Climate change

What challenges for the South?

IRD Éditions

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A Maasai cattle farmer in Tanzania.

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Preface

It is fundamental to understand the climate system and on-going and coming changes—whatever their form—to make it possible to gauge the scale of the issues and to conceive the appropriate responses to be made in the various fields. This is the approach used in this important contribution by IRD and its partners in the South.

The tropics have been chosen as the field of investigation of this book, making it stand out by its relevance and originality. It is precisely the zone for which there is a cruel lack of information needed for gaining comprehension. The quantity of work and observations is indeed fairly limited there, as are the resources used. With the rigour and caution that are features of any scientific approach, this clear, simple and instructive publication makes it possible to understand the entire specific complexity of the climate changes in this part of the world. It also gives a glimpse of their many consequences. Such comprehension is essential for drawing up the policies and action programmes that should be implemented. The book also indicates the grey areas in which knowledge is limited, fragmentary or such as to prevent the drawing of conclusions or the taking of action.

In this remarkable work resulting from vast, fruitful cooperation and an interdisciplinary approach, the means to be developed, priority lines of work and the methodological approaches to be favoured to find appropriate, expected responses for the tropics are identified. If it is wished to keep the increase in world temperature by mid-century at less than +2°C in comparison with the pre-industrial period, this knowledge is essential for formulating and implementing appropriate climate policies. The conclusions of the last IPCC report state this clearly.

This book is an important contribution for decision makers, especially at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change. The conference should lead to important decisions. It will certainly be a historic turning point in negotiations on climate and on combating climate change. In the past two years, all countries—without distinction—have undertaken to describe as a prerequisite the efforts that they are planning to make in a communication entitled 'Intended Nationally Determined Contributions'. As they are voluntary, the contributions are guided by national priorities. They reflect the capacity of each country to take action and cover in many respects the Sustainable Development Goals adopted in New York last September. Their relevance falls within the framework of increasingly precise knowledge of the reality and scale of climatic malfunctions, their human causes and their consequences.

The work is without a doubt a major contribution to the improvement of knowledge.

Youba Sokona
Vice Chairman of the IPCC

Combating climate change: science in the forefront

International negotiations concerning the climate have never been the subject of as much media attention since the report of the International Panel on Climate Change (IPCC) in 1991 and the drafting of the United Nations Framework Convention on Climate Change in the following year on the occasion of the Earth Summit in Rio de Janeiro. The Kyoto Protocol at the third Conference of the Parties (COP 3) in 1997 was the first international accord ever signed to reduce global emission of greenhouses gases (GHGs), the major cause of global warming. The failure of COP 15 in Copenhagen in 2009, that should have planned the follow-up to the protocol, and the long years of fairly unfruitful negotiations that followed mean that COP 21, to be held in Paris in December, should be perceived internationally as the last-chance summit for a significant reduction of GHGs by using UN multilaterism as a basis. Such an agreement—the obtaining of which is a major issue for French diplomacy—can only result from the shared view of public opinion and world decision makers that climate warming is a great threat for the future of the planet and for more harmonious coexistence of its major civilisation zones.

Climate warming is a reality whose scale is still limited (world average + 0.85 °C since the beginning of the industrial era), but the effects are already significant in certain regions, with heat waves in the Sahel, disturbed monsoon systems, the melting of the Andean glaciers, threats to biodiversity, a rise in sea level and the formation of tropical storms in the Mediterranean. Regions in the tropics and the adjoining semi-arid zones are twice as vulnerable in this respect. On the one hand, their small inter-annual temperature variation means that they are the first to go outside their reference climatic envelope. On the other, this is where the strongest population increases are expected, whatever the demographic scenario examined. In other words, climate change will be felt more rapidly in these regions and will affect a continuously increasing proportion of the population of the world, with the obvious risk of a major increase in inequality leading to the instability of societies that will thus be even less well equipped to handle the problem.

It is not by chance if COP 21 comes at the end of 2015, a year in which the international framework of North/South relations and aid for development were redefined with the Addis Ababa International Conference on Financing for Development and the adoption by the UN General Assembly of the Sustainable Development Goals (SDGs) of the 2030 Development Agenda. These follow the previous Millennium Development Goals (MDGs) for 2000-2015. The close date and the objectives set out (SDG 13 makes explicit reference to combating climate change) reflect the need for the convergence of climate-related societal issues and those related to sustainable development. These issues are addressed in this book using the results of research conducted by the Institut de recherche pour le développement (IRD).

The convergence defines the specific responsibilities of scientists. For climatologists, it means going beyond the climate warming stage alone and addressing in greater depth—together with physicists, chemists and biologists—the complex causal chains that link the climate and other environmental and human parameters. It leads economists, sociologists, anthropologists and medical researchers to addressing the impact of these environmental changes, which do not have solely climatic causes, on health, social balances and economic opportunities. IRD teams have a long tradition of multidisciplinary research conducted in collaboration with colleagues and institutions in developing countries. The emergence of research questions related to global changes redirects this research towards the assessment of the resilience capacity of ecosystems and the people who live from them in order to propose solutions that reconcile the mitigation of climate change and adaptation, conservation of the environment and a reduction of inequality. Above all, it calls for the emergence of new scientific fields for the study of the interactions between the environment in the broad sense and societies in the 'Earth system'.

Progress in scientific knowledge is a typical example of what Joseph Stiglitz, Nobel Prize in Economic Sciences, described as a 'global public good'. This term highlights the essentially universal nature of scientific results as regards both free access for all and the overall validity of the results. Science must fully assume its values of humanistic universalism in the face of the threats that climate warming holds for the future of the world and the historically unprecedented increase in inequalities in the present distribution of world wealth (between and within countries). It must help to better reconcile the agenda for combating climate change with that of sustainable development by being involved in the building of an integrated view of the interactions between environmental changes and the harmonious development of societies. It must also contribute to the use of objective facts to forge national and international policies that can respond to both the climate challenge and the building of a fairer world. This is the modest ambition of this book, aware of its limits but marked with conviction and determination.

Thierry Lebel
Director of the IRD Interdisciplinary and Intersectorial Mission

Jean-Paul Moatti
Chairman and Managing Director of IRD

Introduction

Climate change, multiple issues

Awareness of climate warming and its global consequences has not yet made it possible to reduce the effect of human activities on the climate. The failure of international policies to coordinate a reduction of **greenhouse gas** emissions together with the observation of certain effects of warming that are faster than expected means that a shift in the direction of negotiations is necessary today.

Greyed words are listed in the Glossary, p. 253.

The 21st Conference of the Parties (COP 21) of the United Nations Framework Convention on Climate Change to be held in Paris in December 2015 should be a turning point in the political handling of the climate question. Beyond the ambitious universal and restrictive agreement that is hoped for, COP 21 will be more pragmatically the venue for a bottom-up approach to national contributions and the schedule for solutions, with each country contributing according to its means and according to the priorities in national policy with regard to the effort made to fight climate warming and its impacts. The final objective of the Convention is no longer that of spreading greenhouse gas emission reduction undertakings among states but that of incorporating the question of the climate in broader problems. This being so, the climate question is joining the sustainable development goals (SDGs) negotiated by the United Nations in 2015 and is also open to local initiatives by all stakeholders in society.

This new framing of the climate question thus requires better understanding of local greenhouse gas emission conditions in order to limit them (**mitigation**), whatever the human activities concerned. It also involves better description of the diversity of the impacts of global warming on the planet, bearing in mind that all environments and all humans are concerned, and even the regions with small emissions or those that are remote from major sources of emission. This evolution matched the scientific approach aimed an explaining how local emissions contribute to the warming of the atmosphere and how this then has different repercussions in different regions of the world. These specific effects depend on the climatic risks in the region, the degree of exposure and sensitivity of the environment to these risks. Distinction between the direct impacts of the increased concentration of greenhouse gases and other pressures related to regional and local socio-economic activities is another challenge to scientists. Finally, the responses to be provided are conditioned by the variety of local social, health, cultural and economic contexts. Such complexity requires reflection on the definition and implementation of appropriate solutions for adaptation and innovation.

Faced with such issues, interdisciplinary research must respond to three priorities: issuing the necessary alerts and monitoring climatic and environmental evolution, accompanying evolution by local innovations and recommendations concerning public policies and finally providing a critical analysis of international policies in order to render them compatible with sustainable development goals. The reality of climate warming and its repercussions is now clear but monitoring on-going changes is no less crucial. Setting up coordinated mitigation measures requires continuous monitoring accompanied by continuous information for civil society. This is aimed at sharing knowledge about the evolution and scale of changes with the largest possible number of people and reducing the zones that lack clarity in order to better quantify and anticipate the environmental and societal risks to come. This approach is based in particular on the strengthening of socio-environmental monitoring facilities and the improvement of integrated modelling tools.

In the field, research must bring the question of climate change out of isolation by giving it social, economic and geopolitical dimensions and enabling better hinging of practices and means of action. This approach is more closely integrated than ever and must make it possible to link the diversity of environmental and societal dynamics and assess the degree of **resilience** of ecosystems and populations. By better taking local practices into account, the approach should also make it possible to devise solutions that reconcile **adaptation** to climate change, conservation of the environment and the enhancement of sustainable human development.

For IRD, the mobilisation centred on COP 21 in France is an opportunity to take a long look at the research related to climate change conducted with its partners in the North and the South. In this book, the institute wishes to promote its most recent research results, highlight the specific features of environments and populations in the South and justify its engagement in a resolutely involved research approach. The linear structure running through the three parts results from a wish to make this complex reality more accessible, but the work is firmly founded on an 'integrated' scientific approach to the climate question in the South.

The first part, entitled 'Observing and understanding climate change', is aimed principally at repositioning global climate warming with human causes in the perspective of the natural climate changes observed over long periods in tropical environments. Their exceptional nature is demonstrated. But the scientific approach is also highlighted—the rigour and caution required for pinpointing the causes of a variation or an **extreme event** observed at the local or possibly regional scale. Indeed, even if the reality of global climate warming has been shown, it is primordial not to wrongly hold it responsible for all the changes observed. Such errors could lead to ineffective or possibly counter-productive adaptation policies. In order to be pertinent, the approach must be based on observation networks adapted to the critical spatial and temporal scales for the continuous monitoring, detection and precise description of possible **anomalies** in the evolution of the climate and the environment. It must also benefit from high-performance modelling tools to determine the mechanisms involved and to identify the factors causing the anomalies. The reliability of these **models** also determines the confidence that can be awarded to the climatic scenarios compiled for the coming decades.

The second part, 'The impacts of climate change in the South', addresses socio-environmental repercussions by major type of ecological environment in order to show the complexity of the processes involved and the large number of determinants. Oceans, coastal and island zones, semi-arid zones, highland zones, humid zones and forests and large cities are all environments threatened by climate change. However, the risks are expressed in distinct ways as each environment is subjected to specific climate threats with variable amplitudes (cyclones, floods, droughts, heat waves, rise in sea level, etc.).

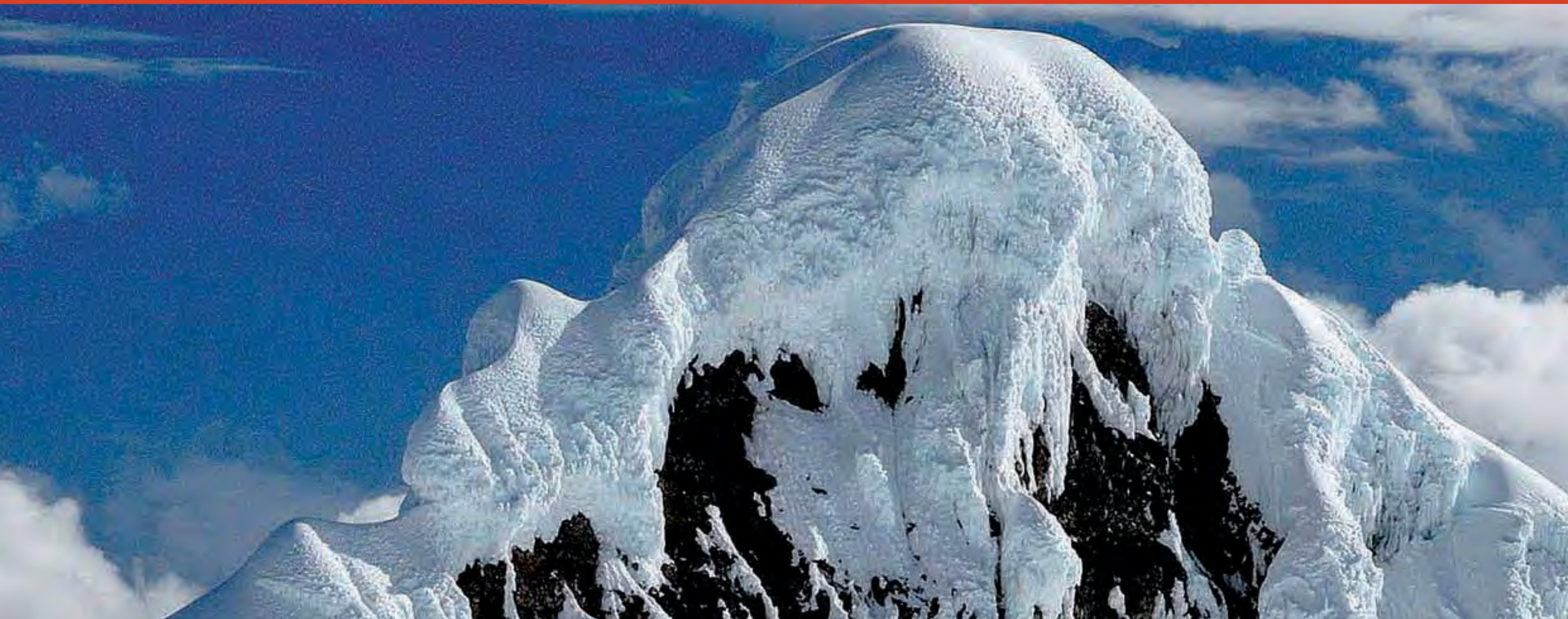
Furthermore, climate change is just one factor among other changes (deforestation, population growth, pollution, over-exploitation of natural resources, etc.) that can have drastic short-term effects on ecosystems and resources that sometimes outweigh climate change. It is then very difficult to discern the respective influences. Each environment also features vulnerability to a particular climate risk that is often aggravated in southern countries for reasons of poverty, inequality, poor governance and limited means for control. This means that the risks caused by climate warming take very different forms according to the environments concerned. This justifies the regional approach used in the second part of the book.

The third part, 'Societies and the test of climate', puts political and social reality at the centre of preoccupations concerning the climate. The initial framing of the climate question by the United Nations Framework Convention on Climate Change (UNFCCC, 1992) as a planetary pollution problem did not allow, in particular, the mobilisation of societies and the world economy in a search for solutions to reduce the influence of human activities on the climate. Critical analysis of international negotiations on climate makes it possible to question this framing of the climate question. Beyond the climatic dimension, international climate policies are studied as a process of construction of global environmental governance affecting national environmental policies.

The expected consequences of climate change in questions of health call for a strong international public health policy that would enhance the resilience of societies in the South with regard to the new health risks and improve their wellbeing. Health research must also use long-term studies of populations performed by monitoring facilities devoted to the environment, demography, farming and farming processes and also the socio-economic evolution of societies. Even when changes are extreme and have immediate health repercussions, monitoring facilities must analyse and monitor them over long periods of time. This long-term analysis will lead to adaptation scenarios that fully take into account the health and well-being of populations.

The capacity of populations to face climate change issues does not depend only on the desire of decision makers to mitigate its effects: populations in the South have not waited for decisions by experts to adapt their strategies and behaviour to environmental changes. Indeed, mobilising populations requires an effort to understand the diversity of sensitivity and ecological practices. The question for scientists and politicians is therefore that of drawing inspiration from cultural experience of climate change in order to better design the actions to be undertaken. The numerous studies mentioned in Part 3 illustrate the adaptation capacity of rural populations in the South that are in close interaction with their environment. This applies in particular to their farming practices and management of resources. Using examples of recent programmes implemented in the South, the last part of the book thus shows the major role of men and women and of social and political aspects in the face of the climate challenge.

A GREATICE team
on a glacier of the Antisana
volcano (5,700 m)
in Ecuador.



Part 1

Observing and understanding climate change

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Emissions of greenhouse gases resulting from human activities have increased since the beginning of the industrial era to the extent of having a significant impact on the increase in mean global temperature and, more generally, on the evolution of the climate. The influence of these emissions on the climate has been identified increasingly clearly in the successive reports of the Intergovernmental Panel on Climate Change (IPCC), set up in 1988 to evaluate scientific information on climate change. Climate projections for the coming decades confirm the present heating pattern whose scale will depend on future greenhouse gas emissions. The scientific community considers that we are thus entering a new epoch, the **Anthropocene**, in which the influence of man on the global system is predominant. Although its chronology has not been determined definitively, the Anthropocene is taking the global climate system out of the Holocene, the geological period that encompasses the last 10,000 years.

Human activities are thus adding an anthropic marker to the main geological eras. At this time scale, past evolution of the climate features alternate glacial periods and hot and humid or more temperate periods (interglacial periods). These glacial transitions are caused by the redistribution of the solar energy received by the earth as a result of the slow changes in the parameters of the earth's orbit. Its eccentricity varies in two periods: 400,000 and 100,000 years. Its obliquity varies about every 40,000 years and, finally, the precession of the equinoxes varies in a cycle lasting some 22,000 years. On a more short-term basis, volcanic activity also has an impact on climate by dust emission that reduces solar radiation for several years. These natural **forcings** determine most of the **variability of the climate**. Their effects are in turn amplified or reduced by internal retroactions in the atmosphere-ocean-continental surface system. The natural greenhouse effect of the atmosphere is an example of **retroaction** (in contrast with the additional greenhouse effect resulting from anthropic emissions) caused mainly by atmospheric water vapour. It is estimated that without an atmosphere, the average temperature at the surface of the earth would be -18°C and not +15°C as is observed.

Finally, the atmosphere-ocean-continental surface system also has its own natural variability. This 'internal' climatic variability is seen at different time scales ranging from seasonal, such as monsoons, to pluriannual, such as for example the El Niño and La Niña phenomena. These climatic variability modes have a strong impact in the tropical zone. Furthermore, certain **physical processes** between the surface and the atmosphere or within the atmosphere have strong amplification or reduction effects on the internal variability of the climate system. Internal variability can thus modulate or even replace the effects of anthropic **forcing**.

In this context, one of the difficulties is that of knowing how to 'attribute' the cause of climate change observed at a regional or local scale—whether to natural forcings, the natural internal variability of the climate or anthropic impact. Climate scientists use the notion of 'time of emergence', that is to say the time required, depending on the region and the climatic variable considered (temperature, precipitation, etc.), for the signal of the forcing of the anthropic greenhouse effect to exceed the 'noise' of internal climate variability. In terms of temperature for example, this emergence is fastest in the tropics as internal temperature variation is smaller than elsewhere. This question of **attribution** is all the more complex as anthropic activity is expressed by other environmental changes such as land use (deforestation, agriculture) that can cause local climate modifications.

The first part of this book illustrates research aimed at understanding present climate change. Paleoclimatology sets this change in a much longer climate context in order to evaluate amplitude and rapidity. Monitoring the ongoing evolution of climate and interpreting the changes observed and determining the probable cause/s require the use of long-term multidisciplinary observation networks and also modelling facilities that represent the complexity of the processes and physical mechanisms involved. It is thus possible to identify the various spatial and time scales and better understand the functioning of the climate and environmental system of the world. Observation networks and models are also essential for evaluating the confidence and **uncertainty** level of climate projections.

At IRD, this research is strongly focused on the tropical regions; these have their own dynamics of response to natural and anthropic climate forcings. The tropics also affect the various global climatic variations. The classic example is the El Niño phenomenon that starts in the tropical Pacific and is the main mode of climate variability at the global level. Stress is laid in the first part of the book on the importance of the research conducted in the tropics for understanding climate change. The most recent advances are described, accompanied by coverage of the limits of the models and information about the main issues of climate research sciences it possible to interpret present regional climate variations and also climate change at the global level.

Chapter 1

Learning about tropical climates in the past

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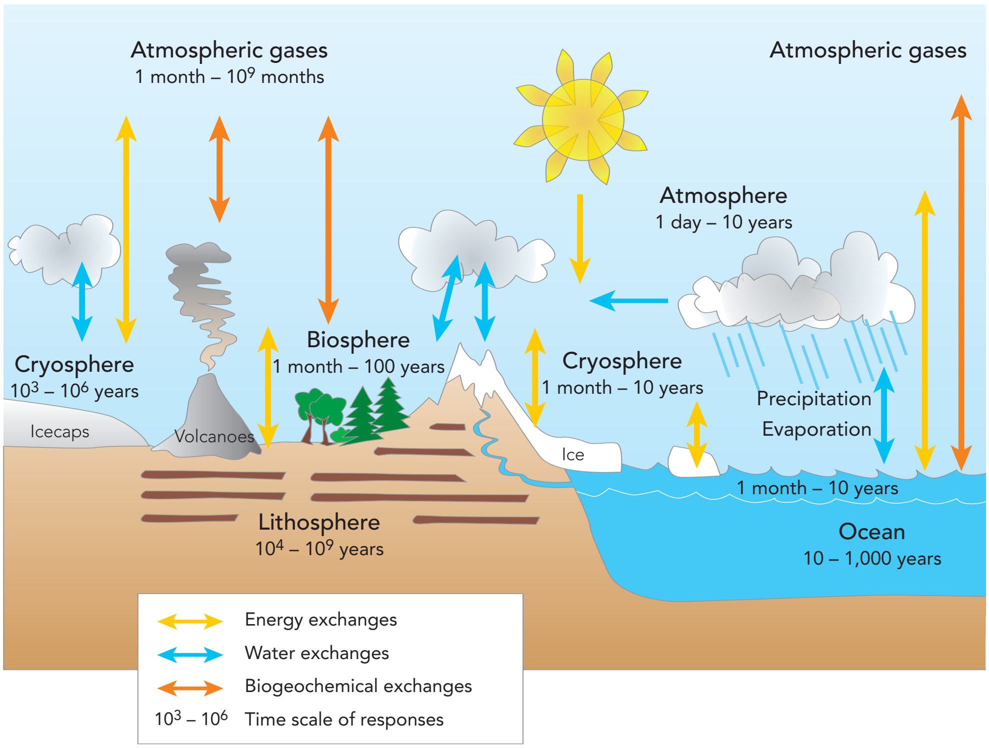
Drilling camp at the summit of Monte Valentin (3,900 m), Chile.
Glacier core drilling in the Andes provides access to more than 20,000 years of climate records.

Knowledge of past trends is essential for understanding the present climate. Thus paleoclimatology gives a picture of the natural variability of the climate and puts into perspective the variations observed today. It also gives better understanding of the mechanics of climate and especially the dynamics of tropical climates. The **water cycle** in these regions is different to that of temperate latitudes as evapotranspiration is much greater and tropical **convection** plays a major role in the water balance and that of terrestrial energy. The study of climate variability over a long period also gives better knowledge of seasonal and interannual climate variation, such as monsoons and the El Niño phenomenon that strongly affect the tropics.

This study of past climates is based on the many traces left at the surface of the earth. Glacier ice core samples, sea and lake sediment, stalactites and stalagmites in caves, coral, etc. all form natural climate records. Subjecting them to physical, chemical and biological analysis makes it possible to reconstruct and quantify past climate changes as long as these records can be dated reliably.

Figure 1.
The main components of the climate system and their response times.
The numerous interactions between the atmosphere, the oceans, the biosphere, etc. play a determinant role in the evolution of the climate and take place at scales ranging from a day to tens of thousands of years. Paleoclimatology makes it possible in particular to study slow interactions.
Source: JOUSSAUME, 1999.



The secrets of tropical ice

Ice in Greenland and the Antarctic has made it possible for about 50 years to reconstruct the climatic and environmental variations during the last glacial-interglacial climate cycles. The rich results drawn from polar ice encouraged several international research teams to extract glacial ice cores in other cold parts of the world. IRD and its partners started to study the tropical and subtropical glaciers in the Andes (Sajama and Illimani in Bolivia, Chimborazo in Ecuador, Coropuna in Peru, San Valentin in Chile) in the 1990s.

Andean ice cores gave information about the pattern of the tropical climate in the southern hemisphere over periods going back as far as 25,000 years for the oldest ice. They also enabled better understanding of regional climatic phenomena such as the South American monsoon system.

© IRD/B. Francou

The GREATICE Laboratory team at work on the glaciers of Antisana volcano (5,700 m) in Ecuador.
Core drilling operations in tropical glaciers are carried out under difficult circumstances because of the high altitudes and strong winds.

The discovery of a Small Ice Age in South America

Past variations in precipitation recorded in Andean ice provide precious information today. Study of these combined with observation of the advances and retreats of glaciers in the past has proved recently that there was a Small Ice Age in the Andes. Although less strongly marked than in Europe, the phenomenon resulted in colder, wetter conditions than those of today from the mid-15th century to the end of the 18th century.

Interpreting analyses of Andean glacial ice cores was not easy. One of the tracers used classically to recover information is the **isotopic composition** of water that reflects its various forms ($H_2{}^{16}O$, $H_2{}^{18}O$, HDO). Isotopes of polar ice provide information about temperatures. But the question is different in the tropics where the atmospheric water cycle is much more complex. Substantial research showed that the composition of Andean ice is controlled at a regional scale mainly by precipitation (Box 1).

Box 1

Tropical ice provides more information about precipitation than about temperature

Andean ice forms excellent tropical climate records. However, interpretation of the information drawn from the cores is still a subject of discussion among the scientific community. Scientists at the HydroSciences Montpellier research unit have shown that this ice provides information about variations in precipitation and not about those of temperatures as is the case in a temperate climate.

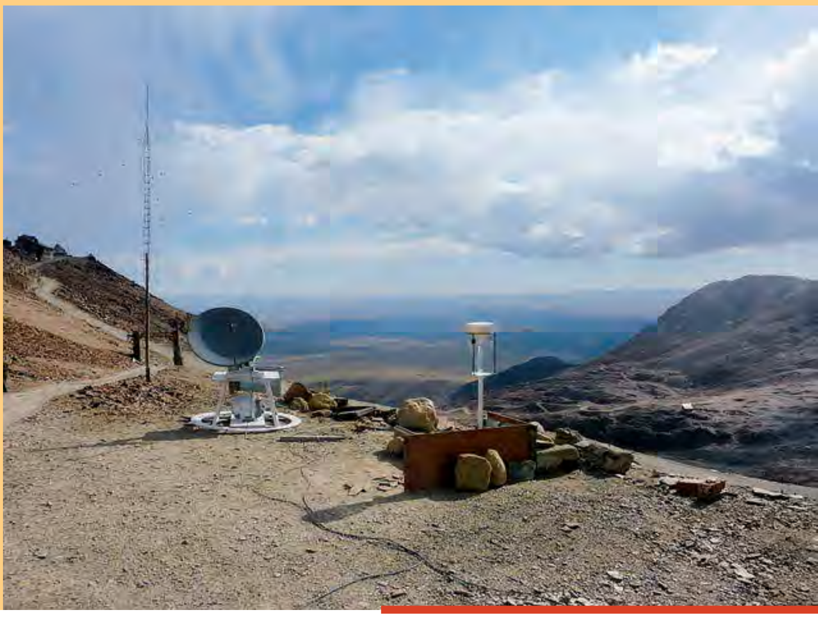
The isotopic composition of tropical ice provides valuable information for the quantification of past climate variability.
But the interpretation of this geochemical marker is more difficult than at the poles because of the complexity of the atmospheric convection processes that cause the major part of rainfall.

The distribution of isotopes in water between the various reservoirs (water vapour, condensate, rain) in the polar regions depends on temperature, as this controls the quantities of precipitation that form. However, this correlation is not valid for a tropical climate.

In order to understand this difference in processes, scientists at the HydroSciences Montpellier laboratory calibrated the isotopic signal from present precipitation data.
They set up a precipitation collection network in Bolivia, Peru and Ecuador, as close as possible to the core extraction site.

Analysis of rainfall samples combined with the results of climate modelling of tropical South America shows that the isotopic composition is controlled mainly by the quantity of rain that an air mass has lost during its trajectory since it formed above the sea.
At the inter-annual scale, the Andean glaciers would therefore record the history of regional variations of moisture rather than temperature variations.

These results have shown that some parts of Amazonia were wetter during the last glacial peak 20,000 years ago and that a global change in temperature thus plays a determinant role in the rainfall regime in this region.



Rain sampling for the measurement of water isotopes, Chacaltaya (5,240 m), Bolivia.

© IRD/J.-L. Guyot

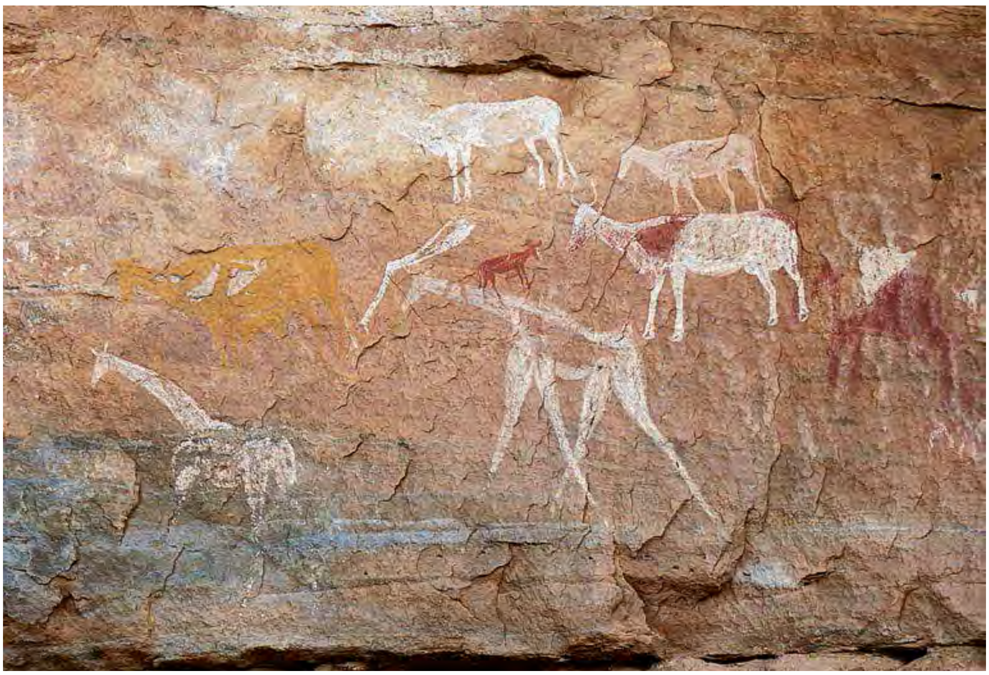
The Sao Bernardo cave in Brazil.
Stalagmites (speleothems) are good tracers of the past variations of precipitations in South America.

Sediment, coral and other climate records

Glacial ice cores are not the only climate records used in the study of past climates. Outside the polar regions and high-altitude glaciers, lake and marine sediment, coral and speleothems (stalactites and stalagmites) are also environmental markers that are valuable for the reconstitution of past climates.

Environmental markers that tell us about the past

Carbonated concretions (stalactites and coral) are particularly useful for the reconstruction of variations in precipitation and temperature and of sea level. Their rate of growth, isotopic oxygen and carbon ratios and the presence of trace elements (magnesium, calcium, strontium, etc.), with help from dating methods, have been widely used to study changes in the global monsoon system at different time scales.



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Tadrat Akakus, a prehistoric site in the Libyan Sahara.
These rock paintings show that the climate was formerly less arid than it is today.

Box 2

An exceptional rise in sea level revealed by coral in the Pacific

Scientists at the CEREGE unit and their partners used cores taken from coral reefs off Tahiti to reconstitute one of the major events of the last deglaciation—an exceptional rise in sea level combined with the break-up of ice.

© IRD/J. Orempüller

Study of corals (*Diploastrea* formation) in the Fiji Islands.
The core extracted will be examined to provide information about the history of the climate in the South Pacific.

Global sea level has risen by 120 m since the end of the last ice age 21,000 years ago.
The rise has not been steady but on the contrary punctuated by rapid acceleration combined with massive break-ups of icecaps.
The most marked of these accelerations, referred to by paleoclimatologists as '*Melt-Water Pulse* 1A', was poorly known until the CEREGE team, in collaboration with the universities of Oxford and Tokyo, analysed reef cores collected around the island of Tahiti during the international expedition IODP 310 '*Tahiti Sea Level*' in 2005.

This work made it possible to describe the chronology, amplitude and duration of the event.
The acceleration of the rise in sea level started precisely 14,650 years ago and coincided with the so-called 'Bølling warming' at the beginning of the warm period that marked the end of the glacial period.
Sea level rose by some 14 m in less than 350 years. Furthermore, in contrast with the hypothesis accepted to date, the Antarctic icecap probably contributed to half of this rise.
The massive inflow of soft water strongly disturbed world oceanic movements and affected the global climate.

These results are also very important with regard to the present and future rise in sea level.
Indeed, they highlight the dynamic behaviour of the polar icecaps in response to a rise in temperature, a phenomenon still poorly taken into account in IPCC forecasts for 2100.

Sediments record several types of information related to the origin, quantity and state of conservation of minerals and organic substances in the ground. Organisms with very short life cycles, such as diatoms and some algae are good markers of changes in the physical and chemical conditions of the environment. The degree of conservation of organic substances and their mineralisation also provide information about the temperature, the acidity and the oxygenation of the environment of the deposit. For example, researchers used analysis of pollen grains collected in sediment from Lake Chad to reconstitute the vegetation and precipitation in the region 6,000 years ago in the mid-Holocene. The results are particularly interesting as during the period the Sahara was gradually becoming the desert that we know today. They make it possible to construct models that are useful for understanding present changes in a similar climate context featuring warming.

Reconstruction of Andean paleoclimates

In South America, the gathering of indices from the various paleoclimatic archives has made it possible to reconstruct the changes in continental precipitation on this continent. Analysis of fossil pollen grains and lake sediment gives information about the past and an image of the climate 6,000 years ago. It was much drier than it is today, causing a large decrease in the area of Amazonian forest. In parallel, the discovery of layers of microcharcoal, a sign of ancient fires, in lake sediment and soil proves the exceptional decrease in atmospheric moisture during the period. These interpretations are also confirmed by the trend in oxygen isotope values that indicate a decrease in precipitation. Paleoclimatic simulation shows that the dry phase was caused by an increase in air temperature and a warming of tropical seas in response to an increase of the solar radiation reaching the surface. This gradual increase in insolation in the southern latitudes of the tropics for 10,000 years caused the weakening of the South American monsoon and also accounts for the slow, gradual retreat of the high glaciers in the Andes during this period. In particular, this information has shown the exceptional nature of the melting of the high-altitude glaciers in South America since the beginning of the industrial era. The present speed of melting since 1820 is therefore not accounted for by variations in insolation but by other mechanisms related to the increase in greenhouse gases in the atmosphere.

Hibiscus tiliaceus
Malvaceae pollen grain under optical microscopy.
Pollen grains can be valuable indicators for study of the climate.

Chapter 2

What are the signs of current climate change?

© IRD/V. Ballu

A flooded coconut plantation on the island of Loh in Vanuatu.
The rise in the water level is caused by both global warming and the sinking of the islands.

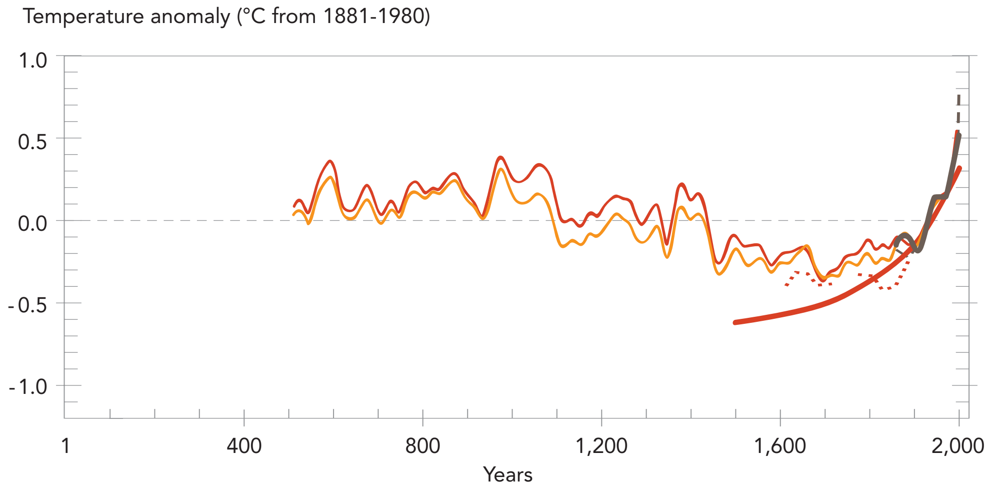
The main indicator of climate change is the unprecedented scale and speed of the increase in temperature at the surface of the globe. But there are others such as the retreat of ice, changes in the global water cycle and in certain climatic extremes, the warming of oceans and an increase in average sea level.

Surface warming

Reconstitutions of the climate over the last 2,000 years show periods of several decades in which temperatures were locally as high as they are today. However these warm periods were not in synchrony in the various parts of the world, which makes them different to the recent 'global' warming. The present rapidity of warming has not been observed previously (Fig. 2).

According to the IPCC's 2013 report, the average temperature at the surface of the globe —measured 2 metres above ground level—has increased by 0.85°C since 1880. This global average hides substantial variations according to the region (Fig. 3) and the time of year. For example, the temperature has increased by 1.5°C since the 1950s in the hot part of the Sahel.

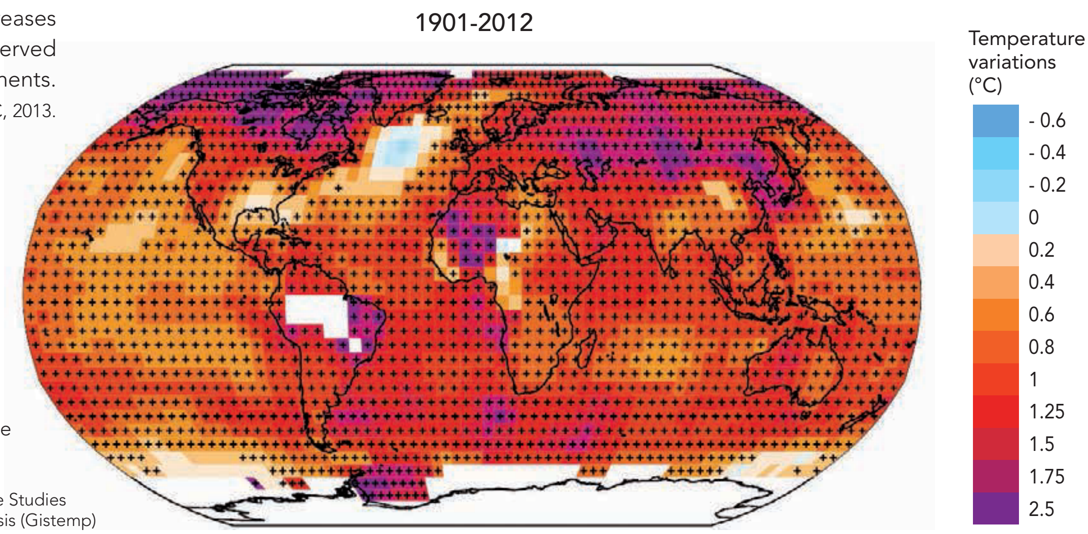
Figure 2.
Reconstitutions of the annual land and ocean temperatures during the last two thousand years.
Since 1950, the temperature has increased more than its natural variability.
Source: IPCC, 2013.



In orange: land and ocean temperatures;
in red: land temperatures only;
in black: temperatures observed by instrument readings since 1860.

The anomalies are given in relation to the average (line 0.0) and smoothed to reduce fluctuations lasting for less than 50 years.

Figure 3.
The evolution of surface temperature observed from 1901 to 2012.
Temperature variations are unevenly distributed at the scale of the world as a whole.
The strongest increases are observed on the continents.
Source: IPCC, 2013.



The white zones indicate incomplete data.

Data source:
Goddard Institute for Space Studies
Surface Temperature Analysis (Gistemp)

The retreat of the tropical glaciers

Melting of ice is another important marker of global climate change. Glaciers have retreated in practically all the regions of the world in recent decades. Those in tropical regions—with 99% of these being in the Andes—are among the most affected. Indeed, global warming is particularly marked at the elevation of these glaciers. Several IRD teams have shown the spectacular retreat of the Andean glaciers over the past 30 years, with a decrease in surface area of 30 to 50%. This research confirms the acceleration of climate change at the end of the twentieth century in this part of the world. A continued increase in temperatures combined with negative changes of the rainfall regime could result in the disappearance of most of these glaciers by the end of the century.

The Zongo glacier (6,090 m) on Huayna Potosi Mountain in Bolivia.
The length of the Zongo has decreased by over 800 m since 1940.

© IRD/B. Francou

Box 3

The spectacular retreat of Andean glaciers over the past 30 years

The glaciers in the tropical Andes have retreated gradually since their maximum between the mid-seventeenth and mid-eighteenth centuries. But the decline has been on a spectacular scale during the last 30 years.

Using studies of the glacial moraines, IRD scientists and their international partners mapped and dated the past positions of glaciers throughout their retreat that started in the 1730s.
Aerial photographs and satellite images were also used to trace the changes in the areas of glaciers after 1950.
In parallel, the scientists modelled the response of the glaciers to present variations in temperature and precipitation to establish a relation between climatic conditions and the retreat of ice.
They thus reconstituted the fluctuations in climate that may have caused the variations in the glaciers observed.
The results show clearly the singularity of recent decades with the fastest ice melt for 300 years.
The areas of the glaciers in Colombia, Ecuador, Peru and Bolivia have decreased by 30 to 50% since the end of the 1970s and as much as 80 to 100% in the most extreme cases.

A single cause?

All the Andean glaciers respond to the same mechanisms of climatic variability.
Precipitation has changed little but the air temperature in the Andes has increased by 0.7°C as a result of the warming of the tropical Pacific since the 1970s.
The temperature is not directly responsible for melting at the altitude concerned but is caused above all by the balance between absorbed radiation and reflected radiation at the surface of the glacier.
However, temperature affects the nature of precipitation—solid or liquid—and hence the conditions for the maintaining or not of the snow layer that contributes to reflecting the greater part of the solar energy received.
Absence of snow considerably increases the melting of the glacier.
This situation of glaciers with no cover—in summer in the tropics or at the equinoxes on the equator—has tended to be more frequent in recent decades.

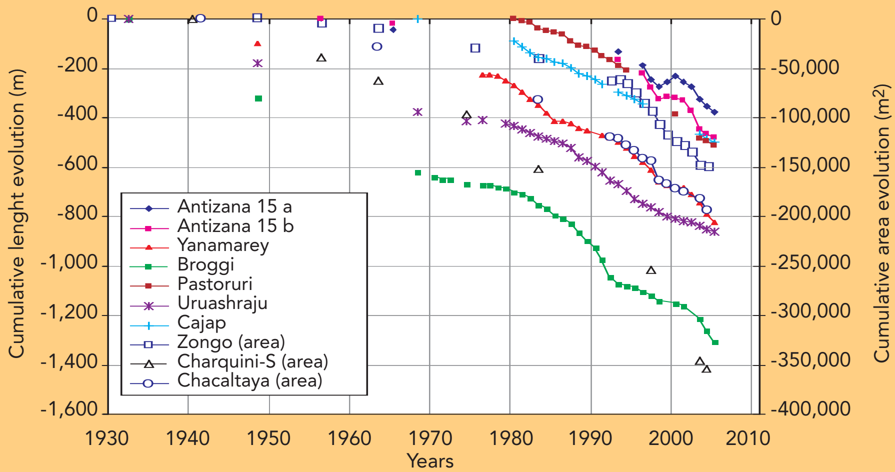


Figure 4.
The spectacular decrease in the areas of ten glaciers in the tropical Andes during the last 80 years.
Source: FRANCOU and VINCENT, 2007.

Precipitation and extreme climatic events

The rainfall regime has also changed in tropical zones in recent decades. However, it is very difficult to identify overall trends. Research in the Sahel is a good illustration of this complexity. The rainy period in the 1950s and 1960s was followed by a very dry period in the next three decades. Rainfall has practically recovered in the last 15 years. But this return of rains is not a return to the 1960s reference period, first of all because it concerns only part of the continental Sahel whereas precipitation is still decreasing in the west of the continent. And then the increase in rainfall in recent decades results above all from increasingly intense rainstorms. In fact, although storms have become more frequent they are still fewer than before the drought (p. 116).

Direct observations in South America show that the frequency of floods and severe droughts varies from one decade to the next, without any clear trend emerging at the regional scale. For example, the Paraná Plata region in the plains of Argentina has experienced an increase in the rainfall regime since the mid-1970s. The change has caused the formation of a lake with an area of several hundred square kilometres, flooding villages and cropped land.

The 'record floods' of the Amazon

Large rivers are also good indicators of climate change. For example, scientists have reconstituted the levels of the Amazon over a period of a century (HYBAM scientific observatory), showing the increase in extreme phenomena over the last 30 years or so, with an increase in the frequency of floods and historic low water levels and a gradual decrease in flow during the dry season. In recent years, exceptional Amazon floods in 2009 and 2012 successively increased the level of the 'record flood'.

Nevertheless, the series of reliable instrumental observations are only available from 1950 onwards, a period that is too short for the accurate identification of possible trends and the deduction of their causes. This uncertainty is even stronger for extreme

The Amazon River in flood in 2008. Brazil.

© IRD/F. Sontag

events that are exceptional by definition. There is thus no scientific consensus with regard to a higher frequency of cyclones for example. Indirect observations such as the study of lake sediments to describe floods, the analysis of speleothems, etc., are used as valuable sources of information that can broaden the temporal window of observations necessary for understanding recent climatic changes.

Warming of the oceans

The warming of sea water is another climate change marker. According to the fifth IPCC report, the temperature at the surface of the oceans has increased by +0.11°C per decade since 1970, that is to say +0.44°C in less than 40 years. The increase is unequally distributed. For example, recent research shows that the temperature of the eastern part of the tropical Atlantic has increased by more than 1°C since 1975. The surface water temperature of the tropical Pacific has increased by 0.3°C in the last 50 years.

© IRD/C. Maes

The warm water of the tropical West Pacific generates intense interactions between sea and atmosphere. This immense quantity of warm water is the cradle of the El Nino and La Nina phenomena. Ecuador.

Box 4

The western tropical Pacific is warming

Researchers at the LEGOS unit and their partners have shown that the increase in temperature of the surface water of the tropical Pacific warmed by 0.3°C during the last 50 years. This is one of the first estimates drawn from *in situ* data in this part of the Pacific.

The area of the Pacific Warm Pool, an immense mass of warm water in the west of the tropical Pacific, is 15 million sq. km, 27 times the size of France.
LEGOS unit researchers and their partners have studied the evolution of the Warm Pool.
The water temperature increased by 0.3°C.
The area of water warmer than 29°C has doubled in half a century and zones where the water temperature is higher more than 30°C —rare 50 years ago— are now very widespread.

Furthermore, the average depth of the Warm Pool has increased by about 10 m and is about 100 metres today. The research work conducted thus shows that a much larger volume of heat is thus stored in the water.
In 50 years, the Warm Pool has also shifted east by about 2,000 km.

This work is one of the first estimates, using *in situ* data, of the increase in the temperature of the tropical Western Pacific.
To obtain these results, the research team assembled data and observations gathered over the last five decades by merchant ships, oceanographic campaigns, deep sea data and satellite measurements.

