CLIMATE CHANGE RESEARCH IN FRANCE

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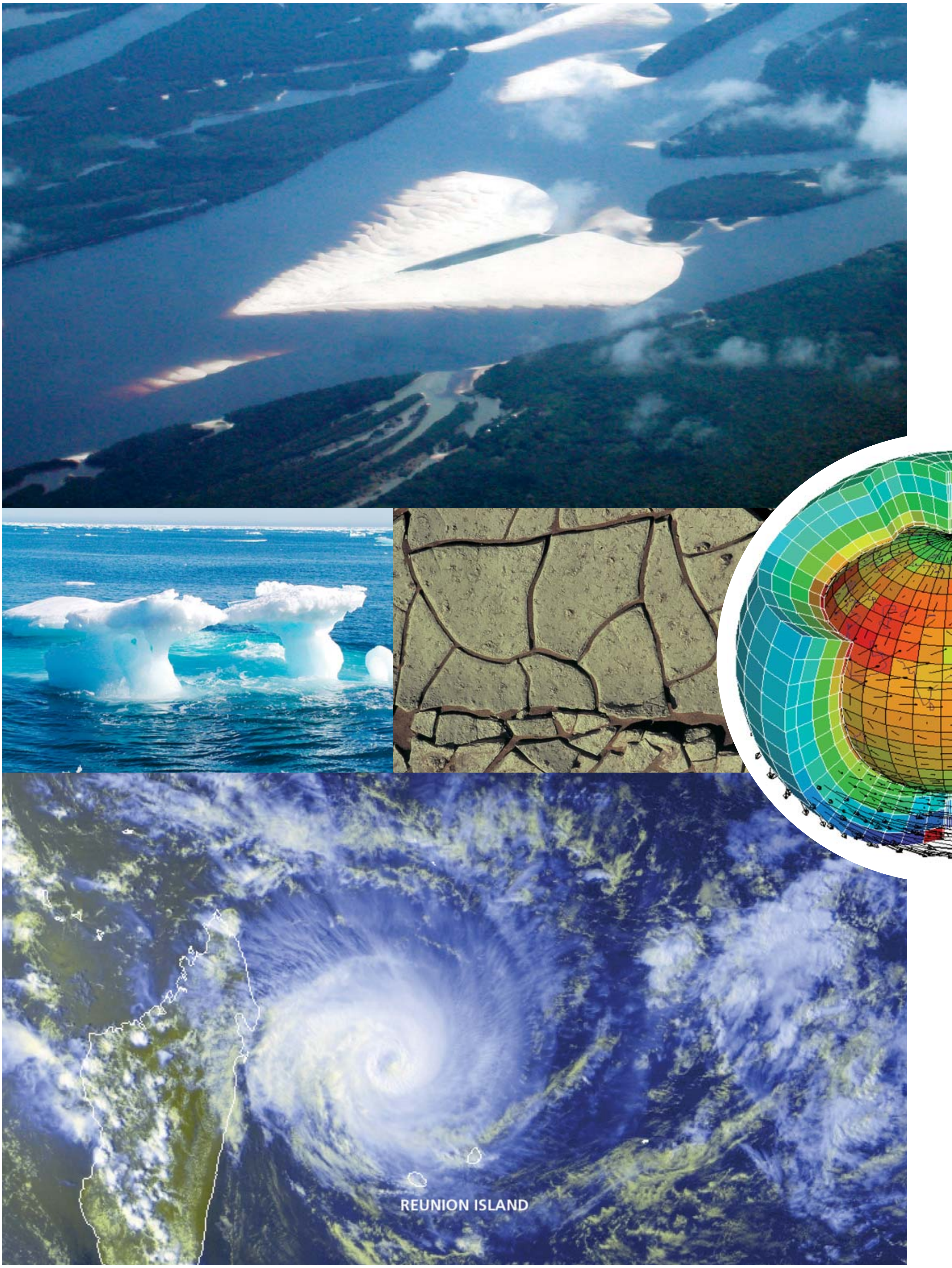
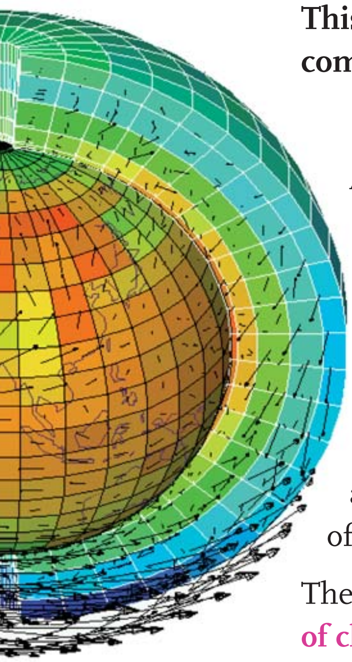

REUNION ISLAND

The scientific community was the first to draw the attention of decision-makers to the risks arising from climate changes associated with greenhouse gas emissions from human activity. Climate prediction, which requires a thorough understanding of fundamental climate mechanisms and, in particular, of the role of human-induced climate disturbance, has now become a matter of major global concern. The 3rd IPCC report assessed that most of the observed warming over the last 50 years is likely to have been due to human activity.

