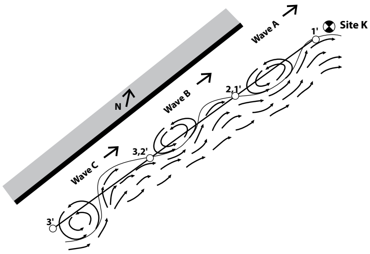
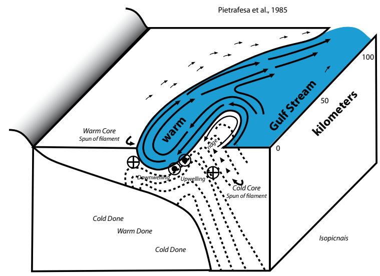


Figure 32.
Profile of the Florida Current at 27°N during the WOCE programme; nitrate-rich layers (in *red*) pass through the Gulf Stream, from a depth of 600 m to the continental shelf break at a depth of only 200 m, over a distance of 60 km.
D. Hansell, RSMAS, Miami, Fla., USA. Software: Schlitzer, R., Ocean Data View, 2004. www.awi-bremerhaven.de GEO/ODV

Florida Current: dynamic upwelling



Undulations



Formation of a small eddy
at the shelf break

Figure 33.
Dynamic upwelling in the Florida Current. Undulations and formation of a small cyclonic eddy.
Physical oceanographic processes in the Carolina Capes, by Pietrafesa et al.(1985), ***Oceanography of the South-eastern US Continental Shelf*****, Atkinson et al. (editors)**

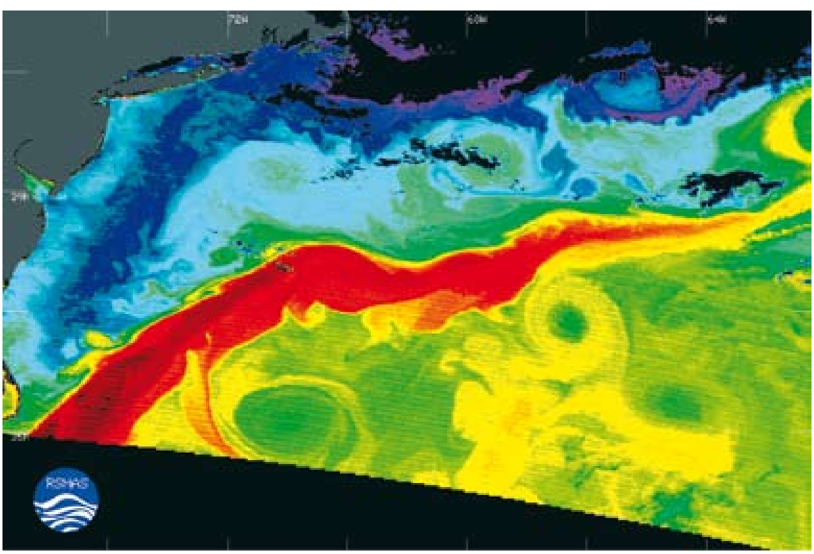


Figure 34.
Gulf Stream eddies (sea-surface temperature) seen by MODIS in June 2000. Three cold eddies to the south and three warm eddies to the north, of which one incomplete, can be distinguished on the *upper right-hand side*.
NASA Visible Earth

The Gulf Stream returns to the Sargasso Sea the nutrients it borrowed

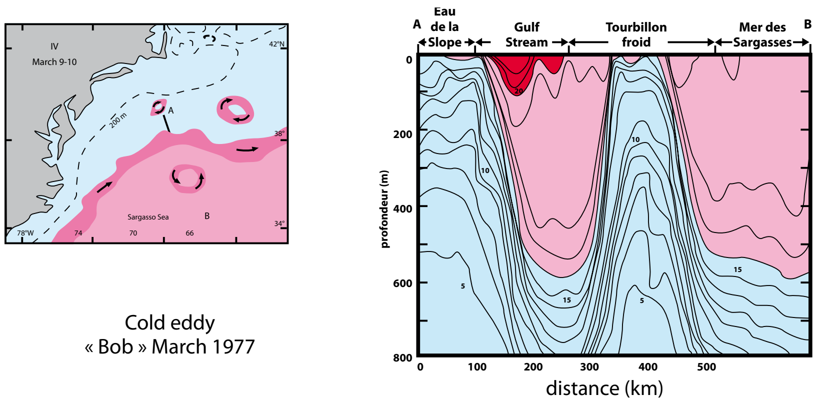


Figure 35.
Temperature profile of the cold eddy 'Bob' in 1977.
***Ocean circulation*, The Open University, Pergamon Press, 1989, after Peter H. Wiebe, Rings of the Gulf Stream, *Scientific American*, Vol. 246, No. 3, 1982**

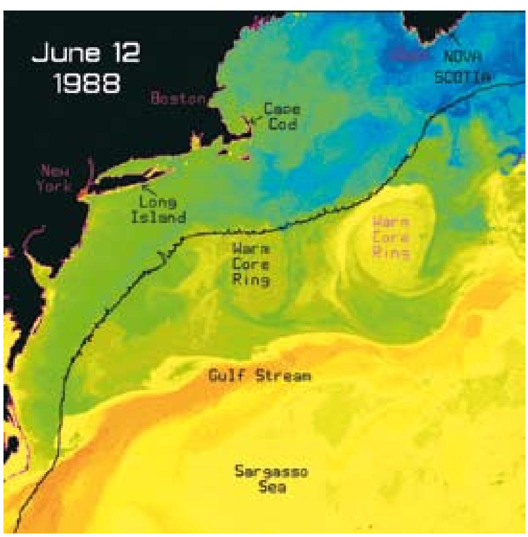


Figure 36.
Sea-surface temperature: warm eddies in the 'Slope Sea', between the Gulf Stream and the continental shelf, in which the limit is marked by the *black line* at a tangent to the eddies.
The Space Oceanography Group, Applied Physics Laboratory, Johns Hopkins University

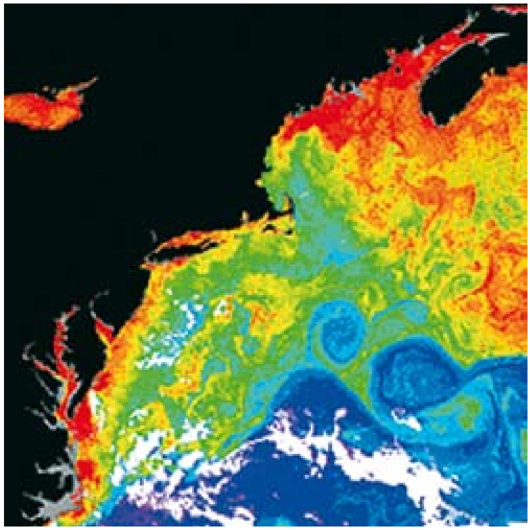


Figure 37.
Chlorophyll in a warm eddy. Ocean colour as seen from the CZCS satellite on 8 May 1981; warm-core eddies are as nutrient-poor as the Gulf Stream and yet they enrich the 'Slope Sea'.
NASA

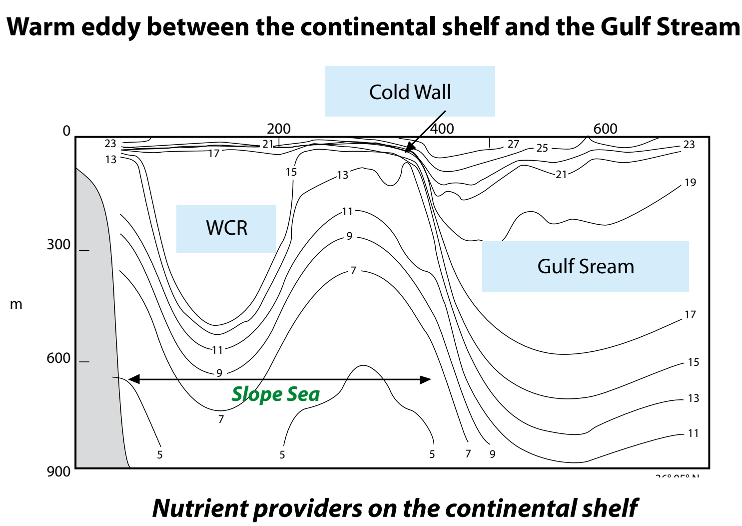


Figure 38.
Temperature profile of a warm-core ring.
K. H. Mann and J. R. N. Lazier, *Dynamics of marine ecosystems*, Blackwell Science, 1996, after G. T. Csanady, The life and death of a warm-core ring, *Journal of Geophysics,* Res. 84: (C2): 777–780, 1979

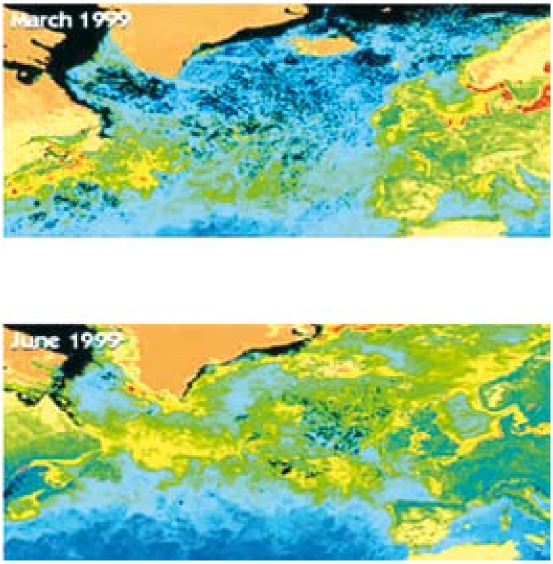


Figure 39.
The spring bloom in the North Atlantic, in 1999. March: bloom begins; June: it is at its maximum.
NASA, GSFC Earth Science DAAC SeaWIFS Project

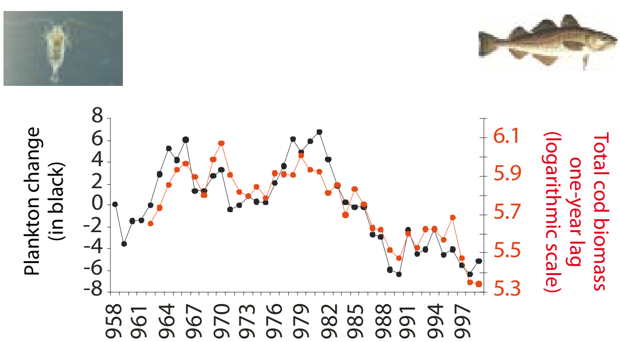


Figure 40.
Evolution of cod biomass in the North Atlantic according to an index characterizing the composition of zooplankton; they evolve together, with a one-year time-lag. The period of abundance (1965–1980), known as a 'gadoid outburst', corresponds to a low NAO Index. The subsequent decline corresponds to the strengthening of the NAO. The conjunction of unfavourable climatic conditions and intensive fishing can be fatal to fish stocks.
Beaugrand et al., *Plankton changes and cod recruitment in the North Sea*, International Symposium on Quantitative Ecosystem Indicators for Fisheries Management, Paris, 31 March–3 April 2004

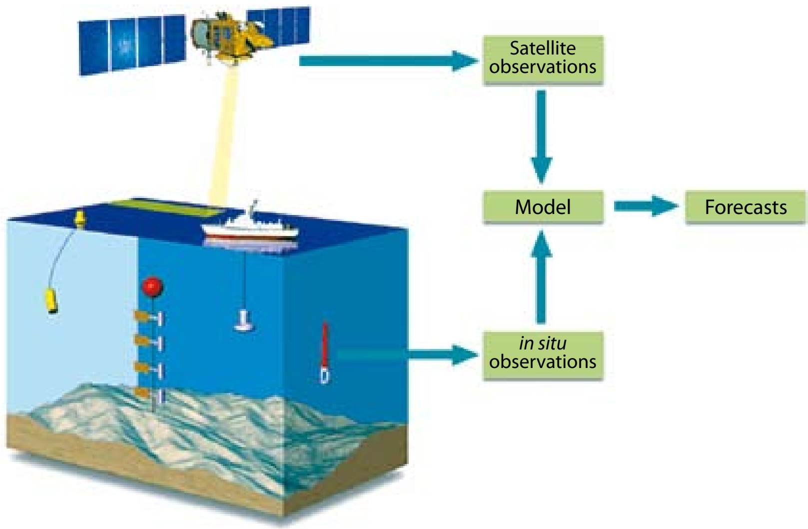


Figure 41.
Diagram of operational oceanography. The model is central to the system, which can only function if it is supplied with the data from satellite observations and *in situ* measurements, the latter being located and transmitted by satellite.
Mercator Oceans: http:www.mercator-ocean.fr

Figure 42.
The status of the international Argo programme at the end of February 2005; this programme aims at deploying 3,000 floats throughout the world ocean. These floats drift at a depth of 2,000 m and rise regularly to the surface, 'sounding' the water column (temperature and salinity measurements), then, at the surface, transmitting their position and data by satellite.
Argo Programme: http://www.argo.ucsd.edu/

Figures

Figure 1.
The Gulf Stream, as seen by Winslow Homer (1836–1910) in 1899
Metropolitan Museum of Art, New York

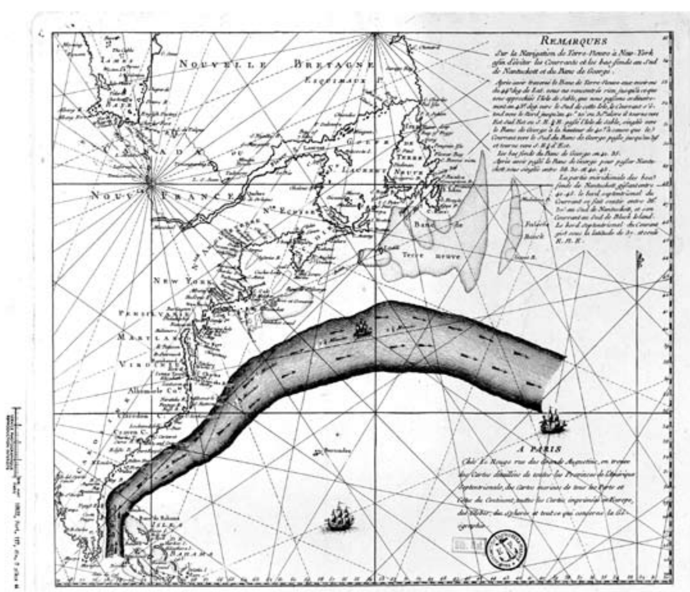


Figure 2.
French copy of the Franklin/Folger chart of 1769–1770
Bibliothèque Nationale de France, Paris

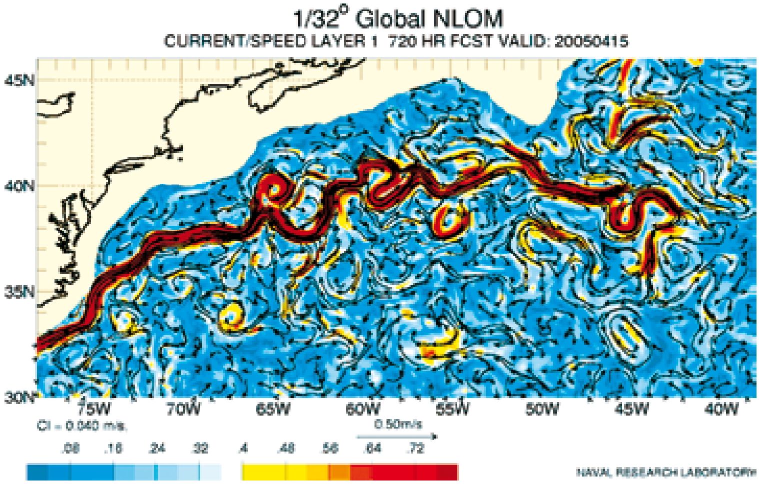


Figure 43.
Operational forecast of the velocity field of the Gulf Stream, made on 16 March 2005 with a time horizon of 15 April 2005. Scale: 1:32°.
US Naval Research Laboratory Real-Time Global Ocean Analysis and Modelling
http://www7320.nrlssc.navy.mil/global_nlom/

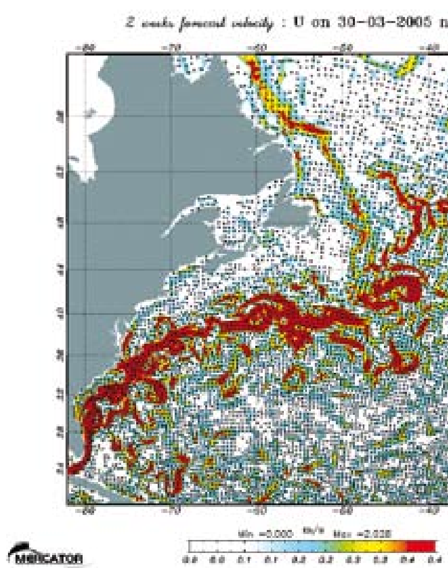


Figure 44.
Operational forecast of the velocity field of the Gulf Stream, made on 16 March, 2005 with a time horizon of 30 March, 2005. Scale: 1:15°.
Mercator Oceans. www.mercator-ocean.fr

in winter than in Canada at the same latitude, because in the present climatic context, due to the rotation of the Earth, the western shores of the oceans are under the influence of prevailing westerly winds, which in winter pump from the ocean the energy that the Sun has deposited during the summer. Likewise, this also applies to the shores of the Pacific and to the Kuroshio.

Norway and Alaska

To evaluate the importance of the Gulf Stream and the heat it transfers to the Atlantic eastern boundary climate, it would seem appropriate to assess comparable, that is to say, qualitatively similar situations. This entails examining the differences between the marine climate on the east side of the Pacific and the Atlantic Oceans, to see if the Gulf Stream plays a role that the Kuroshio does not. There is no doubt that, at the same latitude and the same type of climate, Norway's climate is not the same as Alaska's. The chart of anomalies (Figure 16) even indicates a positive anomaly of 10°C along the coast of Norway relative to the temperature along the American coast at the same latitude. Has the Gulf Stream (or its extensions) anything to do with it? That is the question. It is possible to think that the answer is yes, since the northward heat transport by the currents is much greater in the Atlantic than in the Pacific, owing to the contribution of the thermohaline circulation in the Atlantic, which does not exist in the Pacific. However, Seager et al. concluded that, with the exception of the north of Norway, the temperature difference observed between the west of Europe and Canada is independent of heat transported by the ocean. To arrive at this result, they carried out experimental modeling: they compared the results of various models by coupling the general atmospheric circulation model with a simplified ocean model (a mixed layer of the ocean with uniform depth), forcing successive scenarios with or without transport of ocean heat. They then noticed that the temperature difference in January between the Canadian Pacific coast and the European coast at the same latitude was approximately the same in both cases and close to the differences observed, between 5°C and 10°C. Hence, the logical conclusion: heat transport by the ocean has nothing to do with the observed differences since, with or without transport, the temperature differences are unchanged.

Certain doubts may arise about the validity of this result. To start with, unlike the previous study carried out on both sides of the Atlantic, which depended on an effective heat balance based on actual observations under the present climatic conditions, here only the data of models corresponding to radically different climatic situations are compared. The climatic situations of the North Atlantic and North Pacific Oceans, with or without heat transport northwards by ocean currents, have nothing in common with each other. With heat transport, we are in the present situation, whereas, without this transfer, we find ourselves in the coldest of the cold glacial periods, with a completely different circulation pattern. What does a similar difference of temperature between Great Britain and Canada at the same latitude really mean, while nothing is equal anywhere else? In addition, the representation of the ocean in the models was not very realistic.

Based on their results, Seager et al. explain these differences in temperature by the different configurations of the ocean basins. The Atlantic Ocean stretches northeastwards, beyond 60°N, to the Norway Sea, Greenland and the Arctic, whereas the Pacific is closed by the Bering Strait. In addition, the Icelandic low-pressure zone in the Atlantic is centred more to the north and relatively more to the east than the Aleutian low-pressure zone in the Pacific. This configuration favours the concomitant northward path of warm winds from the south-west and of the Norway Current. This situation has no equivalent in the Pacific, and the coasts of Canada and Alaska are more subject to continental influence. In other words, it is nevertheless because northward heat transport by the ocean via the Gulf Stream and its extensions is much greater in the Atlantic than in the Pacific where it is generally colder in the North Pacific than in the North Atlantic.

THE GULF STREAM AND THE NORTH ATLANTIC OSCILLATION (NAO)

The climatic variations in the North Atlantic are dependent on a coupling between the anticyclone of the Azores and the Icelandic low-pressure zone, which regulates the intensity of the atmospheric flux – in particular, the westerly winds circulating between the two and controlling the climate in Western Europe (Figure 17). Beginning with the effects and going back to the causes, we can say that, to strong westerly winds in both the southern anticyclone and in the northern depression, there corresponds a reinforcement of the atmospheric circulation in these two structures. Hence, particularly low pressures at the centre of the Icelandic depression and markedly high pressures in the Azores anticyclone. The logical conclusion is that the difference in atmospheric pressure between, on one hand, the anticyclone and, on the other hand, the Icelandic depression, is characteristic of the North Atlantic climate. This is called the North Atlantic Oscillation Index. The higher the values of this index, the more active the two circulations and the stronger the westerly winds in temperate latitudes – but not only these winds (even if, here, they are of particular interest to us), for it also influences the Trade Winds, and the cold northwesterly winds, which bring polar air to North America via the western boundary of the Icelandic depression.

It is particularly during the winter season that the influence of the NAO is evident. The immediate climatic consequences are numerous. To start with, the increasing westerly winds over the North Atlantic favour heat transfer in winter from the ocean to the atmosphere, resulting in mild, wet and stormy winters in northwestern Europe and as far as northern Siberia. On the other side of the Atlantic, the strengthening of the northwesterly winds on the western side of the Icelandic depression bring particularly cold winters to the coasts of Canada and the northern USA. A high NAO Index therefore accentuates the climatic contrast between the two sides of the Atlantic. During a period of low NAO (negative anomaly of the NAO), the situation is reversed: the Icelandic depression weakens and shifts southwards, leaving a place for the high pressure prevailing over the Poles, thus facilitating the descent of polar air over Western Europe. The zone of westerly winds occurs farther south and with a reduced intensity which nonetheless brings rather rainy winters to southern Europe. These climatic variations linked to the variations in the NAO do not call into question the previous pattern, which 'balanced' the amount of heat stored and/or released in summer and in winter by the ocean. Indeed, for a positive NAO anomaly, the strong winds in winter have two effects: further cool down the ocean and increase the depth of the mixed layer, which further increases the ocean's capacity to store heat in summer. We may therefore remain with a zero balance, without recourse to the heat transported by the ocean, to explain the mild climate of Western Europe.

NAO variations have other effects. The acceleration of the north-northwesterly winds on the western side of the Icelandic depression would increases evaporation, hence the cooling and thus the density of the water of the Labrador Sea, resulting in an increase in the volume of water that, in winter, sinks and contributes to the formation of deep water. In a more distant way and conversely, on the eastern side of the Atlantic, the increase in the Trade Winds favours the upwelling of deep water along the coasts of Portugal and of Africa from Morocco to Mauritania.

If the NAO varied randomly from year to year, none of these effects would have much importance: the ocean would hardly have time to keep lasting records of disturbances in a year, which in the following year would be completely erased. It would be no more than background noise of little consequence in the medium and long terms. However, this is not the case, and this is why we talk about oscillation: the anomalies have a certain life span, as can be seen in Figure 19, showing the variation in the NAO since the middle of the nineteenth century. For example, the period 1980–2000 is clearly a period of high NAO Index values, even if it is possible to observe some local inversions of the NAO anomaly; it was also clearly the contrary between 1955 and the beginning of the 1970s. It has not always been like that. It has been possible to 'reconstruct' the variation in the NAO since 1650, with the analysis of successive snow layers accumulated in Greenland, on the assumption that there was a relationship between the NAO (and therefore the North Atlantic pressure field) and the abundance of snowfall in Greenland. It clearly appears that organized and regular oscillations are intermittent. It is easy to identify the organized alternating periods of low and high values of the NAO Index: 1675–1725, 1875–1925 and 1960–2000. On the contrary, it is difficult to detect any coherence between 1725 and 1850. This situation has not been clearly interpreted, but it seems to indicate that, if the NAO is essentially a form of variability peculiar to the atmosphere, the organized decennial fluctuations must introduce other elements of the climatic system with a 'slow memory' – compared with the rapid response of the atmosphere. It is likely that the ocean plays this role, although we cannot help establishing a link between the weakness of the NAO between 1675 and 1690 and the persistent weakness of solar activity during the same period (the Maunder Cycle).

We may question (as indeed researchers do, in the hope of finding an answer one day) the meaning of the positive anomaly at the beginning of the 1990s, which had a temperature range without precedent in the history of the NAO, and we may wonder whether there is a link between global change and the increase in the concentration of greenhouse gases in the atmosphere. We are therefore uncertain about the variation of the NAO in the context of global change. It is nevertheless almost certain, taking into account the length of the different phases, that the ocean registers this variation and integrates it into its dynamics, and relays it, at its own pace, to the atmosphere, which also responds at its own pace – though much more rapidly than the ocean. This is referred to as ocean–atmosphere coupling. Some examples follow to illustrate the complexity of this coupling and the action/retroaction that can take place.

Anticyclonic circulation, the Gulf Stream and the NAO

Surface anticyclonic oceanic circulation responds, with a certain lag, to the variation in the NAO. The increase in the atmospheric circulation during phases of high values of the NAO Index stimulates the ocean currents constituting the anticyclonic circuit, which are the Gulf Stream, the North Atlantic and the Norway Currents. There are two indexes.

