OCEAN AND CLIMATE EVOLUTION

Edouard Bard
Professor at the Collège de France,
Associate Director of CEREGE in Aix-en-Provence, France

A brief introduction on ocean and climate changes

The climate system comprises numerous compartments such as the atmosphere, the oceans, marine and continental ice, and even the Earth's crust. These various compartments exchange heat, mechanical energy and matter, in particular water and carbon dioxide. The complexity of the climatic system arises from the fact that all its compartments are undergoing perpetual change. The atmosphere, in particular, is driven by rapid and ceaseless movements that are studied by the meteorologist. The atmosphere is also coupled to the ocean that evolves over much longer periods, from times spans of a year for surface waters up to several centuries for the deep ocean. The continental ice sheets are evolving even more slowly with time reactions ranging from the century to several millennia. The climate system is also coupled to the biogeochemical cycles of carbon and water.

Figure 1: Ocean, atmosphere, biosphere
(Maré, Loyalties Islands, New Caledonia) Photo: E. Bard

The global ocean is a huge carbon sink that is currently absorbing about a third of the carbon dioxide emissions associated with anthropogenic combustion (fossil fuels and deforestation). Since the beginning of the industrial period the ocean has been the main carbon reservoir to curb rising atmospheric CO_2, a trend which has inevitably been accompanied by a slow acidification of surface waters. The ocean also plays an important role in absorbing the bulk of the excess heat attributed to global warming, heat which is spreading from the surface into the great depths. Sea level has also increased over the past century, in particular through the input of fresh water from glaciers and continental ice sheets such as Greenland and Antarctica. Two-thirds of the current rise is due to melting ice and one third to thermal expansion caused by heat uptake.

To better evaluate and understand the evolution of today's environments, it is necessary to study natural variations, including the exchange of heat, water and carbon between ocean, atmosphere and ice, on long time scales. Because variations of the climate system involve mechanisms operating at very different time constants, it is crucial to have this long-term perspective in order to distinguish the effects of climatic disturbances according to their geological, astronomical and anthropogenic origins.

This type of study at the interface of climatology, oceanography and geology, has given rise to the field of paleoclimatology, and more specifically, to palaeoceanography which focuses on changes in the oceans on time scales ranging from centuries to millions of years. To document these changes more fully, to date them precisely, to understand and to model the mechanisms correctly are all important tasks within the framework of projects aimed at predicting the future evolution of the climate.

For this type of research, I have used techniques of analytical chemistry to determine the extent and the timing of climatic variations. Over the last three decades, new quantitative methods have enabled me to reconstruct past climates using varied archives such as oceanic sediments, lake sediments, corals, stalagmites and polar ice. My guiding principle has been the wish to study the same climatic phenomena, for example the glaciations, using complementary and often innovative geochemical techniques. Another characteristic of this research is the back-and-forth nature of the information gleaned from recent and older periods. In order to go back into the past, I have employed "time machines" - i.e. complex mass spectrometers with which I have been able to measure radioactive isotopes and thus date the climatic variations imprinted in the various archives.

In the following pages, I describe my main scientific results focusing first on the various roles of the global ocean as an enormous reservoir of carbon, heat and water, and then on the implications of cosmogenic isotopes to study the Earth and its environment.

The ocean as a compartment of the carbon cycle, today and in the past:

Figure 2: Tandetron accelerator mass spectrometer (Gif-sur-Yvette)
Photo: Ph. Plailly CNRS

In the 1980s, I took an active part in the development of the accelerator mass spectrometry (AMS), which makes it possible to measure radiocarbon (^{14}C) directly on samples of very small size. This technique truly revolutionized the application of ^{14}C in the Earth sciences, particularly in chemical oceanography

With this approach, my team and I were able to quantify the penetration of ^{14}C of thermonuclear origin in the Indian Ocean. Indeed, large amounts of ^{14}C atoms were released directly into the atmosphere in the early 60s after the atomic bomb tests. We published the first AMS measurements of oceanic samples in 1987, the same year as two other international groups (Heidelberg-Zürich and Miami-Uppsala). This isotopic labeling by bomb ^{14}C allowed us to follow the fate of CO_2 of anthropogenic origin and to test mathematical models of general circulation in the oceans. These studies paved the way toward the inclusion of a sampling program dedicated to AMS in the World Ocean Circulation Experiment (WOCE) and subsequent programs.