This document presents the most significant results from the French research community over the last five years.



Advances in *in situ* or satellite **observations** of the state of the planet and the recent deployment of new long-term observation systems, are helping to quantify trends in the atmosphere, oceans, ice and land surfaces.

Ongoing studies of past and present climate variability are essential to ensure a better understanding of the mechanisms of the climate system and therefore to improve climate modelling. Field studies are analysing patterns of variability in the North Atlantic sector and the tropics. Studies of ice core samples, sediments and other climate archives are helping to gain insights into climate patterns of the past, from the last millennium back to the glacial and interglacial periods.

The French research community has been devoting major efforts **to the development of climate models** and simulations built up around the different scenarios used for the 4th IPCC report.

Finally, specific analyses and projections are being conducted for metropolitan France.

Research on the **impacts of climate change** on the marine and terrestrial biosphere and on the health of populations has been intensified in response to increasing evidence of global warming in France and of its first observable effects on ecosystems and human activity. In-depth studies have been made on the drought and heatwave of the summer of 2003.

In order to provide tools to support public policy making, **socio-economic analyses** of the impacts of climate change have been produced and strategies developed for reducing greenhouse gas emissions.

OBSERVING THE STATE OF THE PLANET

Since the beginning of the industrial age, human activities, which have expanded at an ever-increasing pace along with population growth, have been modifying the composition of the Earth's atmosphere by increasing concentrations of greenhouse gases (carbon dioxide or CO_2, methane and so on) and aerosols. Measuring concentrations, quantifying fluxes, studying reactivity and estimating the impact of these atmospheric components on the environment, and especially on sea level and the state of the oceans, are all of vital importance to achieve a better understanding of the contribution of human activity to climate change and to improve climate prediction.

Monitoring greenhouse gases

The French research community has made a decisive contribution to long-term surveillance of the main greenhouse gases, through its participation in international networks monitoring greenhouse gases in the troposphere (RAMCES) and stratospheric ozone (NDACC). French know-how in inversion methods, based on local observations and simulations of atmospheric transport, has been used to reconstruct the pattern of global carbon dioxide fluxes and their interannual variability (fig. 11).

Aerosols

In recent years, research efforts have focused on improving satellite observations of aerosols, with the development of the POLDER instrument (fig. 12) and participation in the A-TRAIN satellite cluster for example, on developing cadastral emission maps, particularly for carbon aerosols (fig. 13) and on studies of aerosol reactivity in order to improve their representation in models. To optimise the use of satellite and *in situ* observations, data and expert evaluation on interactions between clouds and aerosols are being collated within a thematic research facility (ICARE).

Sea level

Global sea level rise has been accelerating for some twelve years and is now around 3 mm/year (as against 1.8 mm/year over the previous forty years), according to estimations from JASON and ENVISAT satellite altimeters (fig. 14), the successors to TOPEX-POSEIDON. Thanks to their nearly-global coverage, these satellites are also being used to map regional variability in the rate of sea level change (fig. 15).

The challenge today is to identify the different sources of sea level rise and to make accurate calculations of their respective contributions. It is estimated that about 50% of sea level rise in the last decade has been due to thermal expansion of ocean masses. The remaining share is accounted for by the melting of mountain glaciers (0.8 mm/year), of the Greenland