First, there is the intensity of the Gulf Stream. To analyse fluctuations in oceanic circulation over long periods representative indexes are used as is done for the NAO of the atmosphere. This analysis was accomplished by Ruth G. Curry and Michael S. McCartney. Their Index (it was not given a name), measures the anomalies in atmospheric pressure differences between the high point (the Azores anticyclone) and the low point (the Icelandic depression) in the great gyre of the westerly winds. Likewise, for the ocean, the Gulf Stream's transport is proportional to the 'pressure' difference between the high point of the anticyclonic oceanic circulation centred on the Island of Bermuda and the low point of the subpolar gyre in the Labrador Sea (Figure 18). From the anomalies of potential energy differences between the two points, it is possible to derive the variation in the Gulf Stream's flow. The result is clear: the Gulf Stream's flow weakened during the period of low NAO Index values in the 1960s and intensified in the 25 years of high NAO Index values since 1975, with a marked peak in the 1990s (Figure 20, a). This is obviously not an unexpected result. In a period of high NAO values, the cold winds in winter of the Icelandic depression cool down the Labrador Sea, resulting in a decrease both in the sea level and the potential energy, whereas around the anticyclonic circulation the strong westerly winds intensify the Ekman transport towards the centre. This makes the pycnocline sink and the sea level rise, and increases the potential energy. The difference in potential energy thus reaches its maximum, as is also the case for the Gulf Stream's flow. The opposite is true when the NAO Index is low (Figure17).

Secondly, there is the latitudinal position of the Gulf Stream. It may be instinctively imagined that activation of the anticyclonic circulation resulting in an increase in the Gulf Stream's flow will also bring about its northward extension. Compared to other currents of the anticyclonic circulation, in which the boundaries are not clear-cut, the Gulf Stream, which is very distinct, with its northern boundary well defined by the thermal front separating it from the cold water of the 'Slope Sea' and those of the Labrador Current, is easy to locate. The Gulf Stream North Wall (GSNW) Index was conceived to monitor the change in the Gulf Stream's latitudinal position. It is simply the northernmost latitude reached by the northern boundary of the Gulf Stream and lies between 60°W and 75°W longitude. There is also a link between this Index and the NAO Index. A high NAO Index clearly corresponds to a northward extension of the Gulf Stream, with a delay of one to two years, and vice-versa. The range of difference is approximately 100–200 km (Figure 20, b). The position of the 'North Wall' was, on average, 1° farther north in the 1990s (positive anomalies) than in the 1960–1970s (negative anomalies). To summarize, we can say that oceanic circulation responds quite rapidly and significantly to the stress of an NAO anomaly and that an increase in the NAO Index corresponds to an increase in oceanic transport and heat flux northwards.

The deep water of the Labrador Sea

The Labrador Sea, between Greenland and Labrador, is also a zone of deep-water formation. However, the mechanism is not the same as the one described for the Norway and Greenland Seas. There, a prerequisite for their formation is the strong salinity of the water brought by the currents. This high salinity water reveals its tropical origin and thus its transport by various currents in sequence: the Gulf Stream, the North Atlantic Current and the Norway Current. Deep-water formation in the Labrador Sea is independent of the Gulf Stream system and has nothing to do with the saline water it transports. It is not linked to the anticyclonic subtropical circulation but to the subpolar cyclonic gyre. As we have seen, it is the strong cooling in winter under the action of cold winds from the north-west associated with the Icelandic depression that increases the density of the surface water and makes it sink. In periods of high positive NAO anomaly, the particularly strong wind accentuates cooling and increases the volume of the downwelling water. This also corresponds to an extension of cold water and ice coming from the Arctic via the islands off northern Canada and Baffin Bay, between Greenland and Canada. The higher the positive NAO anomaly, the thicker the deep-water layer formed in the Labrador Sea, the colder it is and the lower its salinity (the opposite of deep-water formed in the Norway Sea). The persistence of anomalies over several years thus produces more or less significant masses of water, with characteristics dependent on the variations in the NAO. The temperature of the water layer formed was 3.5°C in 1970 (negative NAO anomaly), whereas in 1993 it was only 2.7°C (positive anomaly). Marine currents will obviously translocate these anomalies. Some of the Labrador deep water mixes with deeper (2,500 m–3,000 m) and denser water from the GIN Seas and continues its course along the conveyor belt and the Deep Western Boundary Current. The upper part, around a depth of 1,500 m, follows the border of the subtropical anticyclonic gyre via the Gulf Stream and the North Atlantic Current. We find traces of the anomalies (thickness, salinity, temperature) of the Labrador water six years later in the vicinity of Bermuda. Eventually, variations in the characteristics of the Labrador deep water are necessarily propagated towards the surface by mixing and diffusion. For example, it is likely that the abundant cold and low-salinity water formation in the Labrador Sea during a period of high NAO Index values results, a few years later, in the cooling and a decreased salinity of the water of the Norway Current, which would reduce the thermohaline circulation and, therefore, weaken the NAO: a negative retroaction to the phenomenon that had originated the initial anomaly in the Labrador Sea. It has been demonstrated that a negative anomaly of surface temperature detected to the southeast of the United States (between 25°N and 35°N) and probably linked to a subsurface anomaly took almost eight years to reach Iceland via the Gulf Stream and its extensions. If this process in fact takes place – it has yet to be demonstrated – it would take fourteen years for an anomaly established during deep-water formation in the Labrador Sea to arrive at the zone of deep-water formation in the Norway Sea. This is more or less the period of the decennial variation in the NAO Index.

The 'great salinity anomalies' and the thermohaline circulation

A 'great salinity anomaly' intersected the surface of the North Atlantic from 1968 to the beginning of the 1980s. Without a doubt, it is one of the most remarkable and well-documented events at a decennial scale ever recorded – but this does not mean that it is one of the best understood. It represented a considerably reduced salinity in the surface layer to a depth of several hundred metres during a period of about twelve years (Figure 21). Detected off northeastern Iceland in 1968, it appeared, in 1971–1972, in the Labrador Sea. It then followed the North Atlantic Current which carried it to the north of Great Britain, via the Faeroe Islands and the Shetland Islands in 1976, to the Norway Sea in 1977–1978, then, from 1979 – 1982, to the Greenland Sea, which is a zone of North Atlantic deep-water formation. This was the Great Salinity Anomaly of the 1970s (GSA 70). There have been others since, perhaps less strong, but which at first sight followed the same course. For example, between 1982 and 1990, an anomaly seemed to carry on where the previous one had left off. This happened again between 1989 and 1997, as if a periodicity of ten years had been established. This periodicity was encouraging for any scientist inclined to think that these anomalies, so similar and repetitive, necessarily had the same causes. Obviously, it would have been too simple, and it seems that these anomalies may have had two different causes – one (GSA 70) corresponding to a period of negative NAO anomaly, and the others (GSA 80 and 90), on the contrary, corresponding to a period of positive NAO anomaly. A clue to this difference can be found at the source of the anomaly: the north of Iceland for the first one and the Labrador Sea for the following two.

Ice formation in the Arctic Ocean also varies with the NAO Index. Analysis of observations carried out over forty years, between 1958 and 1997, shows that, since about 1970, there has been a correspondence between a general decrease in the ice concentration in the Arctic and variations in the NAO Index; that is, there has been a lower ice concentration when the NAO Index is high, and vice-versa. The years preceding the appearance of the salinity anomaly, in 1968, off northern Iceland, corresponded to strong negative NAO anomalies and to high production of ice, which accumulated over the years. The Arctic Ocean around the North Pole underlies an atmospheric anticyclone, which also varies with the NAO Index and is out of phase with the Icelandic low-pressure system. When it is low, as was the case in the 1960s, the polar anticyclone is centred over Greenland, creating a northerly wind regime favouring the exportation of Arctic ice – notably the thickest and oldest ice and, therefore, the least saline – southwards along the eastern coast of Greenland through the Fram Strait between Greenland and Spitzbergen. All the conditions – overabundance of ice and favourable wind conditions – were met for a significant increase in the ice. This increase in ice is estimated to have corresponded to a flow of fresh water through the Fram Strait that was 50% higher than average. It was a simple case of freshwater advection southwards, which spread without the intervention of processes specific to the regions crossed.

A very different situation prevailed at the time of the GSA 80 and GSA 90, which originated not in the transport of water from the distant Arctic, but locally, in the Labrador Sea, within a context of high NAO Index values. The conditions were set in each case by extremely rigorous winters in 1982–1984 and 1992–1994, associated with northwesterly winds over the Baffin Sea favouring the flow of fresh water from the Arctic to the Labrador

Sea through the Canadian Arctic archipelago. Whereas, usually, during a period of positive values of the NAO Index, cold winds cause strong convection, in this case it was their very excess that, by advecting a surplus of fresh water, momentarily slowed this convection down and provoked a salinity anomaly of smaller magnitude than that in 1970. Even so, this water took the same route to get to the Gulf Stream and the North Atlantic Current to rejoin, finally, the GIN Seas where deep water is formed.

The graph of average air temperature, which has increased overall since the end of the nineteenth century (Figure 26), indicates that there was an interruption in this increase and even a drop in temperature from the end of the 1960s to the end of the 1970s. It is possible to think that there is relationship of cause and effect between the emergence of the GSA in the 1970s and this momentary cooling. Indeed, increases in surface fresh water increase stratification and hence, decrease deep-water formation. This was probably the case in the GIN Seas, where the GSA first began in 1968–1969, and in the Labrador Sea, which the GSA crossed in 1969–1970. It could have resulted in a weakening of the thermohaline circulation and the conveyor belt enough to slow down northward heat transport via the Gulf Stream and its extensions. Perhaps a similar phenomenon threatens us with global warming: a super-GSA, which would slow down the thermohaline circulation much more radically and generate an even greater cooling at least the Northern Hemisphere.

The NAO and coupling

We have seen that the ocean responds significantly to variations in atmospheric circulation identified by the NAO Index, provided that the positive or negative anomalies last for a certain time. The question for us is whether there is coupling between the ocean and the atmosphere to generate a decennial climatic variation. In other words, are these actions/retroactions between the ocean and the atmosphere responsible for the fluctuations in the NAO Index when they are coherent, as is currently the case?

Deep-water formation in the Labrador Sea clearly illustrates the problem. A negative salinity anomaly arising in a period of positive NAO Index values, with a significant flow from the Gulf Stream and strong thermohaline circulation, takes fourteen years to reach the Norway Sea. There, it is likely to slow down the thermohaline circulation in the Gulf Stream and, consequently, reduce the NAO and deep-water formation in the Labrador Sea – thus, less abundant but more saline water – which will not, fourteen years later, stop deep-water formation in the Norway Sea, and so on. It is a crucial problem to be resolved at the same time as that of the interactions between the scales of variation in the NAO Index and of longer-term climate variation, if we wish to correctly simulate the climate change awaiting us in future decades.

The period beginning at the end of the 1970s was the longest recorded period of positive NAO Index values, while the periods between 1980 and 1990 were those in which the NAO Index attained its highest levels in 173 years of records. This did not affect the observation of strong interannual variations during this same period – and even dramatic inversions of the Index from one winter to another. This was particularly the case in the winter of 1994–1995, which experienced the second highest recorded positive anomaly ever registered, while the following year, 1995–1996, was characterized by one of the highest negative anomalies ever seen. This proves that, beyond a probable ocean–ice–atmosphere link responsible for decennial or multi-decennial oscillations, the atmosphere's own internal dynamics are capable of producing interannual variations of equal amplitude to that of the decennial oscillations.

On reading what was said above – in an admittadly difficult passage – the reader will probably think that things are not clear. Perhaps the reader will go as far as to think, following the seventeenth-century writer Nicolas Boileau, that 'what is well conceived is clearly stated', and that the author himself has not understood anything. And perhaps it is true, but he might be excused, because things are indeed not clear and scientists do not all agree about the processes at stake nor do they hide their doubts and, sometimes, their ignorance. For example, it is possible to assess all the complexity of the climate system through this example of atmosphere—ocean—ice interaction. However, it is almost impossible to break down the climate system into its component parts in order to analyse them one by one and incorporate the exchange processes among these components. All the time- and space-scales are interlinked. Thus, for example, it is not impossible to find a relationship between sporadic strong positive NAO anomalies and the initiation of a GSA, on one hand, and El Niño events, on the other hand, although the driver of the latter is far from the North Atlantic, in the equatorial Pacific! The climate system is not a jigsaw puzzle – or, if it were, it would be a dynamic puzzle, each additional piece modifying its entire configuration as progress is made toward its solution.

It will take many years to fully understand the functioning of this complex linking, for the time being inextricable, of the scales of variation of the North Atlantic, and the crucial elements also interfering with the thermohaline circulation and, therefore, with climate change in the medium and long terms. The study of the NAO is part of an important international research project Climate Variability and Prediction (CLIVAR) launched for fifteen years and implemented in the framework of the World Climate Research Programme (WCRP) jointly organized by the World Meteorological Organization (WMO), the UNESCO Intergovernmental Oceanographic Commission (IOC) and the International Council for Science (ICSU).

To conclude, let us go back to the Gulf Stream, somewhat lost sight of in this labyrinth of action and reaction. As an element of the system, it seems to oscillate to the rhythm of the NAO variations (unless the opposite is true). It responds to interannual NAO variations (from one year to the next), as shown by the relationship between its latitudinal position (GSNW Index) and the NAO Index. The Gulf Stream also reacts to decennial and multi-annual variation: there is correlation on the one hand with its average latitudinal position and its flow rate and on the other hand with the NAO multi-annual variations. The northward heat flux and the sea surface temperature of the Atlantic Ocean are obviously in phase with the variations in the Gulf Stream and, in return, they force the atmosphere without its being known yet what regulatory retroactions are involved. Finally, the Gulf Stream and its extensions contribute to the propagation of temperature and salinity anomalies arising in the Labrador Sea or the GIN Seas (Greenland–Iceland–Norway). The Gulf Stream is certainly involved, but it does not play a solo and is not the conductor. It is inseparable from the other elements – atmosphere, ice – and together they constitute the main part of the North Atlantic climate system.

THE GULF STREAM AND THE THERMOHALINE CIRCULATION

The inequality of the oceans: why the Atlantic?

The ocean and the atmosphere are the two fluids that redistribute the Sun's heat, mainly absorbed in the intertropical regions. Their roles are not necessarily symmetrical. To start with, the ocean stores energy, which the atmosphere does not; then, the atmosphere draws its energy mostly from the ocean in the form of latent heat (evaporation), radiation (the ocean emits energy in the infrared, at a wavelength corresponding to its temperature, which is absorbed by the atmosphere) and finally, to a lesser extent, 'sensible heat'. Sensible heat corresponds to the heat stored or contained in a fluid at a given temperature, that is to say, the product of $M \times C \times T$ where M = the mass of the fluid; C = heat capacity; and T = temperature. When we talk of sensible heat exchange, it is simply heat transfer by conduction between the two fluids, from the warmer to the colder. The atmosphere returns to the ocean part of the energy it initially supplied in the form of mechanical energy, via the wind-driven surface circulation and the exchange of fresh water by evaporation/condensation, which modify the chemical composition (salinity and, therefore, density of the ocean). These two components operate on altogether different scales: energy supplied to the atmosphere by the ocean is almost a thousand times greater than the energy returned to the ocean by the atmosphere. Yet, this energy is essential, as it generates both surface circulation and deep thermohaline circulation, reinforced by the dissipation of tidal energy. Therefore, the ocean has the upper hand in climate. Ultimately, it is the supply from this ocean reservoir, which enables us to experience climatic variations – as the atmosphere functions on a 'just-in-time' basis - without any reserves. The entire climate on Earth, therefore, depends on the amounts of heat and fresh water exchanged and the place where these exchanges take place.

Looking at the chart (Figure 22) of heat transfer *inside* the ocean (sensible heat), which takes into account the entire oceanic circulation from the surface to the ocean floor – in the Atlantic, for example, both the northward-flowing Gulf Stream and the deep southward-flowing undercurrent – we immediately notice that the three major oceans are not equal. It is hardly surprising for the Indian half-Ocean, where the northern side is closed off. It is, *a priori*, more surprising in the case of the Atlantic and the Pacific Oceans. Indeed, we would expect for both a certain symmetry relative to the meteorological Equator separating the subtropical anticyclonic circulations of the Northern and Southern Hemispheres. It is relatively true for the Pacific; it is not at all the case for the Atlantic, where, from south to north, the heat flux is exclusively northward, as if the Atlantic were a sort of heat aspirator. This is due to the thermohaline circulation and deep-water formation by convection in the GIN Seas and the Labrador Sea, which adds at the surface a northward warm-water flux of 15 Sv to the circulation generated by the wind. This is the 'warm route' of the conveyor belt, which 'pumps' surface water towards the North Atlantic from the Pacific and Indian Oceans via the Indonesian Straits, the Agulhas Current, the Benguela Current and the Atlantic South Equatorial Current. This warm water 'aspiration' towards the north, which does not exist in the Pacific, also increases energy transfer from the ocean to the atmosphere along the Gulf Stream–North Atlantic Current–Norway Current route, up to southern edges of the Arctic. Therefore, due to the thermohaline circulation, the ocean currents and the exchange of energy with the atmosphere, the Atlantic is the main source of heat in the north, at the expense of the south.

Why does the Pacific Ocean not play an equivalent role? First, there are morphological reasons. The Pacific Ocean is closed to the Arctic by the Bering Strait: some dozens of kilometres wide and only fifty metres in depth, the Strait acts as a barrier to all progress towards the Arctic of any possible extension of the Kuroshio. At the same latitude as the Bering Strait, the North Atlantic benefits from a much wider and deeper entry (between 500 m and 1,000 m depth) over the sills between Greenland and the Faeroe Islands, via Iceland, which allows the Norway Current to reach the GIN Seas where deep-water is formed. The western boundary of the equatorial Pacific is porous: a large part of the South Equatorial Current moves towards the Indian Ocean through the straits of the Indonesian archipelago. This is to be debited to the Kuroshio, but credited to the Gulf Stream, as this leak forms part of the return to the Atlantic of the 'warm-water route' of the conveyor belt.

There is also a hydrological reason: the Pacific is considerably less saline than the Atlantic (Figure 23). There are two reasons for this. In the first place, there is freshwater transfer from the Atlantic to the Pacific. For the Atlantic northeast Trade Winds, the Isthmus of Panama does not present an obstacle. They cross it carrying the water vapor they accumulated on their way over the tropical Atlantic, the Caribbean Sea and the Gulf of Mexico, where evaporation is high. On the Pacific side, they converge with the southeast Trade Winds coming from the Atlantic, generating a strong convection and abundant rainfall with water these winds brought from the Atlantic. Therefore, in the Atlantic, since evaporation overall exceeds precipitation, salinity increases. It is the opposite in the Pacific. The Gulf Stream has its source in the very saline water of the concentration basin of the Caribbean Sea. On the western side of the Pacific, at the source of the Kuroshio, there is no such freshwater loss. The monsoon regime over the Asian continent temporarily exports fresh water to the Pacific via the great rivers draining East Asia. Contrary to the Gulf Stream, the Kuroshio has its source in a low saline water 'pool' called the western Pacific 'warm pool': a vast oceanic zone to the east of Indonesia and the Philippines, where the sea-surface temperature exceeds 29°C and considerable precipitation lowers the salinity.

A second element is the Mediterranean concentration basin. In this closed sea, evaporation is very clearly greater than precipitation – the annual rainfall deficit is equivalent to about 1 m of water. Furthermore, salinity can reach a record level of 39.5 PSU in the Aegean Sea. In comparison, at the centre of the oceanic anticyclonic circulations, the maximum values attained are 37.5 in the Atlantic and only 35.5 in the North Pacific. These very saline Mediterranean waters flow out at the bottom of the Straits of Gibraltar into the Atlantic, where it reaches its equilibrium level at about 1,000 m depth. It spreads over the entire basin, contributing, by mixing, to a positive salinity balance in the Atlantic. The Pacific Ocean does not benefit from these favourable conditions and, even when ice forms in the North Pacific, salinity is too low to provoke sinking of the surface water, which remains lighter than the subjacent water.

To the source of long-term climate variations: the Milankovitch Cycle

Is deep-water formation in the GIN Seas and the thermohaline circulation it generates an Achilles heel of the climate system? Is this sensitive component of the climate system capable of tipping it from one state to another? These questions are interpreted in the media and cinema – quite wrongly – by the following question: Can the Gulf Stream stop? Wrongly, because the thermohaline circulation can cease to function and create all the hyped climatic consequences we fear, without the Gulf Stream necessarily coming to a halt.

For several million years, the Earth's climate has oscillated between glacial and interglacial periods, with a periodicity of around 100,000 years (Figure 24). For almost 10,000 years, we have benefited from the mildness of an interglacial period, which is welcomed by humankind. The average temperature on Earth is 4°–5°C higher than at the height of the preceding glacial period, approximately 21,000 years ago. We have to go back 120,000 years to find an equivalent interglacial period. A recent ice core drilled down to a depth of 3,190 m in the Antarctic ice-cap, carried out in the framework of the European program EPICA (European Project Drills for Ice Coring in Antarctica), allowed the recreation of the evolution of air temperature up to 800,000 years ago and thus to the identification of 8 climatic glacial/interglacial cycles.

We know today that these large-scale changes cannot be explained by internal oscillations peculiar to the climate system. There is an outside astronomical influence, as it is the variations in Earth's orbit around the Sun that modulate the intensity and distribution of energy received from the Sun at the Earth's surface. Already presaged at the beginning of the twentieth century, after Louis Agassiz announced, in 1837, his discovery of traces of past glaciations in the form of the scouring (marks left by the passage of the glacier) observed on certain rocks in the Jura Mountains and by vestiges of ancient moraines, the astronomical theory of climates was elaborated by Milutin Milankovich around 1920. He started from the idea that the high northern latitudes, largely occupied by the continents, were more sensitive to energy exchange from the Sun to Earth, and that the start of the glacial periods had to correspond to cool summers preventing snow that fell in winter from completely melting, thus allowing it to accumulate year after year. He constructed his theory by analysing the variations in summer insolation at 65°N latitude, as a function of the astronomical parameters of the Earth and of its orbit around the Sun, and by qualitatively comparing them with what was known at the time about the alternation of glacial/interglacial periods. It worked well enough for the idea to be developed further by refining the calculation of the astronomical components as the climate models improved and the history of climatic fluctuations became clearer, with the observation of glaciers and of marine and continental sediments.

The parameters taken into account were the eccentricity of the Earth's orbit around the Sun, the precession of the equinoxes and the inclination of the Earth's axis of rotation on its orbit. The Earth's orbit is an ellipse with a more or less elongated form characterized by its eccentricity; it varies with a double period of 140,000 years. This results in a significant variation in the difference in the energy received from the Sun between the aphelion (point at which the Earth is farthest from the Sun) and the perihelion (point at which the Earth is closest to the Sun). This difference is at present 7%. It can reach 30% when the orbit is most elongated. The precession of the equinoxes, with a period of 21,000 years, makes this orbital ellipse revolve in space, so that when the Earth is presently at its closest point to the Sun in January – winter in the Northern Hemisphere – in 11,000 years from now, it will be in June. Finally, the angle of the Earth's axis of rotation with the plane of its orbit varies by about 3° with a period of 41,000 years, modifying at this rate the distribution of energy received as a function of latitude. By combining all these periods of variation, Milankovitch demonstrated that there was a good correlation between the variations in the energy received at 65°N and the long-term climate variation. The energy maxima correspond to the interglacial periods, and the minima correspond to the glacial periods. Assuming that solar activity is constant, the total solar energy received annually by the Earth varies during the course of this cycle by about 0.5%. This is similar to the difference between the maxima and the minima of a 22 year cycle of solar activity. Variations are even more significant at a given latitude: for example, at 65°N in summer, Milankovitch's reference point, the insolation varies between 450 W/m^2 and 550 W/m^2, that is, a difference of 20%.

These energy variations do not sufficiently explain the range of climatic variation observed between the glacial and interglacial periods: they are amplified by the specific mechanisms of the climate system. For example, as glaciers continue to expand, the quantity of solar radiation reflected by the Earth's surface and lost to the system increases. Vegetation reacts and variation in carbon dioxide (CO_2), a greenhouse gas, concentration in the atmosphere increases too: during the coldest of the previous glacial periods, 21,000 years ago, the atmospheric concentration of CO_2 was barely 200 ppm, whereas, during normal interglacial periods, it was between 280 ppm and 300 ppm. We have now gone through this ceiling, unequalled over the past 500,000 years with a present concentration of more than 370 ppm, growing at a rate of approximately 1% a year. This is a consequence of our many industrial and agricultural activities, which are major sources of greenhouse gases. Hence, there is the uncertainty and concern for the future, since there was no equivalent situation in the past which would enable us to base a probable climate change scenario on experience.

Lessons from the past

The climate system is not a simple linear system and we are unable to construct a curve that would allow us to determine the climate on Earth at any given time as a function of any given point in the Milankovitch Cycle. Within the glacial and interglacial periods, the climate had a wide range of variations of variable frequency due to the internal dynamics of the climate system, without any relation to the variations in the insolation of the Earth. The history of climate change in the Northern Hemisphere, such as it appears in the 'glacial files' of Greenland, where several core drillings have been carried out, allows the functioning of the system to be analysed – and in particular the ocean–cryosphere coupling, which plays a vital role in this matter and is perhaps the key to our climatic future.

The Heinrich Events

In 1988, Hartmuth Heinrich, analysing a core sample taken to the north of the Azores, noticed six very specific sedimentary layers made up of rock debris and not the usual Foraminifera-rich clays. They were identified as debris transported by icebergs and released when the icebergs melted (ice-rafted debris, IRD). The same layers were found in all the core samples taken in the Atlantic between 40°N and 50°N, from Newfoundland to the Bay of Biscay. Radioactive C_{14} dating revealed that the six layers were of the same age in all the core samples. This implied a major invasion of icebergs. It is estimated that such a break-up corresponded to the melting of approximately 2% of the American and European ice-caps, spread over a period of 1,000 to 2,000 years. The periodicity of these events observed between 20,000 and 8,000 years ago was 7,000 to 10,000 years and had nothing to do with any periodicity of the Milankovitch Cycle. They did, however, correspond to the coldest temperatures of the glacial period.