By measuring the ^{14}C in various compartments of the carbon cycle and by using geochronometers that are independent of ^{14}C, it is also possible to use this isotope as a tracer of past variations in the carbon cycle. Basing my approach on this principle, I showed in 1988 that the $^{14}C/^{12}C$ ratio at the sea surface (so-called surface reservoir age) is sensitive to several physical phenomena such as the circulation of water masses, the extension of the sea ice, the speed of the wind, atmospheric pCO_2 etc. In this way, I demonstrated that this isotopic ratio can be used as a paleoceanographic tracer.

The first application of this new proxy was our study of the ocean-atmosphere exchanges during the Younger Dryas climatic event, which occurred between 13,000 and 11,500 years before present (yr B.P.). From ^{14}C measurements and a chronological marker provided by a layer of volcanic ash in both lake and oceanic sediments as well as in Greenland ice cores, we were able to show that the North Atlantic deep circulation system had slowed down during this period of cooling. Since the publication of this study in 1994, many other authors from various institutions have used this new tracer, applying it to other periods and other ocean basins.

Another aspect of my research on the carbon cycle has been to investigate the climatic control on the marine biological productivity and in particular the importance of insolation cycles as linked to orbital variations. The principal objective of my team has been to study marine sediments in order to better understand the causes of long-term changes observed in the organic matter, carbonates and trace metals buried therein.

By means of molecular and isotopic markers, we evaluate the variations of the accumulation and preservation of organic carbon of marine and continental origins. Our work involves the use of geochemical markers (e.g. $^{15}N/^{14}N$ isotopic ratio, biomarkers such as the diploptene, diplopterol, lycopane and the tetraethers), and also ultra-high resolution elemental analyses by means of XRF scanning. The scientific outcomes concern, among others, the relationships between the Asian monsoon and the presence at intermediate water depth of an oxygen-depleted zone, leading to mid-depth acidification, denitrification and diffusion of nitrous oxide into the atmosphere. Other results deal with the terrigenous organic matter fluxes transported by European rivers during the last ice age and the thermal destabilization of methane hydrates during the last deglaciation.

Marine paleothermometry and ocean-atmosphere heat exchange

In order to quantify oceanic paleotemperatures, we have developed and used several geochemical methods based on the analysis of organic molecules, trace metals and stable isotopes. My team and I have studied a large number of sediment cores taken at low latitudes in the three oceans. In 1997, we proposed a new evaluation of the glacial-related cooling within these zones of approximately 2 to 3°C, an average value subsequently which has been confirmed by other groups. Tropical cooling is a crucial parameter now used for testing climatic models and determining the so-called "climate sensitivity" parameter.

Another aspect of my research on paleotemperatures relates to rapid fluctuations on the scale of the century to the millennium. Here again, accelerator mass spectrometry (AMS) has proved essential for measuring precise ^{14}C ages and evaluating the rate of the climatic variations. Oceanic cores with high resolution have enabled us to find evidence for numerous warming and cooling episodes, in agreement with the atmospheric changes analyzed in the polar icecaps. Our initial work published in 1987 was actually the first to show the existence of abrupt changes of sea-surface temperature on the order of several °C per century, i.e. the same order of magnitude as the average warming predicted for the coming century.

For the North Atlantic Ocean, intense cooling episodes are clearly related to periods of iceberg release, called Heinrich events following the pioneering article published in 1988 by the German geologist of the same name. In 1987, we had already described the most recent Heinrich event centered around 16,500 years B.P. (before present). In that 1987 paper, I had gone so far as to propose an accurate explanation for the phenomenon, describing « a pulse like injection of a large volume of ice or meltwater into the Atlantic ».

Figure 3: Icebergs calving from an ice sheet (Ilulissat, Greenland) Photo: E. Bard

After this early contribution, I went on to study these rapid climatic changes in the tropical oceans, far from the main source of the phenomenon, the North Atlantic. With my team, we analyzed many sedimentary archives from the Atlantic, the Pacific and the Indian oceans, applying geochemical paleothermometers based on various molecules (alkenones or tetraethers) or trace elements (Mg, Sr, U) preserved in deep sea sediments or coral reefs.

At the same time, we compared the records of the Pacific, Indian and Atlantic, which allowed us to identify new amplifications of climate change. These different feedbacks involving the atmosphere and ocean are due to regional aspects such as the topography and the river systems of Central America, the flow of warm and salty water from the Indian to the Atlantic around the Cape of Good Hope, and to the thermal contrasts between the North Atlantic and the European continent. Modelers of the ocean and the atmosphere also study these feedbacks independently.

Our reconstructions of past variations of the oceans have since been complemented by many other records from polar ice, lacustrine sediments and cave stalagmites. The last deglaciation included several phases of intense cooling, of precipitation changes - notably at low latitudes and in the Asian monsoon area, of retreat and decay of glacial ice-sheets - as evidenced in sediments collected in river mouths, and of sea level change as recorded in corals from tropical islands (see more below). Various isotopic proxies of deep-sea ventilation have been used to identify the Meridional Overturning Circulation (MOC), indicating that ocean heat transport was involved in the observed climate fluctuations.