© IRD/P. Laboute

Aerial view of Rédika islet in the southern lagoon of New Caledonia.
The phenomenon of thermal dilation of the sea caused by the warming of the water contributes to the rise in sea level, threating certain low-lying Pacific islands.

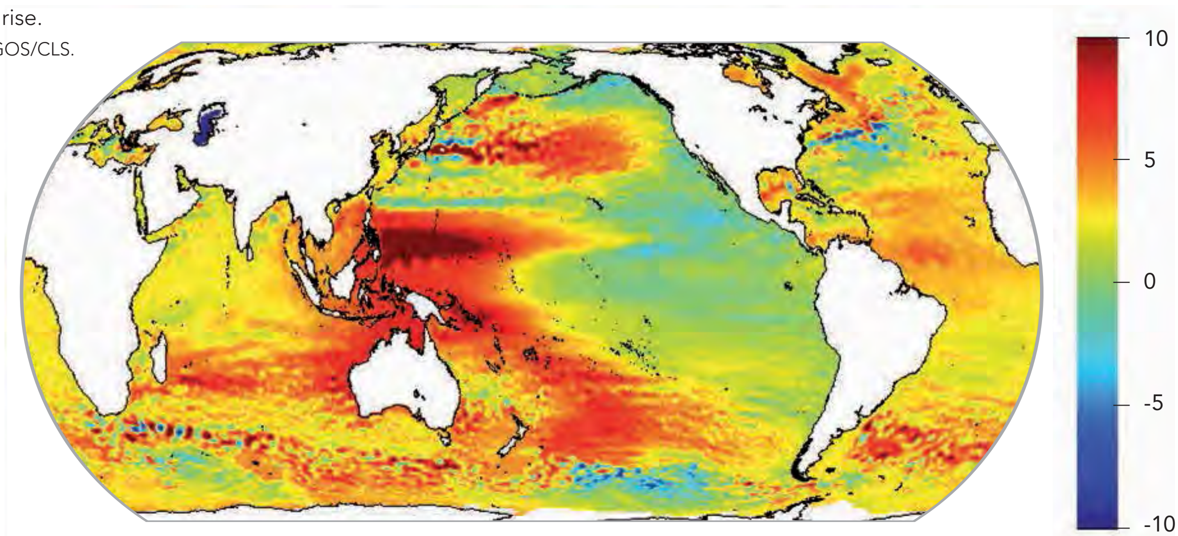
The oceans store the greater part of the warming of the planet: the increase in the temperature of sea water forms 90% of the additional energy stored by the climate system for 40 years. However, in return the changes in this gigantic reservoir of energy will affect the climate. The circulation in the oceans and its contribution to the energy balance of the planet make it one of the main features of the climate machine. Ocean dynamics also interacts with atmospheric dynamics and this is responsible for the natural variability of the climate.

The oceans also have regulating power with regard to carbon through the storage of carbon dioxide (CO_2) present in the atmosphere. Approximately 30% of anthropic CO_2 emissions are thus absorbed by the seas. But the dissolution of CO_2 in sea water causes acidification of the latter (p. 93).

The rise in ocean levels

The rise in sea level is a well-established phenomenon. The average rise has been some 1.7 mm per year for a century. Paired data from satellites and *in situ* measurements show that this average increase is accelerating as the rise was 3.2 mm per year from 1993 to 2010. The rise is a phenomenon to be expected in view of the thermal dilatation of the sea and the melting of continental ice. But other factors are involved regionally, such as winds, air pressure, ocean currents, etc. The rise in sea level is also very uneven in different parts of the world (Fig. 5). For example, the tropical West Pacific displays a

Figure 5.
Evolution of average sea level from 1993 to 2014.
The rise in the level of the West Pacific is distinctly greater than the overall rise.
Sources: CNES/LEGOS/CLS.



© IRD/B. Marty

Rising water level in the Tuamotu Archipelago in French Polynesia. With rising sea levels, atolls that often rise to 1 or 2 metres above sea level may disappear one day.

rise of about 10 mm per year—a much higher figure than the global average. In contrast, the rise is less than 3 mm per year in the tropical Eastern Pacific.

The rise in sea level is also variable in time. IRD scientists and their partners have reconstituted the variations in sea level in the tropical West Pacific since 1950. Their work shows that El Niño has a strong effect on the inter-annual variability in sea level in the tropical West Pacific and leads to variations of some 20 to 30 cm in comparison with the average.

As in the rest of the world, present climate trends in the tropics thus confirm the reality of climate change. The amplitude and acceleration of the heating of the air and seas, the rise in sea level and the retreat of glaciers are all proof of a break. However, other climate indicators are not as easy to fit into the main trends. The pattern of the rainfall regime and of extreme events such as cyclones is particularly difficult to describe because of the complexity of the water cycle and of convection phenomena in the tropics.

Chapter 3

Using monitoring facilities to detect climate anomalies

© IRD/A. Laraque

The Orinoco (Venezuela). August 2006 flood. HYBAM observation system.

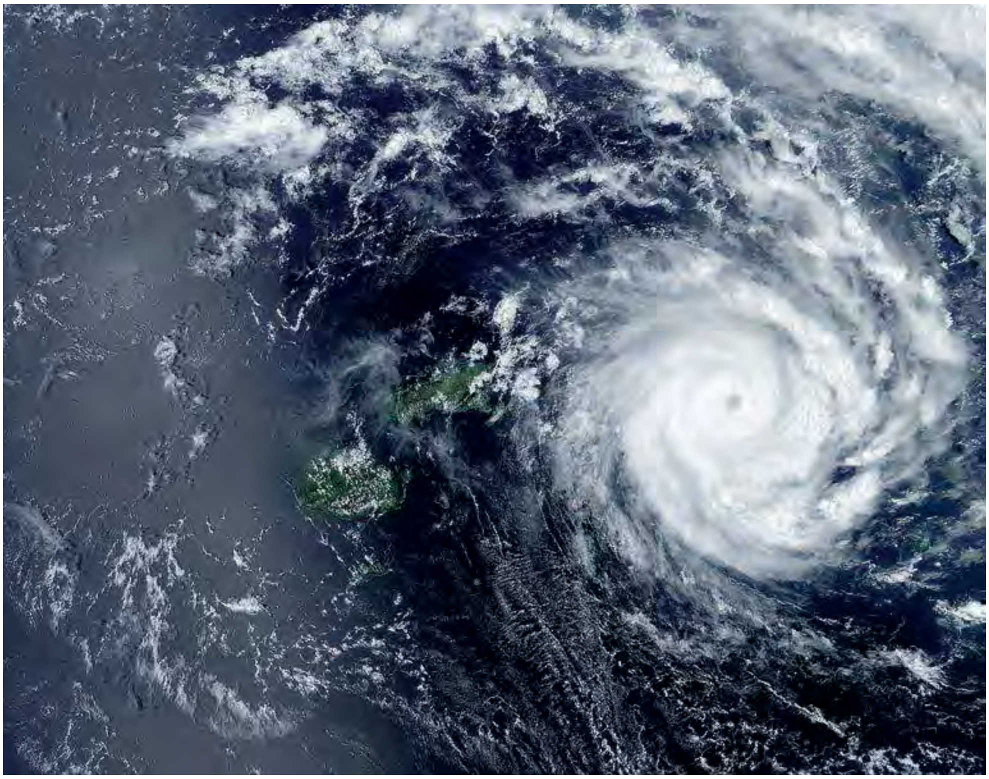
The study of climate change consists of detecting any significant climatic anomaly and then assigning possible anthropic or natural causes. This requires the ability to observe (in order to detect) and then understand (assigning a cause) to finally forecast the evolution of the print of climate change on the environment and societies.

Monitoring the evolution of our climate and more generally of our environment requires first of all observations and hence permanent multidisciplinary facilities. In addition to the quantification of climatic and environmental changes, the observations can also validate data from satellite remote sensing, evaluate models and set up new measurement techniques.

Quantifying ongoing climatic and environmental changes

The meteorological and hydrological networks allow real time monitoring of the evolution and variability of the climate system. However, these networks are not dense enough, especially in the tropics, for sufficiently accurate information over a sufficiently

Cyclone above the Tongan archipelago in the South Pacific.
The frequency of extreme events such as typhoons is an important indicator in the detection of climate trends.



© Nasa Goddard Modis

long period concerning climate and especially the hydrological cycle. Indeed, the different components of the water balance (precipitation balance, river flows, infiltration into ground water, etc.) display strong spatial and temporal variability. The ability to assess this variability accurately is needed for the detection of possible significant trends related to climate change or other factors such as changes in land use.

Changes concerning extreme events are even more difficult to detect as frequencies of occurrence are small and so longer series of observations are required. Indeed, the evolution of extreme phenomena such as cyclones and droughts is an important indicator for the detection of long-term trends.

Several appropriate observation systems are used to monitor changes in climatic variables at scales ranging from regional to local and for sufficiently long periods and to describe their impact on environments. IRD participates in this climate surveillance by developing a number of research watches with environmental qualifications, especially in the tropics (Fig. 6).

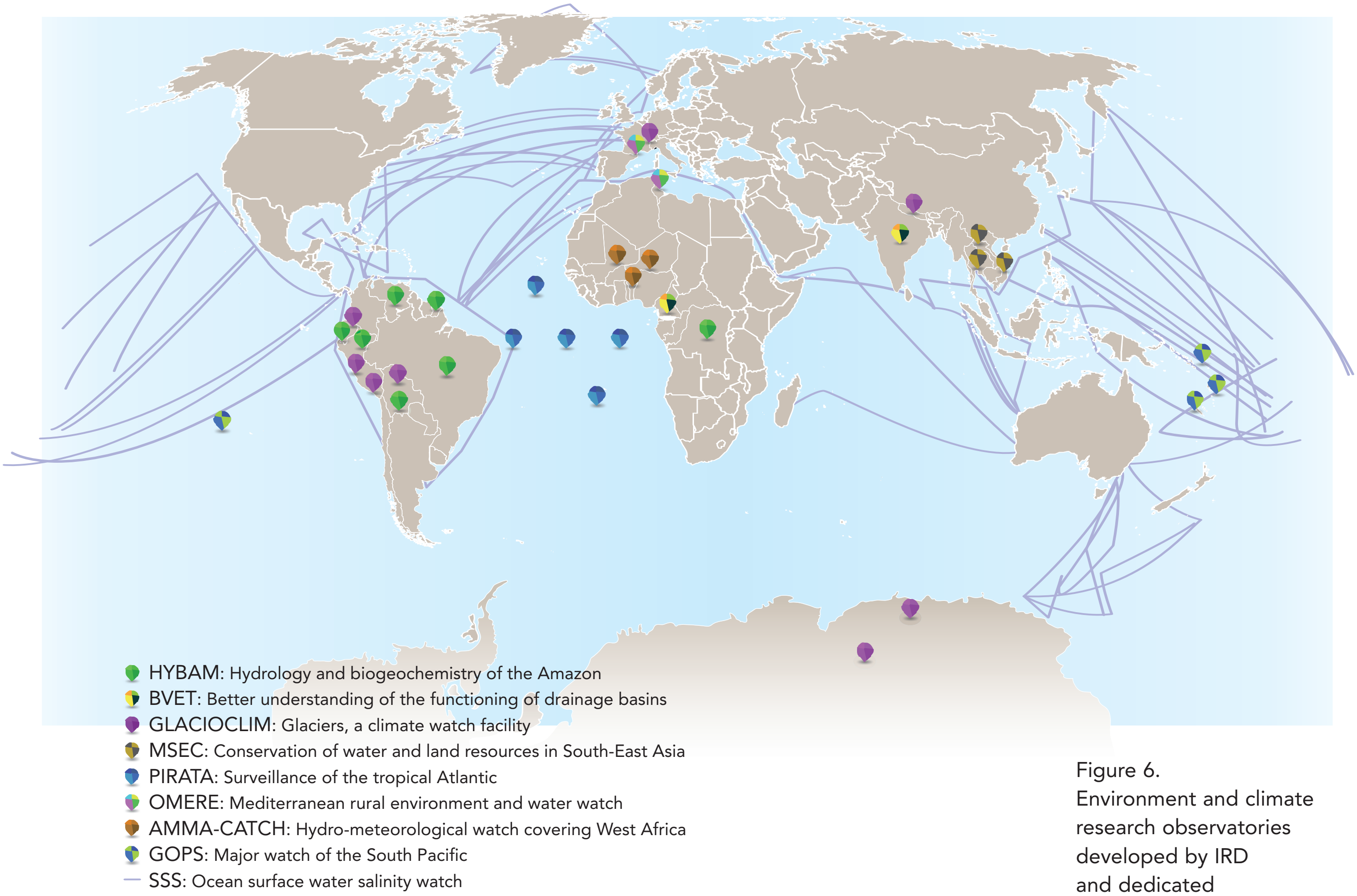


Figure 6.
Environment and climate research observatories developed by IRD and dedicated to a considerable degree to the tropics.
Source: IRD/L. Corsini.

Calibration and validation of data sent by satellite remote sensing

The documentation of global environmental changes (with reference to climate and also hydrology, soil science, oceans, etc.) therefore requires first the basing of diagnoses on precise observations and second the possession of measurements that are representative of variabilities at the regional scale. *In situ* field measurements and satellite data are extremely complementary here: the former allow the direct but local surveillance of phenomena while the latter provide global information and document spatial variability. In the tropics, where operational networks are sparse and fragile, synergy between the two types of information is essential in order to understand climate changes and their environmental impacts. The major watches and their long series of high-quality field data also provide observations for the calibration and validation of satellite data.

Box 5

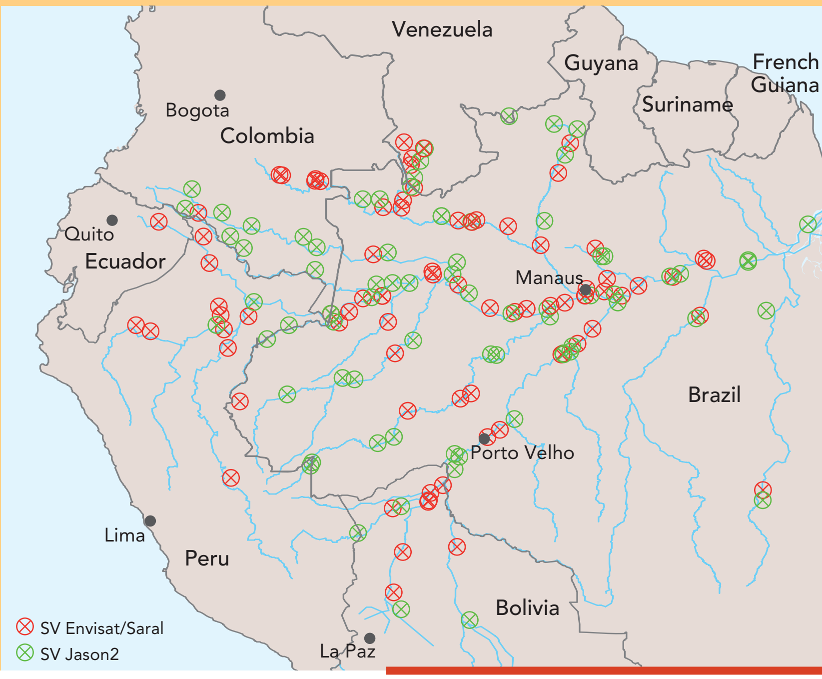
The Amazon basin observatory combines field data and satellite measurements

Since 2003, the HYBAM observatory (geodynamic, hydrological and biogeochemical control of erosion/alteration and material transport in the Amazon basin) has gathered hydrological, sediment and geochemical data, combining *in situ* and spatial observations and a network of laboratories. This information makes it possible to understand the functioning of the largest drainage basin in the world and to assess the impact of hydroclimatic variations and human activities.
17 stations are thus distributed from the foothills of the Andes in the Amazon basin to the Atlantic. Local readings are coupled with a 'virtual' network of data gathered by satellites and covering both the quantity and quality of the water.

To measure river water levels, altimetric satellites (Jason 2 and Saral) make regular radar sweeps of the points monitored to provide an accurate assessment of the quantity of water flowing. Water quality and the presence of sediments are covered by satellite imaging.
Probes (Modis) on the satellites Terra and Aqua analyse the spectrum of the solar light reflected by rivers and show the composition of their water.
These innovative techniques were calibrated and validated using the hydro-sediment databases maintained by the observatory. Automated processing sequences now provide satellite information on the website in record time.

These sophisticated spatial technologies are of special interest in Amazonia where the distances and the scale of water resources require steep budgets for ground-based monitoring that are not matched by the budgets available.
The monitoring and supply of information about water resources respond to needs of all sorts among economic and institutional stakeholders, water boards, electricity production and river traffic—navigable waterways form the main communication network in the Amazon basin.
HYBAM is associated with numerous university and technical partners in the southern countries (Brazil, Bolivia, Peru, Ecuador, Colombia, Venezuela and the Congo).

Figure 7.
The 'virtual' network of hydrological measurements in Amazonia.
Source: SO HYBAM (IRD/INSU/OMP)



© Smos/ASE

Orbiting SMOS satellite launched on 2 November 2009 by the European Space Agency (ESA).
It is the first global climate change observation satellite designed to monitor world marine salinity and soil moisture content.

Uncertainty with regard to the 'real situation' on the ground: a question of scale

Rainfall is intense in the tropics and varies within a few kilometres or a few hours, with local consequences that are sometimes violent (floods). This extreme variability is a challenge for observation using both classic ground measurements and satellite remote sensing. The uncertainty involved decreases—without disappearing— for the comparatively coarse space and time scales of hydro-climatology (a few months, several thousand sq. km) but is still very strong at the scales used in local hydrology. Probabilistic approaches must be used to allow for uncertainties. In West Africa, IRD and its partners have shown the need to allow for uncertainty in the 'real situation' on the ground for precipitations, that is to say high resolution spatio-temporal *in situ* measurements to evaluate the performance of satellite data for reporting rainfall. The results showed a high performance level for all observations at scales of 3 to 5 days and more modest performance for some of these daily scale observations. The latest generation of satellite facilities provides accurate quantitative information on time scales from 1 day to 6 hours, spatial scales of 10,000 to 2,500 sq. km and also gives a very good representation of the daily cycle.

Developing new probes in the tropics

Setting up dense network of measurements on a long-term basis is not sufficient, given the fragility of operations networks in the tropics and the need for the high resolution documentation of climate processes. New types of probes or original approaches should also be developed to enhance measurements and sampling for monitoring climate and environmental changes.

Box 6

Mobile telephony is taking over

While observation networks are still inadequate in Africa, this is not the case of mobile telephone relays. To monitor the quality of networks, the telephone companies record disturbances of signals partly caused by precipitation. Researchers thus had the idea of profiting from this mass of data to improve the monitoring and spatialisation of rainfall.

Meteorological and climatic measurements networks are expensive to set up and maintain and are inadequate in Africa. The density of operational networks has even tended to decrease since the 1990s and the problem is even more acute in the Sahel because of the political tensions there. How can the evolution of rainfall and extreme events with impacts on the population be monitored under these conditions? Strongly developed in Africa, mobile telephone networks have provided a solution.

Indeed a method for measuring rainfall using mobile telephone networks has been tested successfully in Africa. The method makes use of a property of rainfall that is well-known to telecommunications professionals: drops of water cause the weakening of the radio signal between two aerials. The mobile telephone companies measure and record these disturbances to keep track of their state of functioning at all times. They thus have a large amount of information about rainfall in the countries covered by their networks.

Developed since the 2000s in Europe and Israel, use is starting to be made in Africa thanks to a first pilot site set up in Burkina Faso in 2012 by IRD and its partners.

RainCell Africa, a network of scientists and national meteorological offices, was then set up in partnership with mobile telephone operators. The first international workshop on rainfall estimation using mobile telephone networks was held in Ouagadougou in April 2015 and was attended by participants from 18 countries (Benin, Burkina Faso, Cameroon, Côte d'Ivoire, France, Germany, Ghana, Israel, Kenya, Mali, the Netherlands, Niger, Nigeria, Senegal, Switzerland, Tanzania, Togo and the USA) and from inter-governmental organisations (CILSS, UNDP and UNESCO).

This initiative placing information and communication technology at the service of the climate attracted great interest in Africa and, more widely, in the tropics. It should develop considerably in the coming years.

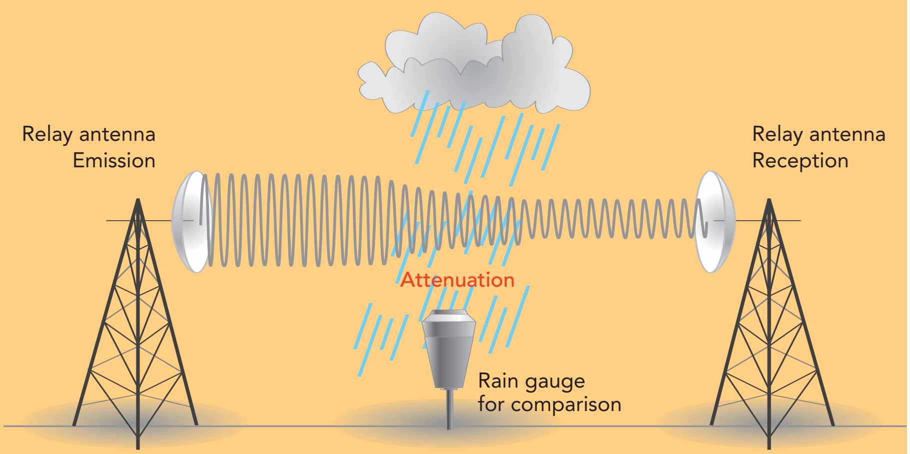


Figure 8.
The principle of rainfall measurement using mobile telephone networks.
Fluctuations in signals between relay aerials are recorded by telephone operators. The measurements could be used to plot small-scale rainfall fields in practically real time to monitor rainfall and the accompanying risks at the scale of a town or a country.
Source: IRD/F. Cazenave and M. Gosset

Box 7

Measurement of emissions by tropical hydroelectric dams

Estimates of greenhouse gas emissions by dams used for hydroelectricity vary considerably from one study to another as not all the sources of carbon dioxide and methane released are taken into account. A study carried out by the CNRS and IRD proposes new tools for improving readings.

The submersion of continental land for the creation of fresh water reservoirs is not neutral in terms of carbon dioxide (CO_2) and methane (CH_4) emissions at the global scale. Hydroelectric reservoirs are not an exception to this, with numerous sources of emissions: the gases are released at the level of the soil between high and low water levels, at the surface of the reservoir and downstream of dams. Methane can be emitted by bubbling. However, very little work takes into account all the CO_2 and CH_4 emission pathways to the atmosphere and this accounts for the considerable differences between estimates. Moreover, the time steps in studies of reservoirs is generally too long to capture intra-day and seasonal variations of emissions.

Emissions from dams are sometimes greater than those of thermal power stations

In an innovative set-up for monitoring methane emissions at Nam Theun 2 dam in Laos, vertical wind speed and the methane concentration are measured continuously. This high-frequency measurement method (every 30 min) has shown that daily variations in atmospheric pressure and variations in the water level control emissions by continental aquatic ecosystems by triggering the release of the gas trapped in submerged soils. The strong variations during the course of the day also make a significant contribution to the total emission balance. This suggests that bubbling (a source of methane emission) in tropical reservoirs has been underestimated in the past.

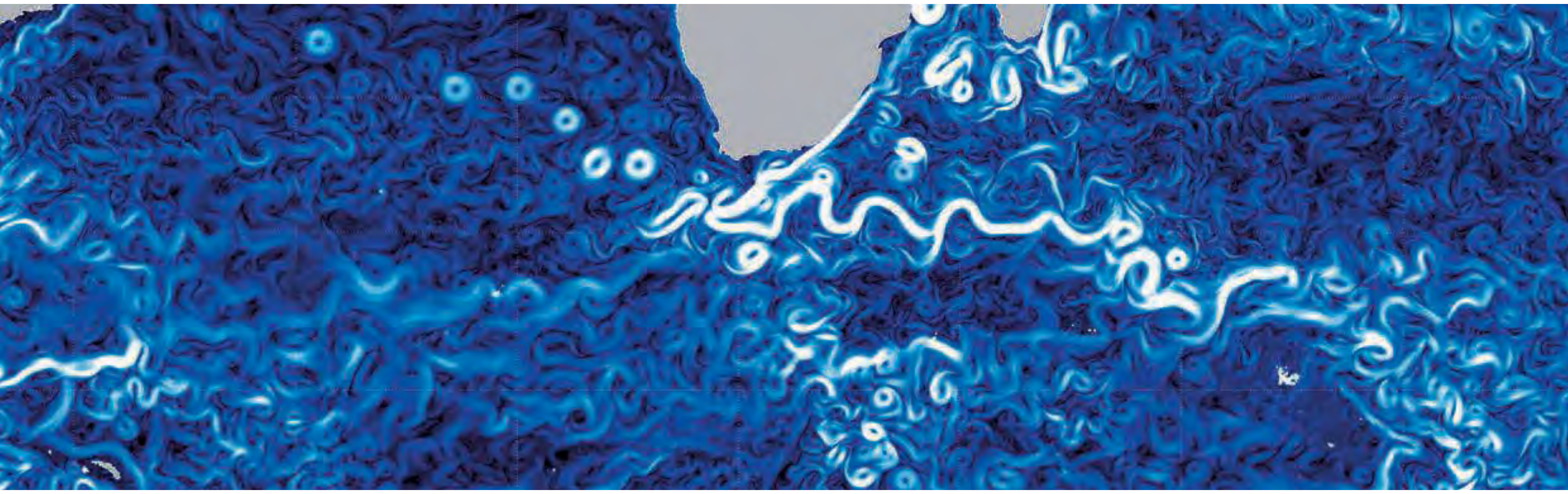
Accurate measurement of total greenhouse gas emissions from hydroelectric dams is of major strategic importance for developing countries where there is strong potential for installation. Indeed, depending on local environmental conditions, emissions from impoundments may be smaller or greater than emissions from fuel-fired power stations with equivalent energy production. The choice of hydroelectricity as alternative energy to stabilise greenhouse gas emissions in 2050 must therefore be discussed, especially for the tropics where emissions are greatest.

Submerged funnels for trapping methane bubbles rising from the bed of a reservoir.
Nam Theun 2 Dam, Laos.

© D. Serça

Chapter 4

Using climate models to understand the climate machine



© EU Copernicus Marine Service / Mercator Ocean

Mercator Ocean Model, a chart of surface currents. The Agulhas Current that flows along the east coast of Africa retroflects when it meets the cold Benguela Current and the Antarctic Circumpolar Current.

Understanding of the functioning of the earth's climate and environment system requires first the use of statistical tools applied to the analysis of observed data and secondly diagnostic approaches using certain concepts or theories and more broadly by using modelling tools that represent the complexity of the processes and physical mechanisms involved in the earth system. These modelling tools are very elaborate but still contain strong bias and uncertainties. Validation work using suitable observations is required. This work is essential for the subsequent evaluation of the confidence and uncertainty level of the climate forecasts provided by these models.

What is a climate model?

Climate models represent the functioning of the physical processes of the land-atmosphere system. They reproduce the movements of the atmosphere and the oceans, energy exchanges with the surface, the hydrological cycle and interactions between the climate and biogeochemical cycles. They function using the digital solving of the equations of atmosphere and ocean physics and are based on the division of a continuous environment into a large number of small volumes (discrete meshes) to be

Box 8

Ocean modelling, an essential component of climate models

The ocean component is very important in climate models. The ocean models developed by IRD are thus incorporated in the work of the IPCC. The models are also useful for forecasting—a kind of oceanic weather bulletin— and for understanding the mechanisms that govern variations of the seas. Applied at the local level, they make it possible to monitor changes of the environment.

IRD researchers contribute to the development of ocean modelling in the tropics. The models were first developed for global seas to represent the physical (temperature, salinity, currents) and biogeochemical characteristics (quantity of plankton, nutrient salts, dissolved oxygen) at the surface and at a depth. The global scale makes it possible to show the contrasts between ocean basins in upper latitudes, in the tropics, close to coastlines and in the centre of tropical oceans. The advantage of global models is that their capacity to reproduce the dynamics of seas and biogeochemical cycles under very different oceanic conditions (strong contrasts in temperature, light and nutrients) can be tested. The results of modelling are then compared with observations, especially by satellites, and *in situ* databases.

Global models ...

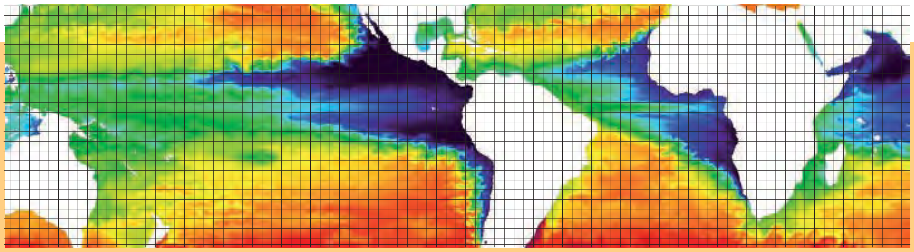
The ocean component is very important in climate models as the seas store heat and react at much longer time scales (from a few years to several hundreds of years) than the atmosphere. The NEMO (physical component) and PISCES (biogeochemical component) models, much of which were developed by the LOCEAN unit, run in two climate models used by the IPCC. The PISCES model can also represent the **carbon cycle** and measure the carbon dioxide pump effect played by oceans at the world scale. These models are also used for operational oceanography aimed at providing public or private users with a realistic picture of the oceans today and short-term forecasts (about a month), opening the way to a kind of 'ocean bulletin'.

... at kilometre scale

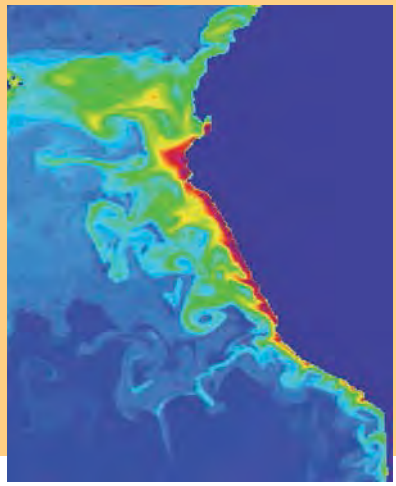
The results of global models are also used to initiate regional models such as the ROMS model developed mainly by LEGOS units and the Laboratoire de Physique des Océans (LPO) that is used to study dynamics and biogeochemical cycles at much closer spatial scales. These regional models have a limited field of application by definition

able to link together the variables in each mesh and to quantify energy transfers and biogeochemical processes. The modelling of continental areas addresses transfers of water and energy and the amount of movement with the atmosphere, together with the continental hydrological cycle. The parameters of processes smaller than a **mesh**—sub-mesh processes: clouds, whirlwinds, waves, surface runoff, etc.—are drawn from field observations or result from the use of more detailed modelling of one process in particular.

(a few hundred kilometres) and their mesh size (up to 1 km) is much smaller than that of global models. Their representation of physical phenomena at a fine scale means that these models are capable of explicit calculation of the mass, heat and nutrient salt flows associated with ocean structures—such as whirlpools for example—whose characteristic size is around 10 kilometres. At these small scales physical mechanisms play a fundamental role in biogeochemistry, especially for the supply of nutrient salts and plankton production in surface water, as for example in the **upwelling** systems off the coasts of Peru, West and South Africa and India where there are very rich marine ecosystems with a great abundance of fish. These regional modelling tools can thus respond to a variety of problems that have a strong impact on populations in the south (resource management for fisheries, disoxygenation of the sea and the accumulation of pollutants in the trophic chain).



Dissolved oxygen concentration at a depth of 150 m simulated by the Nemo-Pisces global model at 1/4° resolution.
The minimum oxygen zones are in blackish blue (O_2 < 150 micromoles/litre) in the eastern Pacific, Atlantic and Indian tropical oceans.
The fine grid of the model is represented roughly by a 4° square grid (each square covers 16 x 16 grid points).



Surface chlorophyll as shown by the regional ROMS-PISCES model off the coast of Peru.
The high chlorophyll concentrations indicate abundant phytoplankton, mainly diatoms.

Since the 1970s, when climate modelling began to develop significantly, these models have been improved regularly, providing a better description of the complexity of processes. In parallel, the horizontal and vertical resolution of the mesh of the models have increased progressively to atmospheric volume dimensions of 200 km x 200 km x 1 km and ocean dimensions ranging from a few kilometres to several hundred kilometres with a depth of 1 m to 500 m. These tools thus enable progress in our understanding of the functioning of the climate system and forecasts of future changes.

Evaluating modelling tools

In spite of the continuous efforts made to improve climate models and in spite of their sophistication, they are less reliable as a whole in the tropics and subtropics than in the other parts of the world. In particular, the different models are not in agreement as regards precipitation forecasts for the tropics in 2100 (Fig. 9). The differences from one model to another are related to uncertainties with regard to certain retroaction mechanisms involving, among other things, clouds, atmospheric convection and continent-atmosphere-ocean interactions. One of the main sources of uncertainty is in the 'sub-mesh' parameterisation of these processes. This often leads to empirical adjustments.

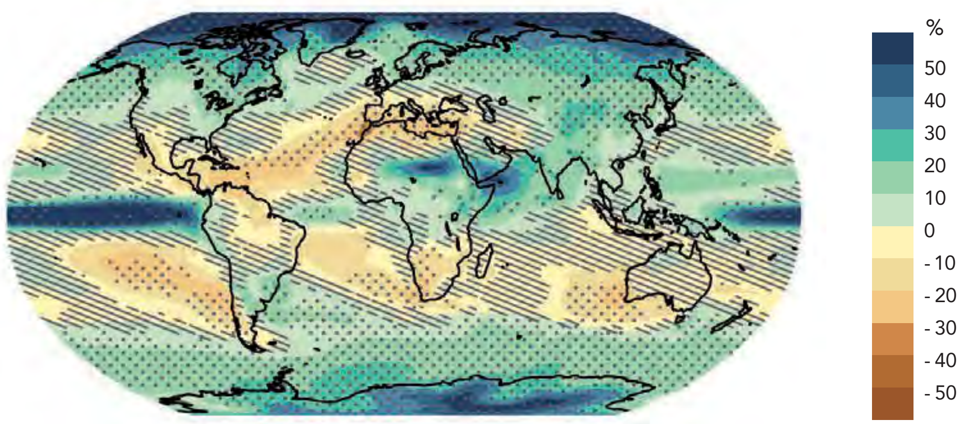


Figure 9.
The evolution of average precipitations during the periods 1986-2005 and 2081-2100 (in percent) in the most pessimistic IPCC emissions scenario (RCP 8.5). The models display greater uncertainty in the tropics.
Source: IPCC, 2013.

Grey points: zones in which the climate models display at least 90% agreement on the change feature: drier or more humid.
Hatched areas: zones of uncertainty.

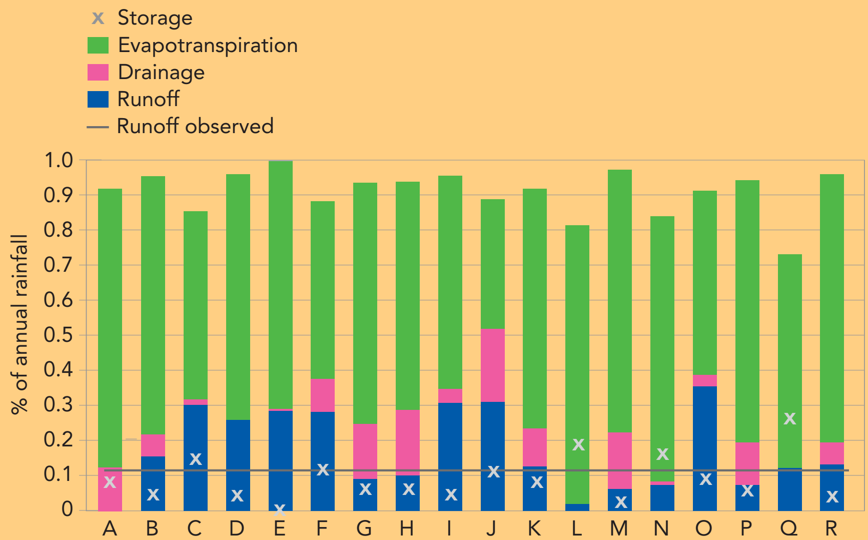
Observed data are thus essential in tropical regions in order to improve the representation of these processes. For example, measurements of the isotopic composition of rain and water vapour make it possible to observe certain processes such as atmospheric convection and thus detect defects in convection parameters in the models. Indeed, water isotope composition is sensitive to many atmospheric and hydrological processes (origin, transport, mixing, phase change, etc.) and is thus a good way of diagnosing physical processes in climate models. These measurements have been developed in recent years by IRD research teams in Niger, Bolivia and now in Réunion in regions where forecasts of changes in precipitation remain very uncertain.

Box 9

Comparing the results of models with a view to improving them

The ALMIP project that has been running since 2007 is the first international experiment on the comparison of continental surface models dedicated to West Africa.
The results show very great variability from one model to another.

Figure 10.
Terms of the hydrological balance of the upper Ouémé basin simulated by 18 surface models (A to R), showing very different responses from one model to another.
ALMIP aims mainly at using the field observations available to understand the reasons for these differences, evaluating the most realistic simulations and seeking ways of improving simulations.
Source: IRD/C. PEUGEOT *et al.*, forthcoming



In climate modelling, models of continental land represent and calculate exchanges of mass (water, carbon, etc.) and energy (radiation, heat, etc.) between the atmosphere and the various surface, soil and subsoil compartments. This type of model is based on equations in fluid mechanics and thermodynamics. Different surface models have been developed around the world, all of which differ a little according to the experiments conducted by researchers in their study regions or their working hypotheses.

Comparisons of models are digital experiments consisting of feeding the same sets of data ('forcings') into the various models.
The results are then compared and also set against reference data such as observations when the latter exist.
The aim is not that of choosing 'the best model' but rather benefiting from their diversity by identifying the strengths and weaknesses of the different modelling principles used and enabling improvements.

Inter-model variability dominates the other sources of variability

The ALMIP project that has been running since 2007 within the framework of the AMMA programme is the first international experiment of this type devoted to West Africa.
The first project phase was dedicated to the regional scale and confirmed the very great variability from one model to another and the very strong impact of uncertainties concerning forcing data—especially precipitation—drawn from satellite imagery. The second project phase (ALMIP2) started in 2013 and is based on high resolution data from the AMMA-CATCH observatory and AMMA project measurements.
The results show that the simulations remain very marked by the constituent principles of each model and that inter-model variability outweighs the other sources of variability.

Incomplete representation of hydrological processes

The models are in relative agreement with regard to representation of the energy balance.
However, biases are observed in some components of the water balance (runoff and the dynamics of underground water) related to the seasonal cycle and quantities of water. These biases are attributed mainly to the incomplete representation of hydrological processes and to the sometimes inappropriate values of the parameters used in the equations (soil texture and depth, hydrodynamic properties, etc.).
Corrections to reduce these biases have since been envisaged.

Box 10

The paradox of the Indian summer monsoon

Projections of the Indian monsoon presented in the last IPCC report are currently being hit by the observations available. Detailed work on observations and simulation of the Indian monsoon carried out by IRD in collaboration with the Indian Institute of Tropical Meteorology provides some explanations for this.

Some 75% to 90% of the annual rainfall in South-East Asia occurs during the summer monsoon (from June to September).

There is a risk that the phenomenon may be deeply disturbed by global climate change.

Models and observations suggest that global warming takes place with fairly constant relative humidity, that is to say with a substantial increase in the water vapour in the atmosphere (proportional to the increase in temperature). In other words, there is a risk that the precipitations and the hydrological cycle associated with the monsoon may be modified. As this warming is more marked on land than at sea, the land-sea thermal contrast (a fundamental ingredient of the monsoon system) will certainly be different as well in the future, with consequences for the monsoon that are difficult to forecast.

Observations contradict projections

Most of the projections in the fifth IPCC report indicate an increase in precipitation in the Indian sub-continent. The frequency and intensity of extreme rain events are also likely to increase in Southern Asia. The credibility of these projections for the Indian monsoon is currently not in agreement with the observations available.

Indeed, Indian monsoon precipitations have displayed a downward trend since 1950.

A problem of scale

The work at IRD goes towards providing an explanation. The projections of monsoon rains in the climate scenarios result from a 'positive' thermodynamic contribution and a 'negative' dynamic contribution. Given the rough spatial resolution of the models used, the positive effect—linked with the transport of water vapour at the surface—is dominant and accounts for the increase in rainfall.

However, the researchers consider that the negative dynamic contribution resulting from anthropic change is strongly under-estimated because the spatial resolution of the models is not high enough for satisfactory simulation of the convection processes and the monsoon system itself.

Finally, digital experiments addressing this suggest that the decrease in monsoon precipitation should be seen in relation to regional factors such as the substantial warming of the Indian Ocean, the role of aerosols and changes in land use that modify the surface **albedo**.

The models used for the projections simulate these factors poorly or only take them into account partially.

Monsoon rain at Udaipur, India.

© Flickr / Creative commons McKay Savage

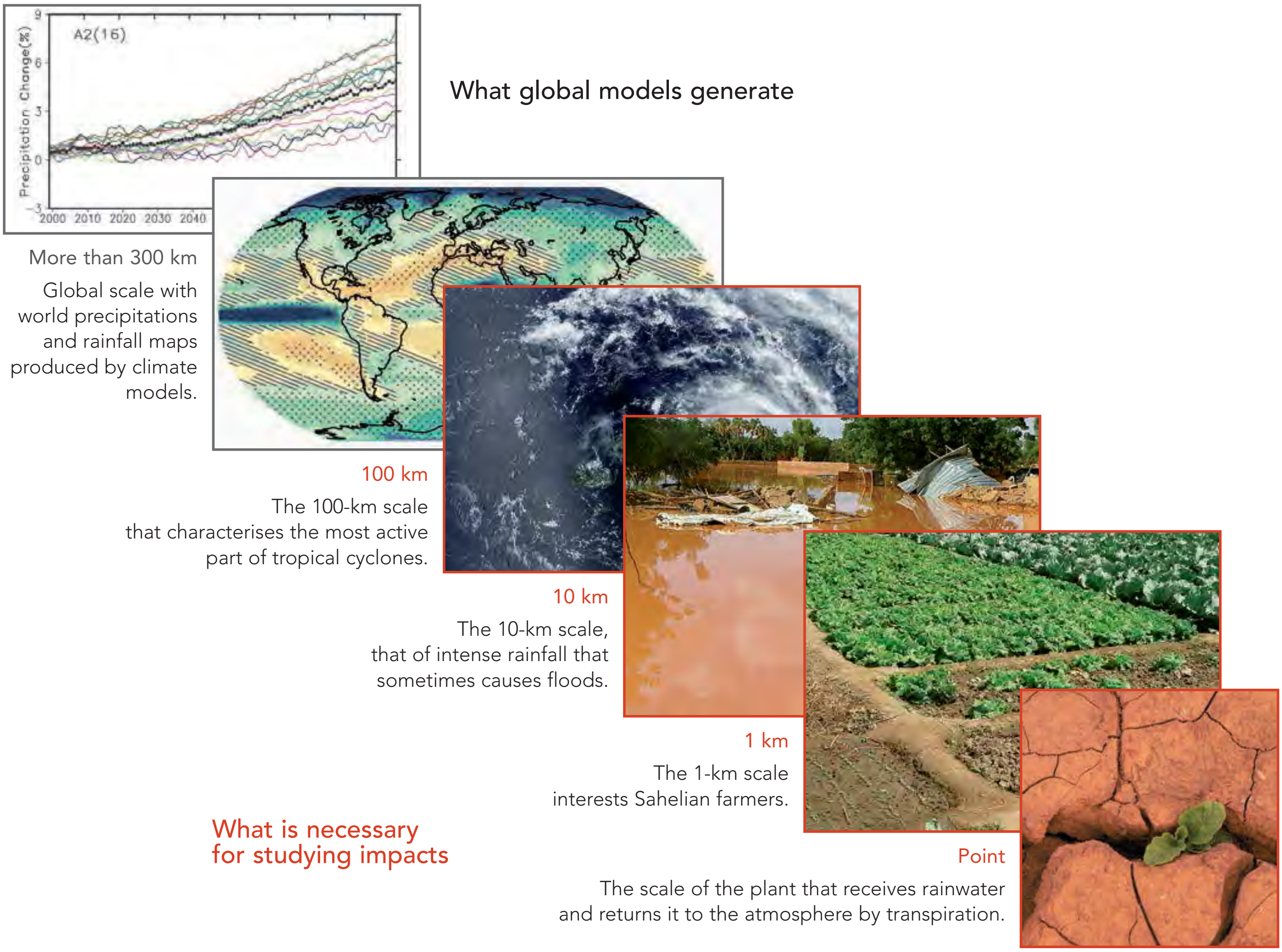


Figure 11.
Illustration of downscaling in climate change and its impacts.
Source: IRD/B. Sultan

Regionalise atmospheric models to reduce uncertainties?

It has been seen that the mathematical and physical equations used in climate modelling are rendered as discrete volume meshes. This approach is not fine enough and means that simulation of the behaviour of the atmosphere and oceans, where there are strong interactions at all scales of space and time, is not sufficiently accurate. This results in marked uncertainties in the simulated evolution of atmosphere and climate. To reduce these uncertainties, 'sub-mesh' parametering is aimed at describing the processes that take pace within the meshes of the model and their effects at mesh scale. But in spite of all the efforts made to quantify these processes, the parameters are often still based on empirical adjustments and only partially respond to the reduction of uncertainties. Finally, it must not be forgotten that the atmosphere remains a very unstable fluid and that an initially weak disturbance can gain amplitude and lead at a larger scale to contrasted meteorological situations (the 'butterfly effect'). Thus 'ensembles' of simulations should be formed in which the initial state is disturbed slightly to obtain a range of possible changes of the atmosphere and the climate.

Box 11

High resolution observations to re-establish the variability of rain in the Sahel

Scientists used the dense pluviographic network of the AMMA-CATCH observation service in Niger to improve hydrological models whose spatial resolutions were too low for simulation of runoff in Sahel hydrological systems.

The West African monsoon is one of the three major monsoon systems that play a key role in the climate of the earth. Its intensity displays strong inter-annual and decadal variability whose causes are mainly unknown. The AMMA-CATCH (*Analyse multidisciplinaire de la mousson africaine - couplage de l'atmosphère tropicale et du cycle hydrologique*) observation service makes possible long-term monitoring of the dynamics of vegetation and the water cycle and their interactions with the climate in West Africa. It is based on facilities set up at three sites along the Sudan-Sahel bioclimatic gradient, in Benin, Niger and Mali respectively.

Underestimation can exceed 50%

Scientists used the dense AMMA-CATCH observation service in particular to assess the uncertainty of hydrological models resulting from the use of spatial resolution that was too low for simulation of runoff in Sahel hydrological systems.

Water balances in the Sahel are directly linked with the interaction between rainstorms and the soil surfaces that governs runoff. Modelling the hydrological cycle thus requires representation of the spatial heterogeneity of the properties of soil surfaces and then supplying the surface models by rainfall forcings at scales that show the intrinsic variability of rainy periods. These spatial scales are of the order of a few kilometres in the Sahel. With resolution of 25 km (the resolution of satellite rainfall data), hydrological models may underestimate runoff by as much as 15%. At a resolution of 100 km (typical of climate models), underestimation may reach more than 50%.

These scale effects justify the use of so-called 'disaggregation' methods that use large-scale climate simulations (of the order of 300 to 50 km) to work down to fine scales of the order of 10 km.