The Dansgaard-Oeschger Cycles

Nearly twenty years before the discovery of the Heinrich Events in marine sediments, Willy Dansgaard and Hans Oeschger had, by analysing an ice core taken in Greenland in the 1960s, detected rapid temperature changes during the last glacial period, particularly with a surprising temperature increase of a range equal to almost half of the maximum difference between the present climatic optimum and the glacial minimum. This discovery left scientists rather skeptical, as there was no similar situation in the ice sheets of the Antarctic continent, which were considered as more representative because they are isolated and therefore less subject to external disturbances. American and European core drillings in Greenland, in 1990–1992, confirmed the existence of these warm events within the glacial period: 23 were counted between 90,000 and 20,000 years ago. Furthermore, they revealed the rapid sequence of these oscillations: temperature variations of 10°C over Greenland could take place in only a few decades, very far from the prevailing idea of smooth starts and endings for the glacial periods. The period of Dansgaard-Oeschger (D-O) events varies from one 1,500 to 5,000 years. We now talk in terms of 'sudden climate change' to describe such events. To simplify, it is possible to describe the climate in the last glacial period as a succession of rapid oscillations inducing temperatures increases (D-O events) in a framework of more extensive events that bring about the coldest temperatures: the Heinrich Events.

The Younger Dryas

Such fluctuations are not limited to the glacial periods. Thus, towards the end of the last glacial period – approximately 12,000 years ago – while almost half of the ice in the Northern Hemisphere had already melted, the oceanic conveyor belt was set in motion and the most favourable time for the Milankovitch Cycle (maximum insolation in the Northern Hemisphere) arrived suddenly, in just a few decades, and a cold climate returned to Europe bringing almost glacial conditions for about 1,000 years. The end of this episode also took place quickly, 11,600 years ago: in about 70 years, the temperature in Greenland went up by more than 10°C, reaching the temperatures still experienced today.

And now, to the Holocene?

The current interglacial period, the Holocene, where we have been living for the last 10,000 years, shows less variability. The last significant change dates back 8,200 years, with a drop of 5°C to 6°C in Greenland and a cooling of the Northern Hemisphere linked to a partial breaking-up of icebergs or perhaps the breaching of a periglacial lake formed in North America during an ice-melting period. Low-amplitude oscillations appeared later, such as the short ice age between the sixteenth and the nineteenth centuries, when temperatures in Europe would were 1°C lower than they are today. At the decennial timescale of the NAO variations, we have seen that salinity anomalies (GSA) also bring about cold weather in Europe. There still remains enough ice in Greenland and in the Antarctic for us not to be safe from a break-up, which, though probably moderate, would be sufficient to have a significant influence on climate – particularly if we add influence of the human activities in progress, for which we are not yet able to assess their consequences, such as the increase in the concentration of greenhouse gases in the atmosphere.

The ocean and the ice

All the preceding events, which are not the same and rely on different mechanisms, have in common the fact that they bring into play freshwater exchange between the cryosphere and the ocean. During the glacial periods, a vast ice-cap covered a large part of the Northern Hemisphere in three blocks on both sides of the Atlantic: the most massive and thickest, was the *Laurentide*, in Canada and northern United States, and the *Greenland* and the *Fennoscandia* in Northern Europe. Ice cannot accumulate *ad infinitum* on the continents; glaciers have their own dynamics and they drift out into the ocean where they 'deliver' icebergs in more or less significant quantities. This process can be in stable equilibrium and, year in, year out, the ice-pack regularly discharges excess ice into the ocean. It can also be unstable and suddenly, like a collapsing dam, discharge great quantities of ice into the ocean. Ice means fresh water, a reduction in seawater density and, therefore, in deep-water formation and the thermohaline circulation.

It is thought that the largest and least frequent Heinrich Events correspond to a collapse of the Laurentide ice-cap. The collapse was due to the extension of the ice-cap into the sea, a highly unstable configuration, and/or instability of the subjacent sediment, owing to the inability of the telluric heat to dissipate under the thick ice layer. The dispersed icebergs melt, injecting a considerable volume of fresh water into the ocean. During this glacial period, deep-water formation was limited but not absent. The katabatic winds coming down from the ice-cap – as is currently the case in the Antarctic – produce a steep drop in temperature at the limits of the ice floe – as is currently the case in the Labrador Sea – provoking deep-water formation and weak but not nil thermohaline circulation. The massive freshwater input, which stratifies the ocean, weakens, if it does not put an end to, deep-water formation, and temperatures reach their lowest level. The end of a Heinrich Event leads to a significant temperature rise and makes temperatures change from the coldest to the warmest observed in the glacial period. When the ice-cap evacuates its excess weight, cold and low-salinity water is pushed back towards the north and oceanic circulation starts again: the conveyor belt is set in motion producing an exceptional warming in a glacial period. Having said this, it is a temporary warming, because we are then in the glacial configuration of the Milankovitch Cycle: the ice-cap reforms and the thermohaline circulation starts the slow rhythm it had before the ice-cap collapsed, until it reaches again its instability level, and a new Heinrich Event occurs.

The amplitude of the phenomenon and the excursions of the 'Heinrich icebergs' far to the south have for a while overshadowed the existence, between two Heinrich debris layers, of other traces of continental debris released by the icebergs and highlighted by the ice cores taken in the Norway Sea. Their quantity is considerably smaller and they are spread over a much more limited area. They apparently correspond to D-O oscillations. In addition, mineralogical analysis shows that the two types of debris have different origins: the 'Heinrich layers' obviously have their origin in the North American continent, while the 'D-O' debris seems to come from Europe following the break-up of the Fennoscandian glacier; each such break-up is much more modest but also more frequent than those corresponding to the Heinrich layers. This suggests that the Fennoscandian, which is smaller than the Laurentide, reached its instability level more rapidly. This also brought about climatic consequences of smaller amplitude. Ongoing studies will allow us to test the validity of this hypothesis.

It has not been possible to find traces of continental debris corresponding to the Younger Dryas in the North Atlantic sediments. Therefore, this time it is not a matter of freshwater input originating from the continental glaciers. Isotopic analyses carried out on Foraminifera skeletons living on the surface at the time of the Dryas and found in sediments testify to the presence of a great cold and low-salinity mass of water with no trace of continental ice. It therefore implies an input, via the icebergs, of frozen seawater of which a trace has been found as far away as the coast of Portugal. Its origin seems to be in the Arctic Ocean. This flood of icebergs in the Arctic can be explained by the sea level variation during the melting period and the morphology of the Arctic basin. The Arctic Ocean currently has a vast continental shelf going from the Barents Sea to the Bering Strait. In the middle of the glacial period, the sea level was 120 m lower than it is today and a major part of this continental shelf was exposed. The Arctic Ocean surface was reduced by 10%. Ice melting made the sea level rise, and the beginning of the Dryas corresponded to the time when the sea covered the entire Arctic continental shelf, thus providing additional space for ice formation. It was also the time when the Pacific and Arctic Oceans joined at the Bering Strait, which at the time was above water. At the same time, melting of the Laurentide increased water input to the Arctic Ocean via the Mackenzie River. The Arctic was then in a state of ice overproduction. Ice was probably exported to the Atlantic, where it melted, leading to further input of fresh water, an increase in stratification and a slowing down of the thermohaline circulation, and, finally, to a drastic temperature drop in the North Atlantic. It is, at a much larger scale, a phenomenon similar to the GSA, associated with the fluctuations in the NAO and variations in the ice dynamics in the Arctic. It can be said that the Younger Dryas was probably a time of a super-GSA.

Deep circulations of the past

The history of the past that we have just briefly recounted is based on three parameters: sea-surface temperature and salinity, which determine sea-surface density, and deep circulation, which is a consequence of the first two. We have already stated that the key to understanding these parameters was to be found in the sediments. More precisely, it was found in the calcareous skeletons of the Foraminifera (microscopic protozoans) discovered in the sedimentary layers: in their abundance and the isotopic composition of the carbon and oxygen constituting their calcareous skeleton. Planktonic Foraminifera, which live near the surface, record the temperature of the water in which they live. To produce their shell, they take from the water calcium ions and carbonate ions containing oxygen in two isotopic forms of different atomic mass: O_{16} and O_{18}. The ratio of these two isotopes in the Foraminifera depends on the temperature: the lower the temperature, the richer their shell is in O_{18}. By calculating the O_{16}:O_{18} ratio of the sedimentary Foraminifera shells, we can estimate the temperature of the sea at the time they lived. However, this ratio also depends on the isotopic composition of the seawater in which they developed. The concentration of O_{18} in continental glaciers is much lower than in seawater; therefore, at the site of a massive freshwater influx due to the melting of glaciers their must be a sudden drop in the O_{18} concentration in the sea and hence, in the Foraminifera. If we add to this the influx of fresh water, which is unfavourable to the survival of Foraminifera, we can understand that it is thus possible to estimate the sea-surface temperature, the magnitude of the freshwater influxes, and their origin (in land-ice or in sea-ice). This is how it was possible to determine the oceanic origin of icebergs in the Younger Dryas.

It is a little more complicated for deep circulation, as it is necessary to find the parameters that take into account the water movements and not just the state of the water at a given moment. In fact, the 'age' of water is calculated by its concentration of carbon dioxide, which changes in the course of time. At its starting point on the surface, future deep water in contact with the atmosphere becomes saturated with oxygen and carbon dioxide. When marine organisms living on the ocean surface die, they sink to the bottom, where the organic matter they contain becomes mineralized – a process that burns oxygen and produces carbon dioxide. During its descent, deep water becomes poorer in oxygen but richer in carbon dioxide. At a given point of its flow, the North Atlantic deep water flowing southwards will be older than at the start and richer in carbon dioxide. The age of the water thus determined measures the speed of flow, since it measures the time elapsed between the time the water left the surface and its arrival at a given point. Primary production, the origin of new living matter in the surface layers of the ocean, takes up the carbon dioxide needed for photosynthesis. This operation is done through isotopic partitioning, that is to say, the synthesized organic matter is poorer in C_{13} than the carbon dioxide dissolved in the ocean. Mineralization of organic matter preserves this lower C_{13} isotopic ratio, so that the older deep water is, the poorer it becomes in C_{13}. There is a benthic species of Foraminifera, living on the sea bed in deep water, whose shells preserve the isotopic ratio of seawater, as they form; they thus record the age of the deep water in which they live. Their retrieval in sedimentary layers enables us to estimate and compare deep-water flow during various climatic periods. This is how the first reconstruction of deep circulation during the last glacial period was carried out, an objective accomplished by the Climate Long-range Investigation, Mapping, and Prediction (CLIMAP) programme, which concluded that the thermohaline circulation had been reduced by one-third (Figure 25).

The accurate C_{13} records of benthic Foraminifera from recent core drillings in the GIN Seas, where the North Atlantic deep water is formed and flows out of, clearly highlighted the very important reduction in C_{13} associated with the Heinrich Events. This corresponds to an increase, up to 62°N, of water originating from the south, a sign of the slowing down or even arrest of deep-water formation in the GIN Seas during these periods. All the Heinrich Events have more or less similar characteristics. The situation is less evident for the intermediate D-O oscillations. However, it is indisputable that the cold phase of these oscillations also corresponds to a decrease in the flow of North Atlantic deep water. This decrease is less marked than in the Heinrich Events, and this is normal: temperature in Greenland is lower during the cold 'Heinrich' phases than during the 'D-O' cold phases. However, this temperature also has a greater variability from one oscillation to another, whereas the observed temperature variations from one D-O event to another are of the same scale. It is as if the same climatic characteristic in Greenland corresponded to different variations in the thermohaline circulation.

Taking into account the complexity of the climate system, the reverse would have been surprising. That is how scientific discovery of complex systems, such as the climate mechanism, is, and it does not lend itself to an experimental approach: we first seek in the set of observations consistency and repetitiveness in the evolution of the system, in order to have reference points and mark out the main processes involved – and eventually build up relationships that explain the change. Starting from this globally satisfactory preliminary pattern, we will inevitably discover 'anomalies' which will call it into question such as indications of the variability of a phenomenon at different timescales, and results of the internal dynamics of the system or the effects of processes not initially taken into account. We can give as an example the discovery of great glacial/interglacial climatic oscillations at intervals of approximately one hundred thousand years, or the search for an external periodic phenomenon to explain it, such as the astronomical Milankovitch Cycle. We should have liked to leave it at that and thus dispose of a relationship between variations in the distribution of the insolation of Earth inferred from this cycle and the climate it brings at a given time. The variability of the system at all timescales and their interference, from El Niño to the glacial/interglacial oscillations, including the NAO, the D-O and Heinrich oscillations, and so on, renders this expectation definitely illusory. There is not, and there will not be, a simple descriptor for the state of the climate system which would allow us to predict its evolution.

We are condemned to simulate climate change with the help of numerical models of increasing complexity, according to the system we wish to explain. It is therefore not surprising that, after having established the relationship between climatic variations and those of the thermohaline circulation, we now discover that there is no simple relationship between, for instance, temperature variations in Greenland and the intensity of North Atlantic deep-water formation. This does not take anything away from the importance of the phenomenon, but calls for caution in the simplistic use of observations of phenomena at a given time to forecast the climate *we shall have* in the decades to come. There are no alternatives to models to simulate future climates and, consequently, there are no worthwhile models without appropriate observations. What is expected of the detailed reconstructions of past climates is the verification of the validity of models and the appropriateness of the observations that feed them. When we have at our disposal detailed data series, such as those we have for the last glacial period, it is possible to test a model starting with an initial chosen time and see whether the forecast corresponds to what effectively happened afterwards.

The Gulf Stream has not come to a halt

The previous account has clearly shown the link between thermohaline circulation and climatic variation during the last glacial period and also now, in the middle of an interglacial period at the much shorter timescales of the NAO and the great salinity anomalies. It has also shown the preponderance of freshwater exchanges between the ocean and the cryosphere (continental glaciers and sea-ice) and the exchanges between the Arctic Ocean and the North Atlantic. In this saga, climate variation has not been about the Gulf Stream at all; it is as if the Gulf Stream did not have anything to do with it. Yet unlike the scientific publications on the subject, it seems to be the only issue in the media, with the press taking up this recurrent and tempting question: What will happen if the Gulf Stream comes to a halt? – as if it alone were the mastermind in the climate game.

The analysis of past situations being our sole 'experimental' source of information on the way the climate system operates and varies, we must first question the Gulf Stream's role during the last glacial period: Did it actually stop? It is not an easy task to recreate what the currents were in the past; even if the Foraminifera 'recorded' the temperature and salinity of the medium in which they lived, these data are insufficient to allow us to reconstruct velocity fields. However, this becomes possible when the current is clearly delimited, as is the case of the Gulf Stream in its Florida Current version, which is well channeled by the Straits of Florida, between the Bahamas and Florida. If it is possible to reconstruct, on each side of the Strait at various depths, past temperatures and salinity – and therefore density – it is possible to determine the hydrostatic pressure differences and the isopycnal gradient between the two sides of the current, from which we can derive the velocity of flow – based on the geostrophic theory. The O_{16}:O_{18} isotopic ratio of pelagic Foraminifera shells was used for this purpose (for surface conditions) and of benthic Foraminifera (for conditions at various depths); this ratio depends on both water temperature and salinity. By knowing the actual density field and the corresponding current flow it is possible, by comparison, to derive the current flow during the glacial period, as there is an almost linear relationship between the two. The conclusion is that the Gulf Stream definitely continued to exist during the glacial periods, but the average transport of the Florida Current, which is at present 31 Sv, with a variation of 4–5 Sv, was then between 14 and 21 Sv.

This result is not surprising if we recall that, contrary to what Arago thought, the driver of the Gulf Stream is the mechanical energy conveyed by the wind and not at all the thermohaline circulation, which is only a consequence of wind action on the ocean. To know whether the Gulf Stream has any reason to stop altogether, it is necessary to question the variability of the causal mechanisms, rather than the phenomena that are its consequences. There is no reason to think that the atmospheric anticyclonic circulation generating the Gulf Stream disappeared during the glacial periods. As already said, the total variation in the solar energy received from the Sun on the Earth during a Milankovitch Cycle is very low, and its variation corresponding to the latitude during the cycle is minimal at the Equator, which does not change its position on Earth. Therefore, the intertropical ocean remains the 'boiler' of the heat engine constituted by the atmosphere, and the resulting Hadley Cell has no reason to disappear any more than the atmospheric and oceanic anticyclonic circulations, which are its consequences. In order for the Gulf Stream to disappear, it would be necessary to have far more important modifications to the parameters of the terrestrial orbit than those of the Milankovitch Cycle. It is possible even to suppose – although we do not have the observations to confirm it – that the atmospheric subtropical anticyclonic circulation intensified during the glacial periods, since the horizontal thermal gradients between the Equator and the polar regions were much stronger than in the present interglacial period. This would better explain the decrease observed in the Gulf Stream's intensity.

Comparison with the Pacific Ocean is still useful: in this ocean, there is no convection, no deep-water formation, no overturning and hence, no thermohaline circulation; and yet, the Kuroshio continues to exist. The difference is that its flow rate is simply lower than the Gulf Stream's, which benefits from the thermohaline pump. The Pacific Ocean is a picture of what the North Atlantic circulation would become if this pump happened to stop working.

On the other hand, what does change during the glacial periods is the heat transport northwards by the ocean and the atmosphere, the latter being itself supplied by the ocean. The coupled anticyclonic circulations of the atmosphere and the ocean then extended less far north, and the previously mentioned Gulf Stream North Wall (GSNW) was then located farther south than it is today. This is a direct consequence of the weakening of the thermohaline circulation, which currently 'aspirates' on the surface a flow of about 15 Sv, which is 'credited' to the Gulf Stream. We cannot help linking the 15 Sv to the difference observed in the flow of the Florida Current between today (31 Sv) and the last glacial period (around 17 Sv). The Gulf Stream was indeed cut off, during the glacial period, from the 15 Sv of thermohaline circulation brought about by the

North Atlantic deep-water formation in the GIN Seas. Not only the Gulf Stream: the entire conveyor belt slowed down as a consequence. This is not in contradiction to the maintenance of the thermohaline circulation during the glacial periods, because even if there is no deep-water formation in the GIN Seas, there are other sites of deep-water formation independent of the high-salinity water input by the Gulf Stream and its extensions, as is still the case in the Labrador Sea.

The driver of the variation in the thermohaline circulation and the associated climate variation is undoubtedly not the Gulf Stream, but rather the dynamics of freshwater transfer between the cryosphere and the ocean in the Arctic, and the resulting exchanges with the North Atlantic. We must abandon the idea, inherited from Maury and Arago, that 'Gulf Stream = thermohaline circulation'. The Gulf Stream does not stop, and its variations are the consequences and not the causes of the variations in the thermohaline circulation.

THE FUTURE OF THE THERMOHALINE CIRCULATION

The preceding conclusion could, logically speaking, close the story of the Gulf Stream since, by extrapolating, we could suggest that it will not be a driver of long-term climate change in the future any more than it was in the past, although it itself is subject to the consequences of such change. As in the past, the problem for us now is to assess probable changes in the thermohaline circulation, which controls the heat flux towards the high latitudes in the North Atlantic and of which the Gulf Stream is an instrument. The question is not, we must insist: Will the Gulf Stream come to a halt? But will future climate changes bring about a slowing down of the thermohaline circulation or stop it altogether, resulting, in spite of global warming, in a drastic drop in temperature in the high latitudes of the Northern Hemisphere? The problem is taken very seriously by the Woods Hole Oceanographic Institution (WHOI), which was created almost exclusively to study the Gulf Stream, and which has remained an extremely fertile research field for the Institution. Its Chairman, Robert B. Gagosian, submitted a report from on this subject to the World Economic Forum in Davos, in 2003, entitled, *Abrupt Climate Change: Should We Be Worried?* It draws attention to the possibility, even the probability, of abrupt climate changes similar to those which took place in the past, such as the Younger Dryas, when North Atlantic temperatures fell 4–5°C in a few decades; this is a not so distant example, and the rapidity of fluctuations in the last glacial period were also comparable. According to this report, under present conditions, the end of the conveyor belt would be equivalent to a rapid drop of 3° to 5°C in temperature in the North Atlantic. Climate does not change in a smooth and progressive way, but by fits and starts, suggesting that there are, in certain particularly sensitive climatic processes, thresholds beyond which the system can flip from one state to another. Deep-water formation in the North Atlantic is one such example. What would happen in response to the new perturbations in the system, caused by the human race, until now considered a negligible influence?

Concerning the possiblity of an abrupt climate change, a report by the Secretary of Defence of the United States, in October 2003, constructed a 'worst-case scenario', based voluntarily on the most unfavourable hypothesis, in order to analyse possible impacts of such changes on the economy, natural resources and potential conflicts and their consequences for security in the United States. The scenario begins with an acceleration of present global warming due to the increasing concentrations of greenhouse gases, leading to the collapse of the thermohaline circulation from 2010 onwards, bringing during a warming period, as in the Dryas, an abrupt drop in the annual average temperature of about 3°C in Asia, North America and Europe, and an increase of more than 2°C in Australia, South America and South Africa. All this would be supplemented by storms, floods and drought that would produce armed conflicts worldwide and massive population displacements. As the authors of this report state, it is 'thinking the unthinkable', based on an extreme scenario, which is not the most probable, but which they consider plausible.

Let us set aside geopolitical and geo-strategic extrapolations, which are pure speculation, and retain only the question: Is such a climate scenario really possible? Is there a threshold beyond which the conveyor belt would come to a halt? R. B. Gagosian quite rightly replies '*We don't know*'. The difficulty is twofold. Climatic numerical models often function on the basis of a constant pattern of change; they can actually forecast a progressive weakening leading to a complete halt in the thermohaline circulation, but they are not capable of defining a hypothetical threshold – for example, the salinity of the North Atlantic above which the climate system will flip. There again, we have no experience, since it is the first time in known climate history that the problem of the arrest of the thermohaline circulation has arisen during a climate optimum, not because of cooling, as in the past, but because of additional warming. Not satisfied with just drawing attention to the possible imminence and suddenness of such an event, the Pentagon report insists, in its conclusions, on research to be undertaken concerning climatic changes and their consequences, including the appropriate measures to adopt and the technical means to control the climate, adding, for example, gases (hydrofluorocarbons) to counteract cooling – in other words, deliberately releasing greenhouse gases… to fight against the effects of greenhouse gases! What in fact this report implies is that the die is cast, and that it is too late to limit the damage by trying to reduce the concentrations of greenhouse gases and that it would therefore be better to start straight away caring about the measures to be taken in order to adapt ourselves. Let us hope that this is not the case and that we can still make this 'unlikely' scenario become an impossible scenario.

The threat: the increase in greenhouse gases in the atmosphere

To say that the atmosphere contains greenhouse gases is nothing new; in fact, it is a blessing: if there were none, the average temperature on the Earth's surface would be -18°C. The main greenhouse gas by far is water vapor. Others are found in much smaller quantities, such as carbon dioxide, methane, ozone, nitrogen oxide and so on. Core drilling in the Greenland and Antarctic ice-caps, which allowed reconstruction of temperature records on Earth over the past eight hundred thousand years, also revealed a parallel evolution in the concentration of greenhouse gases, such as carbon dioxide and methane, through the analysis of the air bubbles trapped in the ice at the time ice was forming (Figure 24). The concentrations of these gases closely followed the alternating glacial/interglacial periods and, within the glacial periods, the great climatic oscillations, such as those of

Heinrich. Warm periods correspond to high concentrations of carbon dioxide and methane, and vice-versa. The reverse would have been a real nuisance for scientific logic. It is more or less established now that temperature variations precede those of greenhouse gases, which subsequently amplify the thermal signal. During the coldest periods, the CO_2 concentration falls to 180 ppm and, at climatic optima, it increases but does not exceed 300 ppm. The problem is that now human beings, through their diverse industrial and agricultural activities and their increasing consumption of fossil fuels, continue to inject greenhouse gases into the climate system. This is causing an unprecedented perturbation in the history of the climate, both through the impact and the extent of these greenhouse gas emissions. The present concentration of carbon dioxide in the atmosphere has exceeded 370 ppm, far above the maximum values attained over the last five hundred thousand years. We have left the beaten track and are now entering unknown territory: we do not have an historical reference to tell us where we now stand. Even if it enables us to analyse climatic processes and to validate predictive models, reconstructed history is not of great help to us in trying to forecast, in an empirical way, how climate will change, because the perturbation introduced here is of a radically new nature.

Forecasts and uncertainties of the IPCC

The impact that the increase in greenhouse gases could have on climate poses a double challenge. First there is a political and economic challenge illustrated by the difficulties in reaching an international agreement on the implementation of the Kyoto Protocol (1997), aimed at reducing, by 2008–2012, the production of greenhouse gases by 5.2% relative to the level in the 1990s. Even though, in the aftermath of the Earth Summit at Rio de Janeiro, in 1992, the Protocol was elaborated within the framework of the United Nations Framework Convention on Climate Change (UNFCCC) and signed by 150 countries. Second, it was also a scientific challenge, proposing feasible scenarios of climate change for the next one hundred years.

In 1988, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) created the IPCC Intergovernmental Panel on Climate Change (IPCC), and charged it with the assessment of the available scientific information and with providing advice on the impacts and the envisaged prevention and adaptation measures. The IPCC published its third report in 2001. It formulated several scenarios of greenhouse gas emission, based on hypotheses of world economic, demographic and technological development. These scenarios have been used to 'force' simulation models of climate change over the next one hundred years.

Based on scenarios from dozens of available models, the rise in the average temperature would be somewhere between 1.4°C and 5.8°C, this range being due more to the variability of the gas-release scenarios than to the models themselves. The rise in the sea level would be somewhere between 11 cm and 77 cm, as a result of expansion of the seawater due to a rise in sea temperature (between 11 cm and 43 cm) and of melting of the glaciers (between 1 cm and 23 cm). The temperature rise would not be homogeneous over the Earth's surface: for example, it would be much greater at higher latitudes than in the intertropical zone.