The various records documenting different climate parameters at many locations over the Earth are also used in meaningful comparisons with numerical model simulations performed in a transient mode. Collectively, these studies permit estimates of the phase relationships between the causes (insolation and the greenhouse effect) and the often-abrupt responses of the various components of the climate system, namely the atmosphere, oceans and ice sheets.

Sea level variations and water exchange between ice sheets and the ocean

Figure 4: Colony of coral in a fossil reef (Sumba, Indonesia) Photo: E. Bard

Figure 5: Fossil reef terraces (Maré, Loyalties Islands, New Caledonia) Photo: E. Bard

Starting in the late 80s, I became interested in sea-level changes over the last deglaciation, and I started to reconstruct them using oxygen isotopes measured in foraminifera. Recognizing the severe limitations of this method, I began using the then-new technique of mass spectrometry to measure uranium and thorium isotopes, in collaboration with colleagues at Columbia University in New York and later at Aix-Marseille University. This approach enabled us to date fossil corals and other coastal materials in order to study sea level changes

Concerning longer time scales, our sea level data have been compared with simulations carried out within the framework of the astronomical theory of paleoclimate. Measurements of exceptional stalagmites sampled in a cave submerged in the Mediterranean Sea enabled us to evaluate the duration of the sea level highstands during the penultimate interglacial periods in very good agreement with the orbital theory.

An additional result of our coral analyses is the systematic survey of the isotopic composition of uranium dissolved in seawater and its past variations through time, as linked to the global geochemical cycles. In 1991, we were first to propose that genuine changes of seawater uranium could be linked to long-term changes of chemical weathering. We also introduced the use of the isotopic composition of uranium as a sensitive tool to detect diagenesis in old fossil corals.

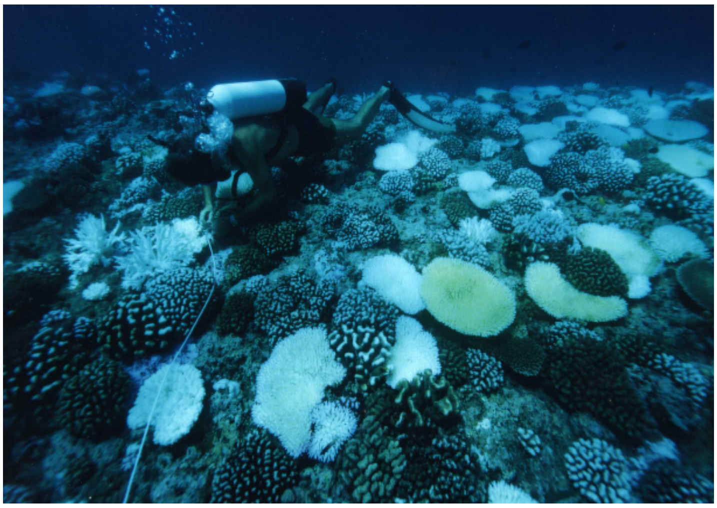

Figure 6: Modern barrier reef (Tahiti, French Polynesia)
Photo: J. Orempüller IRD

By using U-Th dating by mass spectrometry, I conducted detailed studies of the last deglaciation, using samples from coral reefs in the three oceans. The climatic transition between 21,000 years and 6,000 years B.P., led to a tremendous rise of approximately 130 meters in the world sea level. We reconstructed the precise chronology of this unsettled period by studying cores drilled from reef formations on the islands of Barbados in the Caribbean and Tahiti in French Polynesia. During that period, many other climatic and oceanographic parameters underwent first-order variations: global warming rose by 4 to 5 °C, there was about a 40 % increase in the atmospheric contents of greenhouse gases (carbon dioxide and methane), a reduction in wind speeds occurred, oceanic circulation was reorganized etc. One of our major results was the discovery of abrupt variations of the sea level (meltwater pulses MWP) at rates of several meters per century, which is even faster than the rise predicted for the coming century.

Figure 7: Integrated Ocean Drilling Program #310 (Tahiti, French Polynesia)
Photo: IODP

Our two sea level curves from Barbados and Tahiti now form the benchmark records that are used to model the geophysical response to the eustatic changes. In order to complement our studies on cores drilled onshore Tahiti, we succeeded in convincing the international Integrated Ocean Drilling Program's scientists, technicians and administrators to carry out offshore drillings. The coring operations undertaken during IODP Leg 310 in November 2005, recovered more than 400 m of post-glacial reef material, ranging from 122 to 40 m below modern sea level. The new U-Th and ^{14}C results allowed us to study the last two deglaciations, notably the timing and amplitude of MWP-1A and to identify the ice sheets which contributed to this major event.