In order to overcome this stumbling block, regionalisation is based on climate models operating in a limited spatial field (a 'region') with higher spatial resolution (a grid point every 10 to 50 km). This approach conserves the local complexity of the physical processes involved. It does not necessarily correct the bias of global models as the regional models are faced with the same limits of 'sub-mesh' parametering. These uncertainties raise a major problem for quantifying the local impacts of climate change on resources (for example water resources or agricultural yields at field level) because of the possible propagation and amplification of the large scale towards the local scale. Particularly as the models of impacts (e.g. hydrological or agricultural) also have biases and uncertainties.

It was possible to develop disaggregation methods thanks to the high resolution observations made by the AMMA-CATCH team. They make it possible to re-establish the full variability of rainfall when the original resolution of the data—whether from classic ground measurements with low spatial density or given by climate models—is not sufficient for modelling the hydrological cycle.

An MIT radar used in an experimental set-up at the AMMA-CATCH observatory in the outskirts of Niamey, Niger.
Several meteorological radars have been used during these research programmes to study the dynamics of the squall lines causing intense, very variable precipitation events that are a feature of the Sahelian climate.

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Chapter 5

'Attributing' the climate variations observed

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Building a road to exploit timber in West Papua New Guinea, Indonesia. Deforestation is an important factor in climate warming caused by human factors.

In 25 years, the dominant share of the warming measured in the atmosphere and the sea since the beginning of the industrial era is now attributed to anthropic emissions and not to the natural variability of the climate. In successive IPCC reports, the responsibility of human activities changed from uncertain (1990) to possible (1995) and then probable (2001), very probable (2007) and then extremely probable (2013). These scientific certitudes are the fruit of long work on the 'attribution' of climate variations to determine the share of anthropic forcings, natural forcings and natural variability.

The components of climate variations

The share of anthropic forcings

Confirmation of the mainly anthropic cause of climate change at global and regional scales is based on the one hand on the observation networks of climate warming and on the other on increasingly elaborate climate modelling. The models reproduce the temperature trends observed under the effect of an increase in the concentration of greenhouse gases. The influence of human activities is also detected

Eruption of the volcano Cotopaxi (Quito, Ecuador) in August 2015.
Volcanic dust and gas emissions in the upper atmosphere contribute to natural climate variability.

using other indicators such as changes in the global water cycle, the retreat of snow and ice, the rise in average sea level, the amplification of heatwaves in certain regions, etc.

The share of natural forcings

However, natural forcings (solar radiation, volcanic eruptions) also affect the variability of the climate system. According to satellite measurements available since 1978, the solar energy reaching the earth can be modulated by about 0.1% by variations in the activity of the sun itself in cycles lasting approximately 11 years. Volcanic eruptions also modify the amount of solar energy reaching the earth, especially when they occur in the tropics and when the eruption column contains considerable quantities of gases rich in sulphur at a sufficiently high altitude to reach the stratosphere. The fine particles of volcanic aerosols formed in the stratosphere can cover the entire world in a few months and disturb solar radiation because of their reflective quality.

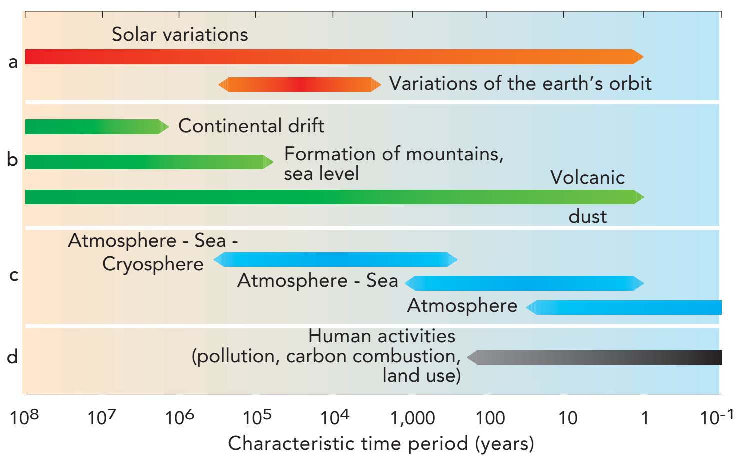


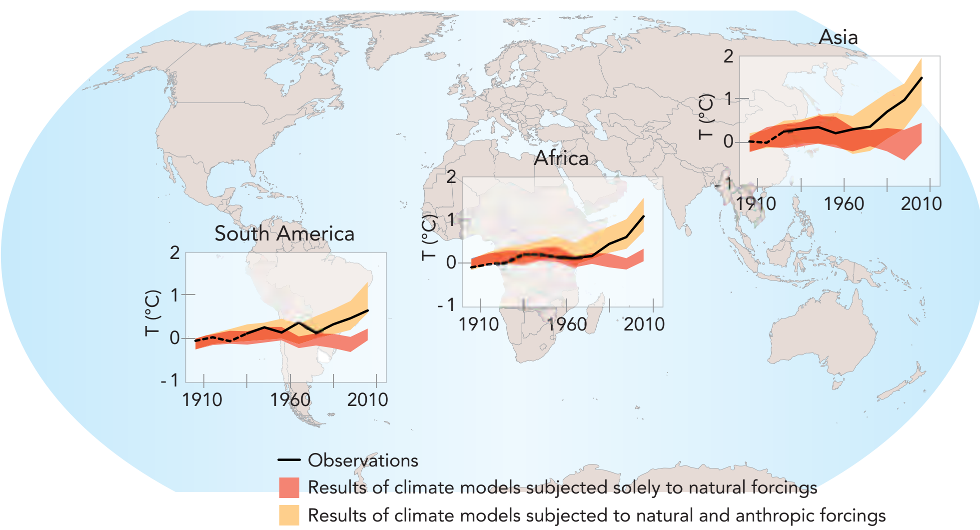
Figure 12.
Anthropic forcings have been added to natural forcings for a century.
At levels a and b distinction is made between forcings that are external to the climate system; c indicates variations that are internal to the system and d indicates anthropic effects.
Source: BARD, 2006.

The share of natural variability

Finally, the internal variability of the climate system—which is chaotic by nature—is always operating and may mitigate or strengthen the effects of anthropic and natural forcings. Within this internal feature, modes of variability such as the El Niño phenomenon have strong impacts especially in the tropics. For example, this variability can result in a cooling of the Pacific. Indeed, modulation of **Pacific Decadal Oscillation** (PDO) was responsible to a considerable degree for the slowing of the global atmospheric warming observed from 1998 to 2012 by greater heat transfer from the surface to the sub-surface of the tropical Pacific Ocean. This slowing was highlighted by climate sceptics to contest the anthropic causes of climate change. In fact, warming is not steady in time. After the slowing observed in the last 15 years, it will probably accelerate in the coming decades as a result of the return to the atmosphere of part of the excess heat stored in the sea.

Changes are difficult to attribute at local scales

In this context, the difficulty is that of being able to attribute a change observed—especially at the local scale—either to the impact of the anthropic greenhouse effect, to natural forcings, to natural internal climate variability or to more local anthropic activities such as deforestation for example. The generic 'detection-attribution' approach thus



The width of the orange and red bands quantifies the internal variability of the climate system.

Figure 13.
Example of a method of attribution of observed climate warming.
The gap between the trajectory of the red and orange curves shows the forcing effect of greenhouses gases. The trajectory of the observations is part of the simulations including anthropic forcings, confirming the anthropic impact on the increase in temperature.
Source: 2013 IPCC report.

combines observations and simulations to determine whether an observed change can be explained by one or more external forcings and in what proportions, and then to validate the coherence of observations and the results of climate simulations.

Climatic variability in the tropics

Interpretation of climate variations at the regional scale is complex, especially for the tropics where certain modes of variability have a strong impact. These modes are on different time scales: intra-seasonal (like the Madden-Julian oscillation), interannual (like the El Niño phenomenon) and multi-decadal (the Atlantic Multi-decadal Oscillation and the Pacific Decadal Oscillation). Indeed, climate variations or fluctuations take place according to preferential variability modes according to the dynamic regional context of the ocean and the atmosphere.

The El Niño phenomenon

Because of its global impact, the El Niño phenomenon—also called the El Niño Southern Oscillation (ENSO)—is the main mode of variability of the global climate. In the tropics, El Niño features in particular substantial warming of the equatorial sea surface water in the eastern Pacific Ocean every 2 to 7 years. These warm episodes are sometimes followed by cold events (La Niña). During the hot periods of this mode of variability, the trade winds (easterly winds blowing in the tropics) are weaker than during normal periods. Ocean-atmosphere interactions enable this type of situation to last for a year or longer with repercussions throughout the Pacific basin (forming almost half of the world's surface). For example, El Niño causes drought periods in Indonesia and strong precipitations in Peru. It also affects the Atlantic and Indian Ocean basins and can cause periods of drought or lasting flooding throughout the tropical monsoon systems (Fig. 14).

Decadal ocean oscillations

At the scale of a decade, alternate hot and cold phases similar to those caused by El Niño are also observed in the Pacific Ocean. Compared to El Niño, the Pacific decadal oscillation (PDO) has a broader spatial signal in the tropical Pacific and oscillates on a 20 to 30-year time scale.

The increase in the number of long series of observations in the north Atlantic region resulted in the identification of another mode of variability: the Atlantic Multi-decadal Oscillation (AMO) with oscillations over much longer, pluri-decadal periods. This mode alternates between the warming and cooling of the entire North Atlantic from the equator to the tip of Greenland.

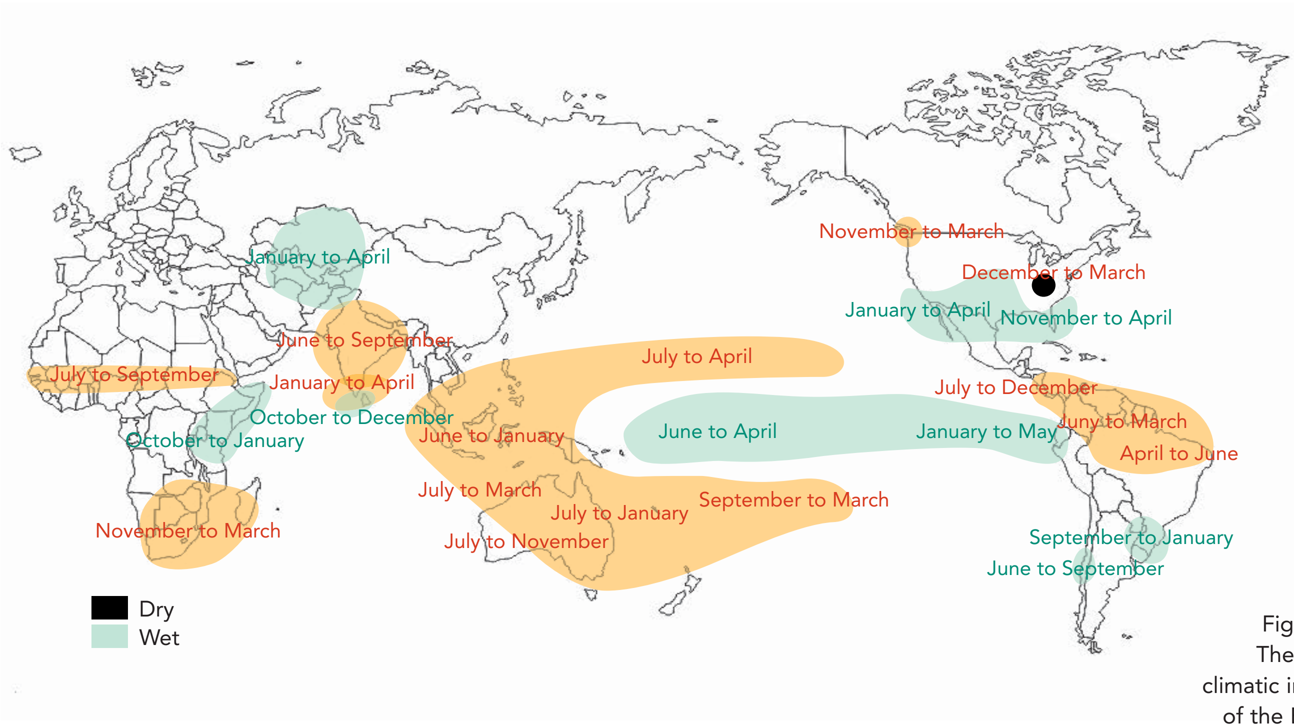
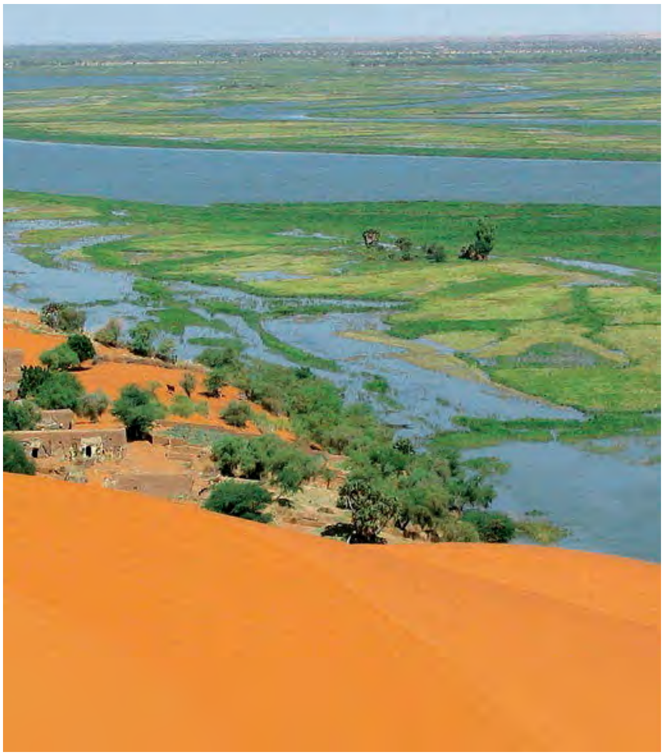


Figure 14.
The global climatic impacts of the El Niño phenomenon.
Source: ROPELEWSKI and HALPERT, 1989

2012 flood in Peru.
Upstream of the town of Iquitos, the Rio Ucayali, one of the main feeders of the Amazon, has eroded about 100 metres of bank and flooded the surrounding villages.



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Flooded rice fields
in the bed of the Niger.
Gao Dune, Mali.
It is difficult to forecast precipitation in the Sahel, while the population depends on rainfall more than elsewhere.

All these interannual to decadal variability modes in the Pacific and Atlantic oceans have a significant effect on the decadal variations of the precipitation regime in South America and the Sahel. However, they also affect the frequency of cyclones in the tropical Atlantic and even the climate of Europe in the summer. It is therefore difficult to separate the roles of these variability modes from that caused by global climate warming (of both land and oceans) in the climate changes observed in the tropics since 1850.

The role of internal climate variability in the return of rainfall in the Sahel

Can the partial return of rainfall in the Sahel from the 1990s onwards be attributed to climate change or is it still within the framework of internal climate variability? Observations covering the 20th century and the beginning of the 21st show that the transition is driven mainly by the Atlantic Multi-decadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO). More precisely, the return of rainfall corresponds to phase reversals in the Atlantic (from negative to positive) and the Pacific (from positive to negative). The positive phase of AMO, that is to say the warming of the north Atlantic, is favourable for rainfall in the Sahel and the positive phase of PDO, that is to say a warming of the Pacific, is unfavourable for rainfall. The signal of the global warming of the oceans, which is unfavourable for rainfall in the Sahel, starts to compete with AMO and PDO, the two other modes, without exceeding them. Simulations using an atmospheric climate model and taking the three modes into account confirm their impact on rainfall in the Sahel and their competitive feature.

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A squall line on the move during the monsoon season in Niger.

The influence of global climate change on variability modes

These different variability modes are comparatively well represented in climate models. Natural or anthropic forcings can affect their trends by preferentially stimulating one or other of the modes. This major influence has been documented over the past 150 years, a period for which numerous meteorological and oceanographic instrument observations are available. It has been studied using statistical detection and attribution methods and a set of climatic simulations with different forcings.

Although it is less well documented, the longer period of the last 1,000 years also provides a relevant temporal framework for investigating the interactions between external forcings and internal climate dynamics. Research teams are currently developing climate simulations of the last millennium and numerous reconstructions of the variations of these modes of variability. They make it possible in particular to evaluate the share of non-forced natural variability in comparison with those related to human activities since the beginning of the industrial era.

Thus although it has been shown that climate change does exist, in the current phase in which anthropic forcing is still moderate scientists remain very careful not to make excessive attributions of any new climatic anomaly to human activities.

Chapter 6

Projections: scenarios and uncertainties

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Rain arriving over the Barotse floodplain in Zambia.

Entrusted with the task of formulating scientific opinions for international negotiations concerning the climate, the IPCC assesses possible climate development with the constraint of the future pattern of greenhouse gas emissions. For this work, the climate modelling community develops climate simulations following joint protocols in order to compare the results of all the climate models used. For the IPCC, assessments of emissions were defined according to four socio-economic scenarios (also called Representative Concentration Pathways, RCP). Each scenario corresponds to an atmospheric greenhouse gas concentration in 2100. The impact of the greenhouse effect on the climate is calculated using **radiative forcing** from the most favourable (2.6 W per square metre) to the most unfavourable (8.5 W per square metre) with two intermediate values (4.5 and 6.0 W per square metre). The scenarios are named as follows according to the different forcings: RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5.

Climate projection

It is important to note that these experiments do not result in a **forecast** but in a '**projection**' of the climate that makes it possible to understand how the climate can change under these new greenhouse gas emission constraints. The projections do

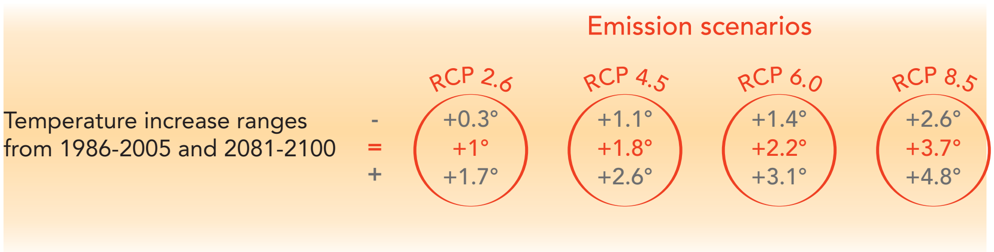


Figure 15.
Climate temperature forecasts for 1986-2005 and 2081-2100 according to the 4 IPCC emission scenarios.
Source: IPCC, 2013.

not take into account either the real initial conditions of the climate at the start of the simulations (for example a positive phase of the Atlantic Multidecennal Oscillation) or future changes in natural forcings (solar activity, volcanic eruptions) that cannot be forecast. However, they are generally performed for each climate model with a set of simulations so as to allow for internal climate variability.

The projections provide a statistical envelope of possible climate pathways for each of the four emission scenarios and for each climate model. Then, considering the global coverage of the climate models used, it is assumed that for a given socio-economic scenario the real climate pathway will be within the overall envelope of these sets of simulations, but without it being possible to predict the precise pathway.

Climate forecasting

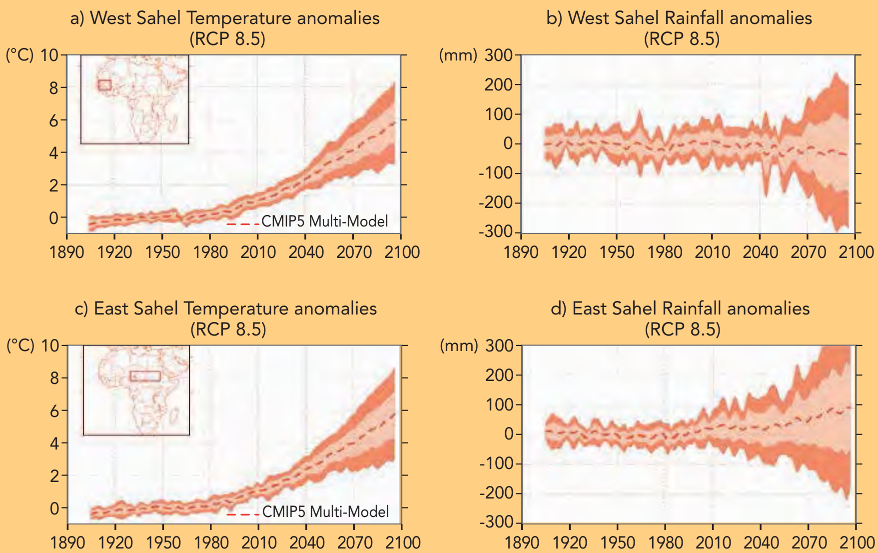
At the request of governments, a climate forecast operation has nonetheless been initiated in the Fifth Assessment Report of the IPCC. Forecasts for 2016-2035 have thus been added to projections for 2100. However, the present results of this exploratory work must be treated with extreme caution, in particular as regards their possible implications in terms of impacts on resources and the decisions to be taken by economic and political stakeholders. The aim is to gain better understanding of the climate modulations for periods of a few years and for some 30 years in order to test the degree to which they can be forecast. These modulations incorporate the internal variability of the climate system, natural forcings and anthropic forcings. In this framework it is essential to take the initial climate conditions into account to make a forecast of this type. The operation is aimed at more precise assessment of climate trends in the coming years and also includes assessments of 'retrospective' forecasts for previous periods (initialisation in 1960, 1965, 1970, etc.)—for which observations are available—in order to assess their performances and biases.

Box 12

Uncertainties are too great for the forecasting of Sahel rainfall

The climate in the Sahel has changed over the last 30 years. Temperatures have risen and there is a contrast in rainfall between east and west. Researchers have addressed the impact of the increase in greenhouse gases on the trend and on the climate projections for the region. They used the IPCC emission scenarios for this. Temperature projections confirmed the observations and indicated continued increase until 2100, with dispersion centred on the comparatively restrained mean change (envelope of uncertainties). This makes it possible, with good probability, to consider the recent warming observed as the imprint of climate change and to suppose that warming will continue.

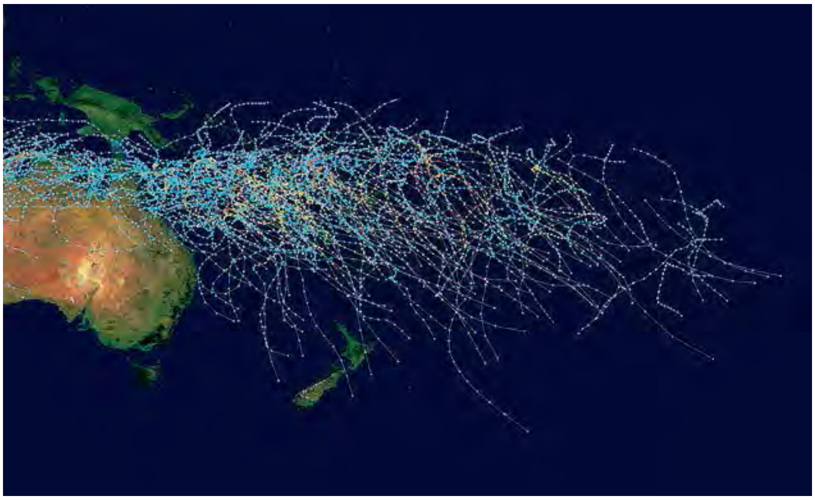
In terms of precipitation, although there is effectively a decrease in the western part of the Sahel (mainly in June and July) and an increase in the eastern part (mainly in September and October), the uncertainties with regard to these trends are much too great for it to be possible on the one hand to affirm that present changes are the imprint of climate change and on the other to indicate a clearly determined direction of change for the future.



Dashed lines show the movement of the multi-model average; orange areas cover the trajectories of all the models. Anomalies are calculated in relation to the period 1960-1990.

Figure 16. Climate forecast for temperature and precipitations for the western and eastern Sahel in the scenario RCP 8.5. The temperature movement forecast is clearly positive for all the models whereas precipitation forecasts are very uncertain.
Source: DEME *et al.*, 2015.

Map of the paths of cyclones in 1980-2005 in the West Pacific.
Careful study of extreme climate events is important to gain better understanding of their links with global warming.



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More frequent extreme events

Certain El Niño events, such as those of 1982-1983 and 1997-1998, were particularly intense. They featured a shift of warm water and rainy regions from the West Pacific towards the East Pacific. The modifications markedly changed the position of the South Pacific Convergence Zone (SPCZ), the rainiest part of the southern hemisphere, with dramatic effects on ecosystems, agriculture, the frequency of forest fires and cyclone activity in the south-west Pacific. The response of this phenomenon to climate warming has been a major challenge for the scientific community for the past 15 years.

Recent studies on the latest climate simulations have shed new light on the links between El Niño and the changes in the Pacific. Although analysis has not led to a consensus with regard to the future amplitude of El Niño events, most of the models indicate that the intensification of the warming of the equatorial Pacific in the 21st century should cause a substantial increase in the frequency of rain events in the eastern Pacific and shifts of the convergence zone towards the equator. The two phenomena characterise extreme El Niño events. The frequency of extreme La Niña events should also increase in response to the rapid warming of water in the region of Indonesia. In spite of the agreement between the different climate models concerning the increase of these extreme climatic events in the tropics, confidence in these climatic projections is still limited because of imperfections in the modelling of the tropical climate.

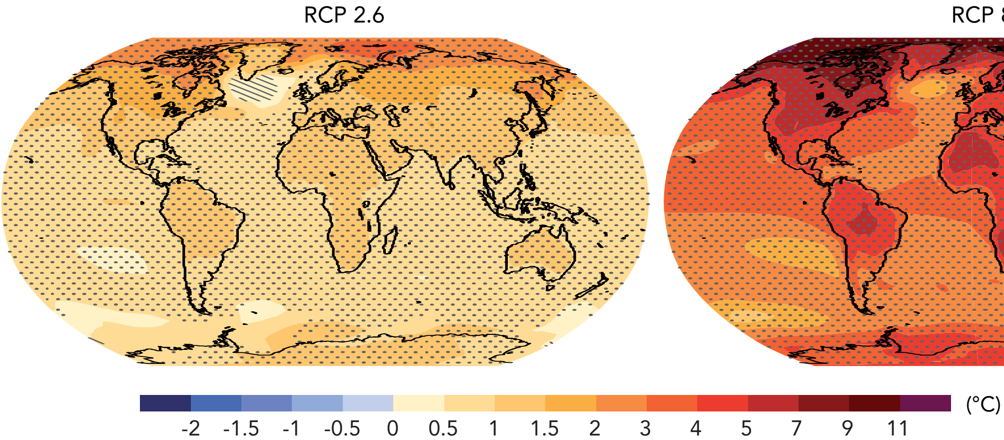


Figure 17.
Movement of average surface temperature from 1986-2005 and 2081-2100.
Source: IPCC, 2013.

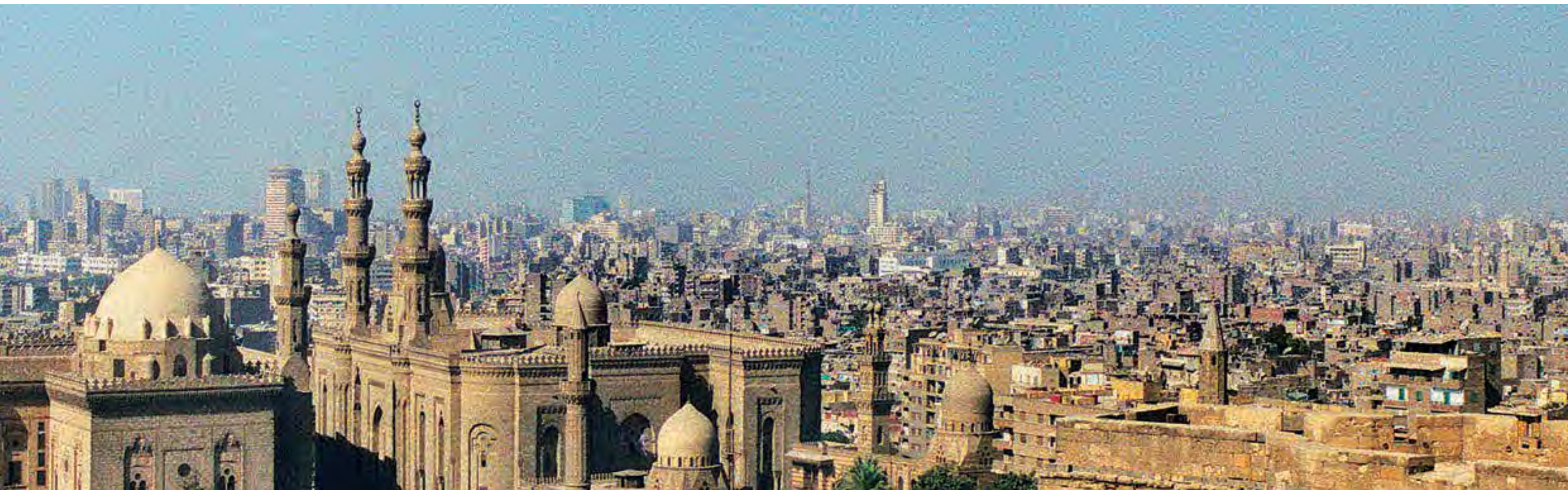
The 2°C threshold

Although the climatic impacts of global warming caused by anthropic emissions are not always easy to identify, the IPCC climate projections for 2050 and 2100 show that the greatest changes are still to come: according to the most pessimistic forecasts of greenhouse gas emissions—but that are possible as they would be the continuation of present emissions—warming could be nearly 4°C in one century.

For several years, the international community has shared the aim of stabilising warming at less than 2°C at the end of the 21st century. This is the threshold at which scientists do not exclude irreversible impacts on the climate and even a spiralling effect. The IPCC report must therefore enable decision makers to identify the socio-economic scenarios that will make it possible to reduce emissions in order to keep the rise in temperature below this threshold.

Chapter 7

Greenhouse gas emissions



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Cairo, Egypt.
This megalopolis suffers from air pollution that is sometimes difficult to bear.

It is clear that human activities affect the climate. Present world concentrations of greenhouse gases (GHGs) are considerably greater than pre-industrial levels determined by using core borings of ice covering several thousand years. The carbon dioxide (CO_2) concentration has increased by 40% since the end of the 18th century. Although carbon dioxide is the main gas emitted (76% of emissions), it is not the only one. Methane (CH_4), nitrous oxide (N_2O) and fluorinated gases also have considerable warming potential, with 16%, 6% and 2% respectively. The increase in the amounts of these gases in the atmosphere disturbs the natural carbon cycle and causes an additional greenhouse effect: the GHGs allow solar radiation to reach the Earth but trap the infrared radiation emitted at the surface and thus increase the warming of the atmosphere.

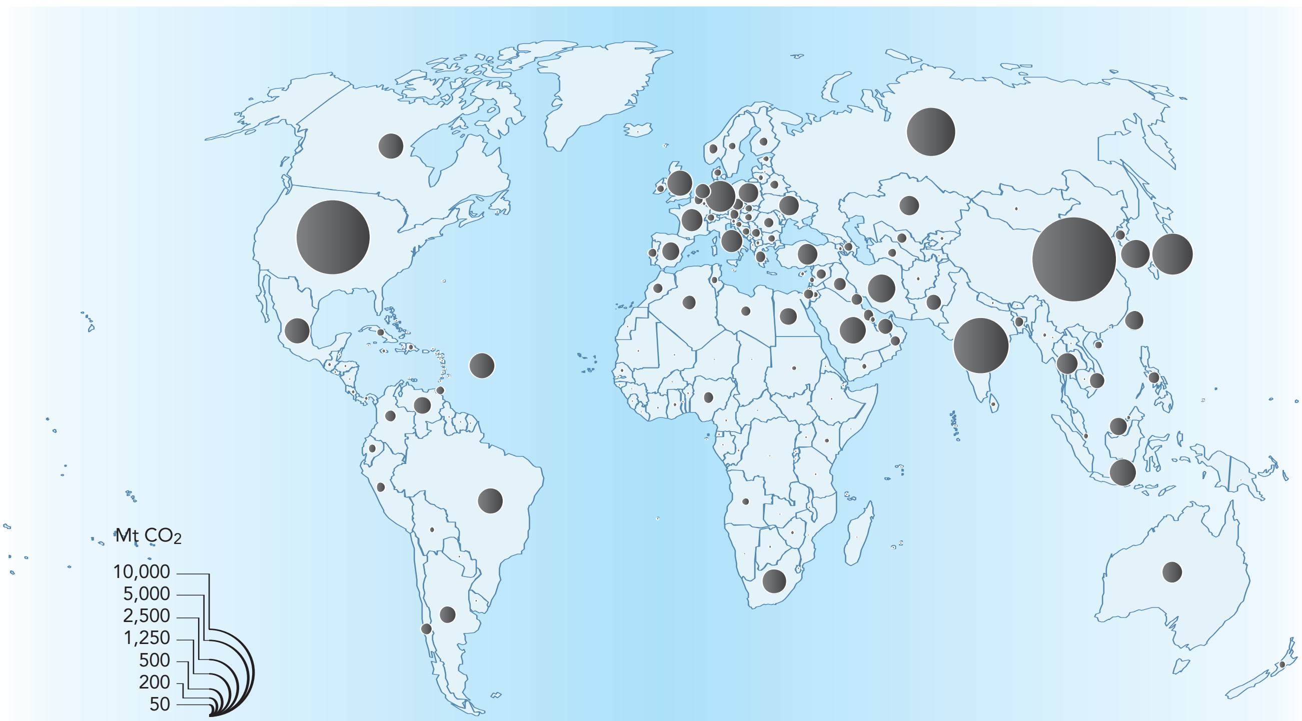
These emissions are linked directly to industrial development that has led to growing use of fossil energy (coal, oil and gas) by industry, agriculture, transport and dwellings and, to a smaller degree, change in land use (deforestation). Anthropic emissions of GHGs thus increased by 70% from 1970 to 2004.

Localised emissions

Although the greenhouse effect is a phenomenon at the scale of the planet, emissions are clearly localised. Emitted in a very heterogeneous pattern at the surface of the earth, greenhouse gases are then redistributed in the atmosphere at the scale of about one year. Thus even the regions with the smallest emissions or those that are furthest from sources of strong emissions—like Africa for example—have similar CO_2 concentrations to those of emission regions and are affected by climate warming.

Historically, emissions are largely from the western countries. Although their contribution is tending to decrease proportionally, their emissions continue to increase. Certain emerging countries like China, India and Brazil have now caught up with the rich countries. China has even overtaken the United States and is now the leader in terms of CO_2 emissions with 9,973 million tonnes (Mt) in 2013, nearly double that of the 5,233 Mt emitted by the USA. The poorest countries are far behind (Fig. 18). According to the 5th IPCC report, the difference in emissions per capita between the greatest and smallest emitters is a factor of 50.

Figure 18.
CO_2 emissions resulting from fossil fuels (2013).
Disproportionate emission levels for the planet as a whole.
Source : BODEN *et al.*, 2013



The accounting of emissions

Accounting world greenhouse gas emission is based on national inventories. Following IPCC guidelines, the methodology used today records the direct emissions related to activities (energy, industrial processes and product use; agriculture, forestry and other land use; waste) and households (motor cars and heating) in a country's territory. The most common methodological approach consists of combining data on human activities with coefficients that quantify emission or use by type of activity. However, the methodological choices, the calculation of coefficients and the estimating of uncertainties are the subject of scientific discussions within the actual work of the IPCC.

Furthermore, scientists have grouped the six greenhouse gases (CO_2, CH_4, N2O and three fluorinated gases) and a category called 'CO_2 equivalent'. The calculation of equivalents in terms of global warming potential is another source of uncertainty, especially as these greenhouse gases affect the climate in different ways, to different degrees and during distinct periods.

Benxi industrial centre.
China is currently the world's leading emitter of greenhouse gases, ahead of the United States.

Imported emissions

In addition, national inventories do not always reflect all the emissions associated with consumption by the population. Indeed, accounting is performed on the basis of the national territory in which they are generated and not the territory in which they are consumed. For example, emissions per inhabitant in France total 8 t CO_2 equivalent according to national accounting. But when emissions involved in consumption are taken into account the figure increases by more than 50%. The difference results from imported products and foodstuffs whose greenhouse gas emissions are accounted for at their site of production—in other countries. Thus China has the largest CO_2 emissions in the world but nearly a third of these emissions concern exported products that are therefore consumed elsewhere. Finally, emerging or developing countries produce an increasing proportion of emissions linked to consumption by industrialised countries. These methodological points call into question the effectiveness of national policies for reducing emissions and certain estimates find that imported emissions form a quarter of global emissions.

Different sources of emission according to the country

A variety of emission activities is added to this global disparity. Since 1970, more than three-quarters of the increase of greenhouse gas emissions is attributed to CO_2 released by the combustion of fossil fuels (in industry, for heating, transport, etc.). The rest is mainly related to changes in land use and particularly deforestation. Agriculture is also the main source of two other greenhouse gases: methane emitted by ruminants, animal faeces and rice fields and nitrous oxide (N_2O) resulting from nitrogen fertilisers.

The different sources of emissions vary strongly according to the country (Fig. 19). In the 84 poorest countries—corresponding to the groups of 'low-income economies' and 'lower-middle-income economies' according to World Bank nomenclature—agriculture and deforestation are the main sources of greenhouse gases (90% of total emissions). The emissions profile of countries with economies in transition in the upper-middle-income economy category, including Brazil and China, are similar to those of the richest countries but with more emission from industry at the expense of transport and construction. These emission profiles show clearly that the political response cannot be the same for all countries, whether in terms of responsibility or priorities to be addressed according to the sector. The same observation can sometimes be applied at the national level when regions are very different from each other.

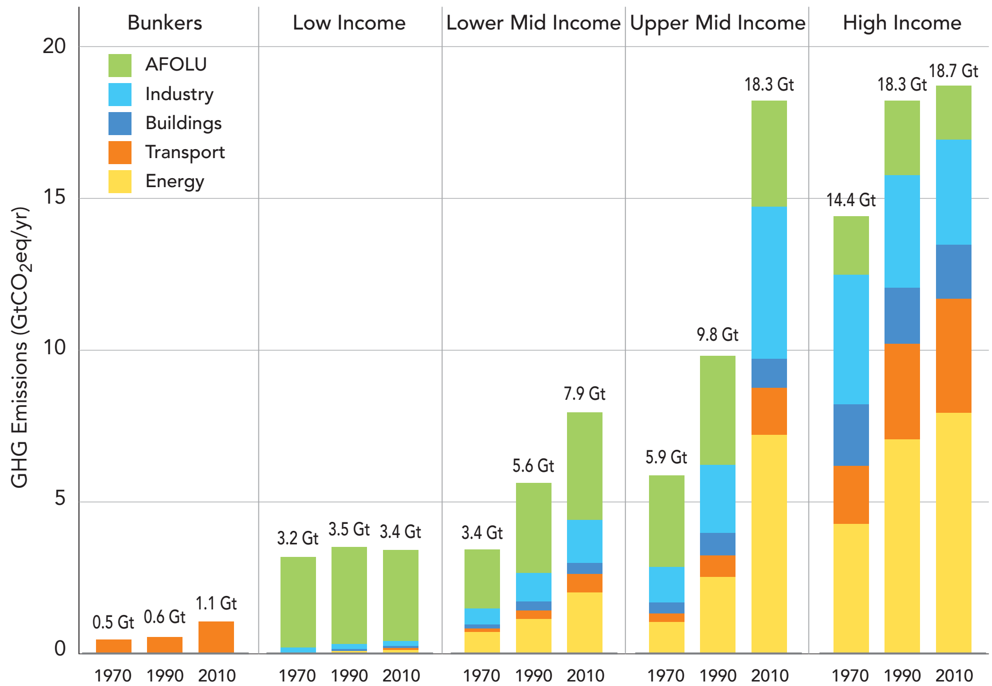


Figure 19.
Distribution of greenhouse gas emissions according to emission activities by group of countries (using World Bank nomenclature and in Gt CO_2-equivalent).
Source: IPCC Fifth Assessment Report, 2013

The clearing of tropical forests

According to the IPCC Fifth Assessment Report, the felling of several million hectares of tropical forest in Amazonia and South-East Asia accounts for the greater part of CO_2 emissions linked with changes in land use since the 1980s. However, the share of agriculture and forestry in global emissions is tending to decrease, forming a quarter of emissions in 2010 in comparison with a third 20 years previously. But it should be noted that this trend is linked with a comparatively faster increase in other sources of emissions.

© IRD/M. Grimaldi

Amazonian pioneer front in the State of Para, Brazil.
The clearing of tropical forest is a substantial source of carbon dioxide emissions.

Tropical forests also play a role of natural carbon sinks and can thus reduce the CO_2 concentration in the atmosphere. Much research is thus addressing the measurement of the **biomass** in these forests in order to gain a closer view of the contribution of deforestation to global emissions and also to assess the carbon storage capacity of forests and soils (see page 147).

Box 13

The singular profile of the African continent

Africa accounts for only 3.4% of world emissions, making it a marginal contributor to global climate change.
Another singular feature is that over half of emissions are related to agriculture and changes in land use. Nevertheless, the deforestation of African tropical forest accounts for a comparatively small proportion of the footprint of world deforestation—in comparison with that in South America and South-East Asia.

In West Africa, the dominance of agriculture as a source of emission (nearly 40%) reduces the scale of carbon dioxide emissions, replaced by other greenhouse gases strongly emitted by the sector. Thus methane and nitrogen alone account for 75% of GHG emissions in West Africa in comparison with 25% in the world as a whole.

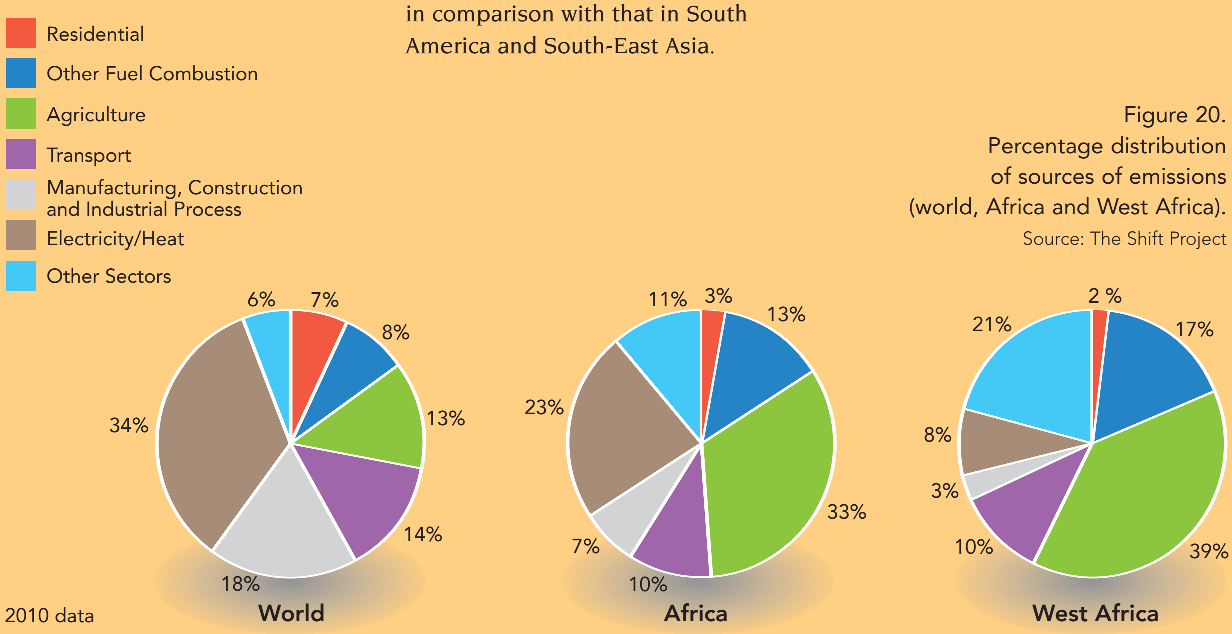


Figure 20.
Percentage distribution of sources of emissions (world, Africa and West Africa).
Source: The Shift Project

© Wikipedia/F. Gonzalez

In spite of a decade of rigorous measures to limit pollution, Mexico City—one of the most seriously polluted cities in the world—is enveloped by a misty halo almost every day.

Urban emissions

Greenhouses gases are produced mainly in cities and their peripheral areas that concentrate industrial emissions, emissions resulting from transport and heating/air conditioning. Although the northern countries are the main sources of urban emissions, urban development in the southern countries is now catching up. Of the ten cities with the highest emission levels in the world, six are in India, three in Pakistan and one in Iran. However, the contribution to global emissions is not always visible as they are 'diluted' in national average figures. For example, average emission in Thailand is 3.8 t CO_2 per person per year whereas the figure for Bangkok alone is 10.7 t per person per year.

Because of this growing urbanisation, scientists must assess the contribution of cities to climate change. In the northern countries, the drawing up of 'climate plans' has made it possible to set up watches and to model emissions on medium scales. However, in the countries in the South observation networks are still not very dense and there are very few systems for observing urban climates.

Reducing global emissions

All economic sectors—industry, agriculture, town planning, etc.—are therefore concerned by the effort to reduce emissions. According to IPCC scenarios, to have a chance of remaining at less than 2°C warming between now and 2100, world emissions must be reduced by 40% to 70% by 2050 in comparison with 2010 levels and reach practically zero at the end of the century. The decreasing of world emissions has thus become the hobbyhorse of international climate policies set up under the aegis of the United Nations. But this focus on a global volume of emissions is now reaching its limits insofar as it has not been able to provide a political response to the climate crisis (see page 177).

Red mangrove
and striated heron.
Mangrove trees are central
to an ecosystem that is
biologically very rich and
contributes to the stability
of coastal zones.

Part 2

The impacts of climate change in the South

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The Fifth Assessment Report published by IPCC confirms with increasing certitude the global reality of climate warming caused by rising greenhouse gas levels and the consequences for the environment and societies. In particular, it warns the international community once again of a general increase in temperature accompanied by a probable increase in the frequency and intensity of meteorological events such as droughts, cyclones and floods. While all natural and human systems are concerned, much uncertainty remains about the consequences of warming at the regional level.

The realities of climate change vary according to the geographic situation and the type of ecosystem. While the average world increase in temperature has been +0.78 °C in a century, it is twice as great in arid environments and in particular in the Sahel. Regional responses to higher CO_2 levels are even more contrasted when precipitation and extreme events are examined. The multidisciplinary work carried out by IRD on different types of tropical environment underlines the complexity of the processes involved and the multiplicity of determinants as each environment is subjected to different climate events (cyclones, droughts, floods, rising sea level, warming) and displays its own vulnerability and degree of exposure to the climate risks that affect it. These risks are often worsened in countries in the South by endemic poverty and the small control resources that can be mobilised.

Ocean warming thus threatens the marine environment through redistribution of marine species, irreversible coral bleaching and a decrease in fisheries resources, with consequences for food security. More recently, scientists have discovered the ocean acidification phenomenon and are just beginning to assess the effect on marine ecosystems.

Coastal systems are also subjected to the effects of ocean warming and acidification, together with the expected rise in sea level and coast erosion.

The semi-arid regions, with a rainy season lasting for several months, are particularly sensitive to the rise in temperatures and change in the rainfall regime. These rapidly affect water and food resources.

In highland regions, warming has consequences that are already clearly visible: the retreat of glaciers accompanied by changes in the hydrological regimes of drainage basins, water supply problems and also loss of biodiversity in these environments with the migration or disappearance of certain species.

Humid tropical forests are threatened by increased risk of fires and the major rivers have experienced exceptional floods with frequently dramatic effects for transport, fishing, agriculture and habitats. Although the erosion of biodiversity seems les obvious than in other environments, it is nonetheless in progress.

Urban environments are strongly affected and are suffering harmful sanitary effects (air pollution, heatwaves) that sometimes cause serious human losses as a result of the increasing number of extreme events. The rise in sea level with submersion and landslides will in time cause many development and safety problems in the large coastal cities.