The experimental method, involving the use of intermediary models, has a handicap compared with classic physical and chemical experiments carried out in the laboratory. Experimental verification, which is the only way to dispel uncertainty, is only possible as we reach the prediction deadlines in real time. This is particularly critical for long-term IPCC scenarios: obviously we cannot wait for experimental verification to validate forecasts when we have a deadline of a few decades to take action on global warming. This, of course, nourishes skepticism for the results of the models. Thus, it is not uncommon for scientists seeking media attention to forget the complexity of the climate system by refuting the relationship between the present rise in temperature and CO_2 levels in the atmosphere, and consider, for example, one poorly known parameter (nebulosity, among others) and hold it as practically the sole determinant of climate change. To validate the models, we nevertheless have palaeo-climatic data available; we can apply a model at a given time in the past and analyse the accuracy with which it explains subsequent changes. From this analysis, we may draw lessons enabling us to improve the formulation of the model.

The IPCC is not just concerned with making projections for one hundred years ahead; it is also concerned about the climatic variations at other timescales, such as those of El Niño, the NAO, and the thermohaline circulation. We have seen that the NAO fluctuations have an impact on the ocean: on surface temperature, the subtropical anticyclonic circulation and the Gulf Stream and, probably, on the thermohaline circulation. On the contrary, the mechanisms whereby the ocean, in return, exerts an influence on the NAO are not well established. Consequently, they are taken into account only in an uncertain way, and there is no consensus on ocean–atmosphere coupled models for the prediction of changes likely to take place in climate variability associated with the NAO fluctuations. However, there is a feeling that recent variations in the NAO and its trend towards strongly positive values since the middle of the 1970s are linked to the continuous temperature rise since the end of the 1970s after a slight cooling in the period 1950–1960 which is probably not disconnected from the cold phase of the NAO in the same period. We can expect this trend to be confirmed, contributing to the amplification of the subtropical anticyclonic circulation, northward heat flux and a temperature increase in the North Atlantic –unless the slowing down of the thermohaline circulation, without necessarily reaching catastrophic proportions, came to curb this trend. Cautiously, the IPCC concludes in its *Projections of Future Climate Change* concerning decennial and multi-decennial variability:

'In summary, there is not yet a consistent picture emerging from coupled models as to their ability to reproduce trends in climate regimes such as the recently observed upward trend in the NAO Index. In addition, whilst several models show an increase in the NAO Index with increased greenhouse gases, this is not true for all models, and the magnitude and character of the changes vary from one to the other.'

Exactly what does the IPCC work reveal about the infamous thermohaline circulation? The ongoing situation regarding Atlantic deep-water formation in the GIN Seas, which are the largest contributors to the thermohaline circulation, requires for its operation a subtle balance among the different factors. At high latitudes, the ocean loses heat and gains fresh water through rainfall and inputs from rivers, two phenomena that cause seawater density to vary. This is compensated by the symmetrical warm seawater input coming from the south via the Gulf Stream and its extensions. Sea-ice formation also plays its part. For example, a decrease in the thermohaline circulation and, therefore, heat transport northwards, leads to more ice formation, which will increase water density, facilitate the convection and, consequently, favour an increase in the thermohaline circulation. It may then happen that there is exportation of excess ice far from the areas where it was formed, which corresponds to a freshwater input unfavourable to deep-water formation and, therefore, to the thermohaline circulation. Changes in the thermohaline circulation depend on the relative influence of all these actions/reactions, which may be modified by global warming.

The foreseen increase in sea-surface and atmospheric temperatures itself has a direct impact: on seawater density, a decrease in sea-ice formation and, possibly, the melting of the glaciers (particularly in Greenland and the Antarctic). The IPCC scenarios also indicate an increase in rainfall around the Arctic and a greater freshwater input by rivers in North America and Asia. All these elements make all but one of the models used by the IPCC predict a reduction of 10% to 50% in the thermohaline circulation between now and 2100. If simulations carried out with certain models indeed foresee a complete stop of the thermohaline circulation, with a global temperature increase of 3.7–7.4°C, none of the simulations resulting from the IPCC coupled ocean–atmosphere models lead to such an eventuality between now and 2100. With this perspective, all of them seem to indicate a continuous temperature rise in Europe, even those announcing the greatest reduction in the thermohaline circulation. Such an event may happen later, but it is not excluded that it may happen sooner. The IPCC, aware of the uncertainty due to threshold effects, which are not fully taken into account in the models, does not exclude it:

'While none of the projections made with coupled models show a complete shut-down of the thermohaline circulation during the next 100 years, we cannot exclude the possibility of threshold phenomena within the range of projected climate changes. Furthermore, since natural variability of the climate system is not fully predictable, there are necessarily limitations inherent in the climatic system itself regarding prediction of thresholds and transition phases.'

In other words, it is a hardly probable but not impossible event, which takes us back to the reports by R. B. Gagosian and the Pentagon.

Recent observations

It is from air temperature that we acquire near certainty about the effects of the increase in greenhouse gases on climate. Since 1860, we have at our disposal reliable and continuous temperature measurements showing a very rapid temperature rise (0.8°C) ever since the concentration of carbon dioxide in the atmosphere began to increase significantly, reaching its current rate of increase of 1% a year (Figure 26). It is a sufficiently long period for us to be able to eliminate from the possible causes of such an increase those phenomena, such as the NAO, taking place at decennial or multi-decennial timescales, and we cannot find in the recent or distant past (the previous interglacial period 120,000 years ago, for example) anything equivalent that would explain it by natural phenomena. Furthermore, climatic models that have best explained temperature changes since 1860, including the slight cooling observed in the years 1950–1960, are those that integrate the production of carbon dioxide by human activities. The same models, forced only by the natural dynamics of climate, do not reveal any significant temperature rise between 1960 and 2000, whereas it was during this period that it was the highest. Obviously, this gives us confidence, because, if these models functioned well over the past century, why should they not function for the next century, when the disturbance, even if it increases, remains of the same nature? Unless it makes us cross the possible threshold that would lead to a complete shutdown of the conveyor belt.

In the ocean it is more difficult to detect equivalent significant signals of global change, because of a lack of adequate observations and measurements. Knowledge of oceanic variability is not very old; as traditional observational means from research vessels allowed only very limited measurements geographically and in time. It was, in fact, the issue of climate itself that imposed the need for systematic observations of the oceans, and the World Climate Research Programme launched in 1980 – only twenty-five years ago – set up the first network of systematic observations of the ocean. It was together with the World Ocean Circulation Experiment (WOCE) between 1990 and 2002 that we first described the circulation of the entire ocean, from the surface to the ocean floor, from north to south and from eddy scales to those of the great oceanic gyres. Under these conditions, it is difficult to make, as is possible for the atmosphere, analyses of the variation in oceanic circulation at different timescales – and particularly those such as thermohaline circulation, which have a long time-span. Moreover, it is significant that the IPCC report, in the chapter entitled 'Observed Climate Variability and Change', which analyses all the indicators of global change in the climate system, evokes, with respect to the ocean, just the ENSO (El Niño–Southern Oscillation) and the NAO, with nothing at all on the observation of the variations in the thermohaline circulation. There is nothing surprising about that: it was an acknowledgement of the Panel's ignorance. Taking into account this lack of ocean observation over the long term, we are, objectively, incapable of saying whether recent measurements and observations are a sign of change in the thermohaline circulation linked to global warming and to the increase in the concentration of greenhouse gases. In particular, it is not possible to take into consideration the decennial changes related to the NAO, for example, and longer-term change. The series of measurements are insufficient and we have seen that the degree of coupling between the ocean and the atmosphere at these scales is too uncertain to enable us to draw any conclusions.

The reports by R. B. Gagosian and the Pentagon are based on two publications that would provide proof of ongoing decline in the thermohaline circulation, sounding the alarm and warning us of the catastrophic scenario of an imminent and sudden failure of the thermohaline circulation.

First, there is the observation (Bob Dickson et al. 2003) of a salinity decrease in the Labrador Sea since about 1975, in the deep water formed in the GIN Seas between the depths of 2,000 m and 3,300 m (Figure 27). The Labrador Sea lies on the route of the deep water coming from the GIN Seas through the Straits of Denmark, between Greenland and Iceland, and the Faeroes Channel, between Iceland and Scotland. It is possible to interpret this salinity drop as a sign of less convection in the GIN Seas, where it is initially produced by the strong salinity of the surface water. Therefore, it is quite probable that there has been a decrease in the thermohaline circulation over the past thirty years.

However, Figure 27 can be interpreted differently, because what is obvious is not so much this salinity decrease since 1975 as the evidence of a maximum between 1960 and 1975. In 1950, salinity at a depth of 2,800 m had the same value as in 1995. If we rely on the relationship between the salinity and the intensity of the thermohaline circulation as a basis for our reasoning, we may conclude that it went through a maximum in the 1960s and, therefore, it was comparable to what it is today; thus, it would not necessarily be a sign of major climate change. Moreover, we note that this alternation is in phase with the NAO variations: maximum salinity corresponds to a period of negative NAO anomalies in the 1960s, and the subsequent salinity decrease goes together with the high NAO values in the years 1970–2000. This does not imply that there is a relationship of cause and effect, but nonetheless, it poses a problem. We have indeed established a rather logical positive correlation between the Gulf Stream flow and the NAO, and we arrive at this paradoxical result: that intensification of the Gulf Stream in a period of strong NAO – and thus more salt transport northwards – corresponds to a decrease in the thermohaline circulation characterized by a salinity decrease! This suggests that there could be an absence of coupling or, at least, phase difference in the Atlantic Overturning Circulation, between the surface – the Gulf Stream and its extensions – and the deep circulation, contrary to what was previously said.

Indeed, nothing stands in the way of accepting the fact that, at the scale of NAO variation, the two components are out of phase, even without their long-term coupling (that of the D-O and Heinrich Events) being called into question. It is perhaps a clue, or even the proof of the existence of a coupling mechanism between the ocean and the atmosphere controlling the NAO fluctuations. A high NAO Index corresponds to an increase in the northward transport of heat and salt by the currents. That is, two parameters that have opposite effects on water density, yet their balance can actually lead to a reduction in convection beyond a certain level of flow. In the end, the slowing down of deep circulation will reflect on the surface current, the anticyclonic circulation, which will lead to a weakening of the NAO and a return to stronger convection, and so on. In other words, decennial fluctuations of small amplitude in the Gulf Stream can exist out of phase with those of the thermohaline circulation via the NAO and these do not contradict the variations of much greater amplitude corresponding to the Heinrich, D-O and Younger Dryas events. This is largely speculative and it may very well be that: (i) the present changes in the NAO are already a consequence of global warming; and (ii) warming and salinity variations already recorded are sufficient to slow down the conveyor belt for a long period. However, we do not know. Time will tell. Nevertheless, we cannot currently hold salinity reduction in the Labrador Sea to be proof of the response of the thermohaline circulation to global warming. This example illustrates the challenge of separating the different scales of variability without the verification of long-term ocean observations.

The second is a report by Bogi Hansen et al. (2001) that gives the results of direct measurements and calculations of deep-water flow through one of the two paths followed by the deep water formed in the GIN Seas: the Faeroes Channel, through which approximately one-third of the total flow passes. In the World Ocean Circulation Experiment, continuous current measurements were made at a fixed point with a Doppler acoustic currentmeter moored on the sea floor, from 1995 to 2000. These measurements indicated a 2%–4% reduction in flow during this period. They also made it possible to calibrate the flow calculation based on hydrographical observations carried out regularly since 1948. The principle behind the calculation is rather simple: the flow is a function of the difference in hydrostatic pressure upstream of the sill and at the sill itself, and we calculate the pressure from measurements of salinity and temperature throughout the water column. The results show a regular decrease of approximately 20% in the flow since 1950. This study did not take into account the fact that half of this flow of deep water passes through the Denmark Strait. Is this information sufficient to conclude that there is an overall reduction in the flow of North Atlantic deep water? Probably not, especially since the dominant mode of the variations in the Denmark Strait estimated by the geostrophic method seem to correspond to the decennial timescale of the NAO. This displayed, once again, a maximum in the years 1975–1990, in phase with the variations in the Gulf Stream derived from the difference in potential energy between Bermuda and the Labrador Sea (Figure 20). This is in contradiction with the preceding analysis based on salinity in the Labrador Sea. Certain models even foresee that maintaining the NAO at a high level would delay the weakening of the thermohaline circulation. These partial and contradictory results are due to the lack of observations, which are the source of all our knowledge of the climate system, and once again to our inability to categorize scales of oceanic circulation variability in the absence of sufficiently long series of direct ocean measurements.

No matter what happens, the Hadley Cell will not disappear, nor will the anticyclonic gyre associated with it, and the Gulf Stream will continue to be the gyre's western boundary current.

4 The Gulf Stream and the Ecosystems of the North Atlantic

The Atlantic biomes

The main ecological regions called 'biomes' are easy to identify based on their climatic and edaphic characteristics, as well as the type of predominant vegetation – for example the savannah, the equatorial forest and the tundra. It is also possible to identify the ocean biomes from the dynamics of the surface layer, which determines the conditions governing the productivity of marine ecosystems. However, the Gulf Stream seems to disrupt the organization of the ocean biomes in the North Atlantic.

The Florida Current

The first section of the Gulf Stream, the Florida Current, flowing between the southern tip of Florida and Cape Hatteras, is a northward extension of the tropical Trade Wind biome. Transporting warm nutrient-poor water, its own biological production is low. Nevertheless, running close along the continental slope, it generates, on its left-hand side, deep-water upwelling and nutrient-enrichment of the water of the continental shelf, which it borders and fertilizes.

THE GULF STREAM – ISBN 978-92-3-103995-9 – © UNESCO 2006

The 'Gulf Stream province'

The 'Gulf Stream province', to the north of Cape Hatteras, is the site of eddy formation generated by the instability of the Gulf Stream itself. Far from being an obstacle, the Gulf Stream is an agent of exchange. It lets the warm and relatively unproductive water of the Sargasso Sea, on its southern side, pass to the 'Slope Sea', on its northern side, between the Gulf Stream itself and the American continental shelf: these are the warm eddies (also called warm-core rings). These rather unproductive eddies are, like the Florida Current, fertilizing agents along the continental slope. Conversely, cold eddies (cold-core rings) allow cold and productive water to pass from the 'Slope Sea' into the Sargasso Sea, which is thus enriched to the benefit of the residents, including eel larvae.

The 'North Atlantic Drift province'

The Gulf Stream's special dynamics do not play a role in its eastward extension via the North Atlantic Current. Therefore, we are in a normal situation of a westerly-wind biome, in which the dynamics of the surface layer is determined by seasonal variation in the insolation and in the predominant westerly winds. Variability of the marine ecosystem here is linked to the NAO, which controls the westerly winds. Nowadays, in terms of exploited resources, this natural variability is often masked by over-exploitation of these resources.

THE GULF STREAM – ISBN 978-92-3-103995-9 – © UNESCO 2006

THE ATLANTIC BIOMES

Terrestrial ecologists have the advantage of the solid Earth as a platform from which they can observe ecosystems at leisure, establish a typology and a geography and relate their functioning to climatic (temperature, rainfall, insolation) and edaphic (soil properties) parameters that they are then able to model. Thus, it is easy and useful to recognize the large ecosystems of tundra, humid equatorial forest, savannah and many other biomes defined by Eugene Odum in 1971. Borders are also easy to assign, as the 'ecotones' or transition zones generally correspond to rapid changes in physical parameters – for example, the drop in rainfall when passing from equatorial forest to savannah. In comparison, the ocean seems monotonous. A traveler flying over Brazil may assume the eye of an ecologist when passing over the luxuriance of the Amazonian forest to the aridity of the Nordeste. If the traveler continued across the Atlantic to Africa, only the shadows of clouds and the glistening of the Sun would give them the illusion of diversity in the marine landscape. Nothing would suggest that the ocean the traveler is flying over is also home to a large variety of ecosystems and that it may be possible to define their biomes. The major difficulty encountered with marine ecosystems is that the plants, except those in coastal regions, do not have roots. The ocean prairies are made of vegetal plankton (phytoplankton) floating freely in the ocean currents. Unlike rooted terrestrial ecosystems which are static, marine ecosystems are controlled by the dynamics of the fluid in which they evolve.

The natural world develops through the synthesis of organic matter from mineral elements. This synthesis is obviously not free: it requires energy. In most cases, it is provided by sunlight. Sometimes, in the absence of light, organisms find the necessary energy resources in chemical reactions. This is the case, for example, in ecosystems that have developed at the bottom of the ocean around hot hydrothermal sources, in the absence of any source of light. Although there are good reasons to think that life developed from these chemosynthetic processes, it is unquestionable that photosynthesis, as a primary source of production, has predominated over a few billion years and has ensured the development of terrestrial as well as marine life.

The basic elements for production of organic matter are carbon dioxide (CO_2) and water (H_2O) which, by means of chlorophyll which is capable of fixing the light energy, are combined to produce basic organic matter according to the following simplified equation: $CO_2 + H_2O + \text{light} = (CH_2O) + O_2$.

Organisms also require other elements: nutrient salts, or nutrients, which are sources of nitrogen, phosphorus, silicon and a whole range of inorganic elements; and these determine whether a region is more or less fertile. On the land, a lack of one or other of these elements can be compensated by external inputs, through irrigation, fertilizers and so on. Given the necessary means, it is even possible to build golf courses in deserts. Regarding the ocean, where there is no lack of water, it is probably difficult to talk about deserts, although, as on land, there are very big differences in fertility from one region to another. In the sea, phytoplankton, the equivalent of grass in terrestrial meadows, is responsible for marine primary production, constituting the starting point of the marine food web that leads to the fish we find on our plates. The abundance of these mono-cellular microscopic (a few microns across) algae determines the fertility of a marine region.

In the ocean, there is obviously no shortage of water nor of carbon dioxide, which is a major source of carbon and is abundant everywhere. The Sun, the only source of light for primary production, floods the sea surface, but water quickly absorbs solar radiation, so this production will obviously be limited to the ocean surface layer; the dark ocean depths beyond one hundred metres are scarcely propitious for the development of life. Only the oases surrounding the major hydrothermal sources, which require other sources of energy, are spared this constraint.

To ensure the fertility of the oceans, the availability of nutrients remains the key. Yet, these nutrients are much more important at depth than at the surface; this is something that can be easily understood. The natural world is a renewable system that continuously feeds on its own dead: the decomposition of dead organic matter returns to the mineral world elements that it had borrowed when alive: water, carbon dioxide and nutrients made available again to living organisms for a new cycle. It is thus possible to have ecosystems close to equilibrium, where life and death are almost quantitatively equal. However, no object escapes the force of gravity, and marine organisms, having lost their capacity to float or swim when dead, are inexorably carried down to the ocean floor, decomposing and mineralizing during their descent to the bottom. It is in this way that they return most of their main mineral compounds to the sea water, not in the surface layer favourable to photosynthesis, but in the deep layer, protected from light.

To ensure its fertility, the ocean must solve this challenge and bring nutrients from the deep layer to the well-lit surface layer. Various dynamic enrichment processes carry this out and thus, it is ocean movements that control marine productivity. The ocean 'colour' is an indicator of fertility in a marine region, but an observer cannot, at a simple glance, detect the subtle variations that would allow the classification of marine ecosystems. This kind of observation has been delegated to better-performing 'eyes', in the form of specialized instruments installed on satellites.

The ocean colour initially depends on the optical properties of water, which has a selective capacity to absorb solar radiation: it transmits blue light more easily, hence the marine blue so characteristic of the open sea. However this blue, which has inspired poets for centuries, can be altered by 'impurities' in the ocean which, in coastal areas, may be muddy water discharged by rivers and streams or simply living creatures – particularly vegetal plankton which, being rich in chlorophyll, tends to colour the ocean green. The greater the quantity of phytoplankton, hence of chlorophyll, the more the ocean will appear green. By analysing the light coming out of the ocean (its colour) and by calculating the light intensity ratio against the characteristic chlorophyll wavelengths (blue for the maximal absorption, green for minimal absorption), we can obtain the chlorophyll concentration in the ocean, and hence its richness. This is done from space by radiometers on board satellites, which measure the light intensity received by the ocean at the characteristic chlorophyll wavelengths.

The image in Figure 28 represents the average chlorophyll concentration of the world's oceans in 1998 and 2003. They were generated using data from the SeaWiFS satellite and allowed the establishment of an inventory of marine vegetation. We can see that in the sea there are important contrasts from one region to another, similar to those observed on the continents: from blue in the poorest zones at the centre of the anticyclonic gyres, via a transition zone of green, to yellow, then red in the richest regions.

The differences observed among the oceanic regions reflect the physical-enrichment mechanisms at work, which vary from one system to another. Moreover, in order to define the biomes in the marine environment, it would be sound to characterize them according to the different types of mechanisms rather than to a characteristic type of vegetation, as is done for static terrestrial systems. Furthermore, in a pelagic environment, marine vegetation limited to phytoplanktonic algae does not provide enough contrast to be used as a criterion of definition.

This is how Alan R. Longhurst (1998) proceeded, in order to present the first 'ecological geography' of the oceans ever attempted, from the analysis of the mechanisms controlling the dynamics of the mixed surface layer. The ocean spontaneously tends to organize itself into a stable system containing two layers: the first is superficial warmed from the energy received from the Sun and homogeneous due to the mixing generated by the wind; the second, subjacent to the first one, is cold and extends down to the bottom. A zone in which the temperature decreases rapidly with depth separates these two layers: the thermocline.

The thermocline is also necessarily a pycnocline (a rapid increase in density with depth). It impedes mixing of the two layers and, in particular, the transfer of nutrients into the well-lit surface layer. Thus it limits primary production and fertility in the system. It is therefore logical to define biomes according to the physical mechanisms that control the dynamics of this mixed layer and this brake to biological production created by the thermocline. The parameters we have to take into account are solar radiation (source of heat), wind (main mixing factor), rainfall and other inputs of fresh water, which can all create stratification of the water column close to the surface.

The intensity of solar radiation depends on latitude: it is obvious that the amount of energy received is greater in intertropical regions than at high latitudes. Less obvious, but nonetheless real, is the influence of latitude on the action of ocean winds. Again, the Coriolis force is in play. The Coriolis force is active only when there is motion; which increases with latitude, and thus it also increases the inertia it induces in the currents with latitude. The Coriolis force is zero at the Equator and inertia is at a minimum, so that wind variations have a very rapid effect on currents. For example, in the equatorial Pacific, the El Niño phenomenon corresponds to a current inversion in quick response to a weakening or a reversal of the Trade Winds. In the same way, the Somali Current along the Horn of Africa, in the Indian Ocean, is reversed in a few weeks, following the rhythm of the monsoon. At the highest latitudes, the Coriolis force is active as long as there is motion, thus in this region it helps to conserve the motion even if the wind stops blowing in these locations. The considerable weakening of the westerly winds at mid-latitudes during the summer has practically no effect on the Gulf Stream. It would take years for an inversion of westerly winds in the North Atlantic to overcome the Gulf Stream. In these regions, wind variations, combined with important seasonal sunlight variations, control the dynamics of the mixed layer but have a small impact on the currents. Close to the Equator, it is the opposite: plenty of sunshine with low seasonal variation, together with the quick response of the currents to wind variations, maintain a relative stability of the mixed layer and its thickness varies according to the currents.

From this analysis, Longhurst defined four primary biomes:

- *Westerly-wind biome* at mid-latitudes, where the depth of the mixed layer is controlled by local wind and solar radiation;
- *Trade-wind biome*, where the mixed layer depends on the adaptation of the currents to wind variations at ocean-basin scale;
- *Polar biome*, where the freshwater layer controls the mixed layer formed every spring when the ice pack melts;
- *Coastal biome*, on the continental slopes and shelf, where, in addition to the previous elements mentioned, local characteristics intervene: morphology, orientation of the coast, topography of the ocean floor and so on.

These are basic biomes, which are obviously not homogenous. To take into account characteristics due to the continents and marine currents, which complicate this latitudinal classification, Longhurst introduced 'provinces' for each biome in each ocean (Figure 29).

If we consider the Gulf Stream in its mythical and popular version, from the Florida Strait to the Norway Current and to the edge of the Arctic, it corresponds, according to Longhurst's classification, to two biomes – polar and westerly-wind – and to three provinces: the Atlantic Sub-Arctic Province (SARC), the North Atlantic Drift Province (NADR), and the Gulf Stream Province (GFST). In fact, the Gulf Stream and its extensions, in the different stages of their flow, run obliquely into the Atlantic: this is the source of the dynamic elements that disturb the neat latitudinal organization of the biomes proposed by Longhurst.

THE FLORIDA CURRENT

From the outset, we notice that the first stage or the first section of the Gulf Stream, the Florida Current, flowing from the southern tip of Florida to Cape Hatteras, does not belong to any of Longhurst's provinces. To the east, the North Atlantic Subtropical Gyral Province (NAST), belonging to the westerly-wind biome, is limited on its western and northwestern sides by the Gulf Stream, which it does not include. To the west, the coastal Northwest Atlantic Shelves Province (NWCS) comprises only the American continental shelf and slope, from the southern tip of Florida to Newfoundland; therefore, it excludes the Gulf Stream. Finally, to the north, the Gulf Stream Province, in the strict sense of the term, goes from Cape Hatteras to the Great Banks of Newfoundland.

We can and must consider this current as an extension of Longhurst's Caribbean Province, which includes the Caribbean Sea and the Gulf of Mexico, bordered on the east by the West-Indian Antilles arc, from Trinidad to the Bahamas, and as a northward 'excursion' of the trade-wind biome. The surface temperature chart in Figure 30 clearly traces the Gulf Stream's course along the continental slope. A stream of warm water (24°C–28°C) 30 km wide and 300 m deep, with a flow rate of 30 Sv, on leaving the Florida Strait, doubles its flow rate at Cape Hatteras due to the recirculation described in the previous chapter. At this point, it reaches 1,000 m in depth and a width of 50 km. This section of the Gulf Stream corresponds more to the trade-wind biome than to the westerly-wind biome, in the sense that local wind variations have little influence on the vertical thermal structure of the current, which is mainly determined by the adjustment of the North and South Equatorial Currents feeding it.