Over the same periods, continental river systems underwent major changes due to the melting of continental ice caps, the emptying of proglacial lakes and because of geomorphological changes of river mouths. We measured geochemical indicators in sediments from the Bay of Biscay, in the Northeastern Atlantic, in order to study the activity of the then-Channel River (La Manche) which collected waters from a huge watershed across Western Europe during the last glacial period. Over the deglaciation, this gigantic river also drained meltwaters from the decaying Scandinavian and British ice sheets.

Around the same period in Central Europe, the Black Sea formed a large freshwater lake that drained the meltwater from mountain glaciers and the eastern part of the Fennoscandian ice cap via the Danube and the Dnieper. We were able to reconstruct the activity of rivers feeding the Black Sea and to reveal the source of sediment they carried during the last deglaciation. Our study demonstrates that the disappearance of an ice cap is not a simple linear phenomenon, due only to surface melting of the cap. We showed that the ice sheet collapsed during several century-long transient phases, shedding huge amounts of ice and spilling meltwater that drastically accelerated ice sheet decay and sea level rise.

Radiocarbon and other cosmogenic isotopes as tools in geochemistry, geophysics and astrophysics

Figure 8: Subfossil oak (Hanover, Germany)
Photo: E. Bard

Corals allow a direct comparison of ^{14}C dating with the U-Th disequilibrium method, the latter yielding ages that are both precise and accurate. As early as the 60s, specialists in ^{14}C dating were already highlighting chronological discrepancies when comparing with dendrochronology, i.e. when comparing the ^{14}C measurements of fossil wood samples whose exact age could be determined independently by counting the annual growth rings on the trees. Working from one tree trunk to another, it was possible to construct a calibration curve going back to 10,000 years B.P. However, these ^{14}C variations lacked entirely for the period between 10,000 and approximately 50,000 years B.P., the limit of application of this radiometric clock.

We filled this information gap by dating the corals from Barbados, Mururoa and Tahiti using ^{14}C and U-Th on the same samples. Our results, published in 1990 and after, demonstrate that the two geochronometers gradually diverge, with ^{14}C giving ages that become systematically too young by several thousands of years. We were able to correct several fundamental dates: the last glacial maximum (LGM) dates to 21,000 years B.P., and not 18,000 years B.P. as was formerly thought, and the duration of the Holocene period is about 11,500 years, rather than the earlier estimation of 10,000 years.

The radiocarbon calibration effort is crucial for scientific fields such as paleoclimatology and prehistoric archeology. Since the early 90s, I have been part of the international collaborative group preparing and updating the radiocarbon calibration curve as necessary to reflect advancing consensus. Our ^{14}C and U-Th results on corals constitute the backbone of this "official" database of the computerized calibration program which is distributed to all users of radiocarbon dating. Following specialized meetings and compilation works, we have released "official" curves every 4-5 years since 1993 (the last one is the so-called IntCal13 curve).

The interest of revealing the bias of radiocarbon age dating also lies in the physical interpretation of the phenomenon itself. The inherent inaccuracy of the ^{14}C method implies that the atmospheric content of this isotope fluctuates over the course of time. The high frequency variations in ^{14}C composition, on the order of centuries to a millennium, are related to changes in the production rate of ^{14}C in response to magnetic fluctuations of the Sun, which modulate the arrival on Earth of protons from the cosmic rays.

Our studies on this subject are based on the comparison of completely independent records: the ^{14}C as measured in tree-rings and beryllium 10 as analyzed in Antarctic ice cores (^{14}C and ^{10}Be are two cosmogenic nuclides formed in the upper atmosphere). These series of analyses have also made it possible to accurately pick out the periods of weak solar activity already known to astronomers from the counting of sunspots and direct observations of aurora borealis. Moreover, we have been able to detect some even older solar minima.

Figure 9: ASTER accelerator mass spectrometer installed in 2007 in Aix-en-Provence. Photo: G. Aumaitre, CNRS

Our solar variability reconstruction over 1000 years has been used by climate modelers to study the link between the Sun and climate over the last millennium. We are now busy extending this work by comparing the past 10,000 years of the IntCal ^{14}C curve with ^{10}Be data measured in new ice cores from Antarctica. ^{10}Be measurements are performed by means of the 5MV AMS facility operating in Aix-en-Provence since 2007.