Using field observations and satellite images and climate, ecological, hydrological and agricultural modelling, Part 2 illustrates the processes operating and recent trends and also future projections should greenhouse gas emissions continue. Although the ‘signature’ of climate change has already been seen clearly in ocean and continental observations over the past 50 years, the risk of major disturbance of these systems will be all the more serious as the warming to come will be rapid and intense.

One difficulty of interpreting changes in environments is that climate change is only one risk among others. In particular, human activities and population pressure often weigh more on environments and resources than climate change itself. This is the case in particular of mangrove ecosystems and coral reefs (Chapter 9) and freshwater fish resources (Chapter 12). It is very difficult to identify the influence of climate warming when it is combined with these other changes. For example, the risk of submersion depends as much on rising sea levels as on the urban development of coasts (Chapter 9).

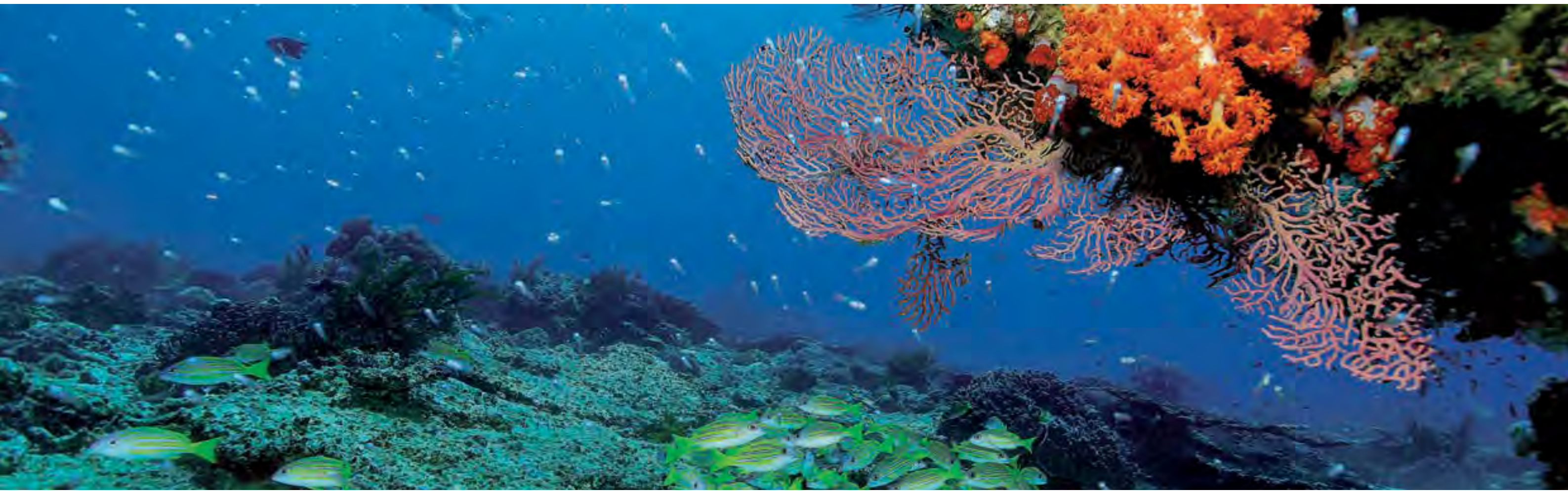
This section also illustrates the difficulties in observing and forecasting climate change; this affects natural and human systems in a very uneven manner. Certain cold ocean regions could benefit from the arrival of new marine species from the warmer zones in the south (Chapter 8). Whereas coastal areas can recover naturally from massive erosion (Chapter 9) and the vegetation can recover in the Sahel after decades of drought (Chapter 10), coastal cities will be fully exposed to the effects of climate change as vulnerability is acute there (Chapter 13).

Finally, certain environments such as the oceans and forests that serve as carbon sinks can also amplify or regulate carbon dioxide concentrations and thus change the trajectory of climate warming.

The specific features of each environment and the complex phenomena involved justify the regional, multidisciplinary approach used in Part 2. This also reflects IRD’s strategy of favouring integrated research on climate founded on multidisciplinary programmes conducted in various regions of the tropics.

Chapter 8

Oceans: marine ecosystems and warming



© IRD/G. Di Raimondo

Gorgonians and shoals of fish in West Papua, Indonesia.

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

Ocean life subjected to environmental constraints

Warming and acidification

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

The role of the environment in ocean life

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

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

© IRD/A. Bertrand

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

Knock-on effects on marine biodiversity

Water warming changes species distribution

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

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

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

Box 14

The Humboldt Current ecosystem changed by increasing upwelling of cold water

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

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

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

Extension of the minimum oxygen zone

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

© IRD/G. Roudaut

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

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

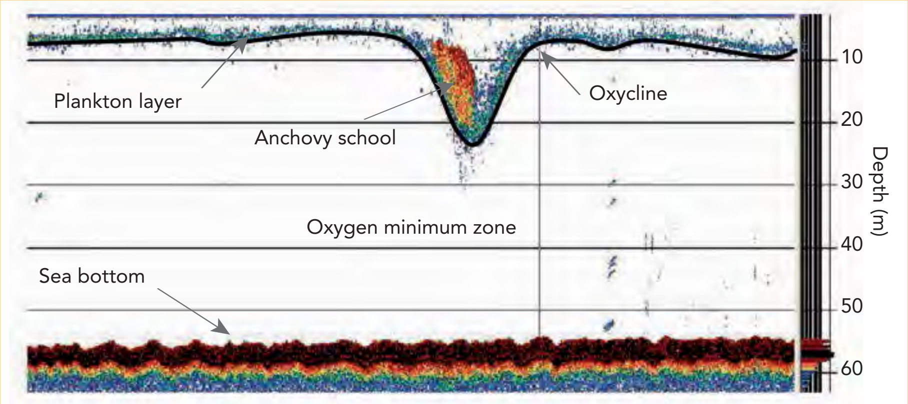
Will boobies, cormorants or pelicans be the winners?

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

End of the golden age

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

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



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

Chain effects of interactions between species

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

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

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

Threats to coral ecosystems

Coral bleaching

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

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

© IRD/J. Orempüller

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

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

The impact of acidification on calcareous organisms

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

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

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

Box 15

Mapping risks to quantify the future vulnerability of atolls

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

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

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

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

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

Modelling the effects of climate change on ecosystems

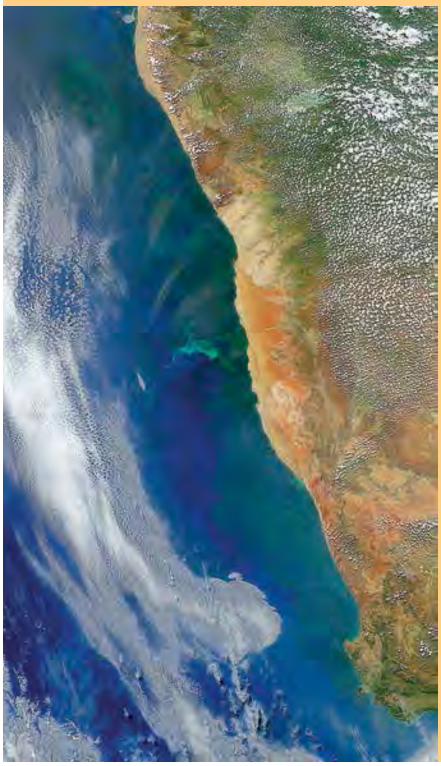
The first global models of the impact of climate change on life in the oceans assess the evolution of fish species distribution according to water temperature. These projections show the shift of species to higher latitudes. Depending on the climatic scenarios used, the tropical zone should see a 15%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

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

Box 16

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

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



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

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

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

The impact on fisheries and world food security

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

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

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

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

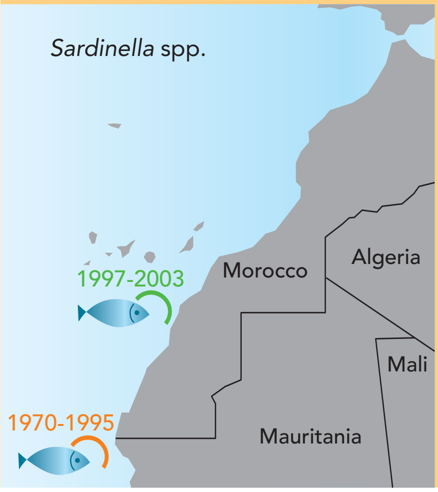
© IRD/V. Turmine

Box 17

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

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

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



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

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

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

Sardinella, a new resource for Morocco

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

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

The shifting of species has changed the map of fisheries

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

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

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

Box 18

EuroMarine: from genes to ecosystems in changing oceans

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

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

Increased risks of pollution

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

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

Chapter 9

Coastal and island zones: areas under anthropic pressure

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Isla Maragarita, Venezuela.

Coastal zones are in the front line as regards physicochemical changes in the oceans. The rise in sea level is pushing back coastlines. The warming and acidification of seawater also disturb ecosystems that are under marine influence. However it is very difficult for researchers to separate climate effects from those—more numerous—that result directly from human activities. Coastal areas pay a high price for their attractiveness, with increasing urbanisation and exploitation of resources. But one thing is certain: these environments have often become fragile and future population growth and changes in ways of life will mean that these direct anthropic pressures will continue to combine with the increasing effects of climate change.

The erosion and submersion of coasts

Marine submersion models are now available for the simulation and forecasting of the movement of the sea into the land according to the rise in ocean water levels. For example, it is estimated in these models that 12% of the islands in the world will be threatened with disappearance. But although projections based on the rise in sea level are sufficient for studies at the global scale, they are not necessarily sufficient for a predictive map of the future submerged areas at the scale of an ocean basin.

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Small island in the Maldives. These islands that are practically at sea level are particularly vulnerable to climate change and the rise in sea level. Coast protection embankments are used to try to limit wave impact during periods of heavy seas.

First of all, the rise in water level is very unevenly distributed. In the Pacific zone, differences in the rise of the level of the sea between New Caledonia and the islands of Micronesia in the past 50 years display a ratio of 1 to 10. More locally, the rise in sea level is also affected by climate disturbances and tectonics. For example, very significant differences in sea level are observed according to the intensity of the El Niño phenomenon.

Box 19

The first 'climate refugees', also victims of plate tectonics

The Géoazur research unit and its partners explained in 2011 why the marine submersion observed in the Torres Islands in Vanuatu is twice as rapid as forecast: the rise in sea level was combined with the sinking of the archipelago as a result of tectonic activity.

The village of Lataw in the Torres Islands in Vanuatu is being invaded by water. In 2004, this small place in the middle of the South Pacific had to retreat by several hundred metres, making the 70 inhabitants the first 'climate refugees' of history according to the United Nations. Were they victims of global warming? Not only that.

In 2011, the Géoazur unit and its partners showed that the archipelago was sinking into the sea at a rate of about 1 cm per year. Vanuatu is at the edge of the Pacific tectonic plates under which the Indo-Australian plate is sliding, causing a lowering of the ocean bed and of the islands at the surface. Over a 12-year period, while the sea level rose by about 15 cm, Torres Islands descended by nearly 12 cm.

The water level thus rose at double the rate forecast by the local authorities. This error of interpretation limited the shift of the inhabitants of Lataw Bay, preventing them from gaining more long-term safety.

© IRD/V. Ballu

A Lataw villager in the Torres Islands in Vanuatu.

Erosion depends on the local dynamics of environments

The rise in sea level and greater frequency of storms increase the frequency of submersion events and hence coastal erosion. However, erosion also depends on the dynamics of sediment systems. After a hurricane for example, beaches may form again naturally from the stock of eroded sand deposited in the forward part of the beach. In contrast, if the 'stock' of sediment has been reduced by the removal of sand, the beaches exposed to the force of waves and swell will retreat.

Coastal ecosystems also cushion erosion phenomena to a greater or lesser degree. Totalling some 600,000 km^2 along tropical coasts, coral reefs are an effective natural barrier to marine erosion. They cause waves to break, dissipating three-quarters of their power. Islands bordered by a reef thus have excellent natural protection. In addition, growth of the reef and coral sediment can also partially compensate a rise in sea level. For example, the Marshall Islands and Tuvalu still have the same surface area in spite of a rise in sea level of 2 mm per year during the second half of the 20th century.

© IRD/L. Descroix

Coastal erosion in Senegal.
Although the causes of the phenomenon are partially human (sand extraction from the beaches and coastal development) and partially natural (fragile coastal soils), the effects of coast erosion will probably be worsened by climate change and the rise in sea level.

Box 20

Recovery of the Chilean coastline after the 2010 tsunami

The LEGOS unit and its Chilean partners showed that dunes and beaches had become re-established less than a year after the tsunami that hit Chile in 2010. The earthquakes resulted from phenomena totally unrelated to climate but the Chilean coast formed a unique 'natural laboratory' for improving anticipation of the impacts of climate warming on coasts.

In February 2010, Chile suffered a severe earthquake that caused a tsunami with 10-metre waves. It hit a coastline inhabited by millions of people and the earthquake and giant waves also changed the features of the shores: dunes and sandbars were washed away and the coast was lowered by as much as 1 m in places.

The LEGOS international team and its Chilean partners made observations to assess the impact on 800 km of coastline less than a week after the event. Topographical and GPS observations showed that the tsunami had had the effect of a bulldozer, destroying existing structures: dunes, underwater sandbars, beaches, etc.

Bi-monthly monitoring of the natural reconstruction of the coastline was then performed. This showed that the coast responded rapidly to the disaster. Most of the sandy coastal structures had re-formed after a few months but their morphology was different. Unexpectedly, the sedimentary system regained balance in a year but the balance was different to the pre-tsunami situation.

The earthquake also lowered part of the coastline by several tens of centimetres. This lowering caused marine submersion, making the Chilean coast a natural 'laboratory' for anticipation of the impacts of rising sea levels. Until now, projections in models were based on a simple equation called Bruun's Law in which the geometrical parameters of a section of beach are used to predict its erosion in case of a rise in sea level. The observations made by the researchers help to show that reality is more complex than this. Since December 2012, a permanent observation system provides continuous monitoring of the dynamics of the coastline.

Homes destroyed by the earthquake and tsunami of 27 February 2010 in the River Mataquito estuary in Chile.

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The village of Cabrousse in southern Casamance (Senegal).
A rice field in a coastal area hit by a storm-driven tide that took salt into the mangrove and the paddy field.

Soil salinisation: a consequence of rising sea levels?

Seawater intrusion has serious consequences for coastal land ecosystems. In particular, soil salinisation makes previously fertile soils non-productive. The salinisation of ground water also causes difficulties when potable water is required. Drought also aggravates the problem: more marked low water periods in watercourses contribute to a slow invasion of sea water in water courses and the salinisation of farmland.

Nonetheless, the salinisation phenomena observed today are less linked to climate than to human activities. Population growth in coastal areas is accompanied by high water consumption. Urbanisation (concrete and tarmac) makes land impervious and this limits the infiltration of rainwater which is then drained by river systems and no longer recharges ground water. Increased use of water and increased runoff thus result in greater salinity of ground water. Coastal works are also strongly involved in sea water/fresh water exchanges and the consequences are sometimes unexpected (Box 21).

Even in the absence of any human presence, the balance between fresh and salt water in coastal aquifers is both complex and unstable (Box 22).

Box 21

When salinisation upsets the whole coastal system in Senegal

The excavation of a breach to release Senegal River floodwater in 2003 resulted in the formation of an opening to the sea several kilometres long in about a decade. The changes in the ecosystem were such that some locals abandoned market garden crops and are now harvesting salt.

In 2003, a major flood alert encouraged the Senegalese authorities to make a breach in the Saint-Louis dunes so that the excess water could flow into the sea more rapidly. The channel prevented the town from being hit by a flood. However, once it had been excavated, the 4-metre breach became wider and wider. A year later it was 1 km wide and in October 2012 the contact zone with the Atlantic was about 4 km wide.

Fresh water was already scarce and the intrusion of seawater made it more difficult to find and the population had to be supplied by bowsers or travel for several kilometres.
Today, scattered wells abandoned because the water was too saline are a common sight in the region.

The conditions were already fairly difficult for market gardening before 2003 and it was now strongly threatened by the hyper-salinisation of water and soil.
With the decrease in vegetable crops and the disappearance of tourist facilities as a result of erosion, the population—especially the women—have now turned to salt production.

Although the cause of this ecological and social upset has a human cause in this case, this study by the Senegalese partners of the Résilience unit illustrates the vulnerability of coastal systems in the face of salinisation and a rise in sea level.

Box 22

Small Pacific islands: a duel between fresh water and the sea

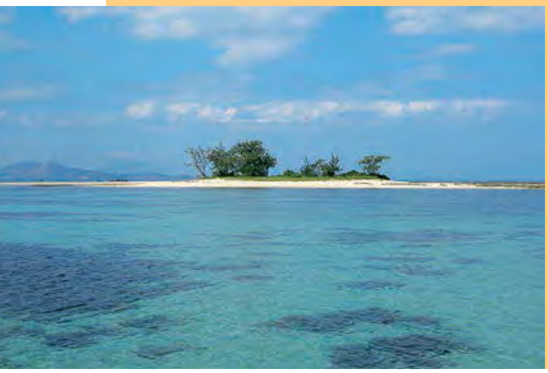
There is practically no human activity in the islets off Nouméa in the south-west lagoon of New Caledonia. Here, within the framework of the 'Interface' project, scientists studied the distribution of fresh water and salt water in ground water.

The researchers examined the spatial distribution of salinity in underground water using measurements of conductivity.
This work was cross-referenced with hydrogeological models to plot 2D and 3D maps of the distribution of island aquifer salinity and also to assess capacity for recharge by rainfall.

Unexpectedly, underground water was more saline in the centre of the coral islets than at the shore, which is nonetheless the zone of interaction between fresh and saline water. The reason is that vegetation is denser in the centre of the island and uses a large quantity of fresh water.

Furthermore, recharge of fresh water by precipitation is minimal in the centre of the island, again because of the density of the vegetation and more developed soils.
In contrast, maximum drainage is observed in the dunes by the sea.
A dilution of the salt content was thus observed in underground water at the edges of the islet and, conversely, concentration in the centre.

This research will lead to the evaluation of fresh water resources on Pacific coral islands within the framework of the search for indicators of vulnerability in the context of global climate change.



Wooded coral islet in the lagoon at Nouméa, New Caledonia.

© IRD/C. Proisy

Amazonian mangrove swamp in French Guiana. Human activities are causing the disappearance of 1 to 2% of these ecosystems. Their fragility is increased by climate change.

Mangrove swamp, a vulnerable ecosystem between land and sea

Mangroves cover three-quarters of the coastlines of the tropics and form a specific ecosystem. However, they are currently disappearing at a rate of 1% to 2% per year. The reasons are population growth, the intensification of urbanisation and the exploitation of natural resources. The expansion of shrimp farming in South-East Asia, Central America and East Africa has had a particularly devastating effect. Climate change exerts further pressure on ecosystems that are already fragile. The disappearance of mangroves leads to the loss of certain essential ecological functions. Mangroves are home to rich biodiversity and form a key element in the balance of coastal ecosystems by allowing the return of nutrients, which, without these trees, would have been definitively lost in deep sediment.

The increase in the number and intensity of cyclones could be fatal for these ecosystems. They have a destructive effect on mangroves, which, because of this, rarely colonise the most exposed stretches of coast, preferring quieter areas where sedimentation occurs. According to recent scientific work, if cyclones were to occur too often, mangrove swamps would be incapable of surviving.

Box 23

Mangroves: exemplary adaptation

Mangrove swamps in French Guiana display a natural capacity for compensating massive, repeated destruction caused by marine erosion.

As along all the coasts downstream of the Amazon estuary, the coastline of French Guiana is ceaselessly remodelled by large-scale hydro-sedimentary processes that are the result of the movement of sediment and fresh water flowing from the Amazon into the Atlantic Ocean.
However, the mangroves in Guiana seem to be well adapted to this permanent coastal instability.
Analysis of the evolution of the area of mangrove swamps since 1950 confirms the ability of the ecosystem to compensate repeated massive destruction caused locally by erosion of mud by swell.

Research by the Amap unit and its Brazilian partners shows that the ecosystem is able to maintain itself at a regional scale by rapid and effective re-establishment on newly formed mud deposits protected from swell.
Avicennia germinans, the dominant shoreline mangrove species, is able to colonise new sediment deposits rapidly thanks to its early maturity, floating propagules (seeds that germinate immediately) that are viable for about 100 days, very rapid rooting (5 days) and strong annual growth (up to 2.25 m).

Colonisation is amplified considerably when sediment inflow and tide patterns combine to turn bare mud into a gigantic propagule collector with an area of several hundred hectares. However, these adaptations that are the result of natural selection are sometimes not enough for reconstitution after rapid destruction.

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Mangrove colonisation zone in French Guiana.
Adapted to erosion phenomena, the mangrove species *Avicennia germinans* can colonise a recently formed mud bank very rapidly.

Box 24

Carbon sequestration: reforestation limits for Senegalese mangrove swamps

From 2006 to 2013, an area of 14,000 hectares of mangroves in Senegal was replanted. However, the international visibility of this success should not hide the ecological and social limits of this reforestation. Work by the Paloc unit and its Senegalese partners shows why the multi-functional aspect of mangroves cannot be reduced to carbon sequestration.

Protection policies for mangroves have been run by Senegal for several decades in order to limit the rapid degradation of these ecosystems. Mangrove reforestation campaigns have displayed renewed vigour over the last 10 years thanks to recognition of its exceptional carbon sequestration capacity.

Interested in carbon credits, private enterprise has financed REDD+ projects implemented by NGOs such as IUCN and Océanium. Danone has invested €4 million in mangrove plantations since 2009.

These operations resulted in the replanting of 14,000 ha of mangroves from 2006 to 2013. However, the work carried out by Paloc unit researchers and their Senegalese partners tempers the success of this reforestation.

The scientists focus first of all on the ecological limits of the REDD+ approach that targets first and foremost the volume of carbon credit produced. Only one mangrove species has been planted whereas six grow in Senegalese mangrove swamps. The priority awarded to the quantity and visibility of the plantations is at the expense of agro-ecological criteria.
The researchers have observed in the field that many plants finally do not grow, considerably affecting success in terms of the carbon balance. Quantification of the carbon credit promised is late as the result will depend on the growth of the forest. And the actual calculation of carbon sequestration capacity is still being discussed.

These reforestation operations also raise questions of spatial inequality while the projects do not address the question of the status of the replanted zones, with risks of not including the local users of these areas.
Finally, the scientists insist on the scientific and ethical issues in restoration taking into account the complexity of socio-ecosystems of mangrove—whose multiple functions cannot be reduced to carbon sequestration alone.

Artisanal oyster fishing in a mangrove swamp in Siné Saloum, Senegal.

Protection against erosion

In the face of long-term changes, it is important to understand how mangroves have managed to adapt to environmental constraints up to now. Work in French Guiana shows the exceptional regeneration of mangroves in the face of strong environmental constraints and their contribution to the stabilisation of sediments (Box 23).

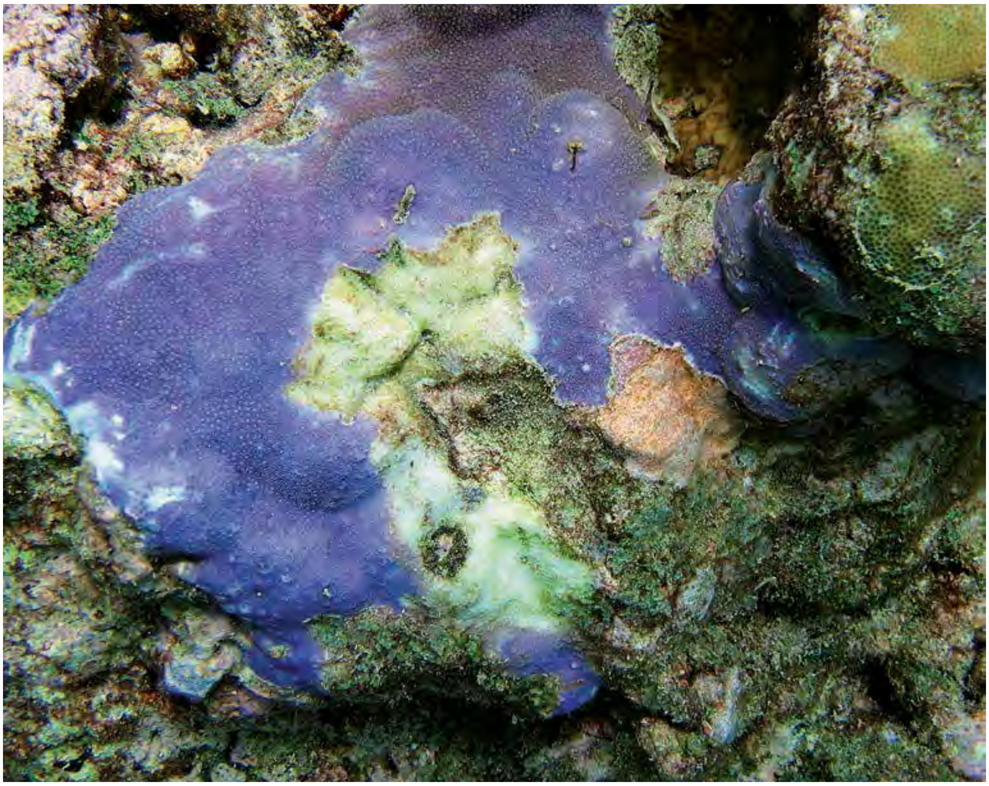
This distinctive ecosystem forms a buffer zone between sea and land and may play a role in the protection of muddy, particularly unstable coasts against erosion. For example, IRD scientists and their partners have shown how a decrease in mangrove swamp would cause large-scale erosion of 370 km of coast in French Guiana. In this South American country, coastal marsh zones have been developed as 'polders' for the development of aquaculture and rice growing. Embankments have been constructed, reducing the 1 km of mangrove fringe to a strip only a few tens of metres wide. But the embankments would not withstand the force of waves and an increase in sea level if the mangroves were to disappear. Furthermore, embankments and rockfill prevent the sedimentation of mud from the Amazon on which mangrove areas are regenerated.

Mangroves also play an important role in the carbon cycle because of their strong capacity for turning atmospheric carbon dioxide into organic matter. Together with primary tropical forest, mangrove forms part of the terrestrial ecosystems that produce most biomass. The quantities of carbon stored in these forests is still a subject for debate among scientists but their sequestration potential means that they are already the subject of protection and reforestation policies within the framework of fighting climate change (Box 24).

The biodiversity of coral barrier reefs threatened

Coral reefs form another tropical coastal ecosystem that is threatened today. Several long-term quantitative studies confirm the degradation or loss of coral communities in numerous reefs. Here again, the causes are to be sought in human activities. Excessive fishing, biological invasions, pollution from the shore, development operations and mechanical damage to reefs are some of the numerous anthropic pressures involved. In some regions and especially in the Caribbean the occurrence of diseases affecting coral in recent years has been attributed to urban development.

Climate change thus has effects in ecosystems that have often been seriously damaged by humans in the past. Coral reefs are sensitive to ocean warming and



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White patch syndrome on a *Porites* colony in Mayotte.
The first report on the health of corals in the south-west Indian Ocean led to the description of the new pathology in 2013.

acidification and have now been made fragile by heat stress and bleaching phenomena (see page 92). Waves caused by cyclones and tropical storms also destroy fragile coral communities. It can take 10 to 20 years for a damaged reef to be reconstituted. However, if the frequency and intensity of climate events and anthropic stress increase, the return to normal will be much slower. In addition, acidification reduces available calcium carbonate in seawater and may also slow the calcification of coral polyps and hence the growth of reefs. However, there are still too many gaps in knowledge of the physiology of these organisms for us to know whether corals are capable of adapting to rapid changes of the environment.

Towards new underwater landscapes

Scientists are addressing evaluation of how the increase in climatic and anthropic pressures will affect coral reefs in the future. Much work carried out in the 2000s on the future of coral reefs was very alarmist. But recent research shows that although numerous coral species have clearly been declining for more than 30 years, others are holding their ground or even becoming more plentiful. A vast international study in which IRD participates has observed the evolution of 7 coral reefs around the world (In the Caribbean and the Indo-Pacific Ocean) for some 15 years. Scientists have shown the spread of certain genera such as *Porites* stony corals that withstand rises in temperature. They also put these recent changes into perspective with regard to past events recorded in fossil reefs; it was seen that the abundance and structure of coral populations had already varied strongly in past millennia. These new data made it possible to revise the projections for the coming decades. As water temperatures continue to rise, a subset of 'winning' species will succeed—those with the greatest tolerance to heat, the best population growth rates or the greatest longevity.

A quarter of known marine fish species

The ecological consequences of the ongoing changes go beyond corals alone as these ecosystems house a quarter of known marine fishes. In collaboration with international teams, IRD studied the impact of coral bleaching on the fish communities housed in this coral. For this, scientists compared coral and fish populations at some 60 coral sites in 7 countries (the Maldives, the Chagos Archipelago, Kenya, the Seychelles, Tanzania and the islands Mauritius and Réunion) before and after massive coral bleaching following an El Niño event in 1998. This scientific work shows that the decline of coral communities is followed by reduction in diversity, a reduction of size and loss of structure in fish populations.

The changes in coral reefs are also preoccupying for food security in numerous southern countries as they provide the protein requirements of neighbouring populations.

© IRD/J.-M. Boré

Shoal of fish in *Acropora branchus* coral (New Caledonia).
Coral reefs provide shelter and are a source of food for numerous invertebrate and fish species.
The degradation of corals causes a decrease in reef biodiversity by a knock-on effect.

Chapter 10

Semi-arid zones: the Sahel is sensitive to variations in rainfall

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Village on the River Niger at Gao in eastern Mali. The Sahel was hit by drought during the second half of the 20th century but precipitation has resumed since the 1990s.

The Sahel-Sudanian strip that runs from Senegal to Sudan is considered by IPCC experts as being one of the parts of the world that is most vulnerable to climate change. The temperature of this semi-arid region of Africa has risen for 60 years and the rainfall regime has changed. The climate forecast is a 3 to 4°C rise by the end of the 21st century, with dramatic consequences for food security, water supply and human health. Paradoxically, the IPCC Fifth Assessment Report indicates the absence of proof of the impacts of climate change that already affects the region in key sectors such as agriculture. This does not mean that climate change has not had any effects yet but that it is difficult to show them as clearly as in other regions of the world. The uncertainty is related to the very strong natural variability of precipitation in the region and also to the dominant role of human activities in the change of Sahelian environments. Rapid population growth in this part of Africa since the 1950s has, in particular, made farming more intense, changing environments and landscapes on a lasting basis.

The lack of information on proven impacts of climate change also results from the shortage of data and studies in the region.

The Sahel is a semi-arid zone among others. It is the focus of this chapter because development issues for the population are important. The interdisciplinary research conducted in the region by IRD allows a close view of the interactions between climate, environments and humans that is essential for understanding the effects of climate change at the regional scale.

Change in the rainfall regime in the Sahel

The Sahel has grown steadily warmer since the 1950s, with an average increase of about 1.5°C. However, the increase in temperature is not homogeneous over the year or throughout the region. The warming observed is particularly marked and regular in the spring, a time of year when temperatures are already very high. It is also distinctly greater at night than during the day (more than 2°C). The temperature can rise by more than 2.5°C when the monsoon arrives. The increase is linked in particular to that of the humidity that is a feature of the start of the rainy season. The temperature also increases more strongly at latitudes where the temperatures are already higher, as in northern Mali.

Although warming can be measured, it is more difficult to describe the evolution of precipitation. The Sahel suffered severe droughts in the 1970s and 1980s. This break in precipitation is one of the strongest climatic signals ever recorded since the start of meteorological measurements. However, precipitation has returned since the 1990s.

Dunes in the Ténéré in Niger.
The temperature in the Sahel has risen by 1.5°C since 1950.

Arrival of rain in Niger.
Storms in the Sahel have been more severe for about 20 years.

'Intensification' of the rainfall regime

Nevertheless, the increase in rainfall is not a return to normal, to the 1960s reference period. First, it concerns only part of the continental Sahel (Mali, Burkina Faso, Niger). Rainfall is still short in the west of the continent and in particular in Senegal. Second, the increase in precipitation for the last 20 years or so results more from the intensity of storms than their frequency. There are fewer storms today than there were before the drought. But they are more severe and consequently the volumes of water recorded are closer to those of the 1960s. Precipitation has also become more uncertain and there are intermediate drought years. Given these alternating extreme events, scientists talk in terms of the 'intensification' of the rainfall regime.

Even though there is strong uncertainty concerning the evolution of rainfall in the Sahel under the effect of the warming of the climate, an increasingly probable scenario seems to be taking shape in the scientific literature. It depicts a western Sahel (Senegal, western Mali) that is dry above all at the beginning of the monsoon season and a central and eastern Sahel with rain especially at the end of the winter season.

Box 25

Increasingly numerous extreme precipitation events since 1990

One of the features of climate change is the increase in the number of extreme events but very few studies address the subject. Work by the LTHE unit in the Sahel shows that rainfall extremes have become more marked after 1990, confirming the marked change in the rainfall regime at the turn of the century.

There have been very few studies of rainfall extremes in the Sahel. The reasons are the shortage of data and also methodological difficulties in studying the most intense rainfall. Indeed, extreme events are rare by definition and particularly difficult to quantify and this, together with strong inter-annual and decennial variability of rainfall in the Sahel, makes it difficult to identify trends.

LTHE researchers overcame these difficulties by working in a set of 43 daily rainfall series available for 1950-2010. Statistical analysis based on extreme value analysis gave a regional view of the spatial organisation of extremes and made it possible to develop innovative methods for detecting trends. This was used to study the evolution of extreme precipitations linked to the decennial variability of the cumulated annual rainfall.

Figure 23 shows a distinct difference in the evolution of total annual precipitation figures (annual cumulated totals) and daily annual maximums in the central Sahel since 1950. Whereas annual totals are well below the average for the wet 1950-1970 periods, average annual maximums are greater than those for 1950 to 1970. The two curves differ markedly from the end of the 1990s. This confirms that a marked change in the rainfall regime took place at the turn of the century as rainfall extremes became more marked.

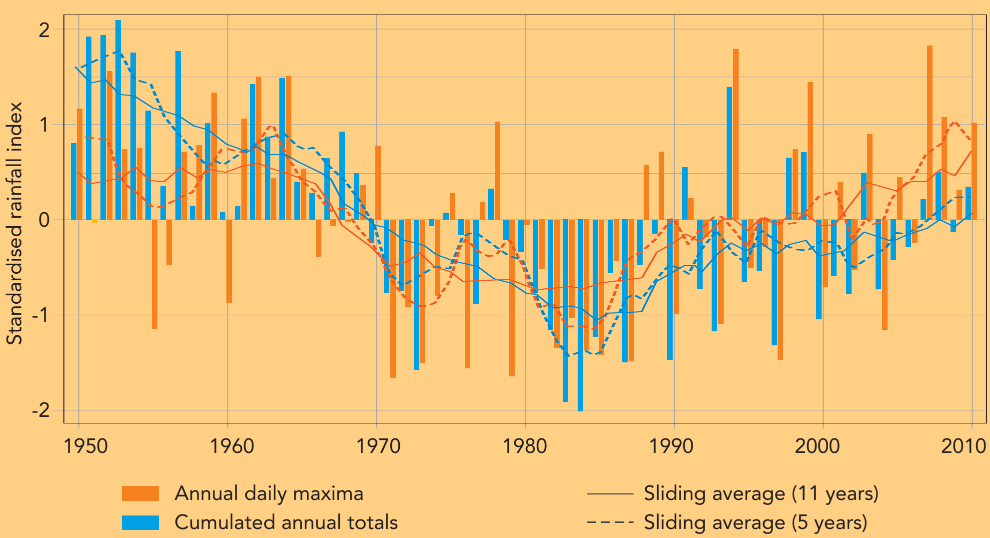

Figure 23.
Comparative movement of annual rainfall totals and maximums in the central Sahel (window: 9.5° N-15.5° N 5° O-7° E) from 1950 to 2010.
Source: after PANTHOU *et al.*, 2014.

Climate change or natural climate variability?

Describing changes in the Sahelian climate is nevertheless not enough to pinpoint the cause. It is very difficult for scientists to understand the mechanisms of warming and of the change in rainfall regime—linked to both global climate circulation and local effects. And at global circulation level, it is necessary to be able to distinguish between the effects of the increase of greenhouse gases and the natural variability of the climate. IRD researchers and their partners have focused on the impact of climate change with anthropic causes on the evolution of the climate in the Sahel. Their research shows that the warming observed recently is imprinted with anthropic forcing to a considerable degree. In contrast, their results suggest that the latter played a minor role in the rainfall transition of the 1980s and 1990s that was driven mainly by the internal variability of the climate system (in particular by the Atlantic Multidecadal Oscillation) (see Part 1, p. 66).

The 'Sahelian paradox': less rain, more water

The hydrological research conducted in the Sahel by IRD clearly shows the importance of long-term observation for anticipating the responses of environments. The great drought of the 1970s first caused a strong decrease in the flows of the major watercourses in West Africa (the Niger, the Senegal, the Gambia, the Volta and the Chari). However, the Sahelian watercourses were seen to behave in a special way: when the decrease in precipitation in the drainage basins was more marked than in the basins further south (more rainy), the flows increased paradoxically and there were record floods. In 2010, the first flood caused by monsoon rains reached twice the highest level previously observed since 1929. The record was beaten again in 2012.

Exceptional Niger River flood in Niamey in August 2012.
The serious flooding caused by heavy rainfall caused 60 deaths and 300,000 victims in Niger.

The phenomenon is sometimes referred to as 'the Sahelian paradox'. But it is only an apparent paradox. The numerous hydrological observations in the Sahel and especially those of the AMMA-CATCH observation service show that runoff has increased in recent decades. This causes water to concentrate more rapidly, changing the regime and flows of watercourses.

Tree roots exposed by floods of the river Bani, a tributary of the Niger (Mali).

© IRD/M.-N. Favier

Increased runoff caused by human activities in Niger…

Work by IRD in Niger shows that the decrease in the water retention capacity of the soil is a direct consequence of human activities. Population increase (from 3.2 million in 1960 to 15.5 million in 2010 in Niger according to the World Bank) was accompanied by increased pressure on the environment to increase agricultural production. The clearing of bush and sparse forest caused a rapid increase in bare surfaces that caused the intensification of runoff. The shortening of fallows also caused the impoverishment of soils, often resulting in crusts, the main factor in runoff.

... but not in Mali

However, the Sahelian paradox is not seen only in the cultivated part. In the northern Sahel, a pastoral zone where rainfall is too small to allow agriculture, ponds that used to be temporary now contain water all the year round and new ponds are appearing. The mechanisms involved have not yet been fully elucidated but the explanation might also lie in an increase of the flow capacity of degraded soils. Indeed, even without land clearance, a significant proportion of the landscape has been stripped and eroded after periods of severe drought. Observations in Mali show that once the soil has been stripped off the vegetation cannot recover when the rains return.

Box 26

Changes in fishing in the Inner Niger Delta

The work of the PRODIG research unit and its Malian partners has shown how the decreased flow of the Niger has reduced fisheries resources and finally led to the reorganisation of the regional fish market.

Unloading fish at Mopti in the central Niger delta (Mali).

© IRD/C. Lévêque

Fish catches in the Inner Niger Delta in Mali decreased from 100,000 tonnes in the 1960s to about 70,000 tonnes in recent years. This decrease in fishery resources is the result of a variation of the rainfall regime in the region that has lastingly changed the flow of the river and flood areas.
But humans are also involved in this degradation as reservoir dams reduce the flow of the river downstream of the dams and reduce flood areas.

The inner delta provides 80% of fish production in Mali.
During the last 40 years, domestic fish supply decreased while demand increased as the population tripled.
Meeting demand has led to the complete reorganisation of trade flows with imports of some 15,000 t per year of frozen and dried fish, mainly from Senegal, Mauritania, Côte d'Ivoire and Guinea.
The decrease of resources in the inner delta has also resulted in Niger losing the dominant position in regional exports of fish that it had in the 1970s, when exports went in particular to Côte d'Ivoire and Ghana.
The substantial increase in catches of small pelagic species in neighbouring coastal countries and the adaptation of Sahelian traders made it possible to adjust the market quickly.
However, this example shows how the deterioration of hydroclimatic conditions in the Sahel has hit the organisation of the regional fish market.

A serious decrease in flows further south

No hydrological 'paradox' is observed further south in the Sudanian savannah zones where the decrease in rainfall is accompanied by a strong decrease in flows. However, this region is also one where much deforestation has been carried out to make agricultural zones. These contrasting responses in Sahelian and Sudanian zones with similar forcings (drought and a change in land use) show the complexity of the mechanisms involved. The different factors have not yet been totally identified but the path taken by water (mainly surface flow in the Sahel and subsurface flow further south), soil type and structure and plant cover play a major role.

The increase in runoff in the Sahel is not the sole explanation of all the severe floods of the last five years. The latter also coincided with a return to wetter conditions and the more intense precipitation observed in the region for the past 15 years. The floods have had serious consequences for the population. In 2012, an exceptional River Niger flood seriously affected the Niamey region. The authorities counted more than 340,000 persons affected, 44 deaths and considerable material damage.

Desertification or re-greening of the Sahel?

The Sahel is a semi-arid region and particularly sensitive to the variability of precipitations. The periods of severe drought in the 1970s and 1980s had devastating effects on ecosystems, the population and the resources of the latter. The massive change in land use, linked in particular with rapid population growth, has also been a driving force in this land degradation.

Village and irrigated gardens, Akodédé, Niger.

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The theory of the desertification of the Sahel thus became topical again, together with that predicting the rapid spread of the Sahara to the rest of the continent. Desertification is the degradation of land in dry zones as a result of various factors including climate variations and human activities. The degradation takes the form of the deterioration of plant cover, soils and water resources and ends, on the human scale of time, with destruction of the biological potential of soils and their capacity to support the population of the area concerned.

The reality of desertification has long been a subject for debate and it is difficult to settle the question for lack of global, continuous data. The arrival of satellite remote sensing in the 1980s has solved this problem by providing daily images of plant cover. Analysis of the first Normalised Difference Vegetation Indices (NDVI) in the early 1990s revealed a distinct increase in vegetation since 1980. This re-greening thus contradicts the idea of the desertification of the Sahel.

General re-greening for 30 years

More recent work even makes it possible to say that there has been a general re-greening of the whole of the Sahel region over the last 30 years. It is explained overall by the return of rainfall, just as the advance of the Sahara in the 1970s was caused by a decrease. The explanation of these phenomena lies to a considerable extent in the inter-annual variability of precipitations.

Nevertheless, plant cover is continuing to worsen in some regions, such as in the Fakara in Nigeria and the central regions of Sudan. In addition, the satellite mesh (9 km) is too large for the perception of the coexistence of degradation and re-greening at a smaller scale.

Today, although there is no doubt about re-greening, scientists are cautious about the future evolution of vegetation, which will be linked with precipitation in particular.

Rainfed agriculture faced with climate change

Most farming in the Sahel is rainfed (93% of the cultivated land) and hence extremely dependent on the rainfall regime. The variability of precipitations affects food production, as is shown by the direct link between droughts and famines in the region (1974, 1984-1985, 1992 and 2002). In this context, researchers are trying to better understand and anticipate the consequences of climatic fluctuations for agriculture. For this, they use complex models that combine climatic, agronomic and economic data. In the IPCC Fifth

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Market garden crops (cabbage and lettuce) in Burkina Faso. Rainfed farming in the Sahel is likely to be strongly affected by climate change.

Assessment Report, the results of crop modelling show losses in world agricultural yields averaging 2% per decade in the 21st century. Particularly severe impacts are expected in Africa where recent research (Box 27) shows that yields could fall by 20% in the western Sahel.

However, forecasting is still difficult because of the strong uncertainties in both regional climate change projections and the response of plant cover to environmental changes (rainfall, temperature, CO_2 concentration in the atmosphere). In addition, the gradual adaptation of farming systems to environmental changes should not be underestimated. Indeed, the climate/plant relationship is not sufficient for forecasting crops. Studies on millet, the main crop in the Sahel, show how varieties have gradually adapted to drought. The biodiversity of millet is well preserved and has allowed natural and human selection: the earliest plants have better resistance to drought and grow better and so are thus selected by farmers for the following season (see Part 3, p. 211).

Box 27

A decrease in agricultural yields in West Africa as a result of warming

West Africa is very vulnerable to climatic events. Better understanding of the impact of climate change on agricultural yields is therefore essential for designing adaptation strategies. IRD climatologists and their international partners forecast a 16 to 20% decrease in sorghum yields in certain regions in West Africa.

What are the impacts of climate change on sorghum yields in West Africa? To find a reply to the question, IRD climatologists in collaboration with American, Malian and Australian teams used agronomic models simulating agricultural yields according to climatic conditions and then compared them with future climate scenarios. In the light of the uncertainties of these different models, the simulations produced by 9 IPCC models and 2 crop models were used in the study.

Future climate scenarios

Climate projections based on theIPCC RCP 8.5 emission scenario forecast average warming of +2.8°C from 2031 to 2060 in relation to a reference period running from 1961 to 1990.

The 9 models used also forecast significant change in precipitation in West Africa, with less rainfall in the western part of the Sahel (Senegal, south-west Mali) and more rain in the central Sahel (Burkina Faso, south-west Niger). The rainfall deficit forecast is concentrated at the beginning of the monsoon in the western part of the Sahel whereas increases in precipitation occur at the end of the monsoon season, suggesting a change in the seasonality of the monsoon.

A greater fall in yields in the western Sahel

In response to this climate change and without taking into account the response of crops to a higher CO_2 level, the researchers' projections show a decrease in yields of about 16 to 20% in the western part of the Sahel. The impact would be more moderate in the eastern part with a decrease in yields of between 5 and 13%. These yield fall projections are consistent from one model to the other and result from a rise in temperature that shortens the length of crop cycles and increases water stress as evaporation increases. This negative effect of temperature is combined with a decrease in rainfall in the western Sahel.

A field of sorghum in Niger.

The vulnerability of rural populations

The Sahel has become an emblematic region as regards the vulnerability of rural populations in the South since the great droughts of the 1970s and 1980s. Their direct dependence on natural resources and rainfed agriculture puts them in the front line with regard to the climatic risks identified in the region. The IPCC highlights in particular the impacts of climate change on water resources, with consequence for food production and access to potable water. However, it is impossible to forecast the impact on the population. Numerous studies have shown how it has always succeeded in adapting to variations of the climate and resources (Box 28 and Part 3, p. 233). Will this adaptation capacity be sufficient to withstand coming climate change? This also depends on the intensity and rapidity of the latter.

Annual return of the river Komadougou Yobé at the frontier between Niger and Nigeria. This is an important moment for the local population (fishing, irrigation, livestock) and for groundwater recharge.

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Box 28

Lake Chad: the population is adapting to the falling water level

Lake Chad used to be one of the largest inland water bodies in the world but has lost nine tenths of its area since the 1960s. Although the level of the lake has always fluctuated, its steady decrease in area has become a symbol of on-going climate change. The phenomenon has caused serious changes in the way of life of the 20 million people around it who live mainly from fishing, cattle farming and crop farming.

Located in the heart of the Sahelian strip, Lake Chad is an essential water resource for the fishermen, livestock farmers and crop farmers in the four countries around it: Niger, Nigeria, Chad and Cameroon.
The lake has changed considerably in recent decades.
With an area of 20,000 sq. km, it was like an inland sea 50 years ago. The series of droughts in the 1970s and 1980s resulted in rapid drying that reduced its area to about 2,000 sq. km.