Extension of tropical species – sport fishing

The Florida Current is poor in nutrients, as it carries warm water from the Caribbean, which are confined below the thermocline at several hundred metres depth, far from the euphotic layer. There, biological production is thus very low, as is shown in the chlorophyll chart in Figure 30, in which the current leaves no significant wake – in contrast to what can be observed on the corresponding temperature chart. Everywhere, except in the coastal water, the chlorophyll concentration is at its lowest throughout the zone. The Florida Current is not necessarily devoid of life: a northward incursion of tropical water contains species that are typical of this water, particularly the big fish prized by the amateur sport fishers; in fact, they find in the Gulf Stream close to the coast an extremely favourable environment. Hence, Ocean City, to the north of Cape Hatteras, proclaims itself to be the 'White Marlin Capital'. Thanks to the Gulf Stream, the swordfish reproduction area extends up to the north of Cape Hatteras. In 1934–1935, Ernest Hemingway, a keen amateur sport fisher and connoisseur of the region, was an infrequent and enlightened collaborator at the Academy of Natural Sciences of Philadelphia, where he hoped to encourage research on marlins, sailfishes, tunas and other prey for sport fishers.

Dynamic upwelling along the continental slope

The trade-wind biome has two main features: the permanence, above the thermocline, of a homogeneous and warm surface layer sustained by considerable sunshine throughout the year, and the rapid response of the currents to wind variations. As we have seen, according to the geostrophic hypothesis, currents can be described to a very good approximation with the assumption that, at a given level, the Coriolis force equals the pressure force. In this case, the result is that the current intensity between two points at neighbouring latitudes is proportional to the pressure difference between these two points. The reverse is also true: it is possible to derive the current from the pressure difference between two points.

Each current corresponds to actual sea level differences. As regards the Gulf Stream, sea level differences of 1 m can be observed over a few dozen kilometres. Concerning the surface currents, in systems characterized by a permanent thermocline, pressure variations are mainly a reflection of the thickness of the homogeneous layer or of the depth of the thermocline. Variations in the depth of the thermocline are the result of pressure variations and, therefore, the currents. Thus, in Figure 31, a temperature profile of the Atlantic equatorial current system shows that the thermocline depth undulates along with the currents. The low and high points, which are the extremes of the pressure difference, also correspond to changes in the current. For example, the separation between the South Equatorial Current, flowing to the west, and the Equatorial Counter-Current, flowing in the opposite direction, is indicated by a trough in the thermocline, hence a thick homogenous layer and a high pressure, at 2°N–3°N. This is easy to understand, if we return to the geostrophic hypothesis. Let us imagine that an observer is positioned at this high point on the sea surface (maximum pressure). The observer will see the current flow towards the right of the pressure force, that is, eastwards, if he is facing north: this is the Equatorial Counter-Current. On the contrary, if the observer is facing south, the South Equatorial Current is seen to be flowing westwards. The same reasoning applies if, on the contrary, we are positioned at the crest of the thermocline, near 12°N, that is, the minimum pressure between the North Equatorial Current and the Equatorial Counter-Current. This adjustment of the thermocline depth by the marine currents is vital for biological production because, as we have seen, the thermocline is not only a 'pycnocline', but it is also a 'nutricline', that is, a barrier to the diffusion of essential nutrient salts for biological production in the surface layer. The deeper the thermocline, the lower the primary production will be – for example, at the centre of anticyclonic circulations and particularly the Sargasso Sea. We speak of convergence when, at the interface between two currents, the thermocline sinks; and of divergence, in the opposite situation. The thermocline slope is, to a first approximation, proportional to the intensity of the current.

How does dynamic upwelling operate in the Florida Current? At the surface, on its left side (north and west), the Gulf Stream is characterized by extremely large and rapid temperature variations: it is typically called the 'cold wall'. This gives the impression of a real barrier between the water of the continental shelf and slope, and the warm water of the Gulf Stream. It is a superficial barrier because – and this may seem paradoxical at first – at depth, the Florida Current is a source of nutrients from the continental shelf. Due to the geostrophic equilibrium, the water in the thermocline layer, which is rich in nitrates from the North Atlantic Central Water, which itself is at a depth of 1,000 m in the Sargasso Sea, is brought to the continental shelf at a depth of a few hundred metres (Figure 32). It is an upwelling driven by simple current dynamics and all the stronger and faster as the current is stronger. Channeled along the continental slope, the current flows sinuously, without its undulations growing to become meanders, which are common beyond Cape Hatteras. These undulations are propagated like waves, with a wavelength of about 200 km and a velocity of 30 km/day. At each undulation, the Florida Current flows away from the continental slope (Figure 33). There is a 'water demand' and the beginning of the formation of small cold cyclonic eddies at the shelf break, between the current and a residual warm-water filament on the continental shelf. It is the final boost, which brings underlying nutrient-rich water up into the euphotic layer to occupy the space created. Simply put, we can say that the Gulf Stream 'plunders' major reserves of nutrients in the Sargasso Sea, to bring them to the euphotic layer at the level of the continental shelf break. We shall see later that, with the cold eddies it generates beyond Cape Hatteras, the Gulf Stream has the courtesy of 'repaying' to the Sargasso Sea the loan it obtained from it.

Corresponding to this dynamic upwelling, vast phytoplankton blooms have been observed, stretching over more than 1,000 km^2. It is a common phenomenon that occurs south of Cape Hatteras, which explains why the entire shelf break region is a reproduction zone for menhaden, *Brevoortia tyrannus,* and bluefish, *Pomatomus saltatrix*, important resources on the North American continental shelf. Menhaden is a pelagic species of the same family as herring (the 'clupeids'), with an overall length of not more than 50 cm. Around 400,000 tons are caught in North America every year. Bluefish is another pelagic species with high commercial value and it can measure over 1 m in length and weigh 14 kg. Around 50,000 tons of bluefish are caught annually.

In terms of flux of nutrient salts towards the surface and of biological production, this phenomenon does not have the scope of what is commonly called coastal upwelling; this appears on the other side of the great anticyclonic circulations, on the eastern side of the oceans, along the coasts of California and Peru in the Pacific, and those of Morocco, Mauritania and South Africa in the Atlantic. There, it is the Trade Winds, which, steadily blowing parallel to the coast carry surface water towards the open sea under the action of the Coriolis force, in accordance with the Ekman theory, thus constituting a real pump of nutrient-rich deep water onto the continental slope. In these zones, biological production is far more significant than anything the 'dynamic upwelling' of the Florida Current can provide. More than 10 million tons a year of pelagic species are caught in Peru and around 5 million tons off the coasts of Morocco, Mauritania and South Africa. The fact remains nevertheless that the Florida Current, although poor in itself, seems to be the main provider of nutrient salts required by the ecosystem known as the 'South Atlantic Bight', extending from Florida to Cape Hatteras.

THE 'GULF STREAM PROVINCE'

Here, we explore the westerly-wind biome described by Longhurst. Inside this biome, Longhurst was compelled to introduce a specific Gulf Stream province, since the impact of the current dynamics on the functioning of the ecosystem was too strong, and disturbed the simple action of the prevailing winds on the dynamics of the characteristic mixed layer of the biome. This province stretches from Cape Hatteras to the Grand Banks of Newfoundland. It is bordered on its western side by the North American continental shelf. While the Florida Current is channeled rather narrowly by the continental slope from Cape Hatteras, the Gulf Stream flows freely, forming meanders and eddies (Figure 9) contrasting with the almost linear course of the Florida Current in the South Atlantic Bight. Between the northern boundary of the current and the continental slope there is a free space occupied by the 'Slope Sea' – the domain of the warm eddies.

The formation of eddies: the Gulf Stream as an 'exchange agent'

The Gulf Stream looks like a river on Benjamin Franklin's chart. It is obviously not the unpredictable, turbulent, and unbalanced, Gulf Stream that we discover in Figure 34. It is far more complex than those who first described it had imagined. This complexity makes the Gulf Stream less a barrier, as symbolized by the 'cold wall', which had so impressed the first observers – like Lescarbot – than an 'exchange agent' ensuring mutual transfers between the Sargasso Sea and the 'Slope Sea'. Yet, it resembles an impenetrable barrier between the two .

A Gulf Stream meander towards the right in Figure 13 corresponds to a movement of cold water from the 'Slope Sea' towards the Sargasso Sea. If the meander stretches out, it will end up being 'constricted' and will break away from the Gulf Stream flow, to become a cold-water inclusion in the Sargasso Sea originating from the 'Slope Sea': a cold-core ring. Conversely, and in a symmetrical way, a meander towards the left can become a Sargasso Sea warm-core ring in the middle of the cold water of the 'Slope Sea'. This is how the Gulf Stream operates as an 'exchange agent', as illustrated in Figure 34. We can see, clearly formed, three cold eddies to the south of the current and three warm eddies to the north.

Cold-core rings as fertilizers of the Sargasso Sea

Based on the way they are formed, cold-core rings necessarily move in a cyclonic (anti-clockwise) direction. They are thus the site of shoaling of the thermocline and the associated nutricline. They 'pump' nutrients into the euphotic layer of the Sargasso Sea, which is completely devoid of nutrients, thus providing the minimum level of fertilization required to maintain the functioning of such a special ecosystem. A vertical profile of the 'Bob' core ring in 1977 (Figure 35) shows that it raised the 15°C isotherm (within the thermocline) from a depth of 600 m up to the surface over a distance of 100 km. At this site the 4 μmol/kg nitrate isopleth (line of constant value) goes from a depth of 500 m to the surface. Thus, it provides a spectacular elevator! Hence, the Gulf Stream, as we have already seen, drawing from the deep water of the Sargasso Sea to fertilize the South Atlantic Bight's continental slope, restores to it with the cold eddies part of what it had taken, but this time to the productive surface layer. Of course, this is not the most direct way to do it, but it clearly illustrates the complexity of the dependence of ecosystems on ocean dynamics.

Cold-core rings have a diameter of 100 km–300 km. It is possible to observe ten of them simultaneously. Their life span is of one to two years. They move southwestwards at a speed of approximately 5 km a day. They are generally 'picked up' by the Gulf Stream at the latitude of Cape Hatteras. They occupy 10 % to 15% of the Sargasso Sea's surface, increasing its productivity by approximately 10%, and the zooplankton biomass by 10% to 15%. They guarantee the Sargasso Sea's supply of 'fresh' nutrients, which are vital for the functioning of all ecosystems. This is called 'new production', in contrast to so-called 'regeneration' production, which functions by consuming, in a closed system, nutrients excreted *in situ* by the living organisms.

Eels: children of the Gulf Stream?

The eel is a migratory amphihaline fish. It is born in the Atlantic Ocean, breeds and dies in the Sargasso Sea, but spends most of its life in freshwater or brackish rivers and swamps in America and Europe. Thus, its migration is a return trip from birthplace to death site.

Yet the eel's reproduction in the Atlantic remains a mystery. At the beginning of the twentieth century, Johannes Schmidt meticulously drew up a chart of the catches of eel larvae (known as *leptocephali*) over twenty years of relentless fishing. He logically concluded that the Sargasso Sea – where only the smallest eel larvae (less than 10 mm long) are found – was the eel's breeding area. The result was accepted, although neither sexually mature males nor fertilized eggs were ever found there. It is believed that final maturation of the adult eels and hatching take place at a depth of 400 m–600 m, at a temperatures in the vicinity of 17°C. The smallest larvae ever found, measuring 6 mm, were at a depth of 200 m–500 m. Afterwards, they rise to the surface, where, feeding on microplankton, they take advantage of the productivity increases brought by the Gulf Stream's cold eddies. Then, they are carried by the currents, the Gulf Stream being the first stage of a long journey carrying

THE GULF STREAM – ISBN 978-92-3-103995-9 – © UNESCO 2006

them towards the American coasts for the so-called American species, *Anguilla rostrata*, and towards the coasts of Europe for the so-called European species, *Anguilla anguilla*, which is found from Iceland to the Mediterranean.

For a long time, it was believed that there was a common breeding area, leading necessarily to genetic cross-fertilization, as if there were only one species. Genetic studies have disproved this theory, and shown that the European and American species are very different. This speciation is undoubtedly a consequence of the different migration paths, one going from the native Sargasso Sea to the continental American habitats nearby, the other going to the European habitats much farther away. Hence, the resulting biological cycles are necessarily different (being shorter for the American than for the European species). The 'European' *leptocephali*, carried by the Gulf Stream and then by the North Atlantic Drift, will take over a year to metamorphose into immature elvers of 80 mm in length, before swimming up the estuaries where, at least in France, they will have to face the greedy anglers waiting for them. The survivors, known as the yellow eels, will grow in their new environment for several years until their final metamorphosis into oily, silver-coloured adults prepared for a long-haul ocean navigation and for reproduction. They return downriver towards the ocean, where they swim at great depth, living on their reserves, to rejoin the Sargasso Sea. That is what is assumed, at least, since we lose track of them in the ocean, and no one has ever seen an adult eel in the open ocean. We simply know that at great depth in the Sargasso Sea, tiny larvae will appear ready to begin a new cycle. The journey of the American larvae is much shorter, but probably more problematic; unlike the European eels, which are passively carried by the currents, the American eels have to leave the Gulf Stream that was carrying them, in order to reach the American coast. They are probably helped by warm eddies, which inject water from the Sargasso Sea, thus carrying larvae onto the American continental shelf.

How do eel larvae, who have a very low swimming capacity, choose their route according to the species they belong to? They probably do not choose, but rather are randomly selected. The reproductive capacity of an eel is exceptional: each female produces about 1.5 million ovocytes. Thus, millions of larvae are carried by the Gulf Stream and are carried by chance onto one route or the other; only those that are on the route appropriate to their species will be able to survive.

The eel is an ancient fish: the oldest known fossils date back one hundred million years. It seems that the two species in the Atlantic had a common ancestor that lived sixty million years ago, when the Atlantic was formed. The common breeding area is to the west of the mid-ocean ridge. However, the continuous widening of the ocean since that time made the migratory route of the European eel steadily longer – and it still does – by a few centimetres every year.

Thus, the biological cycle of the Atlantic eel is linked to the Gulf Stream and its extensions in the North Atlantic Drift. There is no doubt that their distribution in Europe follows the fluctuations of these currents. If by any chance climate change leads to a slowing down, or a complete halt, in the thermohaline circulation and the North Atlantic Drift, then eels would disappear from the shores of the Baltic, the Norway Sea and the North Sea.

Sargassum: the Gulf Stream floating jungle

The Sargasso Sea entered history and legend thanks to Christopher Columbus, who crossed it before arriving in the Bahamas, on the island of Guanahani, which he re-baptized San Salvador. First the 'floating grasses' were seen as a herald of hope – signifying land was nearby; but they soon became a source of anguish for the sailors when, as the weed became more abundant, they began to fear they might be somehow swallowed up by the sea 'much as if they would be by ice'. This bad reputation would never leave the Sargasso Sea, and Jules Verne later exploited the myth in his novel *Twenty Thousand Leagues under the Sea*. He saw his Sargasso Sea as the submerged part of Atlantis, even suggesting that the gulfweed (*Sargassum*) was the grass uprooted from the meadows of this ancient continent.

Sargassum is an alga. Taxonomically the genus comprises two principal species, *Sargassum natans* and *Sargassum fluitans*, both found in the Sargasso Sea and both having the particularity of being free-floating – unlike their fellow benthic species, which are attached to the bottom. It is supposed that they stem from benthic ancestors, fossil traces of which were found in sediments of the ancient Tethys Sea, dating back forty million years. These algae, with a length of almost one metre, are equipped with gas bladders (containing mainly oxygen, nitrogen and carbon dioxide), which ensure their buoyancy. They are sterile species, which propagate vegetatively. They collect in bundles and constitute a very distinct ecosystem, sometimes referred to as a 'floating jungle'. They constitute a habitat for about 145 species of invertebrates (notably: crabs, shrimps, molluscs); so far about 100 fish species have been found in association with *Sargassum* at one or other stage of their life-cycle (eggs, larvae, juveniles, adults), and 5 species of marine turtles, which grow in it after hatching or find food there during their migration. It is surprising to find such a diversity of organisms in a sea so blue, poor in nutritive elements and with so little fertility. It is estimated that the biomass of *Sargassum* is between 800 and 2,000 kg/km^2, that is 4 to 11 million tons.

In fact, such a complex and diversified ecosystem does not need a great quantity of fresh nutritive elements (new production) to maintain itself. *Sargassum* is a primary producer, like the phytoplankton; therefore, they need nutrients to survive. They initially find them in the recycling of organic matter through remineralization *in situ* of organic matter from the excretions of the many organisms they shelter. This near-equilibrium system functions in an almost closed circuit. To compensate for the inevitable losses – the dead organic matter that leave the system which is incorporated into sediments – *Sargassum* uses epiphytic bacteria, which have the capability of fixing nitrogen from the air. Therefore, *Sargassum* does not need to wait for cold eddies to make available to it the nutrients from the deep water, which are normally indispensable for survival.

Floating *Sargassum* can be found elsewhere in the ocean, but nowhere is there an ecosystem like that of the Sargasso Sea. This special ecosystem is a product of the Gulf Stream anticyclonic recirculation, which completely 'fences in' the Sargasso Sea, in such a way, as to make of it a *de facto* closed sea but without a coastline. In such a system, under the action of the Coriolis force, water and everything it contains has a tendency to converge towards the centre. So there is, thanks to ocean dynamics, a natural confinement that allows the ecosystem to thrive (Figure 11).

Warm-core rings: nutrient providers

Warm-core rings are found to the north of the Gulf Stream; they let warm water pass from the Sargasso Sea to the 'Slope Sea' between the Gulf Stream and the American continental shelf. As these anticyclonic eddies turn clockwise the thermocline is deep. Reaching a depth of 2 km, these eddies cannot move onto the continental shelf, which is less than 200 m deep, so they remain confined to the 'Slope Sea' (Figure 36). With less space available, warm-core rings become less numerous – rarely more than three at any one time – and have a shorter life than cold-core rings – rarely more than a year. The diameter of these warm eddies varies from 60 km to 200 km and they move southwestwards along the continental slope at a speed of 5 km–6 km a day. They are recovered by the Gulf Stream at the latitude of Cape Hatteras where their influence on biological production is more complex than that of the cold-core rings in the Sargasso Sea.

We could think that, in symmetry with and contrary to the cold-core rings that enrich the Sargasso Sea, the warm-core rings, which are 'islands' of warm, nutrient-poor water (their nutrient-rich water is found at their centre at several hundred metres depth), impoverish the 'Slope Sea' as they pass through it. This is more pronounced when from time to time they occupy nearly 40% of the 'Slope Sea's' surface. In fact, these warm-core rings can easily be recognized on satellite images of chlorophyll distribution (Figure 37) by their low chlorophyll content at the surface.

The temperature profile of a warm-core ring in Figure 38 shows that we are in a similar situation to that seen in the Florida Current, in which, as a result of simple geostrophic dynamics, cold water rich in nutrients rises at the edge of the eddy and, therefore, along the continental slope. Being anticyclonic, warm-core rings have a tendency to push water from the edge towards the centre. At the edge of the core ring, next to the continental slope, this displacement up towards the centre will create, at the continental shelf break, a demand for deeper water, hence upwelling, towards the surface of nutrient-rich water, which the geostrophic dynamics have already raised towards and not far from the surface. Thus, we come to a result that seems paradoxical: spring production in the 'Slope Sea', in terms of the surface chlorophyll content measured by the SeaWiFS satellite, is all the more significant when the warm-core rings have been numerous and active during the preceding winter, because although they are intrinsically nutrient-poor they also have nutrient sources at their edges. It is indeed the Gulf Stream's dynamics and the warm-core rings that bring enrichment to the 'Slope Sea', and not, as it was believed for a long time, the advection of cold water from the continental shelf originating from the Labrador Current.

Warm 'vacuum-cleaner' eddies

Warm eddies interfere with their environment: their anticyclonic motion draws in neighbouring water. They look more or less like spiral galaxies. As in Figures 34 and 36, they have 'streamers': a cold-water 'streamer' on the eastern side drawing water from the continental shelf towards the open sea, and, on the western side, a warm-water 'streamer' drawer towards the continental shelf. On average, the flow of a cold 'streamer' is some 165 m^3/s towards the open sea (with an observed maximum close to 500 m^3/s); the average for a warm 'streamer' is 62 m^3/s. The average annual flow of the cold 'streamers' in the 'Slope Sea' is estimated to be 180 m^3/s; that is, roughly the same as that of the Amazon River. These 'streamers' not only transport water, but they also carry planktonic species, particularly fish larvae. Therefore, the larvae are in danger of being transported into an environment unfavourable for their development, which risks limiting recruitment and therefore the abundance of species – some of which are of commercial value.

Cod, in Canadian waters are undoubtedly the most controlled and regulated fishery in the world: fishers, fishery managers and researchers are constantly concerned with the state of the cod stocks. Since 1981, systematic scientific trawling campaigns have been carried out in autumn to evaluate and monitor the abundance of the stocks. They were not able, prior to 1991, to detect a decrease in the biomass, thus giving confidence to the fishers and the fishery managers who, reassured or wishing to be so saw no reason for alarm. And yet, in 1992, the stocks collapsed. A moratorium on fishing was instituted, in the hope that the stocks would regenerate – they have not, and we are now in 2006. It was a failure for the fishery scientists, who were intending to launch a salutary debate on the possible causes of such an event. The situation was also a failure for the fishery managers, who were called on to revise their management methods with a view to reducing the chances of such collapses.

Among the possible causes, they invoked the warm eddies: because they transport larvae towards the open sea, and the warm water of the Gulf Stream, which offered no future for the larvae. Analysis of the results of research programmes on the warm eddies, carried out in the 1980s, particularly in the United States, clearly demonstrated that there were negative correlations between eddy activity and the stocks of 14 demersal fish species, notably cod, haddock and pollack, over the continental shelf. In fact, the correlations were weak, which would allow us to conclude that, whatever the intensity of the eddy activity it is not capable of determining variations in recruitment and impacting on the state of the stocks. Studies of the hydrographical characteristics of the water drawn into the cold 'streamers' may explain this low impact – in spite of their relatively important flow – because the streamers come from the edge of the continental shelf, at a depth of around 100 m, whereas fish larvae are generally concentrated in water at a lesser depth and farther coastwards on the continental shelf. We may recall that, on the other side of the eddy, the warm 'streamers' advect warm water onto the continental shelf and are the means of transport used by eel larvae to return to American rivers to develop.

The Gulf Stream, warm eddies and sperm whales

Sperm whales were the first to attract humans to the Gulf Stream; thus they were important drivers for scientific exploration, and hence the resulting development of physical oceanography. Scientific research campaigns to observe the whales confirmed that these marine mammals had a preference for the 'cold wall' bordering the Gulf Stream on its northern side, and even more so for the cold 'streamers' bordering the warm-core rings on the eastern side. Where does the sperm whales' attraction to the Gulf Stream and its eddies, which Folger and his fellow whalers knew so well how to exploit, come from? It was in the abundance of food, in particular the squid found in these regions.

This phenomenon is the outcome of two processes. The first one is biological: it is the result of the role played by the Gulf Stream and its warm eddies as sources of nutrients, which, as we have seen, stimulate biological production. The second one is mechanical: the front at the ocean surface separating the Gulf Stream warm water and eddies from the surrounding cold water (particularly the water in the cold 'streamers') is a zone of weak horizontal mixing. Everything that floats concentrates at this front, especially the zooplankton consumed by squid. The squid are in turn eaten by sperm whales, which are themselves exposed to hunters who, being nobody's prey, have nothing to fear but the weather.

The Gulf Stream and the Kuroshio

The biological dynamics of the Gulf Stream are almost identical to its equivalent current in the Pacific - the Kuroshio. In the Pacific, A. R. Longhurst identified a province, which he called *Kuro* with the same eddy characteristics as the Gulf Stream, Figure 14 illustrates the great similarity between the two currents. As in the case of the Gulf Stream, we must also distinguish two regimes: one linked to the tropical regime – the 'beginning of the Kuroshio', equivalent to the Florida Current – and the eddy regime north of 30°N. Hence, from a biological point of view, there is no difference between the Atlantic and the Pacific.

THE NORTH ATLANTIC DRIFT PROVINCE

Spring bloom

We now actually enter the westerly-wind biome, as defined by A. R. Longhurst. The variations in the westerly winds and the seasonal sunshine are the undisputed masters of the dynamics of the surface layer, independent of the currents. Here, the Gulf Stream becomes diluted and it loses its characteristics as it is defined as a western boundary current. So, the Gulf Stream's journey ends where the North Atlantic Drift, the ocean's response to the westerly winds, begins. This is the realm of the seasonal thermocline and the spring bloom.

In summer, thanks to the length of the day and the height of the sun, solar energy is sufficient to create an almost tropical structuring of the water column, with a warm and nutrient-poor homogenous surface layer separated from the deeper water by a strong thermocline, as in the trade-wind biome. In autumn and winter, the surface layer cools, the vertical stratification weakens and the stronger wind increases vertical mixing: there is no longer a barrier to the turbulent diffusion that brings nutrient salts to the surface. Yet, primary production remains poor in winter, in spite of this fertilization of the euphotic layer. It was thought, with a certain degree of logic, that insufficient sunshine in winter brought about this vegetal 'sleeping phase'. In fact, it is more than lack of light, it appears that the real cause is the conditions created by the turbulence, which are unfavourable for the phytoplankton. Phytoplankton cells passively drift with the movements of the water. Thus, in the absence of a thermocline, turbulent motion makes the phytoplankton migrate, from the well-lit surface of the ocean to the deeper, dark layers, where they do not have sufficient energy sources for photosynthesis. The time spent outside the euphotic layer and the difficulties of adaptation to conditions of continuously changing light combine to hamper the productivity of the phytoplankton.