Over the longer term, ^{14}C ages generally underestimate true ages by several millennia, in particular over the last glaciation. Our data indicate that the atmospheric ^{14}C content reached an excess of 50-70 % between 30,000 and 40,000 years B.P. By carrying out numerical simulations, I showed that the dominant factor is the regular reduction in the terrestrial magnetic field, which is also recorded in volcanic and sedimentary rocks. Indeed, any reduction in this field allows penetration of more cosmic rays into the atmosphere, thus enhancing the formation of cosmogenic nuclides. The maximum of ^{14}C production corresponds to the Laschamp magnetic excursion, during which period the geomagnetic field weakened very sharply. These variations were correlated with those visible in the 10Be records of marine sediments and polar ice cores.

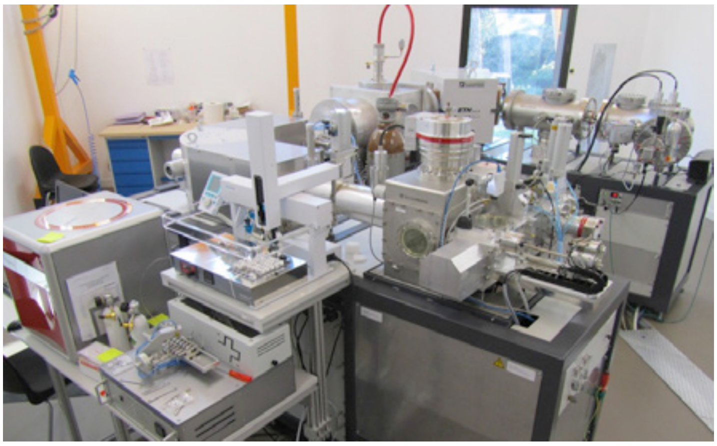

Figure 10: AixMICADAS accelerator mass spectrometer installed in 2014 in Aix-en-Provence. Photo: E. Bard

A second contribution of the shift between ^{14}C ages and true ages is linked to changes in the exchange rates and reservoir sizes of the global carbon cycle, which occurred during the last glacial period. I quantified this contribution by means of numerical box models representing the exchange between the atmosphere, biosphere and soils, and surface and deep oceans. The ^{14}C calibration provides key information about the origin of atmospheric CO_2 fluctuations accompanying, and partly responsible for, large climatic changes over the last 50,000 years.

Past environments as a useful perspective to communicate our science:

Although most of my studies concern naturally-occurring environmental changes that took place over long time periods in the past, useful parallels can be drawn with the evolution of modern climate. In fact, the phase relationships between forcings (such as greenhouse gases and solar input) and changes in regional and global temperatures are also at the heart of modern global climate change. As for deglaciations, the ocean can modulate warming regionally, thereby delaying, or even temporarily masking, long-term changes. The study of past sea level changes also provides a useful perspective on the future evolution of continental ice sheets such as Greenland and Antarctica, notably the western part of Antarctica, whose base is located below present sea level and may be sensitive to future climate change.

Fluctuations over the last century have been smaller in magnitude than those of the last deglaciation. Fortunately for us, there has been no recent collapse of gigantic ice masses such as the Laurentian and Fennoscandian ice sheets leading to changes of the ocean circulation. However, most climate models predict a reduction of the Meridional Overturning Circulation during the 21st century. Even if this change exerts only a minor influence on the projected magnitude of global warming, models indicate that such a slowdown in ocean circulation change would, in general, be sufficient to reduce the simulated warming over the North Atlantic with a resulting impact on adjacent continents, including Europe.

The relevance of this type of academic research for the future of our society also highlights the responsibility borne by scientists working on the evolution of ocean and climate. Our knowledge on this subject is still limited by numerous sources of uncertainty and by insufficient temporal and spatial coverage. The enormity of the task at hand requires that researchers from the world's leading institutions collaborate on these issues. Another reason for collaboration is that all developed countries are contributing to fossil fuel combustion and we are all breathing the same air. This places additional responsibility on climate scientists who must communicate with colleagues from other fields, inform politicians and educate today's youth and the general public.

I thus felt extremely honored and pleased to receive the 2013 Werner Petersen Award. I enjoyed the week I spent in Kiel, lecturing and discussing with students and fellow scientists from the GEOMAR Helmholtz Center for Ocean Research and the Christian Albrecht University. This opportunity strengthened my links with colleagues from Kiel and reinforced my ambition to collaborate with them on projects focused on climate and ocean sciences using isotopic geochemistry. This distinction also incited me to propose combining our strengths in order to improve the university teaching on these subjects at the European scale.

Figure 11: Collège de France & CEREGE (Aix-en-Provence) Photo: E. Bard