The variability of the level and surface area of Lake Chad has been a well-known phenomenon since the 1960s, mainly thanks to work by IRD hydrologists.
The lake is very shallow, with an average depth of 2 metres, and functions as an evaporator with very large losses of water.
Thanks to pluriactivity, rural communities have long developed a system that is well adapted to the annual, inter-annual and even decennial fluctuations in the level of the lake. High water periods were good for fishing and the regeneration of land while low water periods were used for polder crops. The fall in the level of the lake left numerous shallows between dunes that have been developed as cereal crop polders over the years.

A Franco-Nigerian team including the HydroSciences unit studied the changes in ways of life around Lake Chad in recent decades. The results show how Sahelian societies have adapted to a major environmental change through the evolution of farming systems in the Bosso region of Niger.

As the lake receded, the population used the accessible fertile, humid land to plant maize, cowpea, rice and sorghum that grow without irrigation or fertiliser, gradually abandoning rainfed millet on the banks that had become a particularly uncertain crop.

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Port of Doro Léléwa in Niger, near Lake Chad.

Chapter 11

Highland zones: the rapid change of Andean environments

View of Chimborazo from the slopes of the Altar volcano in Ecuador.

Tropical highland areas are among the regions where the impact of climate change is most marked. The retreat of tropical glaciers is spectacular, especially in the Andes, the site of 99% of tropical glaciers. The area of these glaciers has decreased by 30 to 50% in about 30 years. Melting ice has had many consequences for the hydrology of drainage basins and hence on water supply and the dynamics of highland environments. Future changes promise to be just as important as climate projections forecast a very substantial warming of high mountain tropical ecosystems—this could reach +3°C by the end of the century.

IRD has carried out research on Andean glaciers and mountain environments for about 20 years. Glaciologists, climatologists, hydrologists, ecologists, agronomists and modellers are thus developing a multi-disciplinary approach aimed at better understanding of the mechanisms of the melting of ice, its role in the hydrology of drainage basins, the sensitivity of biodiversity to these changes and other features.

The Andes are also an excellent area for observing fine trends such as the evolution of biodiversity in relation to climate change as mountain ecosystems are still comparatively well preserved in comparison with other environments (coastal zones for example) where numerous anthropic pressures make it more difficult to describe climatic factors.

Retreat of glaciers and water resources

Tropical glaciers are very sensitive to global warming. Since the 1970s, precipitation has changed little but the air temperature in the tropical Andes has increased by 0.7 °C. Although the temperature is not directly responsible for melting at this altitude, it affects the nature of precipitations—solid or liquid—and therefore the snow cover. The latter helps to reflect the greater part of the solar energy received. Without snow, the melting of glaciers increases considerably. Glaciers lacking snow cover have tended to become more frequent in recent decades.

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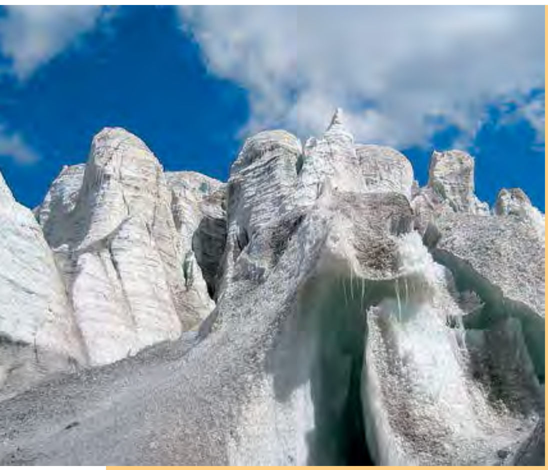

The Zongo glacier at the summit of the Huayna Potosi (Bolivia) has retreated considerably in recent decades.

Box 29

The annual variation of the mass of a glacier is a good climate indicator

Very few climatic data are measured directly by meteorological stations in high mountain regions. IRD is therefore working on strengthening climate observation services in the various Andean countries (see Part 1, p. 43).

Among important observations, the annual variation of the mass of a glacier is a good climate indicator as it represents a balance of inflow and outflow over the year. Snowfalls form the main incoming mass and losses result above all from the melting of ice or surface snow. Measurement of the annual mass balance is thus a direct record of the meteorological conditions that govern the processes of accumulation and ablation of snow and ice at the surface.

LTHE researchers successfully completed for the first time measurement operations on turbulent flow at the Zongo glacier in Bolivia. This research has led to better description of the special features of tropical glaciers. In the tropics, ablation takes place throughout the year whereas accumulation is during the rainy season. The climate change observed for several decades is tending to raise the rain/snow limit, causing more ablation and less accumulation. The monitoring of mass balances gives better understanding of the relation between climate and glaciers. They also provide information for comparing melting and accumulation processes in varied regions (polar, temperate and tropical latitudes), showing marked differences in relation to the climatic context.

The research carried out by IRD and its partners has shown an increase in the melting of Andean glaciers in the last 40 years. The areas of the glaciers in Colombia, Ecuador, Peru and Bolivia have decreased by 30 to 50% since the end of the 1970s. Small glaciers (less than 1 square kilometre) at altitudes of less than 5,400 m are those most affected insofar as their accumulation zone (where snow gathers and then turns to ice) is small. If the increases in temperature forecast by climate model by the end of the century are confirmed, most of the glaciers—large and small—in this part of the Andes may disappear. This happened to the Chacaltaya glacier above the city of La Paz in Bolivia in 2010.

Glaciers, water reserves for dry periods

The role of glaciers in the hydrological functioning of mountain drainage basins varies considerably from one region of the world to another. It is often minimal in temperate zones like the Alps where winter snow cover and precipitation are substantial. However, in tropical regions where the seasonality of precipitation is marked by a dry season lasting for several months when no snow layer can form, glaciers play a significant role in the flow of the rivers below.

The Andean glaciers are thus important regulators of seasonal water cycles. They serve as reservoirs of frozen water and flow during dry periods, feeding watercourses downstream. Glaciers can contribute as much as 25 to 30% of the hydrological regime in certain drainage basins with some 20% glacierisation. In arid regions as in Bolivia and Peru, glaciers can make a very significant contribution to irrigation, hydroelectricity and the water supply for local populations. Thus 15% of the water used in La Paz comes from glaciers and the figure rises to 30% during the dry season.

Better understanding of the impact of glacier retreat on the availability of water

Climate change scenarios for the coming decades predict an increased rise in temperatures in high mountain tropical ecosystems. If the trend continues, the first features will be faster melting and increased runoff in high altitude sub-basins, increasing the quantity of water available downstream. But subsequently, when the volume of the glacial reservoir has decreased, there will be less meltwater than there is today. Droughts could become more serious than they are now and less water will be available for various uses such as agriculture, potable water consumption or hydroelectricity.

The Zongo glacier on Huayna Potosi mountain (Bolivia).
The increased rate of ice melt increases the quantity of water available downstream.
But the trend will be reversed when glacial reserves have been depleted.

Researchers are evaluating the state of water resources according to the degree of deglacierisation to better understand the impact of the retreat of glaciers on hydrology. Work has been focused in particular on the river Santo in Peru, an emblematic river as it is supplied to as much as 50% by glaciers, depending on the season.

© IRD/B. Francou

Box 30

Calculating the contribution of glaciers to water resources downstream

Glacial stream opposite Cotopaxi in Ecuador.
Direct measurement of the flows makes it possible to calculate variations in flows from glaciers.

© IRD/O. Dangles

Glaciers store water at the scale of several decades and thus form reservoirs that directly affect flows downstream.
Understanding and quantifying meltwater supply in the context of climate change and glacial retreat are therefore of prime importance for monitoring the evolution of present and future water resources.
However, studying the role of glaciers in the hydrology of a drainage basin is complex.
Clear distinction must be made between the proportion of water stored annually as snow and then flowing as liquid water when it melts and the proportion truly originating from glacier retreat and the variation of this stock.

The study of these phenomena requires careful monthly measurement of precipitations and the rate of ablation/accumulation of snow on the glacier.
The latter glaciological measurements consist of recording levels on indicators (posts driven into the ice) and digging holes in the accumulation zone to calculate the mass balance.
The measurements of mass balance combined with measurements of precipitation show the volume of water resulting from snow and ice melt at the glacier and flowing downstream.

Combining measurement methods for better evaluation

Three other methods are also used to quantify the contribution of glaciers: direct flow measurements in rivers, measurements using hydrochemical tracers and hydrological balances performed using modelling.
Hydrochemical measurements are based on the analysis of stable isotopes in water and major ions as the different sources of flow have specific chemical signatures and it is therefore possible to quantify glacial flows.
Hydrological modelling consist of simulating the different types of flow by using geomorphological data that are characteristic of the drainage basin and meteorological forcing data (temperature, precipitation, radiation, wind, etc.).

The ideal approach consists of combining several of these methods to evaluate the agreement of the figures obtained. Three drainage basins are being examined thoroughly within the framework of the international mixed laboratory Great Ice: the Zongo basin in Bolivia, the Antisana mountain glacier in Ecuador and the river Santo that is fed partly by the glaciers of the Cordillera Blanca in Peru. Glacier flows vary in time and space. For example, more glacier water flows into the river Santo during the dry season (more than 50% of flows) than during the rainy season (about 30%).

High mountain biodiversity faced with climate change

High mountain regions in the tropics are isolated islets where the migration of new species is limited and speciation enhanced. Low temperatures, low atmospheric pressure, intense solar radiation, irregular rainfall, dry winds, frost, etc. are all extreme conditions that encourage singular adaptations in the varieties present. Glacier streams are also a difficult habitat because of their low mineral content and daily high water generating strong disturbances. The tropical Andes house a high degree of endemism with species that are unique in the world but because of this there is an inexorable risk of extinction if the ice continues to retreat.

The first cases of extinction

Andean aquatic species are among the first to suffer population extinction caused by climate change. As mountain streams have been changed considerably by the acceleration of melting for the last 40 years, scientists focused on the fundamental role of meltwater for aquatic life. They observed that glacier retreat has endangered a proportion of the invertebrates that live in rivers (Box 31). The ecological role of most of the endangered species is still not known and the consequences for higher animals—fish, amphibians, birds and mammals—remain difficult to forecast.

Migration of species

A 3°C rise in average temperature in the tropical Andes could cause plant species to migrate upwards by nearly 600 m. Such a change in mountain ecosystems would result in a significant reduction of the habitat available for numerous species. Indeed, mountain species have limited space and are 'stuck' between high and low. At the high end, factors associated with altitude such as strong UV radiation or lack of oxygen limit the survival of certain species. At the lower end, competition with other, flexible species—that is to say that can prosper in a large variety of environmental conditions—that colonise more favourable thermal niches encourages the mountain species to continue to migrate upwards. They thus suffer stronger reduction of their distribution area than those observed in other places in the world. Isolated in limited areas, the populations of mountain species are particularly exposed to extinction processes.

Sentinel species

Climatic factors other than glacial retreat also affect biodiversity. The rise in temperature and the increase in UV radiation are thought to be partially responsible for the

Box 31

The retreat of glaciers is a threat to aquatic biodiversity

The melting of Ecuadorean glaciers has caused the extinction of several aquatic species. If the glaciers were to melt entirely, 10 of 40% of the regional richness in species would risk disappearing.

IRD ecologists and their European and Ecuadorean partners have studied the biodiversity of streams fed by meltwater in the Andean *páramos*. These very special herbaceous ecosystems are characteristic of Andean peaks at over 3,500 m between the treeline and permanent snow. A fair number of the species—mainly insects—that inhabit the watercourses in these extreme environments are endemic.

The scientists collected samples at some 50 different places in the *páramos*. They counted the populations of macro-invertebrates—mainly larvae of species that belong to the orders Ephemera, Trichoptera or Diptera.

In over a year of regular sampling, the scientists identified more than 150 invertebrate species in the *páramo* of the volcano Antisana alone.

From 10 to 40% extinction

Samplings performed at different distances from the glaciers showed that local species richness in the Andes increases towards downstream. It also appears that the populations of the various streams at the same altitude are markedly heterogeneous. The communities observed about a hundred metres apart in two streams of similar appearance can be very different depending on the glacier drained. Andean glaciers have varied dynamics and melt at different rates according to their size and exposure to the sun for example.

This sampling, combined with monitoring data concerning the aquatic communities, showed that several species start to disappear as soon as the glacial cover decreases to less than half of the drainage basin area. And if the glaciers melted entirely, 11 to 38% of regional biodiversity would risk disappearing, depending on the zone in question.

Analysis of glacial streams in the Paramo region, Ecuador.

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Box 32

Modelling the impact of climate change in a key ecosystem in the tropical high Andes

The international project BIO-THAW, with European (including IRD) and Andean partners is aimed at understanding and modelling the impact of climate change on a key high Andean ecosystem, the *bofedales*. Biodiversity is exceptional in these high altitude (4,000 to 5,000 m) wetland ecosystems.

With organic soils several metres deep, they have exceptional water retention capacity and supply millions of people downstream, even during the dry period. Furthermore, plant productivity is comparatively high all the year round and millions of head of livestock are produced, especially llamas and alpacas.

The multidisciplinary approach in the BIO-THAW project uses recent glacial retreat as an indicator of climate change, with the underlying hypothesis that the decrease in water supply to the *bofedales* will damage their biodiversity and functioning. All the data collected (in glaciology, remote sensing, ecology, agronomy and sociology) will be compiled in a multi-agent model.

Climate change scenarios predict increased warming in high mountain tropical ecosystems in the coming decades. Characterisation of the sensitivity of these ecosystems to climate change and putting forward solutions for maintaining their optimal functioning form a scientific and societal priority.

Sampling water in a highland wetland (4,800 m). Cordillera Real, Bolivia.

© IRD/O. Dangles

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Harlequin frog (*Atelopus* nov. sp. ?) Sangay National Park (2,200 m), Ecuador.
A broad diversity of amphibians including numerous species that are endemic to subtropical forests is found on the eastern slopes of the Andes.

extinction of frogs of the genus *Atelopus*, amphibians that are very sensitive to changes in the environment. This previously abundant group of Andean frogs has now become much rarer and has even disappeared in some regions since the end of the 1980s. Although there seem to be many causes, scientists have demonstrated the contribution of exceptional climatic conditions and high UV levels. These frogs are a sentinel species and also early indicators of the decline of other species.

Climate change and microclimates

The Andean valleys have a mosaic of very heterogeneous landscapes set at intervals on mountains slopes in different microclimates. The study of these microclimates is particularly important today for understanding the response of living species to climate change. The behaviour and survival of organisms depend on the dominant environmental conditions at their scale. These local climatic conditions often differ from the regional climatic situation.

Box 33

Temperature differences that can double between local reality and regional extrapolations

The differences between local temperatures and information provided by the WorldClim database were measured in a study in the Ecuadorean Andes. The results show that microclimate conditions generate overestimates and underestimates of some 80% for the minimum and maximum temperatures predicted by the global models.

In order to evaluate the capacity of meteorological systems to provide information about biological processes, the EGCE unit and its South American partners addressed the difference between the temperature data provided by the WorldClim database (extrapolation for a 1 sq. km mesh) and actual measurements in agricultural landscapes in the Ecuadorean Andes.

The researchers first showed the heterogeneity of temperatures in the fields according to the relief and also according to the precise site of measurement (soil, crops or air). They then compared these data with the WorldClim database. The results show that microclimate conditions, and especially those caused by the structure of the vegetation, generate overestimates and underestimates of some 80% in the minimum and maximum temperatures predicted by the global models. The differences were most marked when temperature was measured at the level of crop foliage or in the soil since these habitats play the role of buffer reducing thermal contrasts.

The difference in the increase of crop pests using WorldClim and local measurements was then examined. The results show the limits of models that are based on too large a mesh for the prediction of the dynamics of insect populations in regions where there are very varied microclimates.

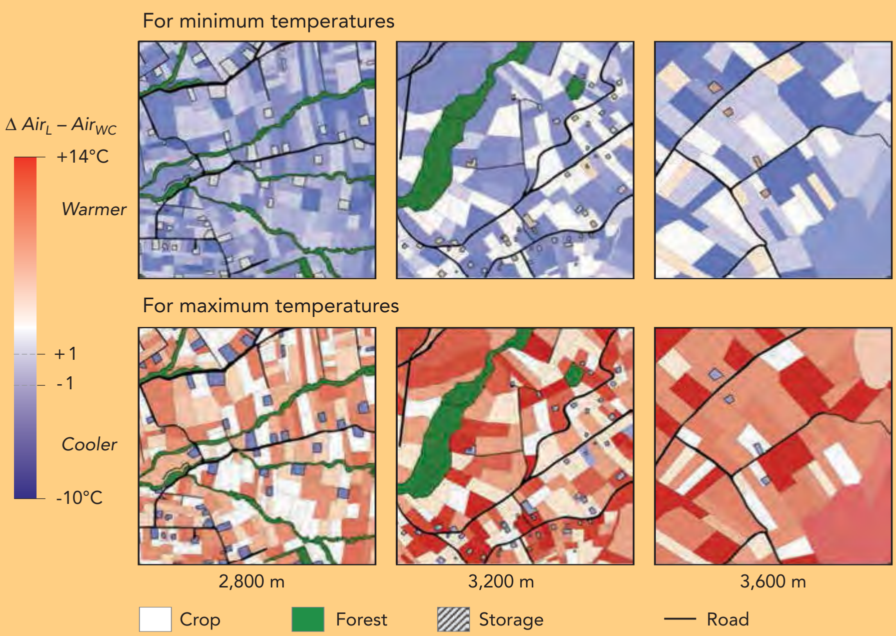


Figure 24.
Microclimates in farming areas in the Ecuadorean Andes.
Differences in minimum and maximum temperatures between local measurements and data supplied by WorldClim. The zones in which local temperatures are lower than those provided by WorldClim are in blue; zones in which local temperatures are higher than those provided by WorldClim are in red, and zones in which the zones are equivalent are in white.
Source: after FAYE *et al.*, 2014.

A question of scale

It is therefore urgent to know how regional warming affects microclimatic conditions in order to find out its effects on species. Scientists are addressing this question of scale—between the large mesh of climate models and the fine mesh of microclimates—by combining global and local approaches. By improving species distribution model at different scales, climate simulations will then allow better forecasting of biological changes. This information is also important for improving agricultural forecasting as crop growth is directly related to local temperatures.

The impacts of warming on crops in the altiplano

Farmers in the high plateaux in the Andes have always had to handle climate uncertainty. Night frosts are a source of major stress for crops at an altitude of nearly 4,000 m. It even freezes in the summer, especially in the plain where cold air accumulates. To handle this climate risk, over the centuries farmers have developed original agricultural techniques and dozens of local varieties with great genetic diversity.

Potatoes grown on terraces in the Peruvian Andes. This crop is found at 2,000 m to 4,500 m with a specific potato variety for each stage of altitude.

Climate risks have changed in the Andes in recent decades because of climate change and also following change in land use. This is illustrated by the increase in quinoa growing in the southern part of the Bolivian altiplano. The commercial success of this grain means that production increases from one year to the next: the cultivated area in the region tripled from 1972 to 2005. Farmers have cultivated land in the plains where mechanisation is easy but it is *a priori* more at risk from frost than the slopes. So far, climate warming has tended to favour the spread of cropping as it has reduced the risk of frost in the plain and extended the climate zones favourable for quinoa, which have gained several hundred metres in altitude.

However, the rapidity and complexity of the changes observed—that depend on both climate and land use—might affect soil and climate conditions more drastically and have negative effects on crops. Projections combining agricultural production and climate scenarios show that after a favourable but transitory effect of a decrease in frost risk, the probable increase in drought periods in the coming decades will reduce yields (Box 34).

A farmer attending a pest control training session at Chaopcca, Peru.

© IRD/O. Dangles

Ecological interactions and crop pests

The effects of climate change on ecological interactions will also influence agricultural yields. All species interact with other species, whether predator and prey, parasite and host or pollinator and the plants visited. The effects of climate change on the most sensitive species will have knock-on effects via these interactions and particularly along food chains. Some biologists consider that these impacts on interactions between species could weigh more on biodiversity than the direct impacts of climate.

In the Andes, scientists have examined in particular how changes in temperature affect the inter-species relations of crop pests and the effects on attacks of plants. The studies show that there is no linear effect between temperature and attacks by insects and other pests because of the complexity of their interactions

Box 34

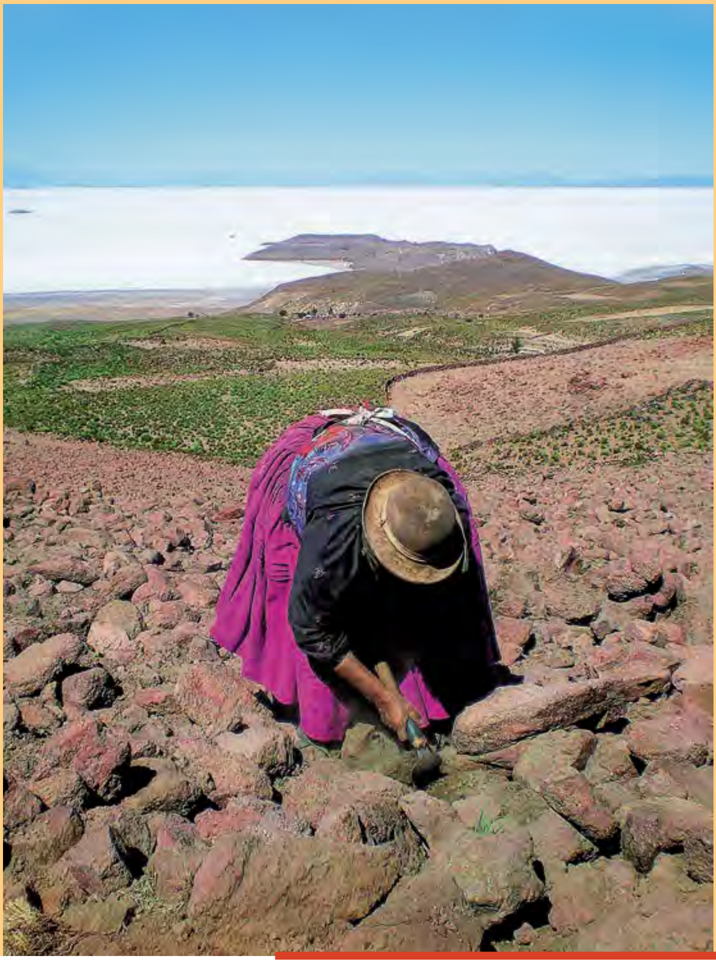
Assessment of quinoa production according to climate scenarios

Quinoa production on the arid altiplano in southern Bolivia depends to a considerable degree on soil moisture and frost risk.
IRD scientists and their Bolivian partners modelled the evolution of the crop in 2050 and 2100 using commonly accepted climate scenarios.

To gauge the local impact of climate change, the researchers made a distinction between two types of landscape while still working at the scale of an entire region—the area around the Salar de Uyuni (a salt flat).
This semi-desert zone with frost more than 250 days a year used to be shared between crop and livestock farming.
It is now the world's leading quinoa export region.

Simulations show that after the present production peak resulting from a decrease in risk of frost and the use of grazing land for crops, production could decrease markedly as a result of the increase in periods of drought, the saturation of agricultural land and loss of soil productivity.

Modelling uses climate and land use, two major components of global change and too often dissociated in research work. For local stakeholders, this forecasting exercise provides material for the debate about the sustainability of their development choices in a changing climatic and socioeconomic context.



Quinoa on the flank of Tunupa volcano in Bolivia.

and different thermal optimums from one species to another. Thus, according to the temperature conditions to which they are subjected, pests may either compete with each other or in contrast maintain positive interactions (facilitation for example). The researchers are therefore refining the forecasting models by incorporating the complexity of biological interactions.

Box 35

Kenya: another example of a highland region where warming will increase pest damage to crops

Maize is the main food resource in East Africa and is grown on nearly 80% of the cultivated area in the region, especially on the slopes of Mount Kilimanjaro and the Taita Hills. The small yields of some 1 to 3 tonnes per hectare are attributed to poor climate conditions and insects. Climate change will probably make these constraints more marked.

The studies carried out since 2010 by unit 72* in these mountainous parts of Kenya provide better understanding of the effect of temperature and altitude on the distribution of the two main pests found on maize (C*hilo partellus*, an exotic member of the Crambidae family and the indigenous moth B*usseola fusca*). The researchers also examined the distribution of natural enemies of the pests (larval parasitoids) to take into account the interactions between species. Their work confirms that temperature is a key factor in these interactions and partly explains the predominance of C. *partellus* at low altitudes and that of B. *fusca* at high altitudes.

The crambid migrates more quickly than its parasite

Using phenological models of the presence and activity of the pests and their parasitoids according to the climate, the researchers generated risk maps based on meteorological data from local weather stations and IPCC climate scenarios.

Their forecasts suggest that increased pest activity linked with warming should result in a significant increase in maize crop losses in all the agro-ecological zones studied; the figure is between 5 and 20% depending on the altitude and the pest species. Altitude aggravates the impact with the extension of the distribution area of the crambid to above 1,200 m

* Biodiversity and evolution of plant/insect pest/antagonist complexes.

and the slower shifting of its natural enemy. This should result in less effective biological control of the pest at altitudes of over 1,200 m.

An increase of silica in maize with temperature

As maize uses an accumulation of silica in its tissues to protect itself against certain pests, including the moth, the researchers also wanted to understand how the increase in temperature could change silica contents in the plants. The results show that concentrations of silica in the soil and maize decrease with altitude and that uptake of silica by maize increases with temperature. This confirms the thermal optimums of the two species and explains the predominance of the moth at high altitudes.
In the future, warming should increase plant uptake of silica and therefore enhance the movement of the crambid to higher altitudes.

Maize infested by the African maize stalk borer (*Busseola fusca*) in Kenya.

Chapter 12

Tropical forests and large rivers

© IRD/L. Emperaire

Banks of the Rio Negro in the Norte region of Amazonia (Brazil).

Humid tropical forests form nearly a third of the forest areas in the world. More than other environments, they have become indissociable from the climate question. Indeed, their role in carbon dioxide sequestration is at the centre of climate policies while deforestation in recent decades has been recognised as being responsible for a fifth of greenhouse gas emissions.

Like these forests, the large rivers that flow through them are emblematic of the humid tropical climate. The large Amazon and Congo River basins—the largest in the world—are directly affected by climate phenomena like El Niño, monsoons, droughts and tropical cyclones. More numerous and more severe floods and low-water periods have been observed in recent years. These events disturb ecosystems and the neighbouring populations and also water supplies for towns.

A climate regulator in danger

Humid tropical forests play an important role in climate regulation. They absorb solar radiation, cool by evapotranspiration and are sources of water vapour for the creation of clouds. Amazonia and the role it plays in rainfall in the South American subcontinent

© IRD/G. Michon

Karnataka (India).
The large tropical forests that play an important role in carbon sequestration form nearly a third of world forest area.

is a much-observed example. According to estimates by scientists, approximately half of the rainfall in the Amazon basin is derived from forest evapotranspiration. Amazonia releases about 20 billion tonnes of water into the atmosphere every day.

Carbon sink

Tropical forests also play an indirect role in the world climate machine by way of the carbon cycle. They store a quarter of the organic carbon of the biosphere. The carbon sink mechanism linked with the positive difference between the carbon used in photosynthesis and that emitted by respiration enables them to capture part of the CO_2 present in the atmosphere (Box 36). Tropical forests can therefore be considered as natural infrastructure for combating the greenhouse effect.

However, climate change may change the functioning of this 'green lung'. We already know that climate warming will disturb the carbon cycle. It is considered in some studies that an increase of a few tenths of a degree could cancel out the present biosphere carbon sink because of an increase in soil respiration. But the sensitivity of organic carbon stocks and respiration to warming is still the subject of intense debate. Scientists are therefore working on gaining better understanding of the impacts of climate change on forest biomass and on the carbon sink function.

Box 36

Carbon sequestration in biomass and soil

The difference between the quantity of carbon assimilated by photosynthesis in land vegetation and that emitted by respiration is slightly positive. Vegetation captures some 120 Gt of carbon from the atmosphere by photosynthesis each year, that is to say about 1 atmospheric carbon atom in 7.
At the same time, plants respire and emit CO_2, returning about half of what they consume to the atmosphere. The other half returns to the atmosphere very broadly via soil respiration (roots, microorganisms and fauna).
As the amount of carbon taken up by photosynthesis is slightly greater than that released by plant and soil respiration, part of the atmospheric carbon taken up by plants is stored in biomass and soil in the form of organic matter: this is carbon sequestration.
This process makes land ecosystems a sink that slows the increase in atmospheric CO_2.

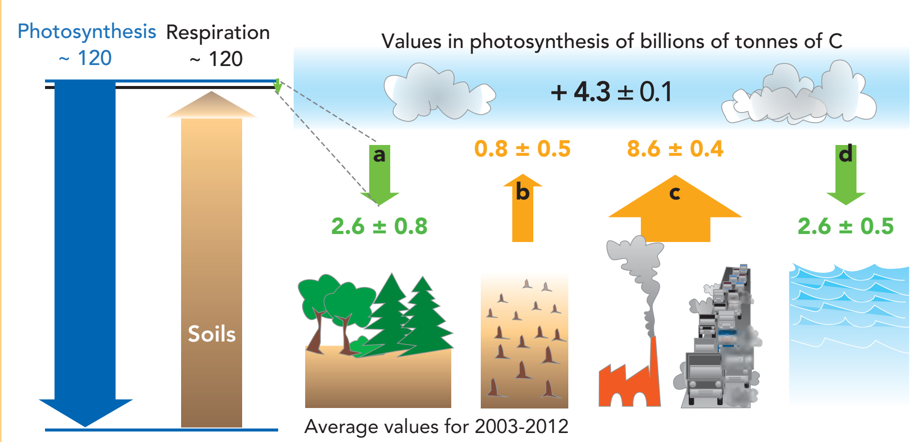


Figure 25.
Carbon exchanges between ecosystems and atmosphere.
a/ Carbon sequestration in soils resulting from gas exchange between photosynthesis and the respiration of plants and soil organisms and microorganisms.
b/ Soil to atmosphere carbon flow following deforestation.
c/ Non-agricultural or forestry anthropic emissions of CO_2.
d/ Ocean CO_2 sink.
Sources: BERNOUX and CHEVALLIER, 2013 and www.globalcarbonproject.org

Deforestation

There is a scientific consensus on the impacts of deforestation on the climate. According to the IPCC Fifth Assessment Report, since the 1980s the deforestation of several million hectares of tropical forest in Amazonia and insular Asia forms the greater part of greenhouse gas emissions resulting from change in land use. In addition to releasing the carbon stored in trees and forest soils, the disappearance of forests also halts their carbon sink function. The sustainable storage potential of the land use replacing forest is generally very small. In addition, degraded forests store less carbon.

With the increase in temperature and droughts, fires in degraded forests can have serious consequences for forests and hence the climate. The southern and eastern edges of Amazon have suffered serious deforestation and the spread of fires has made the natural forest even more fragile.

In spite of a relatively recent slowing, deforestation still has a future. It is the driving force of the economic model of emerging countries, such as Brazil and Indonesia, which rely increasingly on the export of primary raw materials to fund their policies. Forest areas form a land reserve for the spread of crops (soy, maize, oil palm and sugar cane) and cattle farming. Pressure on these areas will increase with world demand for these goods. Land holding security policies are necessary in such a context but are often weak. But the fight against deforestation is bearing fruit in some countries such as Brazil thanks to national nature protection policies (50% of Brazilian Amazonia is listed as protected areas) and surveillance by remote sensing. Carbon market mechanisms will also play a role in fighting deforestation although they are slow to gain power and their effectiveness is called into question by part of the scientific community (see Part 3, p. 180).

Bukit Barisan Selatan National Park in Sumatra (Indonesia). The park has lost about 20% of its area as a result of deforestation, mainly for coffee planting.

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Measurements of biomass.

Evaluating carbon sequestration in tropical forests

Given the international objectives of mastery of greenhouse gas emissions, a mechanism to encourage the conservation of carbon stocks in tropical forests was set up in 2009. REDD+ (Reduce Emissions from Deforestation and forest Degradation) is aimed at preventing deforestation and the degradation of forests in tropical countries. The measurement of forest carbon, the links between deforestation that has been avoided and its effect on the carbon stocks together with the monitoring of emission reduction undertakings form a scientific and methodological challenge, especially as regards the quantification of forest degradation other than deforestation. Research institutions have thus been called upon to provide methods and synthesise carbon stock census data for these forests.

Carbon stocks consist mainly of the above-ground biomass of the trees (trunks and branches) and also forest floor plant debris, soil organic matter and tree roots. Field estimation of tree biomass is based on simple measurements that can be made during forest inventories, such as trunk diameters. 3D imagery can also be used. But given the constraints of forest areas that are vast and to which access is often difficult, the spatial coverage of forest inventories is limited in terms of area. Biomass censuses are very expensive and not regular enough for good measurement of the evolution of stocks. These *in situ* measurements must therefore be combined with aerial and satellite remote sensing techniques. Field records are then used to sample the different types of forest in an area and to calibrate tree biomass and population prediction using remote sensing data.

Numerous remote sensing facilities

Estimating forest biomass using remote sensing is a strongly developing field of research. Unlike deforestation monitoring, a comparatively well-mastered technique, that of forest degradation and more generally of variations of forest biomass in space and time is difficult as most signals saturate at intermediate biomass levels. In recent years the diversification of sensors and of data sources have improved biomass measurements. Canopy heights are measured by laser altimetry (Lidar) allowing effective measurement of standing biomass. However, it is still dependent on airborne support that is costly and subject to over-flying authorisations. The European Space Agency's future radar satellite designed for biomass estimation should give results in a few years.

Box 37

How much carbon is stored in deforested soils in Amazonia?

Together with oceans and forest, soils form one of the main carbon reservoirs of the planet. This stock decreased considerably in the 20th century as a result of deforestation and intensive farming. IRD researchers and their Brazilian partners have been particularly interested in the evolution of the quantities of carbon in the soil following deforestation in Amazonia. Land that is stripped and then cultivated releases into the atmosphere as CO_2 the carbon hitherto stored as organic matter.

The response of soil after deforestation is very heterogeneous. To understand it better, researchers analysed a large amount of data on the evolution of soil carbon stocks in the region. They examined the results of about 20 studies conducted since 1976 on cattle grazing or fields of soy or maize that replaced forest.

They then compared the quantities of organic carbon measured in these deforested soils with those of the initial forest.

Soil carbon decreases with crops but not with grazing

Unsurprisingly, the Franco-Brazilian research team showed that the replacement of forest by large-scale annual crops such as maize and soy causes an average decrease of 8.5% in soil carbon. This feature is explained by the small quantities of organic matter returned to soil with no forest cover and also by cultural practices that favour carbon loss.

In contrast, the quantity of inorganic carbon in the soil has increased slightly in grazing land since forest clearance. The figure is an average of 11% in prairie that is not over-exploited. The vigorous root activity of grasses improves soil carbon storage. However, researchers expected much higher figures in grazing land as this is assumed to have a greater carbon sequestration potential. In addition, the increase in the amounts of carbon from grasses reaches a threshold after about 20 years and therefore in no way compensates the global greenhouse gas emissions resulting from deforestation.

Finally, the synthesis shows that in contrast with what is observed elsewhere in the world, the quantity of precipitation has no effect on soil carbon storage capacity in Amazonia.

Pastures replacing Amazonian forest in Brazil.
Intense deforestation for agricultural purposes contributes to reducing the carbon reserves stored in tropical forests.

© IRD/P. Léna

GeoEye 'false colour' very high spatial resolution image of the canopy.
The grain texture of satellite images of canopies is a good indicator of forest biomass.

© IRD/Amap

Finally, the increasing availability of very high spatial resolution (pixels of 1 m or less) optical satellite images also provides ways of predicting forest biomass. IRD and its partners have developed a method (Foto) in which the grain texture of satellite images reflects the size of crowns and hence that of the dominant trees that often form nearly three-quarters of the biomass of a forest. The approach has been validated in case studies involving very varied forests in Central Africa, French Guiana, India and New Caledonia. Other research has shown how to apply these methods to heterogeneous images in terms of illumination and the angle of aiming of the sensor. The research carried out in the last decade makes it possible today to envisage the combining of different complementary remote sensing techniques with each other and with field inventories.

Climate has had effects on humid tropical forests for thousands of years

According to the IPCC Fifth Assessment Report, tropical forests might be more sensitive to climate variations than temperate forests as they have evolved within a smaller temperature range than forests at high latitudes. It is necessary to examine the past to gain better understanding of the role of climate in forest dynamics. For some 20 years, several international multidisciplinary teams have worked in the Amazon and Congo basins on studying the evolutions of tropical forest in the last few thousand years and the role played by climate.

Box 38

The carbon balance of the Amazon is probably neutral

The carbon balance of the river system in central Amazonia is close to neutral: water releases the same quantity of carbon into the atmosphere as that fixed by the vegetation in its wetlands.

Considered up to now as a source of greenhouse gas emission, the river Amazon in fact shows carbon neutrality. A 2013 study by the GET and Epoc laboratories, within the framework of the HYBAM watch, shows that the CO_2 released by the river is only drawn from the river system itself.

Until now, scientists thought that the rivers received carbon from trees and other terrestrial plants via the soils of the drainage basin. The carbon would then be turned into CO_2 and released into the atmosphere. The watercourses, and particularly the gigantic river Amazon, were therefore considered to be net sources of emissions, with CO_2 released exceeding uptake. But researchers have demonstrated recently that the 200,000 tonnes of carbon released as gas annually by the waters of the Amazon is drawn mainly from the respiration and decomposition of the organic matter produced by semi-aquatic vegetation in the Amazonian wetlands. In contrast with what was thought previously, the river thus operates as a 'CO_2 pump'.

The study also highlights the need to examine the specific properties of wetlands in global carbon balances.

© IRD/J.-M. Martinez

The River Amazon emits 200,000 t of carbon annually.

© IRD/R. Oslisly

Mosaic of forest and savannah, Lopé National Park, Gabon.

Research on the last 5,000 years in central Africa contradicts the vision of unchanging humid tropical forest. Forests became fragmented 2,000 to 2,500 years ago to the advantage of savannah. The regression of forests seems to have been linked with the weakening of the African monsoon 3,500 years ago. After this period of drought, forest gradually regained land. Pollen analysis revealed the renewed presence of herbaceous and other plants characteristic of degraded forest or savannah during the Small Ice Age (14th to 19th centuries). Archaeological studies show that technical and cultural evolutions ran in parallel with these regional environmental changes. The influence of humans does not seem to have been determinant in changes in the environment even though it very probably enhanced certain dynamics, especially through fires. The work shows that African forest—generally drier than Amazonia—swings more rapidly to savannah landscapes as a result of fires in particular. But the continued existence of refuge zones for forest species in certain mountain areas or near rivers makes reconquest periods possible, as was the case in recent centuries.

Climate is also one of the driving forces of biodiversity. Species diversity in Amazonia is among the greatest of all terrestrial areas and results from evolution in an environment where there have not been any mass extinctions of species caused by glacial intrusions in northern latitudes and that has been comparatively well protected from the accompanying spread of dry tropical climates. However, recent work by an IRD team and its South

American partners shows that the exceptional fauna and flora of the Amazon basin are also the result of a long geological and climate history. Active tectonics in the Andes and the variability of precipitation appear to be what drive the development of biodiversity hot spots in the foothills of the Andes. Changes in the relief (tectonics, erosion, changes of courses of rivers) would set up an unstable regime favouring considerable species diversification.

The hydrology of large rivers: more severe flooding and low water periods

The increase in extreme events (droughts, very heavy rain) observed in the tropics has resulted in more frequent and more intense floods and low water periods in the large tropical rivers. Much research has been carried out on Amazonia, the largest drainage basin in the world with an area of some 6 million square kilometres. Since 2003, the HYBAM environmental observation service has made precise, regular records of water flows and levels using a vast network of hydrological stations and satellite spatial altimetry (Box 39).

Water level surface elevation of rivers in Amazonia can vary by 20 metres

Over the past 15 years, there has been a succession of periods of exceptional low water (2005 and 2010) and of floods (1999, 2009, 2012 and 2014). While the average discharge of the river varies little, these events form the main marker of the change in hydrological regimes observed in the Amazon and its tributaries. Floods and extreme low water are related to the influence of oceans and possibly amplified by local factors. For example, deforestation reduces the moisture available during droughts and increases runoff during rainy periods.

These extreme events have had major local impacts. The surface elevation of the rivers in central Amazonia can thus vary by more than 20 m between low and high water periods and the Amazon can be as much as 10 km wide during the most severe floods. Floods and low water disturb communication in Brazil along waterways that are the sole lines of communication for a large proportion of the population of Amazonia. During these phenomena, the people who live along the rivers do not have their usual resources—fishing and farming in particular. Floods can also kill. In Bolivia in 2014, the catastrophic flood of the river Madeira, one of the main tributaries of the Amazon, caused 56 deaths and affected 58,000 families.

Box 39

Monitoring the exceptional Amazon basin flood of 2014

HYBAM teams used spatial altimetry and field measurements to monitor the start and evolution of an exceptional flood in the river Madeira from Peru to Brazil. The spatial hydrology facilities developed by IRD were made available to South American national technical divisions.

Shared between Peru, Bolivia and Brazil, the area of the river Madeira drainage basin is twice that of France. An exceptional flood occurred in 2014, caused by heavy rainfall in the basin from the beginning of the year onwards.
The level reached by the river at Porto Velho in Brazil was 2 metres higher than the previous maximum observed since measurements started in 1967.
At Rurrenabaque in the Bolivian Andes foothills, cumulated rainfall of 1,100 mm in 17 days was four times the usual figure for the period.
The Bolivian government considered the floods to be the most catastrophic for 30 years.

Cooperation with national agencies and universities in the three countries

HYBAM teams used the network of gauging stations of the Peruvian and Bolivian national meteorology and hydrology services and support from the Brazilian water agency to monitor the start and the progress of this exceptional flood.
Discharges of the river Madeira and its tributaries were measured at field stations. River water levels were also monitored using spatial altimetry. As the floods had washed away numerous gauging stations in Bolivia, water levels in this extreme context were monitored using the satellite data method.

© Inegracao Nacional/A. Marques

Damage caused by a flood of the Rio Madeira, Brazil, in 2014.

Box 40

Groundwater mapped from space

Researchers at the LEGOS, Espace-DEV and GET units and their French and Brazilian partners have developed a new method for satellite measurement of groundwater.
They have plotted the first maps of the groundwater beneath the Amazon and the Rio Negro.

They indicate aquifer depth during low water periods from 2003 to 2008 and show groundwater response, particularly to droughts such as that of 2005, thus giving a better description of its role with regard to the Amazon climate and ecosystem.

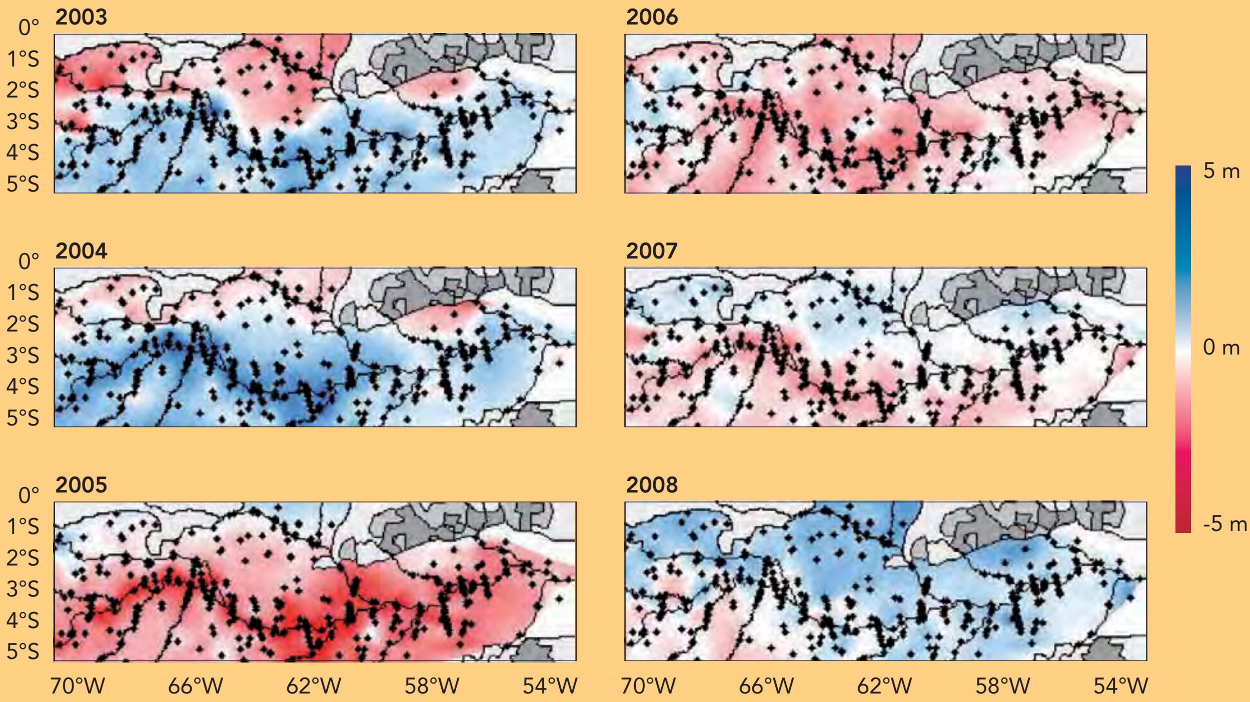

Figure 26.
Monitoring of the situation of Amazonian alluvial groundwater from 2003 to 2008.
Black diamonds = virtual altimetric stations.
Range of colour = height of the groundwater level in comparison with an average situation.
Groundwater did not return to its average level for two years after the severe drought of 2005 even though rainfall returned to normal in 2006.
Source: PFEFFER *et al.*, 2014.

Box 41

The lesser impact of climate change on the extinction of freshwater fish

In 2013, scientists at the BOREA research unit and their partners showed that current cases of extinction of freshwater fish as a result of anthropic pressure is probably much greater than those caused by climate change.

The models used to date by ichthyologists forecast that the reduction of the habitats of certain species caused by climate change would be one of the major causes of their extinction. However, these models did not allow for the time factor whereas it may take several decades or even several thousand years for a species to become extinct.

The BOREA researchers integrated the time dimension in their work and showed that the effects of climate change will only marginally affect the natural rate of extinction of freshwater fishes, except in semi-arid and Mediterranean regions.

The extinction rates caused by human activities in the last two centuries are much more disturbing as they are an average of 150 times greater than natural rates of extinction and 130 times greater than the extinction rates predicted in the light of climate change.

However, stress linked with temperature and limited oxygen could cause gradual changes in the structure and composition of present fish communities. In Amazonia for example, populations of species tolerant to a rise in temperature, such as *Arapaima*, will increase while those of populations sensitive to this will dwindle.

Nannostomus trifasciatus Steindachner, 1876. Bolivian aquatic environments from the Andes to the Amazonian plains house 900 fish species, representing 6% of the freshwater fish that have been described.

© IRD/M. Jégu

These major rivers are also an important source of energy in the regions that they cross. Amazonia is still seen as an excellent area for the continued construction of large hydroelectric dams (Tucurui, Belo Monte, Santo Antônio, Girau) to supply large regional industries and towns. But the capacity of these installations might have been overestimated in the light of the strong climate fluctuations seen today (droughts and floods).