In spring, the Sun recovers its strength: it moves higher in the sky, rises earlier and sets later. The surface layer of the ocean warms up and the thermocline barrier re-forms more easily as the wind intensity decreases. Phytoplankton above the thermocline again find steady access to light, and benefits from the presence of nutrient salts brought about by the winter mixing – which were previously unavailable – thus they can now proliferate and flourish. This is the phytoplankton spring bloom. The sea surface turns green, and colour measurements of the ocean taken from space allow tracking of these changes, Figure 39 illustrates this phenomenon in the North Atlantic. With time, nutrients will be consumed, the summer thermocline will weaken and the turbulent mixing – the source of nutrient salts – will end. Hence, vegetal production will decrease and the ocean will return to its winter lethargy, regenerating nutrient salts for a new bloom the following spring. Thus, the solar cycle and the seasonal variations in the wind ensure, at a convenient time and simultaneously, the availability of solar energy, the fertility of the surface layer and its stability – all the necessary conditions for the development of the marine meadows.

The NAO and the interannual variations

The North Atlantic westerly winds circulate between the high atmospheric pressure of the Azores and the low pressure of Iceland. The greater the pressure differences between these two pressure zones, the greater the intensity of the westerly winds – and vice-versa. This is the North Atlantic Oscillation (NAO), characterized by an index, which, as we have seen, is simply the pressure difference between the Azores pressure maximum and the Icelandic pressure minimum.

The marine ecosystem is, of course, not indifferent to the NAO fluctuations; it responds to variation in the intensity of the westerly winds, which are associated with it. We should keep in mind two main consequences. First, according to the definition of the westerly-wind biome, a strong NAO Index will correspond to a stronger and longer mixing in winter, which will delay the formation in spring of a stable homogeneous layer above a reconstituted thermocline; hence, a late spring bloom, which should have an impact on the trophic sequence leading to fish recruitment. The second consequence is that, if the NAO positive anomaly persists, the North Atlantic Drift will grow in size and extend northwards, bringing about an increase in ocean-surface temperature, modifying, for example, the zooplankton structure of the ecosystem and thus the conditions for survival of fish larvae feeding in it.

Zooplankton of the North Sea and the North Atlantic are continually monitored by the Continuous Plankton Recorder Programme, which has been carried on without interruption since 1946 by the United Kingdom. Sampling is carried out along navigation routes by merchant ships towing, at a speed of 10 knots, a device that filters the seawater to collect the plankton. Thus, we have available a remarkable database for the study of the variations in the North Atlantic ecosystem.

Two closely related species of copepoda have been studied in particular: *Calanoides finmarchicus* and *Calanoides helgolandicus*. The first prefers relatively cold water, and it develops before the other, following the spring bloom, when the water is still quite cold. There is an indisputable correlation between the NAO Index and the composition of the North Atlantic plankton. *C. helgolandicus* predominates when the NAO Index is high, and vice-versa. In fact, the entire zooplankton structure in the ecosystem (species, sizes, dates of occurrence) is modified, and this is not without consequences for the development of exploited fish stocks.

Cod

Cod was particularly abundant between 1962 and 1983; this period is called the 'gadoid outburst' (Figure 40). Over-exploitation was held responsible, not without reason, for the decline in the stocks. Yet the state of the stock not only depends on fishing, but also on recruitment, hence on the survival of the larvae feeding on zooplankton and, in the particular case of the cod, on the survival of the two copepod species mentioned above. Fishing, already at a high level at the time, did not stop the stock explosion at the beginning of the 1960s, when the recruitment (of cod at one year of age) was very high. Larval survival greatly depends on the trophic conditions that are offered to the larvae. In simple terms, we can say that the composition of the food on offer (abundance of available zooplankton species); the presentation (size of the prey) and the moment when it is served must be well adapted to the larvae's stage of development. Conditions were met during the 'gadoid outburst', a period when the NAO (Figure 19) was weak and surface water was relatively cold. The developmental sequence of the copepods, starting with *C. finmarchicus* in spring, followed by *C. helgolandicus* in summer, ensured the continuity in food supply necessary for the larvae's survival. Thus, recruitment was high and stocks were high. In the 1980–1990s, with a predominantly high NAO Index, conditions were considerably less favourable. The substitution of *C. finmarchicus* by *C. helgolandicus* in warm waters also resulted, for the larvae, in a deficit of prey until the summer, when *C. helgolandicus* took over from the declining *C. finmarchicus*. Thus, recruitment diminished without any decrease in the fishing intensity, with, as a final outcome, the collapse of the stocks and the need to take conservation measures to prevent compromising the stocks definitively. By combining information on the copepod biomass, their specific composition and their size, we can define a biological indicator of the larvae's developmental conditions – hence cod recruitment, as well as the state of the stocks. The condition, of course, is that over-exploitation does not endanger recruitment by exhausting the stocks (Figure 40).

Herring

Other fisheries in the North Atlantic and the North Sea are sensitive to variation in the NAO, particularly sardine and herring. They do not live in the same waters. Sardines, which are slightly more sensitive to cold than herring, are generally fished in areas more to the south than the latter's, which is considered an arctic-boreal species. In the northeastern Atlantic, the area in which the most adventurous specimens of both species may nevertheless meet is at the latitude of the English Channel. In this region, cold periods correspond to profitable herring fishing, whereas milder temperatures are more favourable to sardine fishing. A high NAO anomaly, favouring westerly winds, also makes it easier for water from the North Atlantic Drift to extend towards the northeastern Atlantic, bringing about a positive anomaly of the sea-surface temperature in the North Sea and the Norway Sea. The herring's and the sardine's cold and/or warm distribution limits migration northwards: herring becomes more abundant in the north of the region (the so-called Atlantic-Scandia stock), it disappears from the southern part (English Channel), to the benefit of the sardine, and varies little in the intermediate zone (North Sea). Conversely, during a cold period (negative NAO anomaly), herrings go southwards: catches in the Norway Sea decrease considerably, to the benefit of the area farther south, down as far as the English Channel, from which, the sardine disappears.

European herring fishing in the North Atlantic is a very old practice and well documented. All stocks taken together, the catch reached nearly 5 million tons a year, in the 1960s. This represented 11.5% of the world fish catch. Only the Peruvian anchovy, with a total catch of more than 10 million tons, at the beginning of the 1970s, exceeded this figure. However, in certain cases, particularly for the Atlantic-Scandia stock in the Norway Sea, fruitful fishing periods alternated with others during which herring fishing disappeared almost entirely. It has been possible to link these variations to the decennial fluctuations of the NAO Index, which were indirectly reconstructed up to the beginning of the eighteenth century on the basis of the length of the season during which the Icelandic coasts were ice-bound, the study of tree rings and the abundance of snowfall in Greenland. The ice cores taken *in situ* have allowed the establishment of annual estimations. By the 1960–1970s, all stocks in Iceland, the Norway Sea and the North Sea collapsed, there being no regard for the climatic signal that would have led to a distinction between the northern and southern regions. It was a 'cold' period (negative NAO anomaly) reputedly favourable to the southern regions. This was not, however, the case, and the considerable increase in the fishing intensity, regardless of the zone, had a general effect: the collapse of the stocks due to over-exploitation, which completely masked the climatic signal.

Managers learned their lesson from this event: after a total ban on fishing, the building-up of stocks was monitored by systematic evaluation campaigns. Fishing was allowed to restart, once the abundance criteria were satisfied. At the beginning of the 1980s, this was the case for the majority of herring stocks in the North Atlantic. Regulations were put in place: catch quotas were established, a minimum allowable size of fish in the catch was decided, and limits to fishing seasons and areas were fixed, and so on. Fortunately, stocks of herring, which is a pelagic species with a rapid reproductive cycle, are relatively robust and can build up again rather easily after a moratorium, in contrast with cod, which has a much longer reproductive cycle, and this can weigh heavily on the chances of recovery from below a certain threshold. Canadian fishers have been waiting for 15 years or so for the recovery of the cod stocks – which may never happen.

The Gulf Stream and the NAO

In this 'province', contrary to what we have seen previously with the Gulf Stream, the dynamics of the North Atlantic Current have hardly any impact on the surface layer and therefore on the functioning of the marine ecosystem. If wind is indeed the 'director', the fact remains that the current is only an actor – a passive actor responding to variations in atmospheric circulation. A positive NAO anomaly increases and broadens the westerly-wind field. If the anomaly is sufficiently persistent, it will have a similar impact on the North Atlantic Drift, that is, an increase in flow and an extension northwards, with, above all, an increase in sea-surface temperature and therefore consequences for the structure of the ecosystem, particularly with respect to zooplankton. The opposite is true if the NAO anomaly is negative. In this way, it was possible to establish a correlation

THE GULF STREAM – ISBN 978-92-3-103995-9 – © UNESCO 2006

between the Gulf Stream's position (GSNW) and zooplankton composition in the North Sea, both of which are related to the NAO. However, a correlation does not mean a deterministic relationship, as those who still like to think of the Gulf Stream as having an all-powerful influence, right up to the Arctic Circle, would like to suggest.

It would be risky to propose scenarios for the future of the North Atlantic ecosystems and their resources in the context of climate change brought about by human activities, especially since, unlike climatic scenarios based on the reconstruction of past climates over long periods, we do not have at our disposal biological archives allowing palaeo-ecological analysis.

Today, satellite data on sea colour – provided the observations are continued – now allow monitoring and analysis of marine ecosystems. Thus, for example (Figure 28), comparison between 2003 and 1998 shows a dual movement: a reduction in chlorophyll concentration in the anticyclonic gyres, already quite poor in chlorophyll, and an increase on the continental shelf. The reduction within the gyres could be due to an increase in the sea-surface temperature, which, by increasing stratification, decreases vertical mixing and the already weak upward flux of nutrients into the euphotic layer. In fact, it seems clear that, over the same period, sea-surface temperature has increased in those regions, except in the North Atlantic where no significant change in surface temperature has been detected.

For coastal regions, the explanation is more challenging. It may be due to climatic phenomena: for instance, strengthening of the wind in the coastal-upwelling areas. However, this could also be the result of run-off or discharge of agricultural fertilizers, which favour phytoplankton blooms leading to excessive oxygen consumption. Unfortunately, the continuity of satellite observation of ocean colour into the future, as well as those of other essential oceanographic parameters (wind, sea level) is far from being guaranteed.

Conclusion

TOWARDS AN OPERATIONAL OCEANOGRAPHY

If, at the end of this journey, the Gulf Stream has seen its magical aura fade somewhat, it has not lost any of its importance in the climate system, as a transporter of heat northwards in the Northern Hemisphere. The confident self-assurance of Maury, who attributed an unwavering constancy to the Gulf Stream and asserted its total independence from the rest of the ocean, is now replaced by the uncertainty about its fluctuations and by the recognition of its complete interdependence with the other factors of the climate system. The Gulf Stream had to be put in perspective: in order to understand the climate system, the entire ocean has to be known, understood and taken into account.

According to Plato, Socrates reported to the judges who wished to know why the oracle of Delphi had declared him 'the wisest of men': *because I know that I know nothing*. It was a way of insulting the judges, since he led them to understand that they themselves knew less than he did. He also proved that they did not even realize this, causing them further insult, as they pretended that they did. Of course, Socrates was condemned for impiety – a more substantive reason than contempt of court. There is a kind of Socratic half-wisdom in scientists even if it means they are accused of being 'scientistic'. Indeed, they will not say that they do not know anything, but they will recognize

THE GULF STREAM – ISBN 978-92-3-103995-9 – © UNESCO 2006

that they do not know everything and that uncertainty is at the heart of science – not least regarding the climate.

This caution is shown in the scientific report by the IPCC, whose major concern for its next – the fourth – report, to be published in 2006, is to *minimize the uncertainty for a better quantitative evaluation of the risks*. Scientists know what they lack, from this perspective, and the NAO and the future of the thermohaline circulation have provided several examples. We still lack the basic knowledge needed to improve climate models, notably in terms of cloud/radiation interaction and the coupled ice–ocean dynamics, among others. However, we are often lacking the information required to exploit acquired knowledge, such as environmental observations and measurements. Experimental methods are not applicable in this case: it is not possible to put the Earth in a laboratory. Therefore, scientists create virtual laboratories by means of numerical models, and possible changes are simulated by playing with the parameters. However, in order to construct these models, it is necessary to know the processes intervening in the dynamics of the system. How do we recognize them, if they have not been previously observed or measured, so as to be able to incorporate them into an equation?

One hundred and fifty years of history in meteorological science illustrates the approach well, which, based on observations and measurements incorporated into models, has allowed progressive reduction in the uncertainty of prediction from one, three, then seven, and even fifteen days. The models themselves cannot function without first being based on real measurements and observations; anything virtual must be anchored in reality. Models assemble and manipulate knowledge about the functioning of the climate system, the observations are their 'fuel', without which they would only be beautiful but useless intellectual constructions. Again it is the observations that will tell us afterwards what those simulations are worth. The process is continuously interactive between the observations and measurements, and the simulation models. The need for measurements is therefore placed: firstly, upstream, so as to improve knowledge of the processes at the present time; secondly, in midstream, so as to set up the models and assimilate the data; and thirdly, downstream, so as to validate the simulations, evaluate the residual errors and uncertainties and develop applications. Just as climate change is a continuous dynamic process, the establishment of observation and measurement mechanisms, with a view to reducing uncertainties, should be a continuum both in time and in scientific approach: from the acquisition of knowledge to the applications. We urgently need to guarantee the continuity of our irreplaceable source of knowledge: the 'Earth-observation system'. Sustainable development presupposes sustainable knowledge and, therefore, sustainable systems of knowledge acquisition. Where are we, concerning the ocean?

Research programmes

The scientific research that feeds the IPCC is a major key to making progress. Such research was established about twenty years ago, through pluridisiplinary international programmes under the leadership of international organizations.

- *The CLIVAR programme (Climate Variability and Prediction)*

The first among them was the World Climate Research Programme, launched in 1980. It was jointly organized by the ICSU (International Council for Science, inspired by the National Academies of Science), the WMO (World Meteorological Organization) and the IOC (UNESCO Intergovernmental Oceanographic Commission). Its objective was the establishment of a scientific basis for understanding the physical phenomena that affect the functioning of the climate system, with a view to evaluating to what degree these phenomena are foreseeable and how human activities will modify them. It had therefore to take into account all the compartments of the system: atmosphere, ocean, cryosphere, terrestrial surfaces and flux exchange. Concerning the ocean, the WCRP organized two principal programmes in the period 1980–1990. The Tropical Ocean and Global Atmosphere Study (TOGA), from 1985 to 1995, for the study of interannual climate variability, and in which the El Niño phenomenon, in particular, was a chance to set up the first ocean-observing system of an operational type in the tropical Pacific. The World Ocean Circulation Experiment (WOCE), between 1990 and 2000, was concerned with the whole ocean, in all three dimensions, with a view to evaluating the currents as well as the transport of heat and carbon, with the best resolution possible. It was the first overall oceanographic experiment, both because of its global objective and the variety of means made available, from research vessels to satellites.

The baton was then taken by CLIVAR, started in 1995, with the following objectives: (i) to better understand the physical processes governing the variations of the whole climate system, from seasonal to centennial timescales, in such a way as to develop coupled models linking all the components: atmosphere, ocean, ice, earth; (ii) to improve, using these models, climate forecasting at an interannual timescale; (iii) to understand and forecast the climate system's response to the increase in greenhouse gases, and to compare the predictions with past climatic records, in order to test the quality of the models and to evaluate the importance of human activities in climate change. The oceanic component of this programme is important; it includes the NAO and the thermohaline circulation in the Atlantic, which, as we have seen, are sources of uncertainty and, therefore, of consequence for the Gulf Stream and its complex relationship with these two phenomena.

- *The IMBER Programme (Integrated Marine Biochemistry and Ecosystem Research)*
  Physics alone cannot solve the problem. The natural world, and human beings, through their impact on the carbon cycle, are key factors in the climate system as the carbon cycle determines the carbon, in gaseous form, in the atmosphere. At the same time they also suffer the consequences of climate change, which can be dramatic both for the ecosystems and for humanity. The International Council for Science, in 1986, took the initiative of establishing a vast programme to describe and understand the interactive physical, chemical and biological processes regulating the functioning of the whole-Earth system, the changes this system undergoes and the way the changes are modified by human activity. This programme is named the International Geosphere–Biosphere Programme (IGBP). Initially, a vast programme was organized for the ocean, and comprising two projects: the Joint Global Ocean Flux Study (JGOFS) and the Global Ocean Ecosystem Dynamics (GLOBEC). JGOFS, which ran from 1987 to 2003, had as its objectives the understanding

and quantification of the carbon cycle in the ocean, to evaluate the carbon flux (the flux of carbon dioxide gas, the main greenhouse gas produced by humans) at the air–sea interface and between the oceanic surface layer and the ocean depths, and to forecast its evolution. The GLOBEC project started in 1991 and, as its name indicates, it aims at understanding how global change can modify the functioning of marine ecosystems and affect the abundance, diversity and productivity of marine populations at the lowest levels of the food web, from primary production to small pelagic and immature fish, which are decisive stages for exploited resources. The scientific plan for the Integrated Marine Biochemistry and Ecosystem Research (IMBER) programme has just been published (*IMBER Science Plan and Implementation Strategy*, IGBP Report No. 52, Stockholm 2005); it includes the concerns of the two projects just mentioned, as well as the mutual interactions between marine ecosystems and the human societies that use and modify them. The IMBER programme is decennial, organized around four themes formulated as four questions: (i) How do major biogeochemical cycles interact with the dynamics of food chains in different marine ecosystems? (ii) How will marine ecosystems respond to global change affecting biogeochemical cycles? (iii) How, in return, will marine biochemistry and the ecosystems be able to influence climate change? (iv) What are the relationships between marine ecosystems and the human societies for which they provide goods and services; how must they develop and adapt to be able to face the impact of global change and the multiple human activities at sea, and maintain the quality of marine environment that the marine ecosystems need?

GODAE (Global Ocean Data Assimilation Experiment): a test of operational oceanography

These research programmes referred to so far are long-term and they have already allowed the IPCC to refine its forecasts, as it is their results that feed the simulation models. Their implementation and those of the models require the establishment of permanent ocean-observing systems.

The IOC took the initiative to create a Global Ocean Observing System (GOOS) whereby, in liaison with the World Climate Research Programme (WCRP), a pilot project was launched in 2000 to demonstrate that it is now possible to make forecasts for the ocean as is done for the atmosphere. The initial parameters are the distribution of temperature and salinity, current velocity and direction and sea level. The structure of GODAE was based on the one established for meteorological forecasting, which has long since proved itself (Figure 41). It is made up of three elements: spatial observations; *in situ* observations; and models that function by assimilating these data.

At the heart of the system: a global ocean model

It is impossible to make forecasts if we do not have effective models. More than knowledge of physical processes, which has made considerable progress, it is the calculating power of computers that, for a long time, has been a limiting factor in the development of the ocean models required to resolve the hectokilometric scale of eddies, which are at the base of ocean dynamics. Models are now available, with a grid as small as 1:32, that is, one point calculated every 2 or 3 km.

Measurements from space

The sensors loaded on satellites ensure global coverage of the ocean. They can provide measurements of all the oceans, at appropriate resolutions. They can also provide this information on a permanent basis. This allows resolution of the very difficult problem of overlapping of time- and space-scales. They ensure continuity and coherence of the observation systems. Onboard scatterometers measure the effect of the wind on the ocean surface, which is the main driver of oceanic circulation. The infrared and microwave radiometers record the sea surface temperature and the water vapor contents of the atmosphere; based on these parameters and wind velocity, it is possible to calculate thermodynamic exchanges between the ocean and the atmosphere, that is to say, thermodynamic forcing. Certain radars on specific satellite platforms have shown that it is also possible to evaluate rainfall at sea. Altimeters, which measure the sea height to the nearest centimetre, also provide a direct access information on to ocean dynamics, currents and eddies. The recent measurement of sea colour, also allows an evaluation of the intensity of biological production in the oceans. Between 2007 and 2009, the launching of two satellites Soil Moisture and

Ocean Salinity (SMOS) – and Aquarius, capable of measuring ocean salinity, is foreseen. We thus have at our disposal, for the whole ocean surface and on a continuous basis, an evaluation of surface currents, their forcing and their impact on biological production.

Measurements *in situ*

From a dynamical point of view, sea level measurement integrates the entire water column; it is a measurement of hydrostatic pressure similar to that of the atmospheric pressure on the ground, which integrates the air column. Although it is possible to derive the surface currents directly, it is necessary to know the density stratification of the water column as well, to determine ocean circulation as a function of depth. Taking into account the opacity of the marine environment to electromagnetic radiation, there is, to this day, no other way to sound the ocean other than by *in situ* measurements. Thus, high spatial resolution was an impossible task with traditional oceanographic methods. However, the solution came from space, with satellite systems for localization, data collection and data transmission that allowed the deployment of fixed (moored) or drifting (on the surface and at depth) measuring platforms. Each platform is located, and it transmits the recorded measurements via satellite. At the beginning of March 2005, under the guidance of the Data Buoy Cooperation Panel (DBCP), there were 983 drifting floats measuring the sea-surface temperature; some of them also measured atmospheric pressure, wind, salinity and the partial pressure of dissolved carbon dioxide. In 2006, the objective of the ARGO programme is to have 3,000 floats deployed and drifting at a depth of 2,000 m; periodically, these floats rise to the surface to transmit their measurement data and their position by satellite. During each surfacing and descent they measure the temperature and salinity of the entire water column. Thus, 100,000 vertical profiles will be compiled annually, with a spatial resolution of around 3°. Each float is designed to remain operational for several years. By the end of February 2005, 1,671 floats were active, or 55.3% of the 2006 ARGO objective (Figure 42).

GODAE, as a project of international cooperation, is also a competition. If the collected data belongs to all concerned, their use is the business of each modelling and data-assimilation center – it is up to each of them to show proof of the quality of its ocean forecasts. There are six countries in the running: Australia, France, Japan, Norway, United Kingdom and USA. The experiment is not over and conclusions will be drawn in 2007. However, right now, it is possible to affirm that operational ocean forecasting is possible, judging by the results obtained. Thus, for example, some of the GODAE centers, by assimilating satellite and *in situ* data into the ocean models, provide forecasts on a daily or weekly basis with a forecast horizon of 15 days to one month, for temperature, salinity, velocity at several depths and thickness of the mixed layer. Two examples of forecasts concerning the Gulf Stream are given in Figures 43 and 44.

What next?

GODAE will end in 2007. It will probably have proved the feasibility of an operational ocean-forecasting system and will have demonstrated the quality of three-dimensional ocean models for forecasting climate change. It would be absurd to leave it at that, and lose the expertise acquired by not taking the right decisions at the right time to ensure the permanence of operational ocean-observing systems, and by failing to organize operational structures capable of ensuring production continuity. Nothing is assured as there are no operational observing systems for the ocean comparable to those existing for meteorology under the aegis of the World Meteorological Organization (WMO), a specialized agency of the United Nations. In most countries, ocean-observing systems are implemented by research laboratories with research budgets and without any guarantee of continuity and of service, which is the responsibility of operational teams. Spatial remote-sensing systems are particularly critical, firstly because they are essential to the system, and then because it is necessary to allow from five to ten years between the decision to undertake a satellite remote sensing project and its launch into space. The timetable to be followed is therefore crucial and decisions must be made in time to avoid gaps in the measurement of parameters whose continuity is essential. Notably for the altimeters Jason 1, GFO and ENVISAT no provision has been made to ensure their future beyond 2008. At the present time, there is no guarantee of this and no such guarantee will be forthcoming unless ocean observation reaches a truly operational stage, as is the case for the atmosphere in meteorological forecasting. Nor is there any guarantee of the permanence of the ARGO programme, nor indeed of that of most of the experimental data-processing centers now participating in GODAE. This must all be consolidated, the decisions required are political and are now a matter of great urgency.

'Geoscopy'

In studying Earth it is necessary to consider the whole planet: let us not be narrowly 'oceanocentric'. The Earth evolves at all timescales, from that of the mantle dynamics, which 'manages' the plate tectonics and shapes continents and oceans, to that of the atmosphere, which determines day-to-day weather. All these scales are interconnected: for example, plate tectonics are of great relevance to today's atmospheric and oceanic circulations – hence the climate on Earth – as they would not be what they are if the oceans and continents had another configuration. Palaeoclimatic studies have shown this well. It is possible to say that Earth is the most complex and 'dynamic' of all the known planets. It has evolved more rapidly and it is the only planet where life actively participates in its evolution. Scientifically speaking, it is, therefore, the most interesting planet to study. From an anthropocentric point of view, it should be given priority. Whether we send probes to explore Mars now or one hundred years from now, Mars will not have changed significantly, while on Earth, those environmental compartments concerning us directly – biosphere, atmosphere and hydrosphere – risk being profoundly modified – to our detriment.

Earth began to be scientifically considered as a 'planet' during the International Geophysical Year (1957–1958) and, for the very first time, there were attempts to analyse globally the interactions between the Earth's upper layers and solar radiation. It was a coincidence that the first satellite was launched in October 1957, and thus a new means of Earth observation could begin. Neil Armstrong's footprint on the Moon is perhaps less important than the first images of the Earth, which we could see for the first time from outer space. Observed in the same way as other planets in the solar system, Earth was finally seen as a planet in its own right.

The study of climate change and its consequences for human beings and their habitat compels us to study the 'Earth system' prioritizing timescales from decades to several centuries, with particular attention to such aspects as the dynamics and coupling of its upper layers – atmosphere, continental surfaces, oceans, cryosphere and biosphere – as well as their relationship with the energy source that brings them life: solar radiation.

'Après moi, le déluge' (suggesting 'After my reign the nation will be plunged into chaos and destruction) is an expression attributed to Louis XV. A failure to establish permanent Earth observing systems could induce such a scenario, as without such systems the knowledge needed to constantly improve climate change simulations and scenarios will disappear and they are our best means of prediction. Why not implement a global project of Earth observation: a 'Geoscopy'? This will possibly be the result of the GEOSS programme.

GEOSS: Global Earth Observation System of Systems

During the Third Earth Observation Summit, held on 16 February 2005 in Brussels, 61 countries and 40 international organizations adopted a strategic decennial plan for the implementation of a Global Earth Observation System of Systems (GEOSS). It was a most welcome conclusion to an initiative that began in the United States, in 2003. Benefits to society are expected in nine areas:

- improvements in weather forecasts;
- protection and monitoring of marine resources;
- reduction in casualties and loss of property to natural catastrophes;
- forecasting of climate variability and global change, to take the necessary measures to mitigate their effects;
- promotion of sustainable agriculture and forest resources, and improved information with which to fight against land degradation;
- understanding of environmental effects on health;
- development of capacities for ecological predictions;
- protection and monitoring of water resources;
- monitoring and management of energy resources.

The task is enormous and a very wide variety of observing systems are needed. Some of them are already operational and others are at an experimental stage – as we have seen for the ocean – whereas others do not exist at all. In the framework of GEOSS, it is a matter of completing the systems in order to make them operational and incorporate them into a network, in such a way that the 'system of systems' would be 'seamless', so that the data from any one system would be accessible and available to all the systems in the network. Thus, we would have a permanent 'geoscope' available as well as the tools to predict changes on Earth. The ocean observation and modelling systems will obviously be part of this, and our knowledge of the Gulf Stream – which we have reviewed in this work – will be improved.

This decision to create the GEOSS is a good omen. Let us be optimistic and wager that there will not be a wide gap between intention and accomplishment.

Glossary

Advection

The transfer of ocean surface water, usually by a prevailing wind system, from its usual source into another part of the ocean surface.

Altimetry

Radar measurement, accurate to within a centimetre (in 2006), of the distance between the remote-sensing system (e.g. satellite) and the sea surface. It enables construction of the *sea-surface topography* and hence the *geostrophic* currents.

Amphihaline

Refers to species (notably, eels and salmon) able to live in fresh and in salty water (though not usually at all times throughout their life-history).

Amplitude

The measure of the range of a disturbance (e.g. a signal, as in the fields of radio and radar, or of wave height in oceanographic and electromagnetic terms) relative to a specified standard or mean value.

Anemometer

Instrument to measure the speed or force and the direction of the wind or of other flowing gases. Usually based on pressure tubes or rotating cups, vanes, or propellers.

Angular momentum

The product of the *momentum* of *inertia* and the angular velocity of a rotating body.

Anomaly

Difference between the value of a parameter at a given time and its average value over a specified period of time and, where appropriate, of space.

Antarctic Circumpolar Current (ACC)

Major ocean current driven by prevailing westerly winds, circulating the Antarctic continent between 65°S and 45°S.

Anticyclone

Zone of high atmospheric pressure.

Anticyclonic circulation

A clockwise horizontal movement around zones of high oceanic and atmospheric pressure; see also *cyclonic circulation*.

Atlantic Overturning Circulation

The sinking of Gulf Stream water as result of a large increase in its density, due to cooling, combined with its already high *salinity*, in the Norway and Greenland Seas; at depth this dense water feeds the *thermohaline circulation*, creating a water 'demand' that will increase the Gulf Stream flow accordingly. This Atlantic Overturning Circulation has no equivalent in the Pacific Ocean.

Aphelion

The point in Earth's orbit around the Sun at which it is farthest from the Sun.

Aquarius

Name of a satellite to measure the *salinity* of the ocean surface; launch foreseen in 2008–2009.

Arctic-boreal species

In the ocean, species adapted to living in regions where the mean annual sea-surface isotherms are between 5°C and 10°C within the area north of the Arctic Circle (at ~66°N); however, the boreal zone does not lie exclusively north of the Arctic Circle; the analogous region in the southern hemisphere is called 'Antarctic-antiboreal'.

ARGO

Array for Real-time Geostrophic Oceanography: a programme of *GODAE* to deploy at least 3,000 drifting floats at a depth of about 2,000 m in all the oceans; the floats are programmed to measure key hydrographic *parameters* (e.g. temperature, *salinity*) at depth and when rising to the surface (at regular intervals) to transmit their data via satellite.

Atlantic Sub-Arctic Province

SARC; a biogeographical domain defined by A. R. Longhurst, typifying the region lying roughly between the mean annual 10°C sea-surface *isotherm* and the Arctic Circle; see *province.*

Atmospheric pressure

The weight of the atmosphere directly overlying, and applying a corresponding force on, a specified area (notionally, a 1-metre square); the unit of pressure (force [$kg.m.s^{-2}$] per unit area [m^2]) is the pascal ($kg.m^{-1}.s^{-2}$), though the practical unit is the hectopascal (hPa), and the 'standard' atmospheric pressure (average pressure at the sea surface) is 101,325 pascals (nearly a ton per square metre). The equivalent pressure in the ocean is reached at a depth close to 10 m below the sea surface.

Benthic

A term qualifying organisms that live in or closely associated with the sea bed, as opposed to *pelagic.*

Biogeochemical cycle

The notional path followed by an element in one or more of Earth's main environmental compartments (atmosphere, *biosphere*, hydrosphere, *cryosphere*, geosphere), as a result of natural processes; nowadays this cycle is being influenced by human activities.

Biome

A major biogeographical entity defined by its climatic characteristics and its animal and plant populations; in the ocean, the parameters controlling the dynamics of the *surface layer* of the ocean facilitate the definition of a given biome.

Biosphere

A notional space (roughly corresponding to the Earth's surface plus the atmosphere) occupied on Earth by living organisms.

Bloom

A local and/or seasonal outbreak of *phytoplanktonic* organisms in response to exceptional environmental conditions; see *spring bloom*.

Caribbean Province

A biogeographical domain defined by A. R. Longhurst, typifying the Caribbean region (roughly the Caribbean Sea plus the Gulf of Mexico); see *province*.

CLIMAP

Climate Long-range Investigation, Mapping, and Prediction: a programme of the 1970s and 1980s investigating the last ice age.

CLIVAR

Climate Variability and Prediction: a component of the *World Climate Research Programme* (WCRP) launched in 1993 for a period of 15 years. It is devoted to the study of climatic variations at all timescales and the response of the climate system to increasing *greenhouse-gas* concentrations in the atmosphere. For the oceans, it is an extension of the *Tropical Ocean and Global Atmosphere* (TOGA) study and the *World Ocean Circulation Experiment* (WOCE).

Clupeid

Referring to the fish family Clupeidae, which comprises such fish as anchovies, herrings, menhaden, sardines, sprats etc.

Cold wall

The cold side of the so-called *Gulf Stream North Wall*; in practice, the cold Labrador Sea water, marking a significant change in the ecological regime when passing from the Gulf Stream 'over the wall' into the sea water coming from the Labrador Sea; see also *Slope Sea.*

Cold-core ring

Eddy in which the bulk of the water is colder than the surrounding water in which the *eddy* is moving.

Condensation

The change of state of a substance from liquid to solid, with the release of heat but without a change in the liquid's temperature; opposite to *evaporation.*

Conduction

The transfer of heat by the molecules of a body as a result of their temperature (excitation), as distinct from heat transfer by radiation (electromagnetic transmission).

Continuous plankton recorder

A oceanographic device (invented by Alister Hardy) to sample *plankton* continuously over long distances and able to store the record, thus allowing the distribution of the *plankton* to be derived and plotted; used in a long-term sampling programmes, particularly across the North Atlantic Ocean.

Convection

The sinking of ocean surface water that has acquired a higher *density* than the underlying water; the increased *density* is due to cooling and/or to an increase in *salinity*; convection generates specific *water masses* in the deep ocean and thus constitutes the driver of the *thermohaline circulation.*

Convergence

A zone in which two bodies of water (e.g. two currents) meet and generate a deepening of the *thermocline.*

Conveyor belt

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

Copepod

Referring to the small-crustacean family Copepidae, which comprises the most abundant (and ecologically most important) crustaceans in the ocean (*zooplankton*).

Coriolis force

A force translating the effect of Earth's rotation to any body in motion on the Earth's surface; it provokes a deviation of marine currents to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. Coriolis force is nil at the Equator and increases with increasing latitude (i.e. polewards).

Counter-current

A current running (either laterally or at a greater depth – an undercurrent) in the opposite direction to a major ocean current; examples are the *Equatorial Counter-Current* (just under and between the North and the South Equatorial Currents) and the *Deep Western Boundary Current* (under the Gulf Stream).

Cryosphere

A notional environmental compartment on Earth, comprising all those places where water exists durably as ice (i.e. the large ice caps of the Antarctic, the Arctic and Greenland, mountain glaciers and pack-ice); see also *ice-caps*, *biosphere.*

Curl

The difference between the velocity of the directional change in component *x* and that in component *y* in a *velocity composition* representing the net effect of such directional changes.

Current intensity

The amount of water transported by a current per unit time; often, for convenience, calculated in *sverdrups*; when related to the area of the vertical plane through which the current passes, it measures also the flow of the current.

Currentmeter

An instrument used to measure marine currents; see also *Doppler currentmeter.*

Cyclone

A large mass of air rotating anticlockwise around an atmospheric low-pressure zone and moving approximately westwards, then northwestwards (in the Northern Hemisphere) or southwestwards (in the Southern Hemisphere), often causing serious damage upon crossing a coastline onto a land mass; also known as a hurricane in the Atlantic Ocean, and a typhoon in the western Pacific Ocean (cyclone in the Bay of Bengal); see also *cyclonic circulation* and *anticyclonic circulation.*

Cyclonic circulation

An anticlockwise horizontal movement around zones of low oceanic and atmospheric pressure; see also *anticyclonic circulation.*

CZCS

Coastal Zone Colour Scanner, an instrument to measure the colour of the sea; it was developed by NASA and mounted on a dedicated satellite which operated from 1978 to 1986.

Dansgaard-Oeschger Cycles

Climatic oscillations during the last glacial period revealed by the analysis of ice cores; they correspond to the warmest phases one to three thousand years ago; see also D-O.

DBCP

Data Buoy Cooperation Panel, of IOC and WMO.

Deep western boundary currents

A *counter-current* at depth beneath a surface *Western Boundary Current* and flowing in the opposite direction, on the western side of the *gyres* in all the major ocean basins.

Density

The ratio of a mass to the volume it occupies (e.g. kg/m^3); the density of sea water is determined mainly by temperature and *salinity*, with *hydrostatic pressure* playing a lesser role.

Depression

An area of below-average *atmospheric pressure.*

Divergence

A zone of separation of ocean surface water in different directions, usually at the interface between two currents or, less often, within a current; divergence causes the *thermocline* to shoal.

D-O

Acronym for Dansgaard-Oeschger, after the names of two palaeo-climatologists: Willi Dansgaard and Hans Oeschger; see also *Dansgaard-Oeschger Cycle*).

Doppler currentmeter

An instrument for determining currents, based on the *Doppler effect*; the change in frequency of the acoustic signal reflected by particles transported by the current depends on the speed of the current in the layer where the measurement is being made; when used over a wide depth range, the instrument is often called an acoustic Doppler current profiler.

Doppler effect

The apparent change in wavelength of an electromagnetic or acoustic wave due to the difference in velocity of the emitting body (e.g. an aircraft engine) and that of the detecting instrument (e.g. the human ear); if the difference is increasing, the wavelength of the signal increases, and if it is decreasing, the wavelength decreases; see aslo *Doppler currentmeter* .

Drift current

An oceanic current driven by a prevailing wind system (e.g. *North Atlantic Drift/Current*).

Dynamic oceanography

The study of motion in the ocean, notably ocean currents and *thermohaline circulation.*

Dynamic topography

The continuous measurement and mapping of the sea height (ocean surface), relative to a predefined 'geoid', with a view to assessing the changes in the *geostrophic* currents.

Eccentricity

Referring to Earth's (elliptical) orbit around the Sun, it is in practice the orbit's difference from a perfect circle, due to the fact that Earth has a small though definite mass which plays a minor role in the Earth's and the Sun's mutual rotation around each other; see also *aphelion*, *perihelion* and *precession.*

Ecotone

A transition zone that generally corresponds to rapid changes in physical parameters – for example, the drop in rainfall when passing from equatorial forest to savannah.

Edaphic

Referring to the nature of soils.

Eddy

A term used in oceanography to designate a medium-scale (~100 km across) ocean 'whirlpool' characteristic of turbulence; see also *gyre.*

Ekman theory

A theory, of V. W. Ekman which stipulates that a current will flow to the right of the direction of the wind driving the current, in the Northern Hemisphere (and to the left in the Southern Hemisphere), due to the equilibrium between the driving force of the wind and the *Coriolis force.* Since this angle of divergence is cumulative, though decreasing, with depth, depending on the force of the wind, the so-called, notional, Ekman spiral is a representation of the change in current direction with depth in the ocean surface layer.

El Niño

Initially the designation for warm marine surface current flowing southwards off the coast of northeast South America (Ecuador–Peru), it now signifies the warm episode of the *El Niño–Southern Oscillation* system (ENSO) which is marked by a strong negative SO

Index and abnormally warm sea-surface temperature at the Equator and generally in the eastern Pacific Ocean.

El Niño–Southern Oscillation

ENSO: An oscillation of the atmospheric pressure field between the high-pressure area of the central Pacific and the low-pressure area in the Indo-Pacific region; the oscillation is coupled to the variation in the sea-surface temperature of the Pacific Ocean; see also *El Niño.*

Electromagnetic radiation

Electrical and magnetic energy propagated at any one of a multitude of wavelengths between the very short-wavelength cosmic gamma rays and the very long-wavelength radio waves and the even longer wavelengths generated by rotating electromagnets; ultraviolet, visible and infra-red occupy only a tiny fraction of the whole known spectrum; the unit of such radiation is the photon (the 'particle' of light).

ENVISAT

Earth observation satellite of the European Space Agency (ESA), launched on 1 March 2002; the satellite carried a *radiometer* to measure surface temperature, an altimeter (see *altimetry*) and an instrument to measure *ocean colour* (see CZCS and SeaWiFS).

EPICA

European Project Drills for Ice Coring in Antarctica.

Equatorial Counter-Current

A major ocean current flowing eastwards between the *North Equatorial Current* and the *South Equatorial Current*, along the *meteorological Equator.*

Equilibrium

A quasi-permanent (stable) or a temporary (unstable) balance among the forces or processes operating in a system, such that an additional outside force acting on the system may establish a new equilibrium (which itself is either stable or unstable).

Equinox

One or the other of two days in the year (21 March and 23 September) on which the lengths of the day and the night are equal.

ERS 1 and 2

European Remote-Sensing Satellites of the European Space Agency, launched, respectively, in 1991 and 1995.

ESA

European Space Agency.

Eulerian

Refers to a system of coordinates (name after Leonhard Euler) used in the determination of (in the present context) a current at a fixed point; (the observer stays fixed while the current passes; a *currentmeter* on a mooring, for example); see also *Langrangian.*

Euphotic layer

Etymologically, a well-lit layer: the layer of water between the sea surface and the depth at which only 1% of the incoming solar radiation at the surface remains (99% having been scattered or absorbed by the water and the marine organisms).

Evaporation

The process by which the most energetic (therefore the highest temperature) molecules at the surface of a liquid 'escape' into the surrounding space (usually air), thus cooling the liquid; the energy is restored to the air as heat only when the 'ejected' water molecules condense back into the liquid phase; see *condensation.*

Field

In the present context, a notional distribution of the values of an oceanographic or environmental *parameter*, whether in two or three dimensions (e.g. *density*, temperature, wind fields).

Food chain

An ecological concept regarding the feeding relationships (predator–prey, host–parasite, etc.) among the organisms participating in a specific ecosystem; often called, more accurately, a food web.

Foraminifera

Pelagic or *benthic* protozoans with a calcareous skeleton. Analysis of the *isotopic* composition of carbon and oxygen in the skeletons found in the seabed sediment layers allows the 'reconstitution' of the sea-surface temperature (from the *pelagic* species) and the age of deep oceanic water (from the *benthic* species) at the time at which they lived.

Forcing

Expression designating extraneous factors intervening in ocean circulation; e.g. wind, thermal exchange with the atmosphere.

Front

An interface between two bodies of water of different *densities* or, possibly, of different speed and opposing directions; given the importance of temperature in determining *density*, thermal fronts can usually be seen easily in satellite remote-sensing temperature images.

Gadoid

Referring to such fishes as cod and their relatives (e.g. hake, pollack, whiting).

GEOSS

Global Earth Observation System of Systems: an initiative of the G8 to establish a world network of Earth observation systems; adopted at the Third Earth Observation Summit in Brussels, in February 2005.

Geostrophic equilibrium

Hypothetical *equilibrium* between the horizontal pressure force in the ocean (due to differences in sea height) and the *Coriolis force*; accurate estimates of ocean circulation can be derived from the pressure differences.

GIN

Greenland, Iceland and Norway: name given to the region of deep-water formation in the Greenland and Norway Seas.

Glacial period

Also known as an ice age, during which, the *ice-caps* have extended significantly south of the Arctic Circle in the northern hemisphere (such extension is not possible in the Antarctic, except through the extension of the pack-ice) and the mean temperature at Earth's surface is significantly below the long-term average.

GLOBEC

Global Ocean Ecosystems Dynamics, a project of the IGBP, devoted to a study of the dynamics of marine ecosystems and their variability.

GODAE

Global Ocean Data Assimilation Experiment, the first '*operational oceanography*' experiment; it took place from 2003 to 2005 to test the feasibility of operational ocean forecasting.

GOOS

Global Ocean Observing System currently being developed under the auspices of the Intergovernmental Oceanographic Commission (IOC), the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP).

Gravitation

The force exerted on each other by two bodies, directly proportional to the product of their respective masses and inversely proportional to the square of the distance between them; at the Earth's surface, a body of 1 kg experiences an attractive force Earthwards of 9.81 kg.m/s^2 (at the surface of the Sun it would be nearly 274 kg.m/s^2).

Greenhouse gases

Gases that absorb infrared radiation emitted by the Earth, thus heating the atmosphere; the most abundant of these gases is water vapor, which ensures an average temperature of 15°C at the Earth's surface, hence livable for human beings. Human beings produce other greenhouse gases (e.g. carbon dioxide, methane, chlorofluorocarbons), with the attendant risk of perturbing the Earth's climate.

GSA

Great *Salinity* Anomaly: the appearance at the ocean surface of significant masses of low-*salinity* water, which circulates over a period of several years in the North Atlantic; these anomalies are due either to an overflow of Arctic ice through the Fram Strait or to the arrival of fresh water and ice from the Canadian Arctic archipelago and Baffin Bay, via the Labrador Sea.

GSNW

Gulf Stream North Wall: an oceanographic feature (the interface between the warm Gulf Stream water and the cold Labrador Sea water) that can be used to mark the variations in the latitudinal position of the Gulf Stream; see also *cold wall.*

Gulf Stream Province

GFST; a biogeographical domain defined by A.R. Longhurst, typifying the Gulf Stream; see *province.*

Gulf Stream Recirculation

Cyclonic circulation, to the north of the Gulf Stream, and *anticyclonic circulation*, to the south of it, which feed and reinforce the Gulf Stream by recuperating the potential energy in *eddies*; see also *gyre.*

Gyre

Major loops of the oceanic *anticyclonic circulation* usually associated with the major *subtropical* currents of the Atlantic and Pacific Oceans, but also the *cyclonic circulation* associated with the major subpolar currents of the North Atlantic.

Hadley Cell

Meridianal atmospheric circulation marked by the ascendance of warm and humid air (convection) above the *intertropical convergence zone* and by its descent in the middle of the *subtropical anticyclones*.

Heinrich Events

Climatic events of the last glacial period, occurring every 7,000 to 10,000 years; they were detected as layers of rock debris in icebergs (see IRD) and are also found in marine sediments. They correspond to the coldest episodes of the glacial period.

Holocene

The present geological Epoch, starting about 10,000 years ago, characterized by the development of human agriculture and technology.

Hydrography

In oceanography, characterization of the oceans and seas principally in terms of water temperature, salinity and pressure. Hydrographic stations allow determination of the hydrographic profile of the *water column* at a given place or along a vertical (or horizontal) section based on a series of stations along a given track.

Hydrostatic equilibrium

In oceanography, a state in which the force of gravity acting on a body (including a 'parcel' of water) in a liquid is equal to the buoyancy of that body (or 'parcel') at a specified depth (the hydrostatic equilibrium depth).

Hydrostatic pressure

In oceanography, the pressure at a specified depth in the ocean in the absence of any motion; essentially the weight of water overlying a notional horizontal surface (e.g. 1 m^2); see also *water column*.

Hydrothermal vent

A fissure in the ocean floor, especially at a *mid-ocean ridge*, from which emerges water of very high temperature (around 400°C) creating an ecosystem in its vicinity populated by unique species (notably crustaceans, tubeworms, and fishes).

Ice-cap

A massive accumulation of ice over millions of years in the Arctic and Antarctic regions; in the Arctic region, the three main ice-caps are known as the Laurentide (Canada and northern USA), the Greenland, and the Fennoscandia (northern European); the Antarctic has a single ice-cap.

Ice-core

The cylindrical 'stick' of ice retained in the interior of a hollow drill used to core ice, normally in an *ice-cap* or a glacier, with a view to determining the 'history' of the formation of the ice; such cores may exceed several hundred metres in length and cover several hundred thousand years of accumulation.

ICES

The International Council for the Exploration of the Sea, founded in 1902; the first international oceanographic organization, with the main objective of preserving the ecosystems of the North Atlantic Ocean, the neighbouring seas and their resources.

ICSU

International Council for Science (formerly International Council of Scientific Unions): a non-governmental organization that brings together academies of science and national research councils to pursue the advancement of science.

IGBP

The International Geosphere–Biosphere Programme, organized by ICSU.

IMBER

Integrated Marine Biogeochemistry and Ecosystem Research: Programme of the IGBP (of ICSU), aimed at understanding and forecasting the responses of marine ecosystems to global change and the consequences, in return, for the 'Earth system' and human societies.

Inertia

The resistance of a body to its displacement (from rest or from its direction of motion) by an applied force; it is a function of the body's mass (normally in the absence of gravity).

Infrared

That part of the electromagnetic spectrum between wavelengths of approximately 780 nm (nanometres) and 0.3 mm; 780 nm is the 'lower' limit of the visible spectrum.

Interglacial period

The geological period between two ice ages (*glacial periods*); their frequency has been variable in geological time but such periods have lasted about 120,000 years during the last million years.

International Geophysical Year

International programme of coordinated study of the different physical compartments of the planet (*geosphere*, *atmosphere*, oceans, *cryosphere*), which took place in 1957 and 1958; it was, for oceanography, the first programme of international cooperation.

Intertropical

Referring to the zone between the northern limit of the tropics (Tropic of Cancer, 23.5°N) in the northern hemisphere and the southern limit (Tropic of Capricorn, 23.5°S); see also *Intertropical Convergence Zone.*

Intertropical Convergence Zone

Zone in which the *Trade Winds* from the two hemispheres meet; it corresponds to the meteorological Equator and does not coincide with the geographical Equator. It shifts seasonally (with the Sun) a few degrees northwards (in the northern summer) and returns southwards (in the northern winter); it is the 'dead-calm zone' (the 'doldrums') of strong atmospheric convection, which activates the *Hadley Cell.*

IOC

The Intergovernmental Oceanographic Commission, of UNESCO, charged the coordination of international marine environment research programmes approved by its Member States and the relevant UN agencies.

IPCC

The Intergovernmental Panel on Climate Change, a high-level group of experts, created in 1988, to evaluate changes in the climate, their impact and the adaptation measures to adopt, based on the best available scientific data; the Panel's Third Report was published in 2001 and the Fourth Report is due out in 2006.

IRD

Ice-rafted debris; continental rock debris trapped in, and transported by, icebergs, and found in oceanic sediments. IRD in icebergs allowed the identification of the *Heinrich Events.*

Isobar

A line linking equal values of pressure in a pressure *field* (e.g. as often used in weather forecasts).

Isopleth

A line linking equal values of a specified *parameter* in a *field* specifying the distribution of the values of said *parameter*; see also *isobar*, *isopycnal*, *isotherm.*

Isopycnal

A notional line linking equal values of *density*, thus allowing description of the *density field* in the ocean.

Isotope

A type of atom of a given element; normally an atomic nucleus of an element contains an equal number of protons (positive charge, attracting one electron) and neutrons (zero charge, attracting no electron). The other isotopes of the element generally have an additional neutron or more; e.g. the very common C_{12} (six protons and six neutrons), the much rarer C_{13} (with seven neutrons), and the very rare radioactive C_{14} (with eight neutrons) which is produced only in nuclear reactions in nature (e.g. absorption of a cosmic ray by a nitrogen atom to produce a C_{14} atom) or artificially (e.g. in a nuclear-research laboratory).

JGOFS

Joint Global Ocean Flux Study, a programme of the IGBP devoted to the study of the oceanic carbon cycle (1987–2003).

Joule

The basic unit of heat energy or work; measured as $kg.m^2.s^{-2}$.

Katabatic

Refers to a flow of a fluid due to its very high density; very cold air overlying glaciers, for example, is very dense and flows, under the action of gravity, down the slope of the glacier towards the periphery, often attaining a speed of 200 km/h (katabatic winds).

Kinetic energy

The energy expended in displacing a body by a given force (e.g. an object falling to the ground under the force of gravity; measured as half the mass times the square of the velocity); equivalent to mechanical energy.

Lagrangian

Refers to a system of coordinates (named after Joseph-Louis Lagrange) used in the determination of (in the present context) a current by following a drifting float (the observer moves with the current and relates the speed of flow to a fixed frame of reference, like sailor measuring his ship's drift) see also *Eulerian*.

Latent heat

The amount of heat that is absorbed or released when a substance changes its state (e.g. water to steam [latent heat of vaporization] or ice to water [latent heat of fusion], respectively) at a constant temperature; measured in *joules* per kilogram × kelvin (a kelvin is a measure of absolute temperature, of an equivalent magnitude of 1°C, but on a different scale).