Seriously disturbed river traffic on the Oubangui

The Congo River, the second largest in the world after the Amazon, has also displayed considerable instability in discharge. This decreased significantly by about 10% in the early 1980s and then returned to normal from 1990 onwards. However, the discharges of the right bank tributaries—the Oubangui and the Sangha—have decreased steadily since the 1970s. But the Congo and the Oubangui are the main routes of access for trade between Kinshasa/Brazzaville and Bangui in the Central African Republic. The number of days of stoppage of river traffic on the Oubangui has increased considerably in recent decades and has been as much as 200 days per year since 2002. However, the very complex hydrology of this river basin with an area of nearly 4 million square kilometres makes it difficult to isolate major trends directly linked with climate change, especially as there are few hydroclimatic data for the region. Developed by IRD, BVET, a system for the observation of experimental tropical drainage basins, contributes to improving knowledge of hydrology in central Africa. With Cameroonian partners, BVET is studying the impact of climate fluctuations and agricultural practices on the hydrosystems of several small drainage basins in southern Cameroon. Another facility for monitoring the humid zone in central Africa is being set up in Gabon.

© IRD/A. Laraque

River traffic
on the Congo River.
The Congo River is an important waterway for trade and passenger traffic between the two capitals, Kinshasa (Democratic Republic of the Congo) and Brazzaville (Republic of the Congo).

Chapter 13

Urban zones: vulnerable megalopolises

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Dhaka, an urban area with a population of some 12 million. With rapid population growth of more than 5% per year, it is subject to serious natural risks (floods, cyclones and earthquakes).

While humid tropical forests and ocean areas play an important role in climate regulation, urban zones generate the major proportion of greenhouse gas emissions. Large cities are centres for industry and also for the consumption of fossil resources for transport, heating and air-conditioning. The countries in the North are historically the main contributors to these urban emissions. However, the economic slumps and mitigation policies set up in Europe in parallel with strong population and economic growth of the megalopolises in the South are gradually reversing the trend.

The cities in the tropics are particularly exposed to climate impacts, mainly because vulnerability is high and town planning policies and measures to combat natural risks are less developed there. The IPCC Fifth Assessment Report stresses the urgency of addressing urban areas with regard to both mitigation policies and capacity to adapt as the impacts on society—poorly assessed as yet—are worrying. The immediate consequences for the population are the effects of pollution as regards public health. The rapid rise in temperatures, related in particular to the urban heat island phenomenon, also has marked consequences. In the medium term, the increase in extreme events and the rise in sea level could have catastrophic results for the stability of societies in the

South, whereas with the extension of precarious districts and coastal towns, present urban dynamics increase the risks for populations.

The research sector must therefore gain better understanding of vulnerability and the impacts of climate change in cities in order to attempt to propose solutions adapted to increasing urban concentration. Such urban research is still little developed in countries in the tropics. IRD has long addressed similar themes such as population-environment relations, natural risks and public policies in cities and the trend today is that of refocusing these themes in a context of climate crisis.

An increasingly urban and coastal world

Nearly 4 billion people, that is to say 58% of the population of the world, now live in urban environments. This massive urbanisation is relatively recent dynamics as the urban population has increased nearly 5-fold since 1950. Urban growth has displayed two new features since the 2000s. First, it is accompanied by concentration in increasing large towns in the South (Fig. 27). In 1975, there were 18 megalopolises with populations of

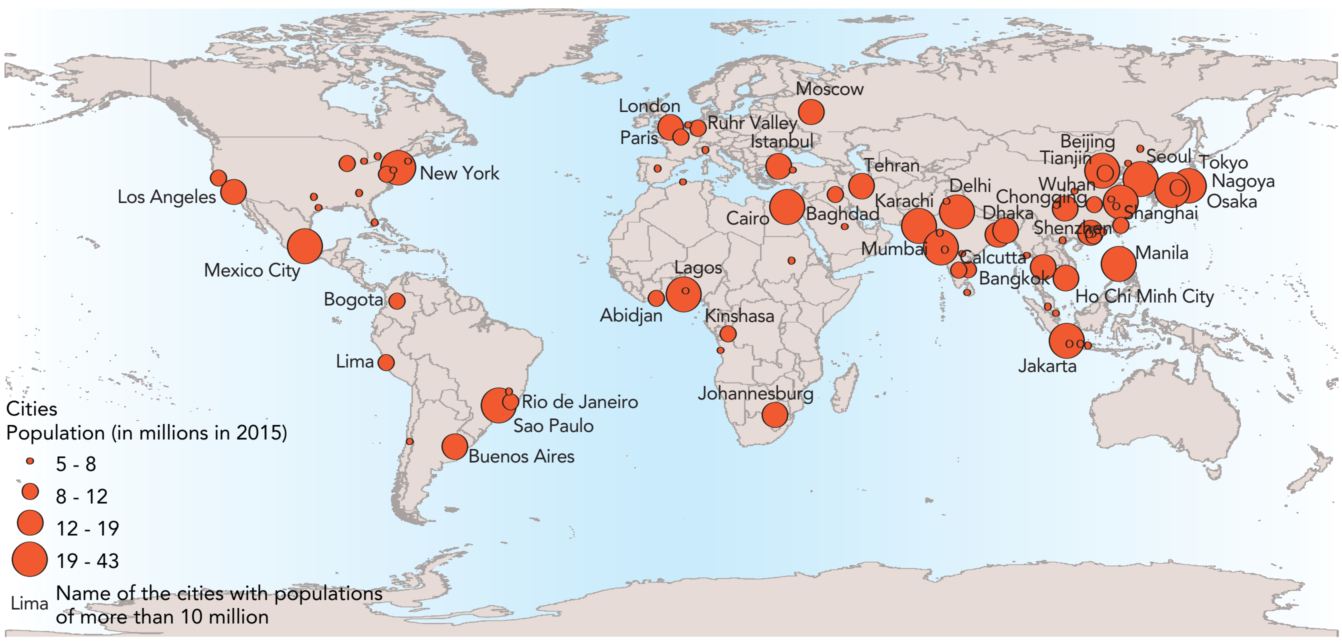

Figure 27.
Evolution of large cities.
Exposure to 10 µm particles in the atmosphere in urban zones (2008-2013).
Source: IRD/LPED


© IRD/G. Roudaut

Lima, Peru.
One of five megalopolises in Latin America (the others being Mexico City, São Paulo, Buenos Aires and Rio de Janeiro), Lima houses a third of the population of Peru.

over 5 million, the whole totalling 170 million people. In 2014, there were 73 megalopolises with a total of 800 million people. The main megalopolises are on the American and Asian continents, mainly in emerging countries (Brazil, India and China). But many other cities in the tropics have become megalopolises at the regional level, such as Lima with 30% of the population of Peru and Lagos with three-quarters of the population of Nigeria.

Another major feature of this urban growth is the greater development of coastal cities. According to IPCC, nearly 145 million people live at an elevation of 1 metre above sea level and 397 million at less than 10 metres. The trend will become more marked in the coming decades because of the intensification of world sea trade.

Increased vulnerability in the face of natural risks

In spite of the lack of observation systems focused on the urban climate in countries in the South, impacts of warming, increased climate variability and extreme events and the rise in sea levels are observed. The IPCC Fifth Assessment Report lays particular stress on two phenomena: landslides and the rise in sea level.

Box 42

What is the relation of cause and effect between climate change and urban catastrophes?

The increase in catastrophes in the Andean capitals has led researchers to investigate the causes and especially links with climate change. But extreme climate events are not the only explanation of the increase in urban risks.

In the last three decades, La Paz, Lima and Quito have suffered a multitude of natural catastrophes involving flooding and landslides. The cumulated damage is very significant for humans and goods and penalises the economic and social development of these cities.

In La Paz for example, the floods of February 2002 caused one of the greatest urban catastrophes known in Bolivia: 69 deaths, the displacement of 200 families and very serious material damage evaluated at 10 million dollars. In February 2011, a landslide made it necessary to evacuate several neighbourhoods of the capital; 6,000 people were placed in shelters and much public infrastructure was destroyed in a 140-hectare zone. But the landslide, caused by precipitation that attained double normal depths, was in soft ground where urban development is not permitted. Urban growth in dangerous zones is often the cause of exposure of the population to risks that have been identified.

More than a hundred catastrophes are reported each year

Given the increase of natural catastrophes observed, the team at PACIVUR (*Programme andin de formation et de recherche sur les vulnérabilités et les risques en milieu urbain*) analysed the statistical pattern of the accidents and catastrophes that occurred in the three Andean capitals from 1970 to 2007. A total of 3,990 accidents and catastrophes—mainly floods and landslides—were recorded

Marine submersion

More than half of the cities in the tropics are on the coast—among other things a heritage of the trading centres of the old colonies. And current urban dynamics continue to encourage the growth of these coastal cities. Increasingly large urban populations are thus exposed to the rise in sea level and, more precisely, to erosion and marine submersion. Among others, this is the case of Nouakchott, Lagos, Lomé, Dhaka, Ho Chi Minh City and Rio de Janeiro. The rise in sea level of several tens of centimetres in the coming decades will accentuate these phenomena, with the destruction of housing and infrastructure and movements of populations. Marine submersion will also cause a loss of coastal resources that are important for local economies.

in the three cities: 76% concerned Lima, 14% Quito and 10% La Paz.
These catastrophes have become increasingly frequent with the passing of time.

It would seem from the scientific literature available that the increase in catastrophes is linked with climate change in the Andes.
The heavy rains recorded in recent decades are correlated with the increase in floods.
However, this kind of conclusion would ignore several difficulties in interpreting the increase in accidents.

Urban vulnerability

First of all, the actual assembly of data is partially biased: data collection varies from one city to another and some places receive more attention because of their strategic importance as regards politics and economics.
These disparities in data are obstacles to the understanding of vulnerability and risks and their links with climate change.
Furthermore, it is difficult to distinguish between phenomena with natural causes and those with anthropic causes because of complex series of events that are typical of urban environments.
What is certain is that accidents and catastrophes in these environments are related to very strong anthropisation (the ground rendered impervious, spread of built-up zones, etc.) and the vulnerability of complex, dense urban structures (high densities of population and activities, multiplication of technical networks, etc.).

Thus although climate change will certainly affect vulnerability in urban environments, it is still difficult to establish a causal relation.

Landslide in February 2011 in the city of La Paz (Bolivia).

© IRD/S. Hardy

Floods and landslides

Through more violent precipitation or serious drought, climate variability will also affect cities further inland. The increase in extreme rainfall events heightens the flood threat that is already accentuated by the imperviousness resulting from town development. Strong precipitations also increase landslide risks. The consequences of these phenomena are often amplified by the vulnerability of urban environments. Human activities over which there is little control, urban concentration in sometimes dangerous zones and precarious dwellings are all factors that can turn climate risks into urban catastrophes. The danger is particularly strong in highland cities. For example, most cities in the Andes are exposed to these phenomena that have been increasing steadily in recent decades.

The change in the rainfall regime also results in more floods, exposing towns near rivers to risk. The historic floods of the Amazon and its tributaries in 2009, 2012 and 2014, linked with exceptional precipitation and deforestation, affected several hundred thousand people. A state of emergency was declared in several regions of Peru, Brazil and Bolivia and numerous towns were flooded.

Avenue Patria Quito, Ecuador.
Slightly more than 28,000 vehicles use this road every day. If it is blocked—by landslides or floods—traffic in the city is paralysed to a considerable degree.

Box 43

Informal neighbourhoods in the face of climate change

IRD studies in Damascus and Cairo show how informal neighbourhoods can bring as many problems as solutions in the face of climate change.

The informal neighbourhoods in both Damascus and Cairo display specific vulnerabilities with regard to risks connected with climate change. Unsurprisingly, the people there often live in areas at risk from floods and that are unstable and subject to landslides. The poor quality of dwellings and the absence of drainage increase the exposure of the population to floods. For lack of means, the people concerned have few alternatives for settling in safer areas.

Then marginalised neighbourhoods also receive less state aid in case of catastrophe. They also suffer from more limited legal and financial protection for lack of landholding rights, insurance cover, etc.

Finally, the informal zones are formed without respect of the regulations that are supposed to protect them. This means double vulnerability as when prevention and risk management policies exist, informal towns grow precisely outside these regulations.

Nevertheless, the IRD studies show the pertinence and flexibility of informal urban development. They highlight the know-how of the builder-occupiers who find solutions when public policies have shortcomings. In addition, some features of these neighbourhoods are considered increasingly as being partially adapted and/or adaptable to the climate changes expected. Their urban morphology makes them better adapted: narrow shaded streets, heat inertia of structures that touch each other, urban compactness; dense buildings and small plots. And they are also easier to adapt: flexible progressive construction, conservation of a pedestrian character, low traffic speed in dwelling zones, etc.

Without being a majority, some professionals underline these 'sustainable' features of informal neighbourhoods and the know-how on which strategies for adaptation to the risks of climate change can be based. These aspects are beginning to be integrated in projects for the rehabilitation of informal areas.

Makeshift accommodation in an outlying district of Cairo (Egypt).

© IRD/J.-P. Montoroi

Greater Bangkok has a population of more than 14 million, forming over 20% of the population of Thailand.
The city is regularly affected by serious flooding during monsoon rains.

The direct sanitary effects of emissions

The effects of climate warming must not hide the direct effects of urban emissions on air pollution and the warming of urban climates. These local effects are very marked today in cities in the South (Fig. 28). Mexico City, Sao Paulo, Cairo, Karachi, Dakar, Bamako, etc. seriously exceed the atmospheric pollutions thresholds accepted by the World Health Organization (WHO) in particular because of ageing public transport and vehicles and the absence of regulation of domestic use of wood or gasoil. The particle count in New Delhi is 153 $\mu g/m^3$, that is to say 15 times more than the WHO threshold and 10 times more than in Paris.

Mastering **urban heat islands** (UHI) is also a challenge in the face of climate change. Increased temperature operates differently in town and in the country. In town, the albedo effects on the surfaces of buildings and tarmac roads combined with heat emissions from transport, building heating or air-conditioning together with high pollution levels can cause local temperature increases of 4 to 6°C. The effects are felt especially at night when the energy stored in concrete walls is released. The phenomenon is particularly marked in Mediterranean and tropical environments where air-conditioning is used continuously.

The combined impacts of thermal stress, heat islands and air pollution form a new health risk, with increased respiratory disease and vulnerability in children and old people (dehydration and cardio-vascular diseases). These risks are particularly marked in zones where there is already thermal stress, such as the Sahel, and in the Mediterranean zone.

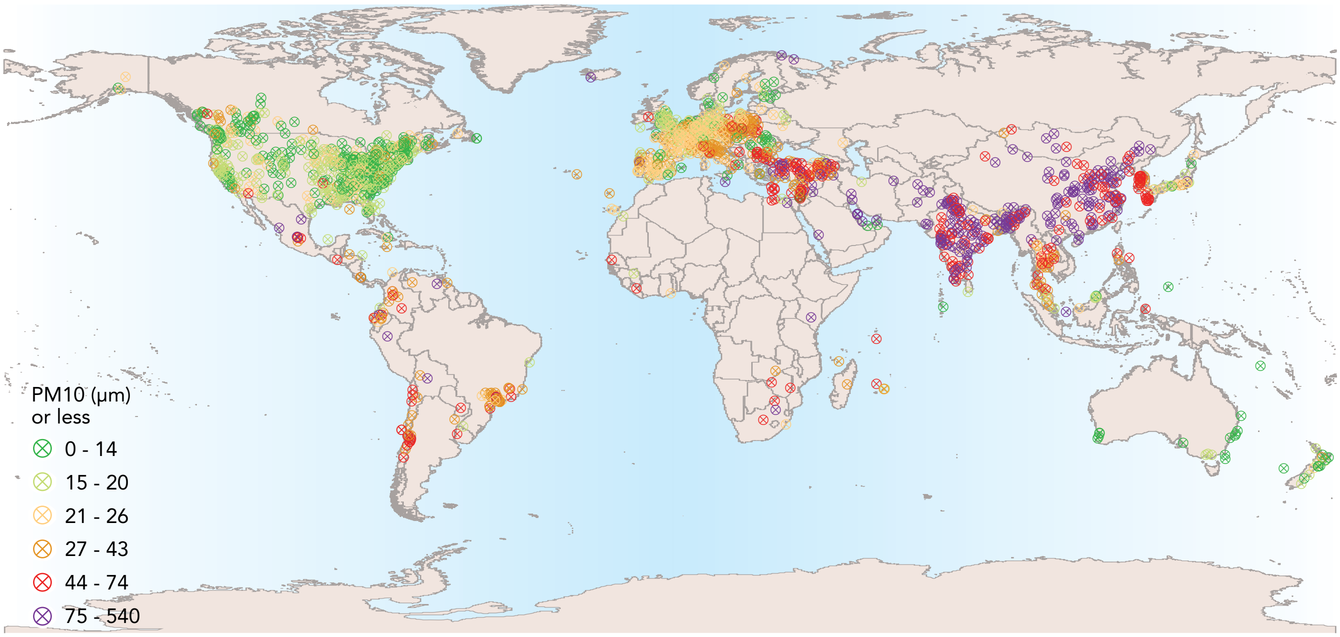

Figure 28.
Map of air pollution
in large cities.
Exposure to 10 µm particles
in the atmosphere
in urban zones (2008-2013).
Sources: IRD/LPED/WHO, 2014

Access to resources endangered

Another impact of climate change in urban zones is the availability of resources to supply an entire city. Access to water is a particularly crucial issue with the threat of extreme climate events. This covers shortage of water during severe droughts, the pollution of groundwater following heavy rainfall (because of contamination resulting from poor treatment of sewage) or the destruction of infrastructure during natural catastrophes. Broken pipes can soon affect an entire city. After the La Paz landslide in 2011, the potable water supply for about 300,000 people was halted for several weeks. This example highlights the fragility that is a feature of centralised urban facilities (Box 44).

Another phenomenon related to climate change and that forms a threat to water supply is the retreat of glaciers. The melting of ice during dry periods is an important source of water. In arid regions, such as those in Peru and Bolivia, the contribution of glaciers to irrigation, hydroelectricity and water supply for the local population can be very significant. Although the melting of glaciers caused by warming is currently increasing the discharge of watercourses, the disappearance of the glaciers is a threat to this resource in the medium term.

Box 44

La Paz without water for 19 days

A long period during which the water supply was cut off after a landslide in 2008 is a good illustration of the fragility of the water supply system in the capital of Bolivia.

When focusing on the water supply for the La Paz urban area, the PACIVUR team showed the vulnerabilities of the urban environment. Climatic factors are marginal here in comparison with human management.

On 25 January 2008, a landslide damaged part of a pipe conveying water from the Hampaturi zone to the Pampahasi water treatment station. During the 19 days needed to make emergency repairs, more than a third of the population of La Paz (about 300,000 people) had no potable water supply, together with companies, health establishments, schools, etc. The event thus caused very serious malfunctions in part of the city.

Distribution of food in a school used temporarily as a refuge for local victims in La Paz (Bolivia).

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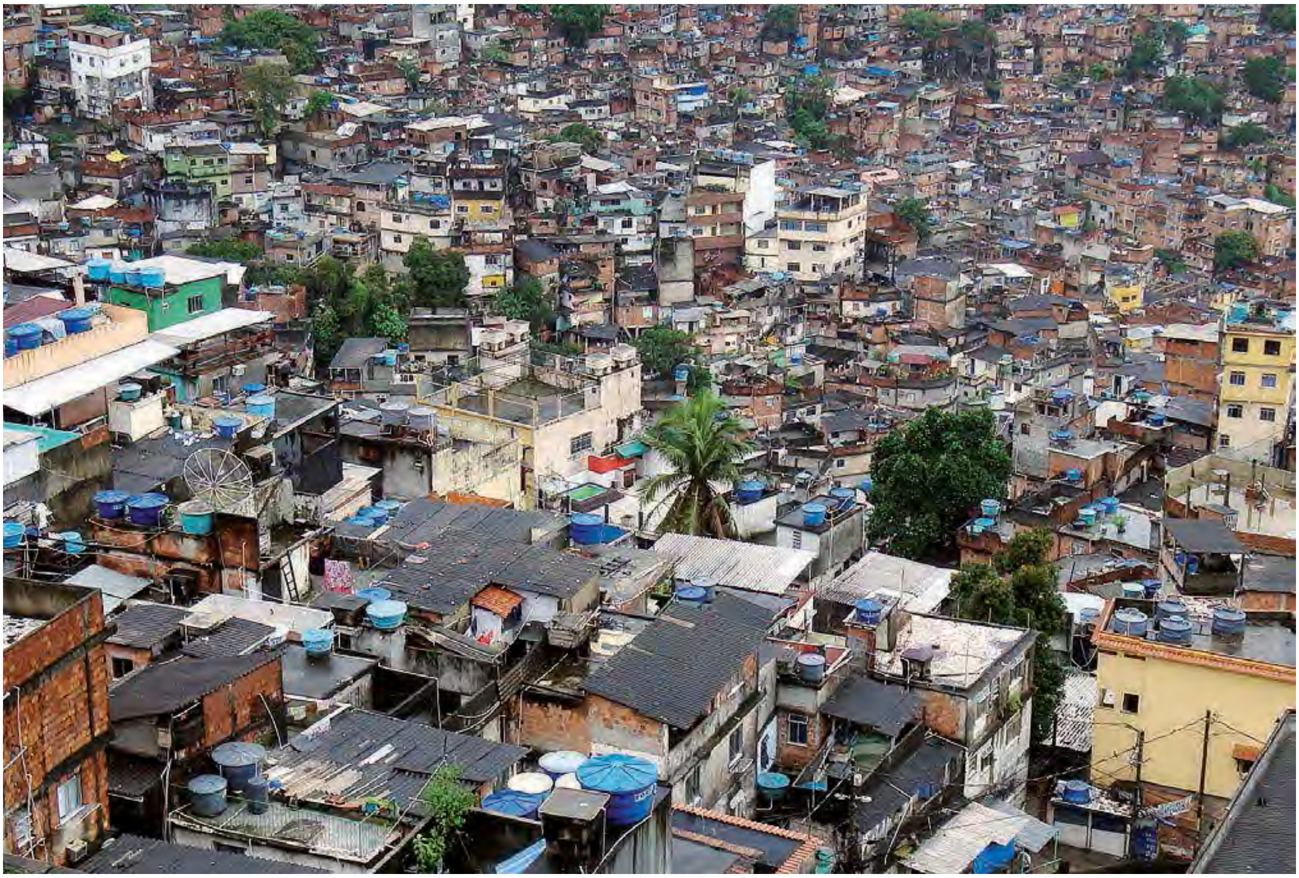
The fragility of centralised networks

The strong precipitations during the days preceding the accident undoubtedly played a role. However, work of the PACIVUR team showed that the fragility of the water supply system was also involved. The option of central production and distribution of potable water chosen in the early 20th century resulted in the construction of substantial infrastructure in risk zones (unstable land). This organisation considerably increased the vulnerability of the system.

But every crisis is also an opportunity to start considering solutions and alternatives. In the case of La Paz, does potable water production justify the continuation of very costly development work in areas exposed to risks whereas it would be possible to use numerous springs? On the contrary, recent studies show all the advantages of favouring small, more local systems.



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A *favela* in Rio de Janeiro, Brazil.
The tanks on the roofs are for storing water as the favelas rarely have mains water supply.

More generally, the availability of resources raises the question of the population-environment relation in megalopolises. The context of demographic change (rural exodus) and change in agriculture (the replacement of family farming by commercial farming) is causing the reorganisation of the supplying of food but this affects the food security of city-dwellers when the distribution networks are down.

Modelling cities

Most of the effects of climate change in urban areas remain to be discovered. Several operations in which IRD is participating are beginning, aimed at observing and understanding changes in the urban environment under the effect of pollution and climate. For example, the operation for monitoring urban environments in Marseilles and Algiers set up by IRD is installing experimental set-ups for the monitoring of fauna and flora in urban environments. This is aimed at evaluating warming (especially in urban heat islands) according to urban structure (height, density, layout of urban components) and explaining their impacts on urban biodiversity.

One of the future challenges is that of modelling urban microclimates and their impacts according to urban structure and the ways of life of the population.

Farmwork in Ecuador:
a potato field.

Part 3

Societies and the test of climate

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Although the climate risk has sometimes been considered to be the ultimate environmental problem, taking precedence over other questions such as decreasing biodiversity, desertification, pollution, etc., it should now be seen more within the framework of social, economic and political realities. The setting of the climate question will thus be one of the major issues at COP 21, in particular for better taking into account of the position and role of the populations in the South. The scientific community—all disciplines and especially health and social sciences—will participate in this broadening of the question alongside numerous political and civil society stakeholders. The questions of governance and the orientation of the framework of the international negotiations will be in the forefront and must be rethought in such a way as to achieve better integration of climate issues in public and social policy realities, international trade and energy policies.

The effect of climate change on human health is mentioned several times in the second part of this book and in Part 3 a chapter is devoted to this subject that is indeed at the heart of the climate question. Paradoxically, research on the consequences for health of climate change is still lacking in countries in the South. Health sciences have hardly anticipated the potential effects of global environmental changes. After concentrating research efforts on detailed levels of understanding (molecules, cells, etc.), they have difficulty in taking positions on more global questions. The lack of long-term monitoring of the population also makes it impossible to draw conclusions based on scientific proof. Certain experts consider that if nothing is done, the measures to be taken to strengthen the resilience and health adaptation of African populations will cost several hundred billion euros. The health and well-being of the inhabitants of the tropics should in the future form a 'rampart' in the face of climate change and be an essential international political priority to compensate the fact that the populations in the South, that are the most vulnerable and the poorest, are often those that make the smallest contribution of greenhouse gas emissions.

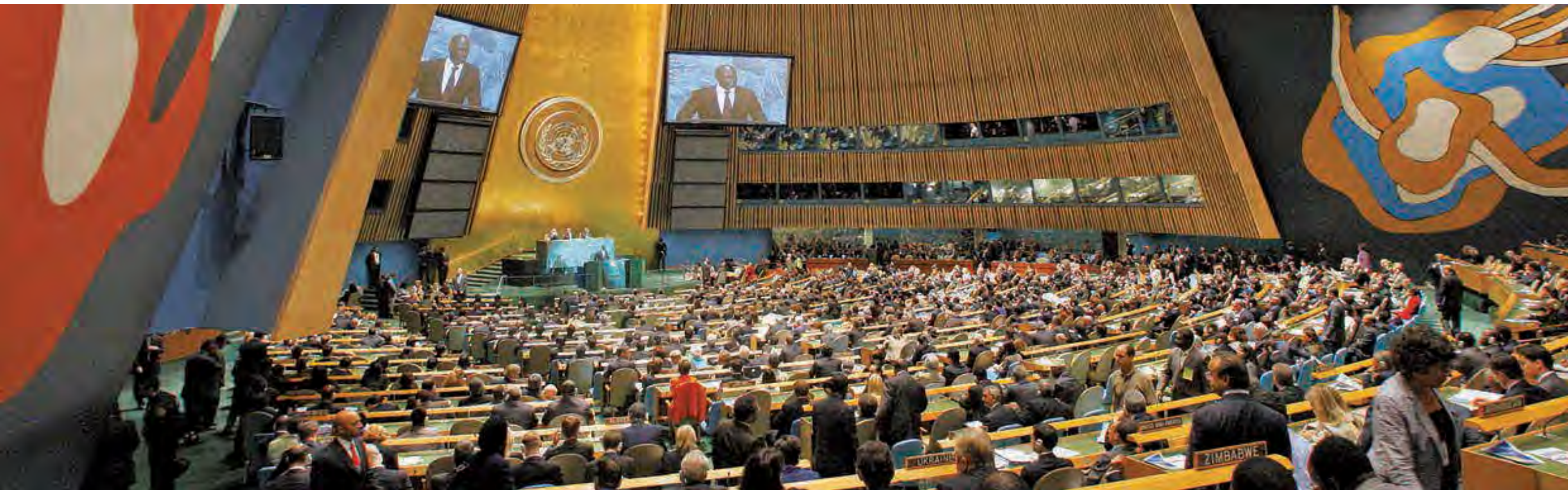
Agriculture will also have a leading position in negotiations concerning climate policies. Indeed, how can this sector reduce its emissions and feed a planet with a steadily increasing population? What agricultural models might respond to the scale of the food and environmental issues? The capacity for carbon sequestration in the ground is one of the keys but the accurate measurement of the quantities stored is still the subject of much research for assessing the potential role of farming in emission mitigation policies.

While mitigation was the main approach used to limit global emissions until the end of the 2000s, it has since shown its limits. In the face of warming that now seems inevitable, the themes 'resilience' and 'adaptation' are gradually gaining weight. Furthermore, the mobilisation of civil society and its participation in the development of new solutions are becoming unavoidable. This opening up is all the more necessary because the populations in the South have not waited for decisions by experts to adjust their subsistence strategies in response to changes that they are able to perceive and anticipate. Much work is thus devoted to the adaptation capacities of rural populations in the South in relation to their environment and to the legitimacy of local knowledge to guide social dynamics. The adaptive capacity of systems and populations is now better integrated. Communities of researchers in social sciences have played an important role in this dynamics and some of the original work carried out in the South is described here.

The main themes addressed in Part 3 are international governance, health challenges, agricultural policy issues, local naturalist knowledge and the resilience and adaptation of populations. They are focused on the effects of climate change on societies in the South and also draw on the solutions adopted by the latter to meet them. Human and societal dimensions are thus placed at the heart of the debate on climate.

Chapter 14

International climate negotiations and their incidences



The United Nations Summit on Climate Change, September 2009, UN Headquarters, New York.

To solve the problem of climate change, international negotiations were first focused in priority on the 'mitigation' of warming through the setting up of market instruments to limit global greenhouse gas emissions. This framework has shown its limits as more than 20 years after the coming into force of the United Nations Framework Convention on Climate Change (UNFCCC), emissions have never been as great as they are today. In the face of what seems to be inevitable warming, the theme of 'adaptation' has gradually gained weight in negotiations. The theme also responds to demands for justice and equity from countries in the South.

Critical analysis of the international negotiations concerning the climate makes it possible to examine the framework of the question of climate and especially its separation from other concerns such as international trade, energy policies, etc. Beyond the climate dimension, international climate policies have also been studied as a process of construction of global environmental governance with incidence on national policies.

Third United Nations Earth Summit, Rio de Janeiro, 1992.

© UN Photo/Michos Tzavaro

From mitigation policies to adaptation policies

At the 3rd Earth Summit in Rio de Janeiro in 1992, a consensus on climate risk resulted in the parties involved undertaking to set up global climate governance under the aegis of the United Nations. A global multilateral agreement was then planned to apply to all states. The UNFCCC is based on a strategy of 'sharing the burden' in which countries share efforts to reduce emissions. This choice put reduction undertakings by countries in the foreground of international negotiations. A distinction in treatment was nevertheless set up between the industrialised countries and the so-called developing countries according to the principle of 'common but differentiated responsibilities'. The countries in the South do not have an obligation to reduce emissions as western countries are historically responsible for increasing the quantities of greenhouses gases in the atmosphere.

Climate negotiations are punctuated by annual Conferences of the Parties (COP) held within the framework of the UNFCCC. The adoption of the Kyoto Protocol at COP 3 in 1997 was the final stage of a multilateral agreement, with the developed countries and certain countries with economies in transition setting themselves precise objectives guided by IPCC conclusions. The agreement was widely praised even though the efforts made to reduce greenhouse gas emissions (calculated as equivalent CO_2) were modest (average 5% for 2008-2012 in comparison with the 1990 level). It was based in particular on the setting up of 'carbon markets'. These market mechanisms were supposed to reduce emissions inexpensively by a system of emission rights trading aimed at industries. The non-emitted CO_2 units then became the unit of measurement in combating climate change. The same market logic was soon applied to deforestation through the mechanism 'Reducing emissions from deforestation and forest degradation' (REDD+).

The actual causes of emissions were not examined

However, it has to be admitted that these choices are ineffective. There is a patent gap between the increasingly alarmist IPCC forecasts and the bogging down of negotiations. Reduced to a purely quantitative view, the global approach has made it possible to separate the climate question from other realities such as increased exploitation of fossil energy, accelerated competition from emerging economies, etc. The causes of emissions were not examined. Negotiations thus long remained independent of questions of international trade, energy policies, geopolitics and the economy and also social questions in general. This led to a form of autism: while timid undertakings were formulated during negotiations, international trade agreements and national policies operated against a reduction in emissions.

Industrial chimneys on the bank of the São Francisco River, Brazil.
Human activities, and mainly the massive exploitation of fossil fuels, result in greenhouse gas concentrations that tend to warm the atmosphere.

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Box 45

Market instruments and the market approach to biodiversity

The Climate Convention gave market instruments an important role in the solving of emission problems. This economic approach then spread to other sectors of environment policies. For this reason, the INVALUABLE project focused on this mercantile approach to nature, with the latest feature being payments for ecosystem services.

So-called ‘market instruments’—carbon markets in particular—were favoured in the Climate Convention. This economic approach to environmental policies that stressed the potential of market instruments for solving global problems has gradually been applied in other areas: biodiversity, fighting deforestation and desertification, etc.

Strongly used by international institutions, this approach appeared in the United States at the end of the 1980s, first for regulating air pollution problems and then those of decreased biodiversity. This use of market instruments was chosen ideologically in opposition to the regulatory power of the state and its so-called ‘command and control’ instruments. The main argument was that of the supposedly greater effectiveness of market instruments than legislation and/or administrative control.

From theory to practice

The INVALUABLE project, with considerable participation by IRD scientists, shows that the difference between theory and practice is often surprising. The IRD researchers used studies based on the comparative analysis of countries, *in situ* observations and even participation in various specific projects combining historical, economic, institutional and legal analysis to show that in practice there tends to be a hybridisation of instruments. In all cases, ‘markets’ are more an incantation than a model of economic theory.

For example, the 76% decrease in annual deforestation in Brazil since 2005 is mainly the result of federal policy, that is to say a state ‘command and control’ policy.

It took time—over and above the question of ineffective negotiations and the increase in emissions—for the ‘adaptation’ theme to come into force. This indicated awareness that in contrast with what was planned in the agreement on the climate, mitigation would not take place at the speed of a natural adaptation of ecosystems to climate change. Adaptation is thus aimed at guaranteeing collective means of action to prepare for a world that is 2°C warmer. The emerging of adaptation also involves developing countries which call into question the rules for mitigation while they are the first to suffer damage resulting from the industrialisation of the developed countries. At the Bali Conference (2007), they imposed the adaptation theme as a second objective of the agreement, seeing it to be as crucial as mitigation.

Planning backed by legislation and other actions (repression and incitation, the development of surveillance techniques and the creation of protected areas) has given results.
The influence of the use of market instruments is not seen in this success.

Ecosystem services

Reducing climate change to CO_2 measurement contributes to the creation of a unit of measurement that can serve as merchandise, that is to say it enables trade between buyer and seller.
This economic approach in environmental policies is indeed the source of the ecosystem services concept current in international biodiversity circles. It generates strong opposition from a non-negligible fringe of civil society that refuses to see nature protection policies based on the economic assessment of the services that ecosystems render to humans.

Illegal deforestation in Mexico.

Countries in the South in geopolitical negotiations

The UNFCCC divides signatories into two blocs: Annex 1 countries (OECD countries and the former Soviet Union countries) that are responsible for most emissions and the non-Annex 1 countries (developing countries in UN terminology). Negotiations concerning the climate have not recovered from this division of the world. The developing countries first lost interest in the climate problem caused originally by the industrialised countries and in which the same industrialised countries awarded themselves leadership.

The division was also at odds with the new geopolitical pattern with, in particular, the economic boom in China and the affirmation of major emerging countries (Brazil, Russia, India and South Africa). By 2030, most emissions will be from the United States and China, neither of which made undertakings within the framework of the Kyoto Protocol. And Europe, which had put all its energy into obtaining the Kyoto agreement, will account for less than 5% of global emissions.

The 'developing country' category called into question

The United Nations 'developing country' category is obsolete and the countries in the group are now questioning the rules governing the climate question. Their strategies are fragmented into as many divergent interest groups, forming pressure groups with variable geometry: oil-producing countries demanding compensation for the forecast decrease in oil consumption, emerging countries refusing any constraints for development, small island states threatened by rising sea levels, the least developed countries counting on aid for adaptation, ALBA countries led by Ecuador and Bolivia stressing climate injustice and problems of the merchandise approach to nature, the Climate Vulnerable Forum (a strategic group focused on losses and damage that wants the development of an aid system to cover the inevitable or irreversible impacts when adaptation has reached its limits), etc.

COP 20 in Lima, Peru, 2014.

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The few 20,000 people who participated in the negotiations (the representatives of 195 signatory countries and also other stakeholders such as industries and NGOs) thus represent specific interests that are increasingly disconnected from the prime aim of the Convention, that is to say limiting emissions of greenhouse gases. The issue is that of obtaining funding, whether as compensation for damage caused by the west (the ecological debt) for performing adaptation actions (reconfiguration of aid for development) or for covering the cost of climate catastrophes (losses and damage, reconfiguration of humanitarian aid).

Reconfiguration of aid for development

The poorest countries in particular have drawn up national action plans for adaptation to climate change (NAPA) in order to receive aid from the UNFCCC and the Global Environment Facility (GEF). This financial opportunity has encouraged them to incorporate adaptation to climate change risks in all their general development and sector plans.

'Climate loans', another form of aid, have developed since the end of the 2000s. Indonesia was the first country to have benefited from a budgetary loan for its climate plan. Funded by development agencies, the World Bank or the Inter-American Development Bank, these loans for countries with intermediate economies can exceed a billion euros.

Some consider that this reconfiguration of aid centred on climate has favoured a kind of depoliticisation of development by imposing climate change as the ultimate environmental problem, overtaking all the other environment-related questions (biodiversity, desertification, etc.) and those of society (economy, governance, etc.).

The issue of COP 21

COP 21 in Paris in 2015 should mark the beginning of a new cycle of negotiations with an important change in the framework of the climate question. This was outlined at COP 20 in Lima in December 2014. The supreme objective of negotiations will no longer be the reduction of greenhouse gas emissions but other strategies incorporating questions of adaptation and losses and damage. But this readjustment does have contradictions: whereas the objective of keeping emissions below the 2°C threshold was maintained, the adaptation objective envisages temperature increases of 3°, 4°, 5°C... The financial aspect will also be essential for the southern countries to accept constraints. The issue is thus that of setting up a fund of 100 million dollars per year from 2020 for developing countries.

Box 46

Indonesia: assesment of international budgetary aid centred on climate change

The cooperation agencies in Japan (JICA), France (AFD) and the World Bank award *ad hoc* Climate Change Policy Loans (CCPL) to provide effective aid for southern countries in fighting climate change, and especially those with intermediate economies that will in time become the main sources of GHG emissions.
The first test was in Indonesia from 2008 to 2010 (800 million dollars of loans provided by AFD alone). It was soon repeated in Mexico, Vietnam and Mauritius. The loans awarded are not for the undertaking of particular actions against climate change but to catalyse the taking into account of the issue in all public policies.

In 2014, researchers at the DIAL unit evaluated the support provided to Indonesia. Evaluation of budgetary aid is obviously very complicated as it is not possible to establish a direct link between incoming funds (paid to the Treasury) and the results of public policies, especially as the Indonesian government launched an ambitious plan to fight climate change in 2007 when the country hosted COP 13 in Bali (Indonesia is world No. 16 in GHG emission ranking).

The emission reduction objective

Researchers had to define an *ad hoc* evaluation procedure because the standard method used by OECD is applied above all in fighting poverty in the poorest countries.
It therefore had to be adapted to the context of a budget loan to an emerging country.

An evaluation showed that budgetary support (especially during the 2008 financial crisis when countries with intermediate economies had no resources) had had a positive impact on the taking into account of climate change by the planning agency (BAPPENAS) which was thus able to exert pressure on the most recalcitrant ministries (especially the Ministry of Forestry) and to a lesser degree on provincial authorities.
Some concrete measures were implemented, such as the introduction of forest management units and an increase in the purchase price of alternative energy (Indonesia has an enormous potential for geothermal energy). In addition, the CCPL supported the dynamics of a country already firmly engaged in the fight against climate change and marked in particular by an emission reduction target for 2009.
An important measure was taken in January 2015 after the change of government: subsidies for the consumption of fossil energy were abolished (except for fishermen and public transport).

Oil palm plantation in deforested areas in Sumatra, Indonesia.
Six million hectares of forest were cleared from 2010 to 2012 in the archipelago as a whole.

© IRD/G. Michon

With the prospect of a new agreement, 'Intended Nationally Determined Contributions' should replace the reduction undertakings calculated according to a global volume of emissions not to be exceeded. The voluntary contributions should allow all countries to put forward plans to address climate change that are anchored in their national policies and match their priorities and possibilities. For countries in the South, this opening is an encouragement to end the aid approach by proposing national GHG emission reduction policies alongside adaptation policies. Of course it is legitimate to doubt that this bottom-up movement of contributions might result in substantial GHG reductions but the top-down governance of undertakings has not really given convincing results.

Message painted on a wall in Vientiane in favour of the protection of the environment (Laos).

© IRD/J.-Y. Meunier

Leadership by the industrialised countries has been replaced by a set of disparate stakeholders. One of the objectives of COP 21 is to involve all stakeholders, NGOs, social movements, local communities and unions in a multi-objective policy framework and award more value to questions of innovation, technological partnership, solidarity and production and consumption methods. All these questions have hitherto been hidden by the emission reduction imperative via market mechanisms. Thus policies to address pollution, waste recycling and public health can operate with mechanisms other than commercial ones and not directly within the framework of a climate policy in order to reduce emissions. This is referred to as 'co-benefits' or 'double dividends'.

The incorporation of climate change in biodiversity conservation policies

International negotiations centred on climate have participated in the development of global environmental governance with effect on national environmental policies. Research at IRD has shown how the emergence of **global issues** has partially reconfigured environmental governance in the countries studied (Madagascar, Brazil, Mexico, Cambodia and Vietnam). Stakeholders, sources of funding, the rules of the game and intellectual property rights or simply the concepts used now go beyond frontiers and, in a way, are involved in debates on national sovereignty. Analysis of policies for the conservation of biodiversity shed light on the balance of power and the new standards involved in this reconfiguration.

Addressing climate warming helps protected areas

National biodiversity conservation policies have incorporated the climate change agenda for about a decade. This took place mainly in the mid-2000s at the international level within the framework of the Kyoto Protocol. It is reminded that initially the latter did not at all cover biodiversity conservation stakeholders. Forest was incorporated in the Kyoto Protocol little by little with encouragement from countries in the South and NGOs concerned with the conservation of biodiversity (WWF, Conservation International, Fauna & Flora International, WCS). The argument is twofold: firstly, photosynthesis in forests captures CO_2 (the carbon sink function) and secondly deforestation by fire releases this CO_2, increasing the greenhouse effect (see Part 2, p. 147). Protecting forests (especially tropical forests) has thus become an issue in the addressing of climate warming and replanting policies were incorporated in the Kyoto Protocol in 2001. To combat single-species reforestation that is harmful for biodiversity and to focus on countries in the South, it was the turn of avoidance of deforestation (REDD+ mechanisms to reduce emissions resulting from deforestation) to enter the field of negotiations.

Work at IRD has shown that the determination to incorporate climate change in biodiversity conservation policies results from the promises of funding of the carbon market. Countries in the South set up large networks of protected areas from the 1950s onwards under the influence of the international community. These biodiversity conservation policies are focused on tropical forests in particular. However, the maintenance of the protected areas has always been a source of problems. On the one hand, the countries in question see these forest areas as a source of economic development. On the other, their budgets are slender and their contribution to funding protected areas is small. To date, public aid for development has financed much of these policies. But funding requirements have increased while aid for development is faced with other undertakings: health, education, crisis management and rural development.

For stakeholders in the conservation of biodiversity, the ‘climate regulation’ function has become an argument for receiving additional funding whether through REDD+ funds linked to the Climate Convention or from voluntary independent funds. Thus pilot projects have taken shape in the last decade aimed at funding the maintenance of these protected forests by multinational corporations that wish to use carbon neutral strategies (this is the case of Air France and Microsoft in Madagascar for example) or to anticipate future regulations.

Protected area in Madagascar.
The conservation of Malagasy forests is also part of the fight against climate change.

A problem of sovereignty

The research carried out at IRD has identified several problems related to the incorporation of the climate question in policies for the protection of biodiversity. The search for foreign funding in the name of the services rendered by these protected ecosystems has often elbowed out countries in the management of protected ecosystems to the benefit of NGOs and multinational corporations. This is particularly flagrant in countries in which there is a strong foreign influence, as in Africa and part of Asia. Western multinational corporations have been the main sources of funding for protected areas in the name of the prevention of deforestation. They have been out ahead in their search for compensation for their CO_2 emissions as they were concerned by national agreements on the reduction of such emissions or used a '**greenwashing**' strategy. Western conservation NGOs operating in these countries were thus perfect partners. Recognised by the western public and an assurance of a certain degree of good governance of funds, they were targeted immediately as key participants in these new features (REDD+ and voluntary agreements). The countries that generally own the land and the forests often play a minor role in these negotiations (Box 47) and this has

Box 47

The protection of Madagascan forests in the name of the climate

A first REDD+ pilot project was implemented in Madagascar in 2005 with the creation of the largest protected area in the country, Makira, covering 400,000 hectares of forests. Within the framework of the SERENA programme, researchers focused on the effects of the taking into account of the fight against climate change in forest protection governance.

Faced with the major challenge of financing its forest conservation activities, the Malagasy government listened to the arguments of conservation NGOs and the World Bank according to which the REDD+ mechanism could cover a third of the annual budget requirements for the management of protected areas. A pilot REDD+ project was thus implemented in Madagascar in 2005 with the creation of the largest protected area in the country: Makira. Steered by the Wildlife Conservation Society (WCS), an American NGO, the project consists of encouraging the local populations to change their practices and activities with the aim of reducing deforestation.

Researchers within the framework of the SERENA programme led by IRD wished to check in the field in what way REDD+ is an innovation for the governance and conservation of the forests of Madagascar. Their work addressed three aspects of the Makira project. What will be the scale of forest management? How would carbon revenue be distributed? How would non-emitted carbon be measured?

The REDD+ mechanism is presented as the first attempt at the international management of forests while strengthening the institutional capacities of countries thanks to the carbon accounting at the national scale (with a view to setting up a carbon market). However, the Makira project is governed in the field by the American NGO Wildlife Conservation Society (WCS) to which the state has delegated the management of the protected area and the carbon fund.

Forest protection is still managed by the traditional conservation stakeholders

Another divergence between theory and practice is that the local population is on the fringe of the negotiations for setting up 'payment for environmental services' whereas this population is the direct supplier of the service by changing practices to spare the forest. Protection of the forest is managed above all by conventional conservation stakeholders, WCS and new controllers in the form of certification bodies. The local population receives half of the financial distribution as in the other conservation projects on the island.

A final point is that the funding related to REDD+ must be based on results, in other words on the certification that hectares of forest have been conserved—and the corresponding amount of carbon sequestered—thanks to the project. But these requirements can only be met at the scale of the entire forest and not at the local scale. The contracts with farmers are based on changes in practices and the measurement of the carbon sequestered as a result of these serves no purpose and is technically impracticable.

The needs of farming communities in eastern Makira result in the use of land for temporary food crops on slash and burn forest areas or regrowth. Other practices (fruit plantations, irrigated rice growing, small livestock, etc.) and the surveillance of forests, whose management has been transferred to them, receive financial encouragement from the conservation project.

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created tension and suspicion on both sides, especially in the light of the sums involved. Negotiations also concern very large areas on a completely different scale to that of local environment management dynamics. Local populations are excluded from these negotiations and share to a considerable degree the feeling that they have been dispossessed.

Another problem concerns the validation of the carbon credits given to the corporations in return for their financial engagement. Procedures for the verification of the carbon stored thanks to protected areas are necessary. This means not only measuring the quantity of carbon held by the forest (see Part 2, p. 147) but also demonstrating that it is clearly the 'purchase' of these carbon credits that accounts for forest conservation. If by any chance forest is conserved by other methods (for example by respect of the law or the dismantling of an illegal export system), carbon credits will not be validated. All this makes the establishment of funding facilities for areas protected by carbon credits extremely complicated, especially as paid international expertise that the host countries rarely possess is usually necessary, and this takes a large proportion of the funding made available for these projects (Box 47).

It is noted nevertheless that although 'carbon' funding gives rise to much hope, it forms only a small proportion of current financing. Biodiversity conservation stakeholders consider that carbon is an innovative funding option but it is in no way the only one. Many conservationists feel that it is dangerous to limit the interest of conservation to the carbon dimension alone as the richness of biodiversity is not always linked to biomass carbon content.

Chapter 15

Climate change and the issues for health in the South

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The Matinhas district in Cayenne, French Guiana. The groups of people rendered most fragile by the effects of climate change are also those in precarious situations and who have received little education.

Climate change will increase inequality and hinder socioeconomic development of countries marked by chronic poverty and therefore have major health implications. According to the World Health Organization (2014), climate change is already having a direct effect on the social and environmental determinants of health but beyond this the repercussions could be more indirect. For example, crop yields and fish catches could be affected and as a result the nutrition of the population, or human migrations might be triggered, further exposing individuals and communities to sanitary threats. The development of transport and industry in the large megalopolises in the South should lead to hitherto unequalled pollution, aggravating cardiovascular and respiratory diseases that are themselves closely clinked to climate upsets.

Although several determinants may thus be involved, it is still very difficult—outside observations that are often very alarmist and not based on scientific proofs—to actually measure the impacts of climate on health in countries in the South as the data are not available today. However, it has to be admitted that there will doubtless be several million victims. The most vulnerable populations that are often located in regions without adequate social and sanitary infrastructure will also be those least able to face these new situations. Improvement of health and well-being must form a major objective in development policies in the light of the foreseeable worsening of health conditions. Such a policy will also make it possible in turn to act on the adaptation capacity of persons and public entities to adapt to these threats. In this context, the levers formed by the promotion of awareness of the population, the gathering of reliable scientific data and the strengthening of health systems are the basis for a major line of research for IRD and its various partners. Extreme events such as heat waves and repeated flooding, air pollution especially in developing megalopolises, soil erosion and the availability of water resources, nutrition and infectious or parasitic diseases are all fields in which the measurements and monitoring that are essential for anticipating the sanitary effects of climate change are still lacking. An overview of the probable or expected health risks ranging from mental health problems to infectious diseases.

The countries in the South are more vulnerable to climatic dangers

According to the last annual report (2014) of the British institute Verisk Maplecroft, 67 of the 194 countries analysed seem more exposed to future climate events, with the most vulnerable being the countries in the South and especially those in sub-Saharan Africa. The study is based on evaluation of the exposure of populations to climate change and also their susceptibility in terms of health, agricultural dependence and available infrastructure and on their capacity to adapt to and combat these impacts. Unsurprisingly, the 67 states in question currently have the poorest and least well-informed population and are those with the scantiest public services. Here, climate change means inequality in the consequences, especially for health, as other regions that are exposed but that possess strong adaptation capacity because of their human, logistic and financial resources will prove to be much less vulnerable.

Although the effects of changes in climate and the vulnerability of poor populations vary considerably from one region to another, it is nonetheless accepted that the impacts of climate change will be added to existing vulnerability. The health of poor people will probably deteriorate and there may be a real threat to food security in many countries in Africa, Asia and Central and South America. According to the OECD, the effects of climate change could thus call development into question in numerous countries in the South.

Not enough long-term studies or reliable data

Paradoxically, there is an almost total lack of scientific data, or at least data available today, on the links between climate change and health in developing countries. In addition,

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Baduel district, Cayenne, French Guiana.
This district is like a Brazilian favela and the precarious conditions expose the population to climate risks and their consequences.

the rare examples that we can consult display an enormous disparity in research on infectious diseases (dengue, malaria, etc.) and that on chronic diseases. The reason is probably a tropical studies tradition in countries in the North in which the focus is only on endemic infectious and parasitic diseases.

As the changes in climate form continuous processes and are by definition complex with extremely heterogeneous consequences, the issue is that of adapting the gathering of scientific data both in time—avoiding one-off examination of obvious short-term features such as those occurring during extreme climatic events—and in space as in a region the zones lacking the necessary health infrastructure will be those most affected. There are thus very strong uncertainties in our understanding of the impact of climate change features in these regions and development sciences must stimulate mobilisation, innovation and militancy in future debates.

The links between climate change and health, a three-stage process

Analysis of the 'conceptualisation' of the consequences of climate change for health from the mid-1980s, when the IPCC was founded, reveals three stages of structuring today. These stages become enriched semantically as calls are made on fields in other disciplines and new knowledge emerges. A linear and hence very simplified understanding of the 'impacts' of climate change on health lasted until the mid-1990s, and especially on the WHO website devoted to climate change (Fig. 29a). Although this essentially environmental and physical concept of the effects of climate on health made it possible to list expected or probable effects on health, it nonetheless had an orientation as it placed climate change upstream of the causes, considering them to have this single environmental determinant.

From then until roughly the mid-2000s, with the broadening of the network of collaborators and scientific and public questioning, although the ontology of the consequences of climate change for health was not upset, better account was taken of the human aspect, especially as regards the capacity of societies to develop scientific knowledge or adapt to these adverse environments (Fig. 29b).

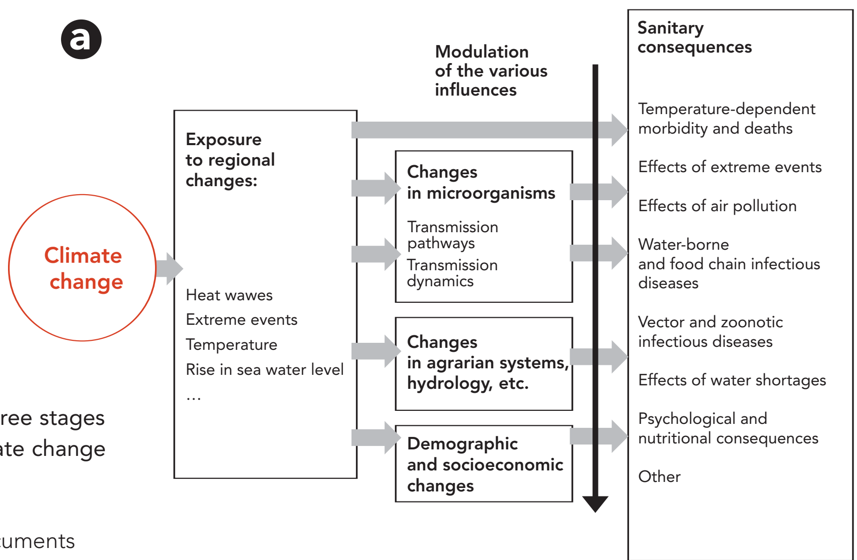
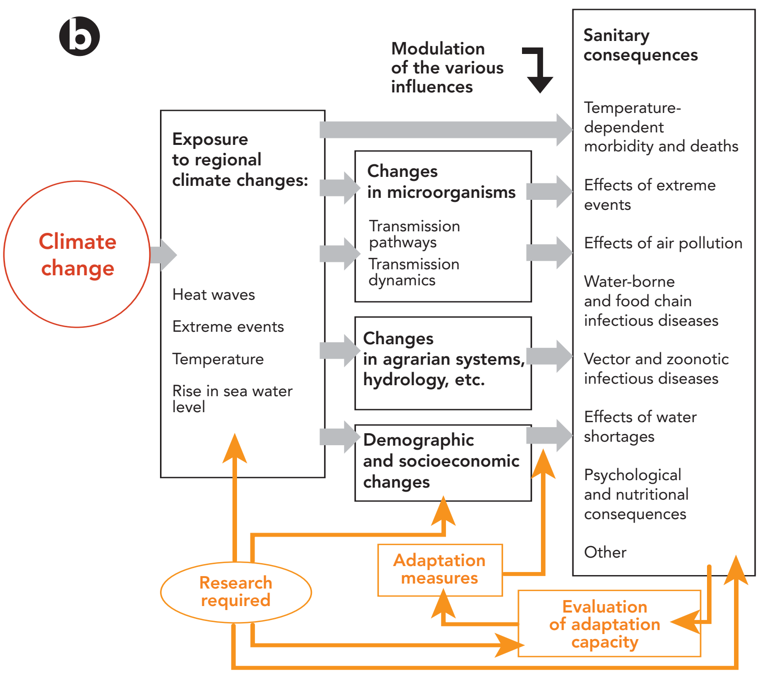


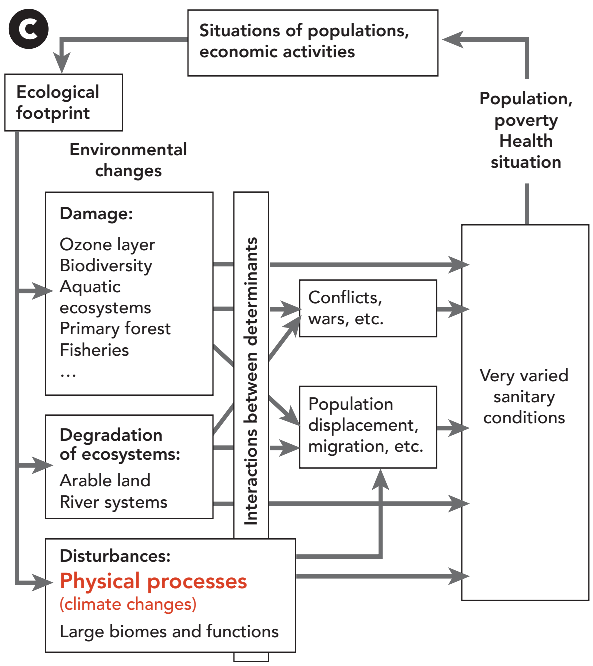
Figure 29.
Illustration of the three stages of research on climate change and health.
The diagrams are from the official documents of various international programmes and organisations (WHO, UNEP, etc.).
Source: IRD/J.-F. Guégan

Climate change, a component of global environmental changes

The third, ongoing sequence is aimed at incorporating climate change as a component of global environmental changes, while awarding obvious importance to human activities and their anticipation and resistance capacities (Fig. 29c). A great many scientific programmes focused on climate change and its consequences have evolved towards closer integration of their work, taking better account of ecological, sociological and economic aspects and of the progress made in green engineering. The setting up of the international UN programme Future Earth (www.futureearth.org) combining four older scientific programmes on environmental and human changes (IHDP, Diversitas, WCRP and IGBP) clearly shows this trend.

The three approaches have oriented research on the consequences for health of climate change. Much research conducted from 1985 to 1995 showed a link between climate malfunctioning and heath (mainly for infectious diseases). From 1995 to 2005 there were serious controversies concerning the direct effect of climate change on health. Finally, much previous work has been questioned since 2005, and human activities and behaviour and the organisation of socioeconomic systems have been placed at the centre of the discussion.





An ecological approach to health

Recent work with ecological niche models to predict the risk of malaria in Africa and using a large number of parameters other than meteorological ones shows that factors such as human population density are preponderant in explaining the present and future distribution of this type of risk of infection. In contrast, the research carried out in the 1980s and 1990s contains numerous demonstrations of the major role played by climate changes in such infections and their future spread.

In parallel, there has been a distinct decrease in the number of pages on the consequences for health of climate change in publications by French and international institutions. Why this decrease at a time when the Director-General of the WHO has announced that 'Debates about climate change are still not giving sufficient attention to the profound effects that climate variables have on health'?

The negative effects of alarmist communication

The three stages described above show the difficulty today in mastering the subject of climate change and health. The passionate statements and production of scientific information in the first stage, with demonstrations that were sometimes not particularly convincing, were followed by suspicion by some of the public and real lack of interest,


Sciences News

Climate change might help spread malaria

Published: March. 4, 2010 at 1:53 PM

Article | Listen | Comments

Figure 30.
An example of an alarmist press communiqué published by Science News on 4 March 2010 and aimed at illustrating the possibly alarming spread of malaria caused by climate change.
In fact the map shows, but with a few doubts, the regions in which various forms of malaria spread in 1900.

even in scientific spheres. The call by the Director General of the WHO comes at a moment when even in scientific circles it is considered that questions of health related to climate, and hence communication messages, are too alarmist and could frighten people! Might communication concerning research on climate change have switched to simplification? The media subject '…the effects that climate variables have on health.' must not harm world health. There is no doubt that health threats linked to climate change do exist. They should be the subject of awareness campaigns targeting the population and national and international public authorities, objectively and without exaggeration. They must also be based on scientific proof. The foundation of this scientific information is based on the establishment of a purpose-designed network of surveillance information services that obviously include countries in the South and on a long-term research approach to avoid a short-term catastrophic view.

What health effects are observed in countries in the South?

This relatively recent (about a decade) research theme shows two main strategic orientations: the first approach is medico-geographical and aimed at understanding the geographic distribution of infectious systems and the evolution of their distribution according to changes in climate; the second is based on a methodological corpus of analyses of time series (cases of infectious diseases and climatic parameters) to study the short and long-term consequences of climate change on the appearance and frequency of infectious epidemics.

Change in the spatial distribution of the infectious system

As regards geographic distribution, research by IRD and its partners in West Africa has shown for example that the spatial distribution area of the bacterium *Borrelia crocidurae* has increased by 350 km in comparison with its original area. Spread by ticks, the illness causes recurrent fever and is a public health problem in this part of Africa. The southern limit of the infectious system is now at isohyet 750 mm and the northern limit crosses the River Senegal and reaches northwest Morocco. The recent change in the geographic area of the disease and its vector has been linked to climate changes in the region. Other similar studies by IRD are focused on the evolution of the geographic distribution of *Leishmania*/Phlebotominae sand flies in several countries around the Mediterranean and also of the mosquito *Aedes albopictus*, the vector of dengue and chikungunya viruses at the Mediterranean and world scales. However, links with climate are

Searching for ticks, the vector of Lyme disease, in Senegal.
The area of distribution of the disease and its vector has shifted northward because of climate change.


© IRD/J.-F. Trape

still difficult to establish while all this research often lacks references for the establishment of past distribution and are also potentially biased by confusing factors such as the spreading of disease by humans and transport. But it remains essential to identify and map the zones most vulnerable to these new health risks and determine the intervention measures necessary for human populations.

The development of early warning systems

A second category of research work is performed on correlating time series (often long) of cases of several infectious diseases with time series of meteorological parameters such as temperature or rainfall or with indicators used as approximation variables of climate changes. Thus work on cases of dengue in New Caledonia and Thailand, on cholera and meningitis in Africa and on Buruli ulcer in French Guiana and Cameroon makes it possible to specify the effects of medium and long-term climate change on the appearance of epidemics of infectious diseases and the increase in their frequency. More generally, this work makes possible the construction of statistical models to explain and predict epidemics of the various infectious diseases, prefiguring the development of early warning systems.

Box 48

An (in)direct link between Buruli ulcer and climate change

In French Guiana, a team of IRD researchers and their partners have shown for the first time and over a 40-year period, the relation between climate change and epidemics of Buruli ulcer. This emerging disease in South America is caused by an aquatic mycobacterium naturally present in tropical freshwater ecosystems.
The research team compared changes in rainfall in the region with the changes in the number of cases of Buruli ulcer recorded in French Guiana since 1969 (Fig. 31).

The rise in surface water temperature in the Pacific tends to increase the frequency of El Niño events that hit in particular Central and South America approximately every 5 to 7 years, causing periods of drought.
The decrease in rainfall and rainfall flow results in an increase in areas of residual stagnant water where the mycobacterium that causes the disease proliferates.
The subsequent greater accessibility of marshy habitats results in more movement of humans there for fishing or hunting for example, intensifying their exposure to the infectious microorganism.

This example illustrates the possible indirect effects of climate change on natural ecosystems, the change in habitats of species that may result and the emerging risk of infection.

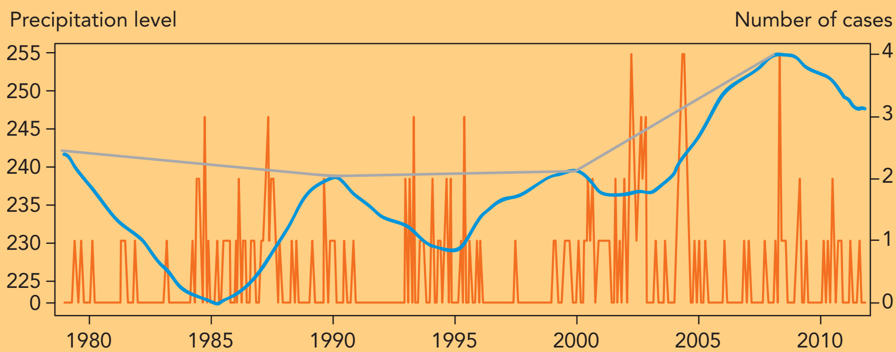


Figure 31.
In French Guiana, the number of cases of Buruli ulcer (in red) changes according to precipitation levels (in blue).
The periods with the lowest precipitation levels, marked by the El Niño phenomenon in the sub-region, display the largest number of cases of Buruli ulcer.
Source: *Nature Publishing Group*, 2014.

Health prospects in the South

While weather conditions have a considerable effect on diseases spread in water (numerous bacteria and viruses) and those spread by arthropods (malaria, dengue, etc.) and even by reservoir animals (molluscs, rodents, bats, etc.), the effects of climate change are not always propitious for the spread of vector diseases. For example, in some parts of West Africa the decrease in rainfall forecast in the medium term would be unfavourable for the malaria parasite cycle and the geographic area should decrease in certain zones. It is very probable that an increase in temperatures and greater variability of precipitation will result in very variable health pictures in tropical regions.

Another source of uncertainty concerns the specific responsibility of climate in relation to the other parameters, especially in countries in the South where anthropisation has many forms and affects all socio-ecosystems and where biophysical and human aspects are closely entwined. In just a few decades, industry and agriculture

Polluted water, a habitat for mosquito larvae in Yaoundé (Cameroon).

© IRD/C. Costantini

have caused numerous cases of soil and water pollution. Accelerated urban spread has resulted in the artificialisation of shores and the degradation of natural environments. The globalisation of transport has caused the arrival in ecosystems of exotic, sometimes invasive species. The impact of these pressures on the environments is combined with that of climate change that leads for example to more favourable conditions for the pullulation of certain species and speeds up the eutrophication of aquatic environments. Likewise, the rise in temperatures results in increased need for irrigation water and in return this generates further impacts on the discharge of coastal rivers, groundwater levels and the creation of new habitats for insect vectors of infectious diseases.

The long list of health impacts expected

Crop yields will be affected in several regions with higher temperatures and less rainfall, aggravating affecting food insecurity. As is said in this Peul proverb: 'Grass isn't growing, millet isn't growing, so you have to leave'. Population displacement will increase tension and increase the risk of conflicts. These movements will disturb individuals psychologically. Longer, more frequent periods of intense heat could cause an increase in deaths caused by asthma-type respiratory complications or cardio-vascular diseases. Such health risks will increase in cities in developing countries where the effects of heat waves and air pollution will complicate the epidemiological situation. The scarcity of water in the driest zones could have anthropological, social and economic repercussions that are still difficult to forecast, as is shown by certain human behaviour in south-west India where men take a second or even a third wife, referred to as the 'water wife' whose main task is searching for potable water for the family. In this context of multiple interactions, the attribution of an observed impact to a given cause is a recurrent difficulty for scientists.

The effects of ultraviolet radiation caused by changes in the ozone layer in numerous southern countries, and especially in cities where pollution by gases may damage the ozone layer, will cause an increase in the number of cases of skin cancer or sensorial disturbances that can lead to blindness. Natural catastrophes such as extreme weather causing floods or landslides will form an increased risk of mortality for populations and regions that are already very vulnerable. These conditions will increase the risks of water or vector transmission, making this aspect more serious.

There is thus no doubt that the effects of climatic evolution on health in southern countries are numerous, with several being preoccupying, and are not limited to infectious vector diseases alone. An ecological transition with serious repercussions for public health will therefore be added to the epidemiological transition experienced by developing regions.

Anticipating crises by adapting health systems

As in the saying 'Prevention is better than cure!', the improvement of health and care systems, including surveillance and health monitoring systems, can form the first measures of adaptation to climate change, especially in developing countries. For example, it is surprising that most of the countries in central and West Africa have not set up health security agencies and national public health councils. It is not just a wager. The improvement of health and the quality of life of the population will result in an increase in capacities to adapt to climatic conditions and also better protection against other threats and catastrophes. The quality of ecosystems, air, food and potable water and better education/information for the public on these subjects will enhance the **compliance** of populations and generate reactiveness in the face of climate threats. This more global approach is the basis of what is called 'health ecology', a relatively new health research discipline.

Although long-term investments aimed at limiting global warming sometimes seem discouraging or even vain, those made in the health sector will have concrete results and benefit the greatest number. The uncertainties that remain with regard to the numerous health, social, environmental and economic consequences must now make it possible to establish a closer link between the mitigation and adaptation agenda and the other development agendas.

Box 49

For a multisite world research programme

Today, IRD is anticipating the consequences for health of climate evolution by conducting research with its partners in the South and with various French and European research institutions on public health in relation with climate change. Historically specialised in tropical infectious, parasitic and nutritional diseases, IRD is evolving and adapting to take better account of the multiple facets of the health effects of climatic evolution on vulnerable populations in the South.

With its history, its knowledge of southern countries and with a procedure of responsibility and exchange with these partner countries, IRD is campaigning for the drawing up of a multisite world research programme allowing comparative approaches. Furthermore, the programme should be run on a long-term basis because health effects may occur after a long time in comparison with the life histories of populations.

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Cairo, Egypt.
Cairo has a population of 18 million and is the largest city in Africa and the Middle East. Intense pollution of water, air and soil is a deeply concerning public health problem for the authorities.

Politicians' need for decision aid correspond to the need to make progress in scientific knowledge. By shedding light on the bidirectional relations between economic development and health, recent work encourages a closer relation between fighting climate change, protection of the environment and the strengthening of health systems. From the scientific point of view, this requires better organisation of interdisciplinarity between ecology, infectiology, plant, animal and human biology, economics and social science, modelling and the strengthening of longitudinal monitoring services focused on the environment and population and health behaviour.

Chapter 16

Agricultural development measured against climate change

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Field of quinoa in the Salar de Uyuni (Bolivia).
Adapted to arid environments and poor or saline soils, quinoa is also highly resistant to cold, frost and wind. Scientists are studying it to test its resistance to climate events.

After being excluded, agriculture is gradually gaining a position in climate policy negotiations. The IPCC Fifth Assessment Report assessed the potential reduction of GHG at between 20 and 60% in land-based sectors (agriculture, forestry and other land use) by 2030. The challenge to the sector is enormous. Greenhouse gas emission must be reduced in agriculture. The latter must also adapt to climate change while responding to food security imperatives. According to the FAO, agricultural production should at least double by 2050 to match population growth.

What are the agricultural models expected for handling these issues? 'Climate-Smart Agriculture' is the name given to project agriculture that can meet all three objectives: mitigation, adaptation and productivity. Supported by those in favour of the incorporation of the agricultural sector in climate policies, the notion covers different views of agricultural development. Between supporters of agriculture centred on technological innovation and those who defend small-scale family or local agriculture used to climatic variability, many pathways for the adaptation of agriculture to climate change are being explored.

One thing is certain. The ecological crisis faced by agriculture in many places in the world, with erosion and decreased soil fertility, water management difficulties, decrease

Cacoa growing in Cameroon is mainly in the form of family farming and is a substantial source of income for the rural population.

© IRD/S. Carrière

in phytogenetic resources and the disappearance of pollinating insects, together with social problems with growing job losses has ruled out the Green Revolution as the sole model. Using the diversity of the practices of small farmers as local responses to climate variability is also an issue for farming in the South where agriculture consists very largely of small farms with areas of less than 2 hectares. Numerous studies conducted by IRD show the capacity of small farming to respond to climate variations, among other things.

In addition to the climatic impacts and ecological crises felt in many regions of the world, it should be remembered that the agricultural sector is also destabilised by international economic approaches and especially the interest of financial markets in agricultural produce and the hoarding of farmland. In this context of climate change and population growth, the forecast decrease in land reserves and water, increased demand for food and, more recently, a substantial increase in the price of food products have led some countries, multinational corporations and international investors to start a race for land. According to the World Bank, 56 million hectares of land was leased or sold in 2009, with the leading target being sub-Saharan Africa.

The sequestration of atmospheric carbon in cultivated land

Agriculture alone accounts for nearly 12% of global emissions of GHG. Counting deforestation, with one of the main causes being clearance for agriculture, the agriculture and forestry sectors are responsible for nearly a quarter of global emissions.

Furthermore, the agricultural sector is the source of most methane and nitrous oxide emissions as a result of livestock farming and the use of fertilisers. But reducing these emissions is not a priority in the tropics as small farming or family farming is still dominated by crops and makes little use of fertiliser. Nevertheless, this aspect seems to rule out commercial farming for small farms in the south as this would risk causing emission levels to rocket. Thus the main mitigation measure that should be used in the South is aimed at carbon sequestration in soil in order to slow the increase in CO_2 in the atmosphere.

Carbon storage and soil fertility

The maintaining of stored carbon is linked to the quantity of organic matter in the soil. Agronomists know well that soil organic matter ensures the satisfactory functioning and sustainability of agro-ecosystems as it allows storage of the nutrients needed by plants and stimulates biological activity, as it is a source of both energy and nutrients for soil organisms. Organic matter also plays a central role in the structure of soils and

Farm work in the High Atlas in Morocco.
Water brought to a field in the village of Agremugzen for growing potatoes between plots of barley.

contributes to stability in the face of aggression (rain, compaction, etc.). It thus enhances soil permeability, aeration and moisture retention capacity. Carbon sequestration is thus accompanied by the maintaining of fertility and moisture in farmland. The farming practices that allow carbon storage are therefore often those recognised and set up for sustainable land management that is propitious for the protection of the environment and soil productivity.

Many techniques—and especially traditional ones—have long been known for improving the organic matter content (compost or straw, fallows and grassed strips that stabilise the soil and improve infiltration of water, sediment retention, etc.). The issue in dry regions is that of improving water management while avoiding loss of organic matter, in particular through the use of mechanical techniques such as zaï. This traditional technique found in part of the Sahel (Mali, Niger and Burkina Faso) is a special form of pit farming in which water and fertiliser are concentrated in micro-basins. Other agricultural techniques recommended for several decades within the framework of water and soil conservation also enhance carbon storage: soil cover techniques, agroforestry, etc. Techniques for addressing desertification also contribute to carbon sequestration in the soil.

Evaluating the quantities of carbon fixed in soil

Although everyone agrees about the sequestration capacity of these different techniques, the question of the quantities of carbon that are actually sequestered is still a subject for debate. Part of agricultural research on soils thus consists of measuring the quantities of carbon in soils according to the management method. The scientists evaluate soil carbon contents according to tillage practices, the type of plants grown and soil composition. This quantification is needed for validating the role that agriculture will play in emission reduction strategies. Another line of work is the development of measurement techniques that are easier to use and cheaper. This is a necessity, in particular in countries in the South (Box 50).

At the international scientific conference on Climate-Smart Agriculture in Montpellier in March 2015, Stéphane Le Foll, the French Minister of Agriculture, called for the launching of a major research programme called '4 per-mille'. The figure is used as a symbol, showing that a very small variation in soil carbon stocks (of some 0.4%) can affect the global CO_2 balance. Field measurements made by various IRD research teams in Mediterranean, subtropical and tropical contexts indicate storage variations that are comparable with this 4‰ objective.

Box 50

New techniques for measuring soil carbon content

IRD is recognised as one of the world leaders in the application of near-infrared spectrometry techniques. These are faster and less costly than conventional methods for soil carbon measurement.

There are two classic types of technique for measuring the carbon content of soils.
Both are destructive.
Oxidation methods are based on the direct analysis of organic carbon after oxidation of organic matter using potassium dichromate.
But the latter is a pollutant and very allergenic and the methods were discarded in favour of combustion techniques. These provide accurate determination of total soil carbon (organic and inorganic) but are expensive at about €15 per sample.

Less costly techniques have been developed over the past decade.
They include near-infrared spectroscopy (NIRS) that costs around €1 per sample.
The new methods can be used to work directly on unprepared soil samples (no crushing or sieving) but require calibration using a reference soil database.

IRD is at the cutting-edge of infrared spectrometry application techniques.
Work on soils from dry regions shows satisfactory calibration of spectra in the near infrared is possible for determining soil carbon and nitrogen contents.
In addition, recent work shows that NIRS technology allows satisfactory discrimination between organic and inorganic carbon in soils, which is still a tedious task using conventional methods.
Finally, studies are currently focused on *in situ* measurements that would overcome the uncertainties of sampling.

© IRD/V. Chaplot

Observation of the result of a chemical test to detect the presence of iron in the surface soil horizon (South Africa).
The red colour indicates anoxic conditions favourable for the storage of organic carbon and the denitrification of water.

Box 51

The evolution of soil carbon in soils under conservation agriculture

Within the framework of the RIME-PAMPA international project led by IRD, the Eco&Sols unit works on the evolution of carbon stocks in conservation agriculture soils. This system used in agricultural development programmes is based on three principles: minimum tillage, the rotation of several crops and permanent soil cover. The contribution of plant cover (dead or alive) is in theory capable of increasing the annual input of organic matter and hence the organic carbon content of soils.

Eco&Sols researchers used both conventional methods and those based on near-infrared spectroscopy to measure the evolution of carbon stocks in soils.

Soil samples in Tunisia, Cameroon, Laos, Vietnam, Brazil and Madagascar displayed sequestration capacities of a few hundred kg of carbon per hectare. The level is thus low in relation to the billions of tonnes released by human activities. Nevertheless, the sequestration potential of conservation agriculture could become significant at regional and global scales.

Fieldwork on rainfed rice in Laos.

The advantages of biodiversity in the face of climate uncertainty

How can crops and forms of livestock farming be adapted to climate change? As it is difficult to make fine forecasts of changes in climate, especially in the tropics, the capacity of adaptation of farming systems must be strengthened rather than performing a search for *a priori* solutions. In this context, the diversity of the plants grown is an advantage insofar as it provides a broad variety of available characters that can be used according to climate conditions. Research conducted by IRD has shown in particular how genetic diversity in millet varieties has allowed adaptation to drought (Box 52). This work also shows the interest of *in situ* breeding making use of local varieties.

However, the role to be given to the management of biological diversity in agricultural development is not obvious as selection conducted by agricultural research has favoured pure lines for half a century in order to ensure stable characters in successive

Box 52

The adaptation of millet to climate variation

Following the various drought periods in the Sahel in the 1970s, 1980s and 1990s, researchers at the DIADE unit and their partners have sought to understand how cultivated millet varieties adapted. Their results show how genetic diversity within varieties made possible adaptation to the decrease in rainfall.

What were the effects on cereal crops of the major drought periods that hit the Sahel between 1970 and 1990? IRD biologists addressed this question in the context of climate change. They sought to understand how the varieties of millet, one of the most commonly grown grain crops in the dry zones of the region, adapted to the changes in rainfall.

The scientists were able to compare genomes using two samplings of millet seed grown in Niger in 1976 and in 2003. The results give much information. First, the diversity and types of millet grown changed little over a period of about 30 years.

Adaptation was thus not the result of the use of new cultivated varieties by farmers. However, within the same variety, the plants grown in 2003 have earlier flowering dates than those of 1976. The diversity of certain genes of the 1976 seed permitted this change. Thus, many plants of the same species were able to respond to new climate conditions.

The adaptation was the result of coevolution between varieties, the environment and the selection pressure maintained by farmers on their seed stocks. In Niger for example, seed was selected and re-sown by farmers from one year to the next. During drought periods, late rains have a less harmful effect on early flowering varieties. Farmers' *in situ* selection makes it possible to favour the more drought-resistant plants and these are sown again in the following year.

The biologists compared the number of alleles in the genome of the varieties at an interval of 27 years and found that this remained constant. Selection maintained genetic diversity and thus did not affect the capacity for adaptation to new conditions in the future.

A millet market in the Niamey region (Niger).

© IRD/M.-N. Favier

Box 53

The traditional farming system in the Rio Negro area, a source of agrobiodiversity

Often criticised, traditional slash-and-burn cultivation does have its advantages. In particular, it ensures a great richness of cultivated plants. The recognition of the Rio Negro Amerindian farming system as an immaterial heritage in Brazil is opening pathways for the use of the remarkable biological resources and knowledge in traditional agricultural practices.

In northwestern Brazilian Amazonia, IRD researchers and various Brazilian institutions have shown within the framework of the PACTA project the great diversity of cultivated plants in the traditional Rio Negro farming system.
More than a hundred varieties of bitter cassava and about two hundred other species or varieties have been recorded. This agrobiodiversity is accompanied by a rich food heritage based essentially on cassava (beer, tortillas, condiments, roasted semolina, etc.).

The existence of this broad range of phytogenetic resources results from agroecological criteria (strategy for resistance to pests and diseases, the staggering of harvests and adaptation of many ecological niches among others) and also cultural and not only farming models of crop management.

In the Rio Negro area, possessing numerous varieties of cassava is something to be proud of, as is taking care of them; there is constant interest and curiosity about the testing of new varieties. The female farmers pass around cassava cuttings, banana plants and seeds of other crop plants all the time. The conservation of plant diversity thus operates at a collective scale covering a radius of several hundred kilometres.
Cuttings and seeds are given, exchanged or passed on according to procedures that depend on the type of plant. Fruit species are passed around mainly among the men and cassava and companion plants more among the women.

The environmental impact of slash-and-burn is usually limited to the annual clearing of less than half a hectare.
It takes about a dozen years for forest cover to become reconstituted in the scarred area.

In 2010, this traditional farming system was recognised as an immaterial national heritage.
For Brazil, it is the first time that such a listing makes explicit reference to the notion of system and concerns a both biological and cultural good.
Official recognition opens pathways for making use of the remarkable biological resources and knowledge associated with traditional types of agriculture.
However, it should not be forgotten that these singular types of agriculture are not limited to the technical aspect but also reveal other conceptions of the world and society.

Cassava tubers set out for retting at Santa Isabel on the Rio Negro (Brazil).

generations. But the recognition of diversity as a source of adaptability contributes to the redefinition by decision makers of certain practices of small farmers whose agrosystems are widely recognised as regards the maintaining of great diversity of species and cultivated varieties.

Through many studies on small farming in the South, IRD contributes to better understanding of local innovation and experiments leading to the diversity of cultivated plants. The example of the research carried out in the Rio Negro drainage basin in Brazilian Amazonia shows clearly how agricultural practices and knowledge generate and maintain considerable biodiversity (Box 53). Through the diversity of the food resources that they generate, such farming systems also form a lever to ensure the food sovereignty of populations.

Practices that adapt to climate variability

As is highlighted by the examples of agrobiodiversity mentioned above, farmers' strategies and practices are far from being immutable, but adapt to changes in the climate and the environment. The large amount of work carried out by IRD in sub-Saharan Africa also shows how a rural population that is very dependent on rainfed agriculture has had to handle a change in the rainfall regime over the last 60 years.

Within the framework of the ESCAPE project run by IRD, thousands of surveys conducted in Senegal, Niger and Benin show that farmers clearly perceive the changes in climate and adapt to them. In Senegal for example, the rains have returned for about 15 years and farmers have changed the millet varieties used, going back to those grown before the start of the great droughts (1960), outstripping the models that would have advised them to do the same thing! Adaptation strategies are complex nonetheless. With the same perception of the change in rainfall, researchers observed many trajectories responding to different constraints and in particular to the economic situation.

Numerous strategies are also used in the Andes to reduce climate risks. Farmers mix several types of crop plant in the same field, cultivate numerous plots to optimise exposure to the sun and spread the risks of frost or adjust sowing dates and the varieties grown to adapt to the changes in rainfall.

The capacity for local farming practices to adapt to climate and environmental changes is often not recognised by those who believe in a productivity approach. Work on beekeeping in Morocco clearly shows the tension between strategies with emphasis on productivity and those favouring robustness in the face of climate uncertainty (Box 55).

Box 54

The agroecosystem in the Niakhar zone is becoming diversified with the return of rainfall

Researchers working within the ESCAPE project led by IRD show that farmers in the Niakhar groundnut area in Senegal have adapted to the climate variations of the past 60 years. With the return of rainfall at the end of the 1990s, the agroecosystem was diversified, with revised use made of the practices that existed before the drought years.

Small family farming in Senegal must ensure food security for a rapidly growing population and adapt to new climate, environmental and market constraints (droughts, extreme events, decrease in soil fertility and biodiversity, shortage of land and the destructuring of the groundnut sector)—while using mainly rainfed systems and tools several centuries old. In this difficult context, farmers have succeeded in extending the limits of their agrarian system and have developed strategies to prevent land saturation through crop intensification, extension of cultivated land, the adoption of certain innovations, the development of a migratory system, etc.

New opportunities have emerged since the beginning of the 21st century. On the one hand urban markets have grown and on the other rainfall has increased to levels close to those prior to the great droughts. The single agrarian model used at the beginning of the 20th century was affected considerably by environmental and economic crises.

In the Niakhar area, the agroecosystem is following diversified agricultural pathways but also using old practices and forms of organisation, especially now that abundant rainfall has returned. The reintroduction of livestock farming, the development of cattle fattening, the beginning of the regeneration of acacias, the return to the cultivation of long cycle millet and market gardening are clear signs of these changes. They reveal reactiveness, flexibility and capacity for the diversification of the **socio-ecological** and production **system**.

However, farmers also perceive the fragility of these innovations that are at risk from climate and market uncertainties. For example, Serer farmers have cautiously started to grow long cycle millet (that requires more rain) but without replacing short cycle grain completely. The scenarios drafted by climatologists confirm these fears, forecasting more extreme precipitation events (violent storms) and even higher temperatures in the near future.

Harvesting and storage of ears of millet in the Niakhar region (Senegal).

Box 55

Moroccan beekeeping in the face of climate uncertainty

Beekeeping is particularly sensitive to variations in climate. For example, poor flowering can decimate entire colonies of bees. Researchers of the GRED unit and their Mediterranean counterparts are examining how beekeepers in southern Morocco are handling climate uncertainties and the increased demand for honey.

Beekeepers in southern Morocco have always been able to handle climate risks with the help of the Saharan honeybee.
This subspecies of *Apis mellifera* is economic in terms of water and honey and can withstand variations in temperature.
However, colonies can be decimated to a considerable extent in very dry years when flowers are rare.
The population of these bees recovers very rapidly when conditions are favourable again. This is possible thanks to their swarming capacity.
Under conditions of uncertain flowering in a semi-arid environment, beekeepers work with this extreme variability in numbers. As much as 90% can be lost.
In difficult years, the stock is partially conserved both by beekeeper who supply a few hives with honey, figs or dates and by wild swarms that occupy and survive in natural cavities.

Beekeeping in Morocco has changed scale and practices over the past decade to meet growing demand.
Beekeepers have adapted to the market and also to climate deterioration in two main ways: by the more or less systematic feeding of bee colonies or by taking hives to reliable flowering areas as they are irrigated (orange groves for example) and also to places with spontaneous occasional but massive flowering periods (euphorbia steppes in southern Morocco or thyme vegetation areas in the mountains).
However, both these forms of adaptation are subjects for controversy within the profession.
Migratory beekeeping has favoured genetic hybridisation that reduces the ecological advantage of Saharan bees under difficult climate and ecological conditions.
Feeding is criticised for its little-known effects on the health and strength of the bees.

Today, the two systems seem to be mutually opposed in a classic 'the ancients versus the moderns' face to face. But mutual recognition, interactions and persistence side by side would ensure greater stability, stemming from diversity itself.
The issue is in particular that of reintegrating environmental adaptation qualities in bee selection whereas agronomic research today favours criteria of productivity and of docility.


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Collecting a swarm of wild bees in an argan tree at Jbel Ghir (southern Morocco).

© IRD/H. de Foresta

Irrigated rice fields
on terraces
with dammar agroforest
in the background
(Sumatra, Indonesia).

Technical solutions to strengthen adaptation capacity

Projections of climate change and its impacts suggest that times will be hard for tropical agriculture if climate warming reaches +2°C. A new phenomenon in its rapidity and scale, might such an increase exceed famers' reactiveness threshold? The agronomic research sector is exploring solutions for strengthening the adaptation capacity of small farming, such as the search for techniques or varieties that improve the resistance of farming systems to drought.

Old practices such as agroforestry are also being updated. This system is found from the humid tropics to semi-arid regions. In a context of climate change, the main advantage of agroforestry is that it lowers local temperatures by several degrees. The shade given by trees also reduces the evapotranspiration of crops. The combination of trees and crops improves carbon sequestration and has many other useful ecological features (erosion control, fertility and infiltration of moisture). In a context of uncertainty, the diversity of the resources generated by crops and also by forests (timber and other forest products) is also an economic strong point.

Beyond agronomic research, innovation pathways are also focused on the development of economic facilities such as access to loans and insurance and also information systems and climate warning systems.

Box 56

Fungi to the aid of degraded ecosystems

In 2005, eleven African countries launched the 'Great Green Wall', a vast tree-planting project running from Dakar to Djibouti and aimed at combating the desertification of the Sahel. In the research work mobilised by the project, that of IRD shows the importance of symbiotic microorganisms in the rehabilitation of degraded environments and the resistance of agrosystems to drought.

In the Sahel, deforestation causes soil degradation and even desertification in some strongly degraded zones. The Great Green Wall project was launched in 2005 by eleven Sahel countries to fight this phenomenon and encourage tree replanting in a strip 15 km wide and 7,000 km long. A committee of specialists on trees and arid environments that included IRD scientists was asked to determine the most suitable techniques and to choose the species best matched to the context of the Sahel.

The researchers recommended in particular the use of mycorrhizal symbiosis, a natural phenomenon of association between a plant and a fungus. The fungus plays a capital role in water and mineral supply for the host plant through the uptake of nutrients in the soil with little mobility, such as phosphorus, and transporting them to the host.

Although it is agreed that optimum plant development is attained when mycorrhizal infection is high, there have been only a few studies under real conditions in arid and semi-arid regions.

In particular, the scientists showed during studies conducted in Senegal and Morocco that the introduction of fungi using facilitating or 'nurse' plants adapted to the environment is more effective than the biotechnological approach with mass inoculation of a high-performance strain of fungus. This *in situ* management allows the development of a richer, more abundant mycorrhizal community.

When the management of fungi present in the soil is successful, symbiosis improves plant growth in degraded soil in arid environments, in particular thanks to better use of water resource, conferring greater resistance to water stress.

Aerial view of a GMV project forest nursery at Widou (north-east Senegal).

Chapter 17

A fresh look at local knowledge

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In northern Cameroon, the Duupa grow sorghum, taking care to maintain great varietal diversity in particular through exchanging seed with family and neighbours.

Most of the studies addressing the impacts of climate change consider that the people in the South—and especially farming communities and the native population of some 350 million people—are passive victims. It is true that these societies are still largely rural and particularly involved in climatic events as they are often dependent on food crops and local resources. However, human sciences have also shown that these societies create knowledge and know-how that are not only useful for their own development in changing climate systems but that are also valuable at the international scale (resources in tools, practices and, beyond this, system viability and relations between man and nature, etc.). The experience and knowledge of these societies as regards climate, nature, the environment and the changes that affect them are thus an essential part of understanding climate change.

However, the international community is slow in taking the measure of these local adaptive responses. Climate change undoubtedly induces new international socio-environmental measures that involve a host of stakeholders, each with frequently divergent legitimacy and interests (see p. 182). Decision makers opt to concentrate their priorities on the economic and environmental consequences of climate warming, thus justifying a top-down decision process that leaves very little room for the analysis and support of local initiatives. The commitment chosen here is to favour a complementary, resolutely bottom-up approach based on understanding local adaptive strategies and taking them into account to a greater degree in the construction of international mechanisms for adapting to the various climatic scenarios.

Local perception and knowledge of climate

Perception of the climate is a key component of popular understanding of climate change. For example, farmers in the Sahel brought back practices that existed before the great droughts of 1970 to 1980, showing their observation, perception and response to the return of the rains since the end of the 1990s. Multidisciplinary scientific work seeks in particular to show all the dimensions involved in representations of changes and risks. For example, the perception of rainfall is related to water requirements and hence to farming systems, water management, etc. When the water requirements of a farming system increase, as is the case in particular of commercial soya and maize crops, the


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Irrigated gardens in a valley bottom in the dry season in Niger.

amount of rainfall considered as sufficient increases and a year considered as being normal in climatology is then perceived as a drought year. Another example was recorded by IRD: farmers in Argentina consider that drought and floods are the most adverse climatological factors rather than frost or heat waves because crop yields are sensitive to the rainfall regime above all. Here, the perception of the climate by farmers is linked to greater or less vulnerability to climatological variables.

The inherent constraints of study of this knowledge

However, understanding local perceptions of climate and the resulting decisions taken is still very uneven and has gaps. Researchers can perform relatively good analyses of farming strategies during the seasons within an annual cycle. There is no lack of research work in the literature that takes intra-annual seasonal variations into account. In contrast, there are fewer studies based on the analysis of inter-annual climate fluctuations as they need to be repeated for several successive years. However, understanding the responses of rural societies to such fluctuations in the short term is hardly sufficient if it is wished to use these responses in long-term management models. Indeed, certain bioclimatic events—especially those following El Niño—may only occur very rarely during a person's lifetime. Responses to environmental changes that take place at a longer time scale remain a matter for speculation, especially when knowledge is only used sporadically and transmission is essentially oral, limiting historical depth. The major tendency to fund only short-term research (with a time step no longer than 3 years) makes it impossible for the scientific community to base its analysis on a long period although this is necessary for addressing these questions effectively.

The legitimisation of local knowledge

The interest of the scientific community in local knowledge (also called native, community or traditional knowledge) as an expression of a type of sustainable management of the environment goes together with the emergence of the biodiversity paradigm. Although anthropologists have always examined the local knowledge that is in essence a pathway for learning about the cosmogonies of these peoples, it was only in the early 1980s that scientists at IRD began to explore this knowledge from the angle of sustainable management.

This research contributed to the legitimisation of local knowledge that had long been ignored or even scorned by experts from the North who wanted to transfer their technological packages to intensify the agrarian systems of farmers in the South.

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Family rice growing on terraces in Madagascar. The know-how of Malagasy farmers contributes to the sustainability of the farming system.

In the 1970s, just a few researchers criticised the arrogance of these expert solutions and demonstrated the relevance of farmers' local knowledge. The debates were extensively reported and empirical work by IRD researchers showed the use of local practices that are adapted to the opportunities and constraints of the environment.

There is now no longer any doubt that the knowledge and know-how of local populations in the South, generally backed by strong social cohesion, show the functional flexibility of their farming strategies as a gage of their capacity to adapt. These societies maintain as a base a range of activities that complement each other in a reasoned succession of crops during the seasons marking annual and inter-annual cycles, together with alternating mobile and sedentary phases to optimise the gathering of both wild and domesticated resources scattered through the territory.

The 1992 Convention on Biological Diversity (CBD) recognised in particular that local knowledge is essential for the conservation of biodiversity. Today, cultural diversity is recognised as an essential dimension of biodiversity and agrobiodiversity. Local knowledge and know-how, whether they concern climate, the environment, farming systems, biodiversity or ecosystem services, are used increasingly in development and conservation programmes for reasons of their importance for the conservation of certain ecosystems. This knowledge is recognised as providing economical and effective solutions that are hence sustainable, and also as bearing ethical and heritage values. It thus becomes the flag of procedures that are more just and fair. Here, reference to this knowledge is an inevitable component of statements that are ecologically correct.