Leptocephalus

Name given to an eel larva; the smallest larvae (of the American and European eels) can be found in the Sargasso Sea, which leads scientists to believe that the eels reproduce there.

Maunder Cycle

A subcycle of the solar cycle (which lasts about 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 during the so-called 'Little Ice Age'.

Meander

An alternating lateral displacement of the main stream of a current, appearing as 'snake-like' forms on satellite remote-sensing images of the temperature field; occasionally a meander loop becomes sufficiently tight to become pinched off from the main stream, thus becoming a quasi-independent *eddy*.

Meteorological Equator

The meteorological division of the two terrestrial hemispheres, which does not correspond to the geographical Equator; see *Intertropical Convergence Zone.*

Microplankton

A component of the *plankton* that is very small and often constitutes the food of other, somewhat larger planktonic organisms.

Mid-ocean ridge

A major, roughly north–south ridge (rising a kilometre or more from the ocean floor) marking a fracture in the Earth's crust under the principal oceans; a feature of Earth's *plate tectonics*, the site of *hydrothermal vents*, and the site of production of new crust; see also *sill.*

Milankovitch Cycle

Cycle of variation in the Earth's orbit around the Sun that principally determines the alternation of *glacial* and *interglacial periods*; it is the expression of the astronomical theory of climate change elaborated by Milutin Milankovitch.

Mixed layer

The surface layer of the ocean homogenized (especially thermally) by the wind down to the *thermocline.*

MODE, POLYMODE

Mid-Ocean Dynamics Experiment; with the derivative POLYMODE, international programmes carried out in the 1970s, devoted to the study of ocean *eddies.*

Model

A hypothetical scenario applicable to a system (e.g. ocean–atmosphere coupling) with a view to defining the probable evolution of the system under conditions set for the scenario, testable by 'ground truth' data by which the predictions generated by a model may be refined.

Momentum

A physical quantity that is the product of the mass of a body and its velocity (in the simple case of motion in a straight line); see also *angular momentum*.

Monsoon

A seasonal wind system, especially over the northern Indian Ocean and the South Asian continent; the direction of the wind is southwesterly in summer (June–October), when the land is hotter than the ocean, and northeasterly in winter (December–April), when the land–ocean difference is reduced.

Moraine

A sedimentary deposit of poorly sorted rock and detritus transported by glaciers and ice-sheets; see also *Heinrich Events*.

NACW

North Atlantic Central Water, a major body of water of comparatively uniform temperature and *salinity*, resulting from various oceanographic processes, and notably predominant in the Sargasso Sea; see also *water mass*. There is an analogous South Atlantic Central Water.

NADW

North Atlantic Deep Water, a recognized *water mass* formed in the *convection* zone of the North Atlantic, which flows into the North Atlantic Ocean from its source (in the Arctic region), at a depth of about 3,000 m: it is the driver of the *thermohaline circulation*, the so-called '*conveyor belt*'.

NAO

North Atlantic Oscillation: it is determined by the difference between the high atmospheric pressure of the Azores anticyclone and the low atmospheric pressure of the Icelandic *depression*. This difference is the NAO Index; the higher the Index (positive value or *anomaly*), the greater the intensity of the western atmospheric circulation in Europe.

NASA

National Aeronautics and Space Administration: the US space agency.

Nebulosity

A measure (usually a visual estimate) of cloud cover.

New primary production

The part of *primary production* based on the input of *nutrient salts* usually, but not exclusively, from the deep ocean to the *euphotic layer*.

New production

The part of *primary production* that uses *nutrient salts* 'imported' from a great distance into the euphotic layer; see *regenerated production*.

North Atlantic Drift

An eastward extension of the Gulf Stream driven by the prevailing westerly winds at mid-latitude; also known as the North Atlantic Current.

North Atlantic Drift Province

NADR; a biogeographical domain defined by A. R. Longhurst, typifying the *North Atlantic Drift* (or Current); see *province*.

North Atlantic Subtropical Gyral Province

NAST: a biogeographical domain defined by A. R. Longhurst, typifying the North Atlantic *subtropical gyre*; see *province*.

North Equatorial Current

Current driven by the northeasterly *Trade Winds* crossing the Atlantic and Pacific Oceans from east to west, on the northern side of the *Intertropical Convergence Zone*, generally north of the Equator; see *South Equatorial Current*.

Northwest Atlantic Shelves Province

NWCS; a biogeographical domain defined by A. R. Longhurst, typifying the all the North Atlantic continental shelves; see *province*.

Nutricline

An ocean layer marked by a rapid change in the concentration of *nutrients* in the sea water; this layer is associated with the *pycnocline*, which, by restricting the transfer, from deep water, of *nutrients* into the *mixed layer*, also limits *primary production*. In typical tropical conditions, marked by a permanent *thermocline*, *primary production* – and therefore chlorophyll concentration – are at a maximum at the top of the nutricline, where the nutrient-rich layer receives most of the available *solar energy*.

Nutrient salts

See *nutrients*.

Nutrients

Designates all the chemical elements (excluding carbon and hydrogen) required for the production of living matter; in practice, this term is reserved for nitrates and phosphates, silicates, sometimes qualified as macronutrients, in contrast to other elements, such as iron, which are present in considerably smaller concentrations (micronutrients).

Ocean colour

The spectrum of the visible radiation emitted by the ocean through its surface; the spectrum depends mainly on the particles and substances contained in the water, particularly the chlorophyll of the *phytoplankton*. Ocean colour is measured by satellite, and the colour allows the concentration of *phytoplankton* in the sea to be estimated.

Ocean dynamics

The ensemble of the processes governing energy exchange within the ocean and between the ocean and the atmosphere, on the one hand, and the ocean floor, on the other.

Operational oceanography

Oceanography applied to the production of forecasts (to a specified time 'horizon') of such characteristics as sea state, temperature/*salinity*/*density fields*, current strength and direction and, more generally warnings of such phenomena as storm surges, *cyclones*/hurricanes, *tsunamis*, icebergs etc.

Overfishing

Excessive fishing, to the point at which recruitment to the fishable stock is insufficient to maintain the stock's size.

Ovocyte

A cell in the uterus destined to become an egg.

Parameter

A measurable characteristic of a given system (e.g. temperature, in the case of the oceans).

Partial pressure

In a mixture of gases, the partial pressure is equivalent to a component gas's concentration in the mixture. For a dissolved gas (here, in the ocean) with a specific concentration, the partial pressure is the same as that of the gas in an atmosphere in *equilibrium* with the solution. When the partial pressures in the air and in the solution are equal there is no exchange between the two media; when they are not equal the component gas moves from the medium of higher partial pressure to that of lower partial pressure.

Pelagic

A term signifying the open water environment and the life it contains (as opposed to *benthic* species, which are closely linked to the sea bed); *plankton* is pelagic as are tuna, salmon, anchovy, sardine and herring.

Perihelion

The point in Earth's orbit around the Sun at which it is closest to the Sun.

Photosynthesis

The biochemical process by which green plants, algae, and many bacteria, convert water and carbon dioxide into food and oxygen using the energy absorbed from sunlight by the pigment chlorophyll; see also *primary production*.

Physical oceanography

The scientific study of the physics of the ocean, its physical properties and its *dynamics*.

Phytoplankton

The body of microscopic green algae in the sea, hence, collectively, the agent for *primary production* by *photosynthesis*; see also *plankton*, *zooplankton*, *microplankton.*

Pilot charts

Navigation charts indicating the winds and currents (as well as ocean depth, if appropriate) according to the season.

Plankton

Organisms living in the open sea, with a very low capacity for displacement relative to the movement of the local water body (= wanderers); see *phytoplankton*, *zooplankton*, *microplankton.*

Plate tectonics

The name given to the movements and interactions of the Earth's major crustal plates; see also *mid-ocean ridge.*

POLYMODE

See MODE.

Potential energy

The energy retained in a body by virtue of its position with respect to a given force (e.g. an object sitting on top of a table and acted upon, but not moved by, the force of gravity; measured as half the mass times the square of the velocity; in practice, for a mass of 1 kg: 0.5 $kg.m^2.s^{-2}$).

Ppm

A convenient abbreviation of 'parts per million' as a measure of relative concentration (e.g. milligrams per kilogram).

Precession

A progressive change in the angle of Earth's axis of spin with respect to the plane of Earth's orbit around the Sun; it has varied from the vertical, in the last million years, between about 21.5° and 24.5°, and its present value is about 23.5°; it is represented by the Tropics of Cancer or Capricorn.

Primary production

Production of organic molecules necessary for the creation of new living tissue in plants directly from mineral elements and light energy; see *photosynthesis*.

Province

A term introduced by A. R. Longhurst for each *biome* in each ocean; for example, the Gulf Stream in its 'mythical' sense (stretching from the Florida Strait to the Norway Current and to the edge of the Arctic), corresponds, in Longhurst's classification, to two *biomes* – polar and westerly-wind – and to three provinces: the *Atlantic Sub-Arctic Province* (SARC), the *North Atlantic Drift Province* (NADR), and the *Gulf Stream Province* (GFST) proper.

PSU

Practical *salinity* unit; 1 PSU is approximately equivalent to 1 mg of salts dissolved in 1 gram of sea water; typical sea water has a *salinity* of about 35 PSU, but, since PSU is only a pseudo-unit of convenience (the *salinity* being now determined as a ratio of two electrical conductivities), *salinity* is more and more referred to by the value (of the ratio) only.

Pycnocline

An ocean layer marked by a rapid change in the *density* of the sea water; in general, it coincides approximately with the *thermocline* (because the temperature is the principal determinant of water *density*). The pycnocline/*thermocline*, being a very stable zone, limits vertical mixing and exchange between the *mixed layer* and the deep ocean.

Radiant energy

Electromagnetic energy, usually though not exclusively originating in the Sun and eventually irradiating first the top of the Earth's atmosphere and later the Earth's surface; see also *solar energy*.

Radioactivity

The spontaneous breakdown of unstable atoms, releasing alpha-particles (basically a combination of two protons and two neutrons) and/or beta-particles (basically, an electron), depending on the initial element and its characteristic decay sequence(s); some radioactive elements may fission (break into two parts) or spallate (break into more than two parts).

Radiometer

An instrument for detecting the presence of electromagnetic radiation, usually in the form of ultraviolet, visible (light), infra-red (heat) or microwave (radar).

Rafos

A type of subsurface float equipped with an acoustic hydrophone and positioned in relation to several emitting stations, which retransmits the float's trajectory by satellite by rising to the surface to transmit accumulated data.

Recruitment

In fisheries, a term designating the quantity (usually annually) of young fish entering the fishable stock for the first time; in practice, only a fraction of the recruits is exploited.

Regenerated production

The part of *primary production* that uses *nutrient salts* regenerated on the spot (i.e. not 'imported' from far away), in the *euphotic layer*; see also *new production.*

Resolution

The capacity of a sensor (e.g. radiometer, altimeter, telescope, microscope) to distinguish two neighbouring features in an object being sensed or viewed; measured in appropriate distance units.

Salinity

Formerly, the mass of salts contained in 1 kg of seawater; now measured in terms of a ratio of the conductivity a sample of sea water to that of a 'standard' sea water. The average salinity of sea water is 35 (~35 g/kg); see PSU.

SARC

Atlantic Sub-Arctic Province; see also *province.*

Sargassum

A genus of algae whose species are several metres in length and float in bundles on the Sargasso Sea, constituting a unique ecosystem that is maintained thanks to its confinement inside the *anticyclonic gyre* of the *Gulf Stream recirculation.*

Scatterometer

A radar mounted on a satellite to determine the speed and direction of the wind on the ocean surface by the analysis of the scattered return radar signals from the ocean surface; see also *altimetry.*

Sea-surface topography

The sea height relative to a reference surface of a specified potential; see *TOPEX–Poseidon* and *geostrophic.*

SeaWiFS

Sea-viewing Wide-Field-of-View Sensor: a NASA satellite to measure *ocean colour.*

Sensible heat

The heat stored or contained in a body at a given temperature; the product of the body's mass, the heat capacity (*joules* per kilogram) of the body's substance and the temperature.

Sill

An extended submarine geological feature rising from the sea floor and often serving to define a hydrological basin; also called a 'rise'. Examples are the sill between Greenland and Scotland via Iceland and the Faeroe Islands (i.e. emerged parts of the sill), and the Gibraltar sill (maximum depth of about 350 m), partially separating the Atlantic Ocean from the Mediterranean Sea.

Slope Sea

A body of cold water 'occupying' the North American continental slope, between the coastal waters overlying the continental shelf itself and the Florida Current/Gulf Stream seaward of the slope.

SMOS

Soil Moisture and Ocean Salinity: A Satellite, capable of measuring the *salinity* of the ocean surface water; launch foreseen for 2007.

Solar energy

The *electromagnetic radiation* received from the Sun; it is differentiated particularly with respect to the top of the atmosphere and to the Earth's surface; also known as solar radiation.

South Atlantic Bight

A convenient geographical/ecological region occupying the North American continental shelf and adjacent sea between the Straits of Florida and Cape Hatteras, N.C.

South Equatorial Current

Current driven by the southeasterly *Trade Winds* crossing the Atlantic and Pacific Oceans from east to west, on the southern side of the *Intertropical Convergence Zone*, generally along the Equator; see *North Equatorial Current.*

Spring bloom

A rapid development of phytoplankton in the Spring, when favourable conditions of light, stability and availability of nutrients are met in a body of water.

Stream current

An oceanic current driven by the prevailing *thermohaline circulation* (e.g. the Gulf Stream, the Kuroshio).

Streamer

A term describing 'ribbons' of either warm water in surrounding cold water, or cold water in surrounding warm water, associated with the eddy dynamics of the Gulf Stream system.

Subtropical

Refers to the regions (in each hemisphere) between the Tropics (of Cancer, in the northern hemisphere, and of Capricorn, in the southern hemisphere, both at about 23° latitude) and 40° latitude. It is the region of subtropical *gyres.*

Sverdrup

An oceanographic unit of measurement of the flow rate of a marine current; a sverdrup, abbreviated Sv, is equivalent to 1 million m^3/s. It is named after H. Sverdrup.

Synoptic

Refers to a set of observations and measurements aiming at describing an oceanic or atmospheric feature (e.g. North Atlantic Ocean temperature *field*) in such a way that the set may be considered as having been effectively simultaneous with respect to the temporal variation of the feature.

Thermocline

A layer of ocean water in which there is a rapid decrease in temperature with increasing depth; it separates the warm surface *mixed layer* from the deeper and colder water. In the relatively wind-free *intertropical* region, a permanent *thermocline* is generally established, whereas in the zones of strong prevailing seasonal wind systems, a new seasonal *thermocline* is established each year and, in some areas, overlies a permanent *thermocline* at a much greater depth.

Thermodynamic forcing

Displacement of ocean water as a result of the redistribution of heat, whether absorbed from the atmosphere or within the ocean itself; see *sensible heat*.

Thermohaline circulation

The deep-ocean circulation driven by the sinking of high-*density* surface water due to cooling and/or an increase in the water's *salinity*; see '*conveyor belt*'.

TOGA

Tropical Ocean and Global Atmosphere, an international study carried out from 1985 to 1995 in the framework of the World Climate Research Programme (WCRP) to determine the processes linking the tropical oceans, particularly in the Pacific, to the world climate at a multi-annual scale.

TOPEX–Poseidon

A Franco-American altimetric satellite launched in 1992 to measure the variation in sea height with centimetric precision with a view to determining the topography of the ocean surface and, therefore, to derive the *geostrophic* currents.

Trade winds

A component of the atmospheric circulation around *subtropical anticyclones*; centred on 15° latitude, these winds are northeasterly in the northern hemisphere and southeasterly in the southern hemisphere. These two Trade Wind systems meet in the *Intertropical Convergence Zone* or *meteorological Equator*.

Tsunami

An oceanic wave usually due to an earthquake, a submarine volcanic eruption or a major subsidence of the ocean floor; the wave travels virtually unnoticeably but at great speed (~700 km/h) in the open ocean; on reaching shallow water (a seashore) it slows down (to about 40 km/h) and greatly increases in wave height (to 10 or more metres), possibly causing considerable physical and ecological damage.

Turbulence

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

Turbulent diffusion

This term designates the distribution of physical (e.g. temperature) or chemical (e.g. salts) properties within a body of water (or other fluid) by the active movement of the components of the water (fluid) in all directions, leading to the eventual homogenization of the water (fluid) with respect to the property; the scale is macroscopic, in contrast to molecular diffusion, in which the excitation of individual molecules involved is propagated.

Ultraviolet

That part of the electromagnetic spectrum between wavelengths of approximately 10 nm and 300 nm.

UNEP

United Nations Environment Programme.

UNESCO

United Nations Educational, Scientific and Cultural Organization.

UNFCCC

United Nations Framework Convention on Climate Change.

Upwelling

A process in which sea water at depth is drawn towards the surface by the stress of the wind on the sea surface, in accordance with the *Ekman* principle; upwelling is generally strongest on the eastern side of the major ocean basins.

Vectorial composition

The resolution of a vector (a line of a length specifying a speed or a force and with a specified direction, usually relative to an *x,y* system of coordinates) into two secondary vectors perpendicular to each other and generally representing two antagonistic motions or forces.

Vertical mixing

The mixing of surface water with underlying water in the ocean, usually due to the wind stress at the surface, and leading to the creation of the surface *mixed layer*; also the outcome of *upwelling*.

Vertical stratification

The subdivision of the *water column* into two or more layers of water with notably different temperatures and/or *salinities* (hence *densities*); see also surface *mixed layer*, *thermocline* and *pycnocline.*

Viscosity

A measure of a fluid's reluctance to flow, corresponding to internal friction in the fluid between two portions, one of which 'seeks' to slide over another; measured in pascal.seconds (Pa.s).

Vorticity (absolute)

The sum of relative vorticity and planetary vorticity, its magnitude is constant.

Vorticity (planetary)

The movement of a body around a vertical axis that is perpendicular to the plane tangential to Earth's surface; the movement is due to the rotation of the Earth.

Vorticity (relative)

The tendency of a body to rotate relative to the Earth's surface.

Warm-core ring

Eddy in which the bulk of the water is warmer than the surrounding water in which the *eddy* is moving.

Water column

A notional vertical column in the ocean between the surface and the ocean floor (or some specified depth, for convenience), customarily conforming to a notional area of a 1 square metre.

Water mass

A substantial body of ocean water that has arisen from a specific source (e.g. *North Atlantic Deep Water*) so that it has a specific, easily identifiable temperature–salinity relationship; other bodies of water not so formed and commonly identified by their 'place of residence' in the ocean are usually referred to as water types (e.g. *North Atlantic Central Water*).

Watt

The basic unit of power; measured as $kg.m^2.s^{-1}$ (*joule* per second).

WCRP

World Climate Research Programme; an international programme jointly organized by the WMO, ICSU and the IOC.

Western boundary currents

Strong currents flowing polewards on the western side of the *gyres* in all the major ocean basins.

WHOI

Woods Hole Oceanographic Institute: Woods Hole, Mass., USA.

WMO

World Meteorological Organization: a specialized agency of the United Nations responsible for the coordination of actions to provide better weather and climate forecasts.

WOCE

World Ocean Circulation Experiment: an international programme of the WCRP, carried out from 1990 to 2000. It was the first such programme ever to produce a global description of ocean circulation.

Younger Dryas

A climatic period (the more recent part of the Dryas); during this period, there was, about 12,000 years ago, a sudden drop in temperature at the height of the melting period.

Zooplankton

Animal *plankton* which lives on *phytoplankton* and small suspended food particles.

To learn more

Appenzeller C., Stocker, T. F. and Anklin, M. 1998. North Atlantic Ocean Dynamics Recorded in Greenland Ice Cores. *Science,* Vol. 282, pp. 446–49.

Atlantic Ocean Circulation. 1994. *Oceanus.* Vol. 37, No. 1. The Woods Hole Institution, USA.

Beaugrand, G., Brander, K. M. and Souissi, S. 2004. *Plankton Changes and Cod Recruitment in the North Sea*. In: International Symposium on Quantitative Ecosystem Indicators for Fisheries Management, 31 March – 3 April 2004, Paris, France.

Belkin, I. M., Levitus, S., Antonov, J. I. and Malmberg, S. A. 1998. 'Great Salinity Anomalies' in the Northern North Atlantic. *Progress in Oceanography*, Vol. 41, No. 1, pp. 1–68.

Belkin, I. M. 2004. Propagation of the 'Great Salinity Anomaly' of the 1990s around the Northern North Atlantic. *Geophysical Research Letters*, Vol. 31 (L08306, doi:10.1029/2003GL019334).

Boorstin, D. 1988. *Les Découvreurs*. Collection Bouquins. Robert Lafont Editions, Paris, France.

Changement Global. 2003. *Lettre PIGB-WCRP*/France No. 15.

Climate Change. 2001. The Scientific Basis: Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Shanghai, 17–20 January 2001. Cambridge University Press, UK.

Curry R. G. and McCartney, M. S. 2001. Ocean Gyre Circulation Changes Associated with the North Atlantic Oscillation. *Journal of Physical Oceanography*. Vol. 31, No. 12, pp. 3374–3400.

Dickson, B., Yashayev, I., Meincke, J., Turrel, B., Dye, S. and Holfort, J. 2002. Rapid Freshening of the Deep North Atlantic Ocean over the Past Four Decades. *Nature,* Vol. 416, pp. 832–37.
Duplessy, J. C. 1996. *Quand l'océan se fâche*. Editions Odile Jacob, Paris, France.
Favier, J. 1991. *Les Grandes découvertes d'Alexandre à Magellan*. Librairie Arthème Fayard, Paris, France.
Fofonoff, N.P. 1981. The Gulf Stream System. In: B. A. Warren and C. Wunsch (eds), *Evolution of Physical Oceanography*. Massachusetts Institute of Technology (MIT), Cambridge, USA, pp. 112–39.
Gagosian, R. B. 2003. *Abrupt Climate Change, Should We Be Worried?* Prepared for a panel on abrupt climate change at the World Economic Forum Davos, Switzerland, January 2003. Woods Hole Oceanographic Institution, USA.
Hansen, B., Turrell, W. R. and Osterhus, S. 2001. Decreasing Overflow from the Nordic Seas into the Atlantic Ocean through the Faeroe Bank Channel since 1950. *Nature*, Vol. 411, pp. 927–30.
Hurrel, J. W., Kushnir, Y. and Visbeck, M. 2001. The North Atlantic Oscillation. *Science*, Vol. 291, No. 26, pp. 603–05.
Le risque climatique. 2004/2005. *Les Dossiers de La Recherche* No. 17, Paris, France.
Le Traon, Pierre-Yves. 2002. Les voyages de l'océan. *Pour la Science*. No. 291, January 2002, Paris, France.
Longhurst, A. R. 1998. *Ecological Geography of the Sea*. Academic Press, London, UK
Mann, K. H. and Lazier, J. R.N. 1996. *Dynamics of Marine Ecosystems, Biological – Physical Interactions in the Oceans*. Blackwell Science, London, UK.
Maury, M. F. 1963. *The Physical Geography of the Sea and its Meteorology*. In: J. Leighly (ed.),The Belknap Press of Harvard University Press, Cambridge, Massachusetts, USA.
Minster, J. F. 1997. *La Machine Océan*. Nouvelle Bibliothèque Scientifique, Editions Flammarion, Paris, France.
Oceans and Climate, 1996. *Oceanus,* Vol. 39, No. 2, Woods Hole Oceanographic Institution, USA.
Orsenna, E. 2005. *Portrait du Gulf Stream. Eloge des Currents.* Editions du Seuil, Paris, France.
Pietrafesa, L. J., Janowitz, G. S. and Wittman P. A. 1985. Physical Oceanographic Processes in the Carolina Capes. In: L. P. Atkinson, D. W. Menzel and K. A. Bush (eds), *Oceanography of the Southeastern*

US Continental Shelf, Coastal and Estuarine Sciences 2. American Geophysical Union, Washington D.C., pp. 23–32.

Physical Oceanography, 1992. *Oceanus,* Vol. 33, No. 2. Woods Hole Oceanographic Institution, USA.

Schwartz, P. and Randall, D. 2003. An Abrupt Climate Change Scenario and Its Implications for United States National Security. A report commissioned by the U.S. Defense Department.

Seager, R., Battisti, D. S., Yin, J., Gordon, N., Naik, N., Clement, A. C. and Cane, M. A. 2002. Is the Gulf Stream Responsible for Europe's Mild Winters? *Quarterly Journal of the Royal Meteorological Society,* Vol. 128, No. 586, pp. 2563–2586.

Siedler G., Church, J. and Gould, J. (eds). 2001. *Ocean Circulation and Climate: Observing and Modelling the Global Ocean.* Academic Press, San Diego, London, UK. 715 pp.

Stommel, H. M. 1955. Direct Measurements of sub-surface Currents. *Deep-Sea Research*, Vol. 2, pp. 284–85.

Stommel, H. M. 1958. *The Gulf Stream: A Physical and Dynamical Description*, First edition. University of California Press, Berkeley, USA.

Stommel, H. M. 1965. *The Gulf Stream: A Physical and Dynamical Description*, 2nd edition. University of California Press, Berkeley and Los Angeles, USA.

Szekielda, K.H. 2004. *Spectral Recognition of marine bio-chemical provinces with MODIS*. European Association of Remote Sensing Laboratories (EARSel) Procceedings Vol. 3, No. 2, pp. 261–275.

Open University Course Team 1989. *Ocean Circulation.* Pergamon Press, Oxford, UK.

Tomczak, M. and Stuart, G. J. 1994. Regional Oceanography: an Introduction. Pergamon Press, Oxford, UK.

Voituriez, B. 2003. *The Changing Ocean: Its Effects on Climate and Living Resources*. IOC Ocean Forum Series. UNESCO Publishing. Paris, France.