'Biotemporal markers'

One of the most astonishing facets of local naturalist knowledge concerning climate is formed by the '**biotemporal markers**' used by populations in the South to plot the calendar of their work. Perception of these signals and hence the ability to anticipate a change of season is a determinant stage in the management of a farming system. This perception governs management of the risks inherent in the fluctuation of the availability of resources in time, affecting the success of sowing, of a hunting operation, of the gathering of a forest product with strong economic value or the livestock reproduction cycle. The signals form a corpus of visual, olfactory, sound and tactile stimuli emitted by surrounding nature, with each signal being just one component among others of a set of convergent indices that society has to use to finalise its choices. The convergent indices may take the form of a flight of migrant birds, the reproduction period of a fish species swimming upstream to its spawning ground, massive leaf drop from a deciduous tree species, the cry of a nocturnal batrachian, the massive simultaneous flowering of certain plants, etc.

Burning *Aframomum* leaves to prevent rain before a Baka people (Cameroon) hunting expedition.

© IRD/E. Dounias

The expression of certain stimuli is so tenuous that perception is almost a question of the unconscious. These societies often popularise the occurrence of these signals through animist beliefs featuring supernatural forces that can rapidly disconcert a western manager. The latter will see only superstition and will consider wrongly that he will have nothing to do with these considerations in the good running of his operations. The ethnoscience approach typically tries to establish a link between the system of representations and its specific modes of expression (founder myths, stories and other forms of oral tradition, rituals) on the one hand and the observed bio-ecological fact recorded by the sharp senses of the local observer and that reveals the operation of bio-ecological cycles on the other.

Insects are particularly remarkable biotemporal indicators as they can react to infinitely small changes in climatic conditions, to thresholds—atmospheric moisture, wind direction, temperature, the lunar cycle and so on—that humans are incapable of sensing directly. The entomological knowledge used in the observation of social insects such as ants, termites and bees is a remarkable illustration of their biotemporal indicator function. Using attentive observation of these biotemporal markers, local populations gain access to information that researchers miss. Their expertise is particularly valuable in ecosystems for which the predictive models covering climate change lack accuracy. Thus although analysis of climate change is easier at polar latitudes and high altitudes (Himalayan peaks) where change is extreme, it is marking time at low elevations in more equatorial latitudes. The effects of climate change in humid tropical forests are subtle and tenuous and usually hidden by more tangible and immediate threats (deforestation). Adding local expertise is even more important in such a context. The cultural diversity of this expertise is all the more valuable as it concerns ecosystems with the greatest biological diversity.

The hybridisation of knowledge

If we talk about local knowledge rather than traditional knowledge, it is because the second term gives a static image and assumes a historical depth that is often difficult to establish when knowledge evolves and becomes hybrid. Study of the speeches of nativist leaders in Latin America shows for example how these community spokesmen are now adjusting their positions according to nativist ideologies that have been developing for some 30 years in the region and are centred on the naturalist or ecologist Indian. The approach draws on the knowledge of the Yanomani in Brazil or the Aymara in Bolivia that is based on the idea of a social totality governed by a system of exchange between human and non-human subjects. This concept contrasts

Box 57

The 'Sentimiel' initiative: bees, humans and local naturalistic knowledge

The 'Sentimiel' initiative run since 2011 by IRD researchers is emblematic of research questioning the effects of climate change using local naturalist knowledge of bees.

Collection of honey by the Baka (Cameroon).

© IRD/E. Dounias

Sentinels of an environment currently under threat, bees warn us of the damage to terrestrial ecosystems caused by humans.

Subsistence economies in the South where wild honey is collected are thus in the front line for the observation and documentation of behavioural changes in bees.
Unfortunately, analysis of the information provided by bees is focused only on the domestic bee reared in professional or semi-professional beekeeping; the expertise based on subsistence honey gathering and that concerns an incredible diversity of honeybees, estimated at around 1,500 species, is still totally underrated and therefore ignored.

Precious signs of environmental changes

However, wild honey gatherers have singular know-how as finding nests is a complicated or even dangerous endeavour as honeybees protect the result of their work from many predators in search of sugar.
The basic aim of the 'Sentimiel' initiative is thus find and federate groups of holders of naturalist knowledge about honeymaking insects and their production.
Through regular observation of the activities of these insects, honey gatherers are valuable witnesses of the effect of global changes on their environment.

Their involvement results in a tropical watch of the effects of these changes on bees and honey production.
Hunter-gathering peoples in Borneo, India, the Himalayan regions, the Congo basin, North Africa and Amazonia are thus mobilised in a joint action to provide researchers with information about the changes observed during the gathering of honey and other substances.

By increasing the visibility of this naturalist knowledge through the forming of an international network inspired by **citizen science**, the 'Sentimiel' initiative is aimed at improving our understanding of the consequences of global changes and especially climate changes on world biodiversity through the pooling of very precise, very local information.
Furthermore, the network works on bringing into the light small local artisanal honey gathering initiatives by enabling them to join a federative international structure whose credibility can provide them with access to sources of funding and support.

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Trampling rice fields in Madagascar. This impressive practice carried out by the men precedes the irrigation of the rice field and serves an agricultural purpose by improving soil imperviousness and also plays a social role.

with the western anthropocentric approach in which the question of the exploitation or conservation of nature makes reference to a 'nature-object' that is reified and cut off from humanity. These native cultures are thus neither ancestral nor simply subjected to others. They create symbols, practices and knowledge in a process of hybridisation with scientific knowledge and with ideologies and standards from the west.

Box 58

The rain trees of El Hierro, a model for the island system?

Ancient rainwater collection practices still provide the water supply on arid El Hierro Island. Work by IRD has contributed to the use of local knowledge, especially by combining it with modern technology.

The first inhabitants of El Hierro used the rain tree to obtain their freshwater requirements.
Water is a valuable resource on this arid island in the Canary Island archipelago, with an area of about 270 km^2.
This legendary tree in the Lauraceae family collects the fine drops of water in mist on its leaves.
The drops are then channelled and collected in wells.

The virtues of the rain tree were rehabilitated by the forest guards on the island after the great drought of 1945.

Mist water was collected again in old wells dug before Spanish colonisation. New tank and pipe systems have been constructed under several dozen trees since the 1960s.

After discussion with professionals on the island and analysis of their knowledge, IRD developed 'mist catchers' consisting of nets attached to stainless steel tree-like structures.
The structures are for collecting mist water in places where there are no trees, such as crests exposed to the wind. In all, these installations only collect a few cubic metres of water per day.
The impact is symbolic so far but it could become stronger.

Since then, several ecological projects have been developed on the island with the help of the local authorities and the European Union.
El Hierro has even become a symbol of energy transition as the island is preparing to become 100 % autonomous in renewable energy.

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A 'rain tree' on El Hierro.

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Pruning argan trees in Morocco.
The argan woodlands are the result of several centuries of domestication.

Between local knowledge and science: joint production of knowledge

Scientists sometimes draw on traditional knowledge. Research actions thus combine a research phase with concrete development projects. The study of the 'rain tree' on the Spanish island of El Hierro is emblematic of the use of local knowledge combined with scientific knowledge (Box 58). This example shows how countries and regions that succeed in using relevant knowledge—whether scientific or native—have a comparative advantage for both their own development and the use of their skills at the international scale.

New research practices

Climate change is also inducing new research practices that change the nature of relations between researchers and possessors of local knowledge. After being subjects for study, the latter have now become full partners in research. Local populations and their knowledge must be associated far upstream in the designing of research subjects;

they must be involved in the implementation of protocols, data collection, the exploitation and ownership of the results and, finally, international diffusion. This involvement also has the merit of making the long duration of the research conducted with them more acceptable and of defining the terms of the continuous back and forth movements between fundamental and applied research.

The involvement of local populations in research can usefully draw inspiration from citizen science programmes and participatory action research. This category includes research projects conducted in countries in the North in which individual volunteers or networks of amateur naturalists who have had no particular training in research perform research tasks: observation, counts, surveys or data entry. It is perfectly possible to transpose the citizen science approach to people with local knowledge of nature and who in a way replace a network of amateurs or ordinary citizens. Initiatives like 'Sentimiel' (Box 57) that is based on a network of honey collecting peoples, are still too few and far between but have opened a promising breach in favour of more formal contribution from local naturalist knowledge to the understanding of the dynamics of complex ecosystems that the scientific community still does not know well.

Another example of innovative research practices consists of the analytical inventories that can be made of all the types of knowledge produced in a given area. For example, IRD and its partners are conducting a climate change study focused on cities in the Mediterranean region by examining the innovative technical know-how in architecture and town planning (in terms of response to climate warming), legislative practices (in control and adaptation to changes) and methods of analysis (climate measurement systems). This technical knowledge of social regulation or analysis of the phenomenon may come from professional and academic spheres but also from indigenous knowledge.

Educational policies concerning climate change

This gradual recognition of the importance of knowledge in the addressing of warming has also led international organisations to wonder about the circulation of this knowledge. Education and training in questions of climate have become strategic sectors for attempting to control at the international scale the emergence of new citizen positions that better match the new economic and ecological situation. World scholastic programmes devoted to climate change have thus been developed during the last 10 years. They suggest to states the new skills that the new generations should acquire, such as how to make decisions in a context of uncertainty, understand world climatic interdependence, master 'good practices', etc.

These international education policies are not neutral and refer today to a specific development model: sustainable development and green capitalism. However, some countries reject this model and prefer another vision of modernity: for example, this is the case of the Bolivarian Alliance for the Peoples of Our America (ALBA) (Box 59). It is hence not certain that models of rationality and development that dominate international education policies will succeed in achieving a concerted approach to teaching concerning the environment and climate change in countries in the South.

This variety of approaches is visible for example in the way in which native knowledge concerning climate is handled. Overall, international organisations are for the transmission in schools of local knowledge that is considered to be effective in addressing climate change and its consequences, but countries have very varied positions in this. Work conducted in Senegal thus shows that in environmental and climate themes, education officials use local knowledge partly remodelled *ad hoc*, together with a religious approach. This research also highlights the fact that environmental and climatic questions are identified as being imported from elsewhere and are little embraced by families and local officials. Studies conducted in other countries such as Bolivia show that teachers use a combination of scientific, native and political knowledge to address these questions. The government is currently for a native view of the environment and the climate in which native knowledge is reconfigured in the light of the criterion of reshaping the country politically to approach a different societal model (Box 59).

Box 59

Other development models, different education in climate?

School programmes on climate change, Bolivia, 2012.

Bolivia has launched a full reform of its education system so that young people receive teaching based on an alternative societal model: '*vivir bien*' (living well). The model features bio-centred ontology in which human beings are just one component of nature. Inspired by different socialist, green and nativist movements, the model is considered to be based on economic, political and cultural pluralism.

As regards climate change, '*vivir bien*' proposes knowledge that does not seek to concentrate only on its cognitive or behavioural aspects but to address the individual as a whole using four keys: knowing, doing, deciding and being. 'Deciding' concerns the political sphere: for example, a young person should be aware of the history of climate change and the inequality of responsibility for its intensification. 'Being' concerns behaviour and, beyond this, the personal position of a young person in a life 'in harmony' with nature.

In the project called SAVE (*Savoirs relatifs à l'environnement dans les Andes*), researchers at the LPED, IRD-CIDES and UMSA units are studying among other things the construction of this reform and the problems that it comes up against. In addition to the complexity of constructing a new model of society and political ecology, its transposition in scholastic programmes and in the training of teachers is a challenge for educational policies. The reception given to the model is very varied among teachers, urban and rural families, etc. This is particularly so as the model sometimes seems to be theoretical, with the country not really managing to move out of a resolutely extractivist economy.

Chapter 18

The adaptation and resilience of populations in the South

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Pulling out rice seedlings for replanting in a rice field (north-east Thailand).

The ability of human civilisation to handle the issues of climate change partly depends on the accuracy of the data concerning this change and the power of forecasting models. The IPCC Fifth Assessment Report is both more precise and more alarming than the previous ones in this respect. It also depends on the determination of decision makers to consult each other to set targets aimed at mitigating the effects of climate change, in particular by a drastic reduction of greenhouses gases, and to strengthen our measures for adapting to an inevitable change, even if there is still disagreement on the scale of the latter. But populations in the South have not waited for the decisions of experts to begin to adjust their subsistence strategies in response to changes that they can perceive and anticipate. These adjustments concern as much the maintaining of their sociocultural integrity as that of the natural ecosystems on which they depend on an everyday basis and with which they maintain progressive interactions. Considering local reactiveness is just as important as considering that of the international select few.

Mitigation, adaptation and resilience

The perception now being confirmed of a break related to climate change has led to a change in the way of qualifying the necessary responses over the past 20 years. Mitigation was the dominant approach used to reduce the effects of warming until the end of the 2000s. Put forward by a community of scientists and experts devoted mainly to risk management and climatic disasters, mitigation consists of reducing the exposure and sensitivity of the system. A central theme of the successive IPCC reports, it is defined there as the human intervention necessary to reduce sources of greenhouse gases or increase carbon sinks, in other words to limit greenhouse gas emissions and store atmospheric carbon. Until recently, researchers and decision makers believed that mitigation would suffice to control the effects of climate change.

Street food vendor in Ho Chi Minh City (Vietnam). Migrants include a 'floating population' of people that work and live in the city while making frequent trips to the rural areas that they came from.

In the face of warming that seems inevitable today, 'adaptation' has become dominant progressively since the end of the 2000s. The taking into consideration of the capacity for systems and populations to adapt has been more the affair of researchers in social sciences. A large amount of literature has been published on the subject in economics, human geography, sociology and anthropology. Numerous studies address the adaptation capacity of rural populations in the South in relation to their environment. Here, pluriactivity and migration clearly show the complexity of the social responses used to handle environmental and social changes (population growth, political crises, rocketing foodstuff prices, drought, etc.).

More recently, the efforts made by climate change specialists have been focused on synergy between mitigation and adaptation. In particular this means examining the 'resilience' of the system with regard to both its biophysical component and that concerning its human population. The popularity of the concept of resilience (defined as the capacity of a system to absorb disturbances or withstand changes without damage to its functions, structure, identity and functioning) thus leads to the perception of risk of failure. But the polysemy that marks this notion still makes operational use difficult. Proof of this is that it is used in very varied disciplines. The word 'resilience' comes from the physics of materials where it defines the quality of a body to conserve or return to its original form after deformation. The concept is also used in psychology to describe the capacity of a person to recover after being badly treated and in ecology to define the reconstitution capacity of an ecosystem after partial destruction by a natural or anthropic catastrophe. The term often has a positive connotation when applied to a society. It is not limited to reconstruction after a crisis but implies a capacity to overcome it and adapt to it.

Applied to public development policies, the notion could begin to provide a response to situations of growing incertitude and vulnerability related to climatic events, economic crises, etc. IRD participates in reflection on the interest of resilience as a new standard to the evaluation of public policies.

Sociocultural adaptation, ecological adaptation: entwined developing processes

The developing adaptation process is clearly revealed by the analytical framework of the 'socio-ecological system' defined by the international network Resilience Alliance as a set of dynamic interactions between biological and social factors, between populations, societies and the environment. These interactions are generic

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Survey on the contribution of livestock farming to the resilience of ecosystems and social groups in Djougou, Benin.

and applicable to all types of societies but are fully relevant for populations in the South whose subsistence mode still depends to a considerable extent on the resources provided by the natural environment.

As societies with subsistence economies are fairly self-sufficient, their socio-ecological system can be seen as governed mainly by endogenous dynamics. However, the increasing effect of changes at the scale of the planet—including climate change—is tending to cause the situation to evolve significantly. The attractiveness of markets and consumer goods, public environmental policies, inter-ethnic relations, rural/urban interfaces, external economic stakeholders such as agro-industries, conservation and development agencies and NGOs, etc. are all 'externalities' that are weighing increasingly on locally drafted adaptive strategies. Analysis of the 'box' formed by these socio-ecological systems obviously assumes that increasing account is taken of what is happening 'outside the box'.

Ecological resilience and social resilience

The resilience of the socio-ecological system of a rural population in the South is only justified if it can ensure the sustainability of resources in parallel with that of the social system mobilised in their management. Figure 32 is a synthesis of the way in which the social and ecological components can interact in the face of climate change, independently of the broad range of subsistence strategies—farming, animal husbandry, hunting, fishing, gathering and so on—that is a feature of societies with subsistence economies. The ecological component is exposed to the effects of climate change and its sensitivity to these effects will damage the environmental services and resources that it provides. The social component developed a degree of vulnerability because of the degradation of the services rendered by the ecosystem (in food supply or water resources for example) and will have to adjust by developing adaptive responses to correct the effects of the change. In this context, the adaptive capacity of the population makes it possible to counterbalance the exposure of the ecosystem or adjust its sensitivity to the effects of climate change. This capacity is measured in a way in the potential of the society in question to maintain or possibly restore the services and resources provided by the ecosystem.

The generally accepted idea about the socio-ecological systems of social groups or communities, especially in the South, whose subsistence and well-being depend mainly on the natural environment, is that ecological resilience and social resilience go together and must be maintained together. However, the work carried out in central Cameroon by IRD for two decades invalidates this idea and shows an interesting case in which forest peoples are obliged to counter-balance the natural dynamics of the **ecotone** to maintain the integrity of their social system (Box 60).

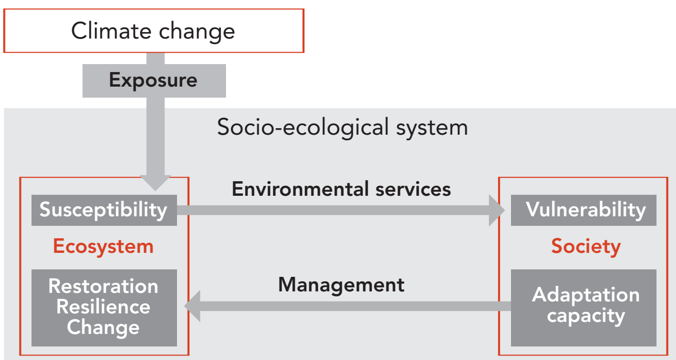

Figure 32.
Exposure of a socio-ecological system to the effects of climate change.
Source: after DOUNIAS *et al.*, 2013.

Box 60

The forest-savannah ecotone in the centre of Cameroon

Since the 1990s, IRD and its Cameroonian partners have conducted a vast multidisciplinary human ecology programme at the forest-savannah contact zone to analyse the adaptive responses of the Tikar to the rapid advance of the forest.

The centre of Cameroon is inhabited mainly by the Tikar, cereal growers who moved south from their original savannah area two centuries ago to reach a humid tropical forest about which they knew nothing. The forest/savannah border area forms a particularly dynamic ecosystem that has evolved naturally for nearly 1,000 years, with the forest advancing rapidly into the savannah. This happens at the rate of 1 to 3 metres per year and is at its most spectacular in the inhabited zones where the spread of seeds from young trees on the pioneer front is amplified.

In this very special socio-ecological context, IRD researchers addressed the attitude of a society with regard to the advance of a forest front that might seem contrary to its cereal growing activities. This field of study is all the more propitious for exploration of the notion of the biological and cultural adaptation of a human society as the environment changes very rapidly.

The same applies to climatic events whose incidence can be seen more easily in an ecological transition zone (ecotone) than in humid tropical forest.

A multidisciplinary human ecology programme

However, the adaptive responses of the Tikar do not operate solely in response to the physical environment. The Tikar organised in ranked chiefdoms, met on their route the local populations of the forest edges and who possessed empirical knowledge of the forest environment. Thanks to a political system that is both malleable and rigorously structured, the Tikar have succeeded in maintaining an improbable balance between the absorption of these local societies and the construction of an ethnic identity.

This work showed first of all that the change in the environment (from savannah to forest)

Migration: adaptation or crisis?

Population migrations are one of the foreseeable consequences of climate change, especially in tropical countries. But migration is not inevitable for these societies. Societies in the North tend to have an opinion of so-called ‘developing countries’ that is somewhat remote from reality. The populations concerned are far from being overdetermined by their environment and frozen in history that they have not understood.

is part of the ecological resilience of the ecotone.
It is not because an environment changes that it is not resilient.
The research also revealed how the Tikar were able to profit from the arrival of exogenous features—the extension of cacao growing in the 1970s and the arrival of an invasive shrub (*Chromolaena odorata*) in the 1980s—to regulate the unwanted advance of the forest around their dwellings and no longer have to move their villages because of the progression of the forest front.
This recent control of forest dynamics is at the expense of ecotone resilience but strengthened the socio-cultural resilience of the Tikar that had been made fragile by the advancing forest.
Finally, factors outside the socio-ecological system allowed this control of natural ecological dynamics, highlighting the fact that the taking into account of external factors is essential for understanding its dynamic balance.

Burning off at the edge of a forest before growing maize in the forest-savannah ecotone in central Cameroon.

Migration is one of the responses of human societies to changes in their environment, whether these are brutal changes (natural catastrophe) or gradual (decreased resources). Seasonal or definitive and operating at all latitudes, this facility for mobility demonstrates adaptation capacity in case of changes. Except in cases of serious catastrophe, population displacement is the result of long and complex processes in which climate change is just one parameter among others. Conditions of access to resources (including land), farming systems and population growth are all factors, among other variables, to be taken into account in the interpretation of migrations.

Loading a lorry with migrant workers and goods in Niger.

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In addition, studies on regions where climate change has already had an impact on the living conditions of the population show that most migrations are stimulated primarily by socio-economic factors. Finally, migration is often chosen as much as imposed.

Mobility is as old as humanity

Mobility goes with the type of occupation of the environment used by the last hunter-gatherers in the world and that was a feature of humanity as a whole before the advent of farming. The subsistence economy of hunter-gatherers is still closely linked to the natural resources available in the environment and mobility is essential for access to these resources that is continuous in space and time. While mobility is not a fatality for these nomadic peoples, the obligatory settlement that states try to impose on them is as painful as migration for gregarious societies forced to move by dramatic circumstances.

Climate refugees?

With land flooded by the rise in sea level, natural catastrophes, wars and conflict for access to resources etc., climate change may cause the departure of millions of people from their regions, creating as many 'climate refugees'. The term certainly makes sense when the effects of climate change are sudden and extreme, wiping out all local capacity to adjust to the suddenness and scale of the event. As researchers are cautious with regard to the links between certain extreme phenomena and global warming, the term 'climate refugees' should be used with caution and the use of 'environment refugees' preferred. Then if the areas affected occasionally or definitively by changes may be very varied, it is rare for changes to result in massive, rapid migrations across the frontiers of states. From this point of view, describing these migrants as 'refugees' is inappropriate with regard to international law.

A family displaced
by drought in Kenya.

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Box 61

The migratory strategies of the inhabitants of Tuvalu

The population of the atoll state Tuvalu has become a symbol of the climate crisis. However, the migration strategies put forward by the people concerned differ from the dominant 'climate refugees' approach. Researchers are wondering in particular about the risk for the choices of the population concerned formed by this alarmist rhetoric from the international community.

A 1-metre rise in sea level would directly affect one person in ten in the world according to the IPCC. Island populations will be particularly concerned and especially those of the low-elevation Pacific islands.

The climate emigrants of Tuvalu have already received considerable media coverage.
The government of Tuvalu has been trying for several years to negotiate climate refugee immigration facilities for its people with the New Zealand and Australian authorities.

Can one talk in terms of climatic immigration in this case when mention is made of the inhabitants leaving for New Zealand or Fiji?

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A woman in Funafuti (Tuvalu).

Surveys of the migration determinants of these islanders threatened by the effects of climate change highlight the contrast between the way in which migrants envisage their migration and how it is generally perceived from elsewhere.

Present migration cannot be understood without associating the history of this migratory people and its migration system, together with the evolution of migration policies. Environmental factors form part of the many determinants of migration because they result in a restriction of access to resources accentuated by population pressure.
Migration is also motivated by the attraction of the economic policies of Fiji and New Zealand—serving as a link for reaching Australia—and based on solid family networks.

The question then arises of considering the migratory behaviour of the inhabitants of Tuvalu as family risk reduction strategies rather than climate migration. The alarmist statements by the international community should also be analysed with regard to the risk that speeches about these victims of climate change may weigh on the adaptation capacity of the population.

Vulnerability factors and adaptation strategies

The climate risk is far from being expressed in a brutal, violent manner everywhere and it would be a mistake to reduce the consequences to environment refugees alone, however difficult the situation may be for the latter. As in the well-known boiling frog allegory—if a frog is placed in a recipient of very hot water it will jump out immediately. But if it is placed in water at room temperature that is then heated, the frog will not react to the progressive rise in temperature, will become drowsy and let itself be boiled to death—it is because climate change in a humid tropical forest environment is slow, progressive and not always very tangible that climate specialists have difficulty in make the general public and decision makers aware that it is urgent for us to get ready.

Much research at IRD consists of analysis of vulnerability factors and the adaptation strategies of populations after serious social or environmental changes. These analyses are of crucial importance as they contribute to the setting up of public policies that can accompany the changes.

Adaptation is thus an essential mechanism for the dynamics of societies. So why should it be a new challenge within the framework of climate change? Doubtless because of the scales involved and especially the speed of global climate change that is unprecedented in human history.

Prospects

Scientific research and climate policies

Several prospects emerge at the end of this work, concerning both scientific research and the way of fitting in the question of climate at the level of regional and international policies.

Climate change with anthropic causes is a key component of global change and is indicated by numerous markers in the tropics. However, as has been said throughout the book, it is sometimes difficult to distinguish between the environmental impacts and the impacts of other anthropic pressures such as changes in land use, deforestation and the exhaustion of resources—all related to our production modes and economic development model. Because of its complex nature, the climate question must be addressed using an 'integrated' approach that is essential for responding to the global challenges now faced by humans and the environment. Given the scale of the issues and the numerous arguments put forward, an interdisciplinary approach seems essential for performing research on the climate and devising appropriate operation responses. In parallel, it is also important to repolitise and re-territorialise the climate question as it cannot remain independent from the international economy, energy policies and geopolitics in general. Territorial approaches must also form part of this integrated approach in order to renew the vision of expertise and action and henceforth include the questions of regional development, access to sustainable energy, public health, pollution and the fight against poverty. The latter should no longer be addressed from the economic viewpoint alone. Climate change has revealed another form of poverty related to environmental vulnerability and that will have to be examined using this interdisciplinary approach.

At the programme level, research must be based on strengthened partnerships and on more effective tools and methods to make closer diagnoses and generate knowledge useful for both regional and local decision makers. The development of public research policies on low carbon technologies and the application of stricter regulations based on new norms and standards must accompany the efforts made in research on the climate process. The success of attempts at 'decarbonisation' will depend on this.

The development of large interdisciplinary monitoring facilities is also recommended in the book. These are essential for improving the monitoring of the environment (climate, impacts on resources and societies, interactions between societies and the environment, etc.), to calibrate satellite facilities devoted to the environment, validate models and propose appropriate adaptation and mitigation measures. Furthermore, these monitoring facilities must also favour training via research of the new generations of teachers and researchers in countries in the south by using an integrative interdisciplinary approach. In health in particular, the setting up of fully-fledged, interdisciplinary watches monitored in the long term is becoming urgent as the accumulation of single-theme watches has shown its limits. These facilities should allow the better monitoring of populations and make it possible to understand how—beyond political and strategic choices—they can evolve according to local individual and collective behaviour, also covering situations in which they are subjected to the same constraints.

Furthermore, the reliability of knowledge of the climate requires the improvement of models of climate and impacts, a reduction of uncertainty in climate projections and natural climate variability in relation to anthropic forcings, thus enabling better attribution of the changes observed. In modelling, improving decadal forecasting is an important objective for improving knowledge of climate patterns in the coming decades.

Questions of scale are also determinant. Digital simulations, physical models of the climate and those in the fields of environment or health cannot be applied in the same way at the different scales of observation. The difficulties of diagnosis and interpretation and for transition from the global to regional or local scales have been highlighted in several chapters. The levels of scales and the organisation of living organisms, of the environment and of societies must be better integrated in models with the aim of showing the complexity of the phenomena involved in the question of the climate.

Adaptation and resilience processes are also complex in their definition and even more so in the assessment of concrete effects or in the evaluation of their potential. Research on the adaptation of populations to climate change and on local know-how forms nonetheless an important source of knowledge that is still too little used. In the light of the regions and the populations concerned and conflicts in use between the various sectors of activity, the research conducted must generate information for decision makers and guide national adaptation plans to improve political responses. The use of regional orientations, national policies and global governance returns in a different way to the theme already mentioned of the hinging between levels of organisation but applied to institutions and governance in this case.

By giving a greater role to national policies and by asking for 'nationally determined contributions', COP 21 is aimed at placing states back in the core of climate governance to set up international agreements according to the respective means available. Indeed, it is not possible to impose climate policies using scientific knowledge of the climate as the sole basis. Research must be reflexive and must question its own position in a geopolitical context in which the question of climate is handled as an economic weapon and crystallises North-South oppositions during international negotiations. The research conducted in the South on a cooperation basis must make it possible for the viewpoints of the partners to be heard—beyond the sharing of knowledge. It is a question of generating and spreading knowledge, of contributing to a long-term vision of the issues and to pass on a 'culture of climate challenge'. But it is just as important to encourage the mobilisation of society in favour of public debate. Whether they are acceptable, in disagreement or utopian, the solutions for responding to the climate challenge can only come from societies themselves and from greater international solidarity.

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Glossary

Adaptation (to climate change) – The adjustments of an ecological and/or socio-cultural system to climate change for protection, enhanced resilience or transformation under the effects of the change. Adaptation is a central concept in the IPCC Fifth Assessment Report (AR5), where it conserves a very broad definition. This means in particular that it can remain consensual in international negotiations.

Albedo – The fraction of solar energy reflected directly into space and not absorbed by the terrestrial system. Pale surfaces reflect much more energy than dark ones.

Anomaly (climatic) – A climatic fluctuation whose amplitude (intensity and spatial extent) is outside the standard of the fluctuations observed, that is to say fairly remote from the climatic mean.

Anthropocene – A term proposed to indicate the present geological epoch during which anthropic activities have a determinant impact of the terrestrial ecosystem, making humans a major geological force at the scale of the planet. The Anthropocene thus follows the Holocene. The chronology of the Anthropocene has not been firmly decided as the date of the beginning of the new period is under discussion.

Attribution – The determination of the cause/s of a climatic anomaly and in particular the separation of the effect of a human forcing, a natural forcing or that of natural climate variability.

Biomass (plant, soil or in a watercourse) – In ecology, this refers to the total mass of living organisms in a specific space at a given moment. It is estimated per unit of surface area or of volume for an aquatic environment. Plant biomass refers specifically to the total mass of vegetation.

Biotemporal signal – A signal detected in the natural environment and that receives a cultural interpretation by a given society as the precursor of a climatic variation. There are generally several signals that form a group of convergent signs that increase the reliability of the prediction and the resulting decision making.

Carbon cycle – The flow of carbon through the atmosphere, seas and continents. Carbon dioxide (CO_2) movements between the atmosphere and land ecosystems are numerous, involving photosynthesis, combustion, the decomposition of organic matter, etc. But oceans also play an important role by absorbing CO2 when the atmospheric level of this gas increases.

Citizen science – Research generally focused on the study of biodiversity in which amateur naturalists who have not had any particular training in research perform research tasks in observation, counting, census compilation or data entry on a volunteer basis.

Climate prediction – Simulation of the future evolution of the climate starting from a known initial state.

Climate projection – Simulation of the response of the climate system to various external forcing scenarios (greenhouse gas emission, aerosols, etc.).

Climate variability (natural or internal) – Intrinsic variations in the climate system as a result of pairings between systems (atmosphere, sea, etc.) with different physical, dynamic and chemical properties.

Climatic model – The use of a set of equations to represent the various components of the climatic system and their interactions. Computer processing is required to solve these equations.

CMIP (Coupled Model Intercomparison Project) – An international project with a common protocol for the performance of climate simulations and the placing of the results at the disposal of IPCC operations.

Compliance – The correct obeying of the instructions for the use of medicines. The term is used here in the broader good response of populations in the face of a threat or with regard to political recommendations concerning such a threat.

Convection (tropical) – Precipitation in the tropics is caused mainly by cloud systems consisting of strong vertical movements (storms, squall lines and cyclones). Such convection is also the main atmospheric transport vector of the surplus energy received by these zones to zones with energy deficits.

Coupling – Transfer of information using certain variables between two parts of the terrestrial climate system, e.g. ocean-atmosphere coupling.

Ecotone – A transition zone between two very contrasted ecosystems. It can take very varied forms ranging from a clear-cut line to vast, widespread interpenetration to the extent that another ecosystem can form, with its own characteristics and dynamics.

Extreme climatic event – A climatic anomaly with very strong amplitude, for example one that is among the strongest 10% observed.

Forcing – A disturbance from outside the climate system that disturbs the energy balance of the latter. Distinction is made between natural forcings (astronomic factors, volcanic activity), anthropic forcings (emission of greenhouse gases and aerosols, change in land use).

Global issues – Questions that go beyond the sphere of intervention by nation states and include climate warming and decreasing biodiversity. The notion refers to the complexity of taking these issues into account, with regard to both understanding them and providing responses.

Greenhouse gases – Gaseous constituents of the atmosphere that absorb infrared heat radiation emitted from the earth's surface and re-emit it towards the surface. They thus contribute to the greenhouse effect by limiting energy loss into space. The main greenhouse gases of the earth are water vapour, carbon dioxide, methane, nitrous oxide and ozone. The increase in their concentration as a result of anthropic emissions is the cause of recent climate warming.

Greenwashing – A deceitful marketing method consisting of advertising using the ecological argument. The aim of greenwashing is to announce ecological responsibility that is far from the reality of the practices of the corporate structure concerned.

Human ecology – A research field addressing the full diversity of the relationship between humans and their environments. 'Dynamics' and 'interactions' are the keywords of this interdisciplinary scientific approach that examines the interfaces between society and nature and between biology and culture.

IPCC – The Intergovernmental Panel on Climate Change set up in 1988 by the United Nations. Its mission is the assessment of scientific knowledge on climate change of human origin and the consequences.

Isotopic composition (of water) – Water (H_20) consists of stable isotopes of oxygen (^{16}O, ^{17}O, ^{18}O) and hydrogen (^{1}H and ^{2}H). Water isotope composition is used increasingly for studying the present water cycle (precipitation, water vapour, recycling) and its past variations, especially in the tropics.

Mesh – Use of meshes in a climate model is based on discretisation aimed at drawing individual values from a continuous environment such as the atmosphere or the sea.

Mitigation – Reducing the exposure of a system by protecting it from strong disturbances in order to moderate the effects of climate change. A central theme in successive IPCC reports, mitigation is defined there as the human actions required to reduce greenhouse gas emissions and enhance sinks.

Modes of climatic variability – Atmospheric phenomena that can be linked to the sea, with a regional to supraregional spatial scale, with temporal recurrence of variable regularity and marked climatic impacts. The best known in the tropics is the El Niño Southern Oscillation (ENSO), a linked sea-atmosphere phenomenon that dominates climatic variability at interannual time scales.

Proxy data – Variables (water isotopes, etc.) that are climate-related and measurable in 'archives' (tree rings, corals, ice cores, etc.) that provide information about past climate conditions.

Radiative forcing – Expressed in energy units per second per surface area (W/m^2). Positive forcing causes the warming of the climate system, as is the case with greenhouse gases, and negative forcing causes cooling, as is the case with aerosols.

Otolith – A mineral concretion in the inner ear of vertebrates. Otholiths are used frequently for measuring the age of fish.

Feedback – The result of an initial process that triggers changes in a second process that in turn affects the initial process. A positive feedback intensifies the initial process and a negative feedback reduces it.

Resilience – A polysemous concept that refers to the ability of a physical, biological, ecological or sociocultural system to absorb disturbance or withstand changes without modifying its functions, structure, identity and functioning.

Socio-ecological system – A coherent entity with a bio-geophysical component and a socio-cultural component. The combination of the two sets the spatial, temporal, organisation and functional contours of the system to enhance study of its dynamics.

Uncertainty – Incomplete knowledge resulting from lack of information or disagreement concerning known features. It can be represented quantitively or by the opinion of experts.

Upwelling – The rise of deep water caused by winds that push the surface water out to sea. The phenomenon results in cold seawater charged with nutrient minerals along the coasts.

Urban heat island – Local higher temperatures—especially maximum temperatures—recorded in an urban environment. Considerable temperature differences can be observed in the same city, depending on town planning features, albedo, relief and exposure.

Water cycle – The water cycle describes the movement of water in all its form. Solar energy causes the evaporation of seawater and continental water. Water vapour is redistributed by complex atmospheric currents and released as rainfall or snow. A proportion of the precipitation that falls on landmass evaporates again in contact with the ground. The rest takes the form of runoff or infiltrates and feeds reservoirs, lakes and rivers. Water from the land then returns to the sea, completing the global scale water cycle.

Acronyms

AFD – Agence française de développement
ALBA – Bolivarian Alliance for the Peoples of Our America
ALMIP – AMMA Land Surface Model Intercomparison Project
AMO – Atlantic multidecadal oscillation

CBD – Convention on Biological Diversity
CCPL – Climate Change Policy Loan
CILSS – Permanent Interstate Committee for Drought Control in the Sahel
CMIP – Coupled Model Intercomparison Project.
CNRS – Centre national de recherche scientifique (France)
COP – Conference of the Parties

ENSO – El Niño Southern Oscillation
ESA – European Space Agency

FAO – Food and Agriculture Organization of the United Nations

GEF – Global Environment Facility
GHG – Greenhouse gas

GIS – Geographic Information System

GPS – Global Positioning System

IGBP – International Geosphere Biosphere Programme.

IHDP – International Human Dimension Project.

INDC – Intended Nationally Determined Contribution

IPCC – Intergovernmental Panel on Climate Change

IRD – Institut de recherche pour le développement

MDGs – Millenium Development Goals

NGO – Non-governmental organisation

NIRS – Near infrared spectroscopy

OECD – Organisation for Economic Co-operation and Development

OMZ – Oxygen minimum zone

ONERC – Observatoire national sur les effets du réchauffement climatique (French national climate warming effects monitoring facility)

PDO – Pacific decadal oscillation

RCP – Representative Concentration Pathways.

Redd+ – Reducing Emissions from Deforestation and Forest Degradation

SDGs – Sustainable Development Goals

SPC – Secretariat of the Pacific Community

UHI – Urban heat island

UNDP – United Nations Development Programme

UNEP – United Nations Environment Programme

UNESCO – United Nations Educational, Scientific and Cultural Organization

UNFCCC – United Nations Framework Convention on Climate Change

WCRP – World Change Research Programme

WCS – Wildlife Conservation Society

WHO – World Health Organization

WWF – World Wildlife Fund

Contributors, research establishments and resources

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UMR: joint research unit
UMI: international joint research unit
LMI: joint international research laboratory

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Research units

Units and laboratories

UMR **AMAP** (Botany and modelling of plant and vegetation architecture)
Inra, CNRS, IRD, CIRAD, Montpellier University

UMR **BOREA** (Biology of aquatic organisms and ecosystems)
MNHN, CNRS, UMPC, Caen Normandie University, IRD, Antilles and Guiana University

UMR **CEFE** (Functional and evolutive ecology centre)
CNRS, Montpellier University, Paul-Valéry Montpellier-III University, EHESS, Supagro, Inra, IRD

LMI **CEFIRSE** (Franco-Indian water science research unit)
IISc, NIO, IITM, IRD

LMI **Ceped** (Population and development centre)
Paris Descartes University, IRD

UMR **CEREGE** (European centre for research and teaching in environmental geosciences)
Aix-Marseille University, CNRS, IRD, Collège de France

UMR **CESSMA** (Centre for studies in social sciences of the African, American and Asian worlds)
Paris Diderot University, Inalco, IRD

UMR **DEVSOC** (Development and societies)
Paris-I Panthéon Sorbonne University, IRD

UMR **DIADE** (Plant diversity, adaptation and development)
IRD, Montpellier University, CIRAD, CNRS

UMR **DIAL/LEDa** (Development, institutions and globalisation/Dauphine economics laboratory)
IRD, Paris Dauphine University

LMI **Discoh** (Dynamics of the Humboldt Current system)
Imarpe, IRD, UPCH, UNMSM

UMR **Eco&Sols** (Functional ecology and the biology of soils and agrosystems)
Inra, Supagro, CIRAD, IRD

UMR **EGCE** (Evolution, genomes, behaviour, ecology)
Paris Sud University, CNRS, IRD

UMR **ENTROPIE** (Tropical marine ecology the Pacific and Indian oceans)
IRD, la Réunion University, CNRS

UMR **EPOC** (Ocean and continental environments and paleo-environments)
OASU, CNRS, Bordeaux-I University

UMR **ESPACE-DEV** (Development)
IRD, Montpellier University, Université des Antilles et de la Guyane, la Réunion University

UMR **GÉOAZUR** (Land, sea and space)
CNRS, Insu, Nice-Sophia Antipolis University, IRD, UPMC, OCA

UMR **GET** (Environmental geosciences, Toulouse)
Toulouse-III Paul-Sabatier University, CNRS, Cnes, IRD

LMI **Great Ice** (Glaciers and water resources in the tropical Andes: environment climate change indicators)
IRD, CNRS, EPN, Inamhi

UMR **GRED** (Governance, risk, environment, development)
IRD, Paul-Valéry Montpellier-III University

UMR **HSM** (Hydrosciences)
CNRS, IRD, Montpellier University

UMR **IMBE** (Mediterranean Institute of Marine and Terrestrial Biodiversity)
Aix-Marseille University, CNRS, IRD, Avignon and Vaucluse University

UMR **LEGOS** (Spatial geophysics and oceanographic laboratory)
Cnes, IRD, Toulouse-III Paul-Sabatier University, CNRS

UMR **LEMAR** (Marine environmental sciences laboratory)
IUEM, Bretagne occidentale University, IRD, CNRS, Ifremer

UMR **LOCEAN** (Oceanography and climate laboratory: experimental and digital approaches)
Ecce Terra, CNRS, IRD, MNHN, UPMC, Institut Pierre Simon-Laplace

UMR **LPED** (Population, environment and development laboratory)
Aix-Marseille University, IRD

UMR **LPO** (Sea physics laboratory)
CNRS, Ifremer, IRD, Bretagne occidentale University

UMR **LSTM** (Tropical and Mediterranean symbiosis laboratory)
IRD, CIRAD, Inra, Supagro, Montpellier University

UMR **LTHE** (Laboratory for the study of transfers in hydrology and the environment)
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UMI **Résiliences**
IRD, Cires

UMI **UMMISCo** (Unit for the mathematical and computer modelling of complex systems
IRD, UPMC

Monitoring facilities

AMMA-CATCH (Multidisciplinary analysis of African monsoons/Connection with the tropical atmosphere)

BVET (better understanding of the functioning of drainage basins)

GLACIOCLIM (glaciers for climate observation)

GOPS (large South Pacific monitoring service)

HYBAM (hydrology and biochemistry of the Amazon)

MSEC (conservation of water and soil resources in South-East Asia)

OMERE (Mediterranean monitoring facility for the rural environment and water)

PIRATA (monitoring the tropical Atlantic)

Multidisciplinary monitoring of the urban environment in Marseille

SSS (observation of surface water salinity in the sea)

Programmes, projects

AMMA programme (Multidisciplinary analysis of African monsoons)

AMAZ programme (Environmental dynamics, resources and societies in Amazonia)

Biothaw project (Biodiversity and People Facing Climate Change in Tropical High Andean Wetlands)

Carboocean programme (Carbon sources and ocean sinks)

Citizen Science programme

Equeco programme (Emergence of quinoa in world trade and consequences for social sustainability and farming stability in the Bolivian uplands)

Escape programme (Past, present and future environmental and social changes in Africa)

Euromarine project (Marbef, Marine Genomics and Eur-Oceans networks)

Future Earth programme (Research for global sustainability)

Great Green Wall project

INTERFACE project

INVALUABLE project

LEFE programme (Fluid envelopes and the environment)

Mégha-Tropiques programme (Water cycle in the tropical atmosphere in the context of climate change)

Pacivur programme (Andean programme for training and research in vulnerability and risks in urban environments)

Pacta project

RainCell Africa project

Rime-Pampa project

Serena programme (Environmental services in rural areas)

Sentimiel initiative (Bees and humans: local naturalist knowledge, honey collection and global change)

Topineme programme (Top Predators as Indicators of Exploited Marine Ecosystem dynamics)

IRD resources used

Indigo photo library

A unique collection of more than 58,000 photographs taken in countries in the South – Africa, Asia, Latin America, Oceania and French overseas regions and communities. The library conserves and distributes images taken and described in captions by IRD scientists. The field and laboratory images cover various disciplines: life and earth sciences, health, human and social sciences. The images are provided free of charge for educational and scientific use.
www.indigo.ird.fr/

Scientific news-sheets

Scientific news-sheets published two or three times a month report the latest research results at IRD. Carefully explained, reliable information enables better understanding of today's major research issues for the development of countries in the South. The news-sheets are also published in English and Spanish.
www.ird.fr/la-mediatheque/fiches-d-actualite-scientifique

The journal *Sciences au Sud*

The various sections of the journal *Sciences au Sud* give a panoramic view of research work in all disciplines concerning developing countries, the ways in which research is organised, expertise and the transfer and use of research results and training and support for teams in the South. It is intended for a broad readership: IRD staff, scientific and institutional partners in France and abroad, journalists, students, teachers etc.
www.ird.fr/la-mediatheque/journal-sciences-au-sud

Exhibitions

IRD is present at major scientific events, those for meeting young people and, more broadly, for the general public. Exhibitions are set up by IRD or handled jointly with—among others— Universcience, scientific and technical centres, associations such as ASTS (*Association science technologie société*) and French institutes abroad. Production and distribution are supported by the Ministry of Foreign Affairs and International Development.
www.ird.fr/la-mediatheque/expositions

Interactive web platform '*Le climat sous surveillance*'

Within the framework of COP 21 (Paris, December 2015), this interactive web platform presents the scientific instruments used to study climate changes in various environments (seas, mountains, forests, rivers, arid zones, urban zones and island and coastal environments: humorous animated films, teaching resource file, explanatory videos, links to complementary documentary resources (exhibitions, films, books, etc.), personal pages and video interviews of scientists and a dialogue facility.
www.climat-sous-surveillance.ird.fr/

The website section '*Climat et changements climatiques au Sud*'

Climate changes form a major line of IRD's research in the South. A section of the website describes the multidisciplinary research programmes conducted by the Institute and its partners in more than 25 countries. The work is closely associated with training operations in and through research in order to enhance expertise in countries in the South so that they can play an active, visible role in international scientific mobilisation on climate change.
www.ird.fr/climat

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The Cotopaxi (5,897 m) awakening, Ecuador.

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The mobilisation centred on the 2015 Paris Climate Conference (COP 21) is an opportunity to highlight the vulnerability of environments and populations in the South in the face of climate warming. Some tropical regions are already suffering from its effects, with heat waves in the Sahel, disturbances to monsoon systems, the melting of the Andean glaciers, threats to biodiversity, a rise in sea level and other features.

Research conducted by IRD and its partners provides key knowledge for better understanding of the complexity of these phenomena. This book is a synthesis in three parts: observing and understanding climate change, analysing its main impacts on environments and setting societies and national public policies at the heart of the climate challenge.

Focused on the capacity for resilience of populations and ecosystems in the face of trends in the climate, the book explores solutions that reconcile mitigation and adaptation in response to climate change, conservation of the environment and a reduction of inequalities. The work is both well documented and explanatory, reviewing operations and the results of research that is firmly involved and interdisciplinary, closely associating partners in the North and the South.

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