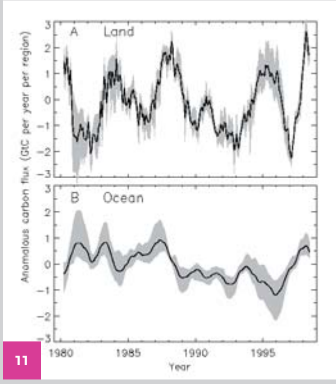


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Figure 11
Interannual variations of CO_2 global fluxes on continents and oceans (difference from the 1980-1998 mean, the seasonal trend is filtered). The variations are twice larger over the continents than over the oceans, and are correlated to the major climatic events, like El Niño.
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Figure 13
Global distribution of carbon soot emissions (from fossil fuels and bio-fuels) with the A2 scenario in 1900, 1997 and 2100.
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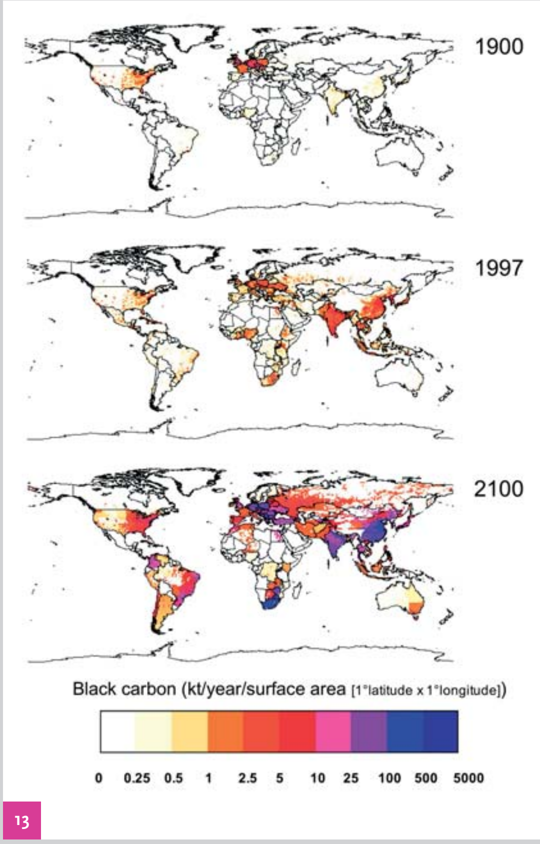

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Figure 12
Optical thickness of small-sized aerosols (r < 0.5 µm) from pollution and forest fires, measured in September 2005 by the POLDER instrument on board the PARASOL microsatellite; the order of magnitude is proportional to the total quantity of these aerosols in the column.
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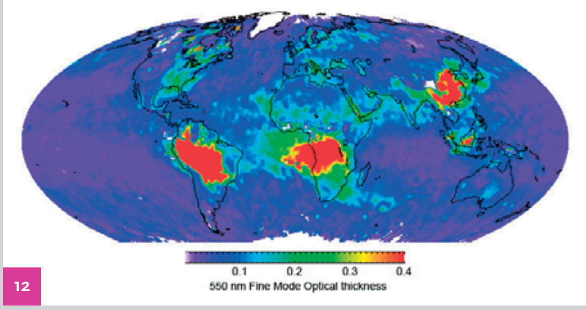

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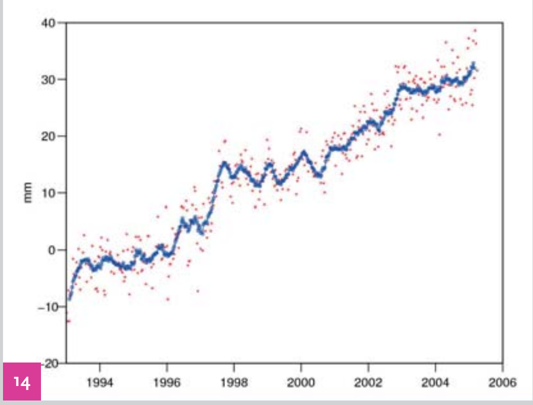
and, to a lesser extent, of the Antarctic ice caps (0.2 to 0.4 mm/year). The low contribution of melting Antarctic ice cap is related to the fact that ice-melt is compensated by a significant increase in snowfall, which is helping to stabilise the ice cap even though there are visible regional variations between east and west. The contribution of inland waters is as yet uncertain, but initial quantifications have been obtained from the GRACE satellite gravity measurements since 2002.

While there is no doubt that the intensifying greenhouse effect is accelerating sea level rise, the time-span covered by these altimetry measurements (barely ten years) is still too short to allow natural variability to be separated from human-induced change.

The state of the ocean

Major research efforts are under way to monitor variations in the North Atlantic ocean conditions. As well as routine salinity measurements using the Sea Surface Salinity network of merchant vessels, hydrographic soundings are taken every two years along a section between the Bay of Biscay and Greenland (OVIDE project), with deployment of a dense network of ARGO floats. The system is producing a coherent set of *in situ* data, which are combined with satellite data and assimilated into a regional model of the North Atlantic to enable analyses of decadal ocean trends in association with atmospheric trends. Initial results indicate that ocean circulation from the Labrador Sea slowed down between 1997 and 2002 (fig. 16).

Oceans also play a vital role in the carbon cycle by absorbing some 30% of the CO_2 emissions generated by human activity. However, recurrent measurements in the North Atlantic are showing that the capacity for CO_2 absorption has lessened in this area. Oceanographic campaigns have demonstrated the role of ocean eddy dynamics in the North Atlantic (POMME), led to a revised estimate of carbon sequestration through natural fertilisation in the Southern Ocean (KEOPS) and revealed the existence of previously unknown species in some of the least biologically productive waters on the planet (BIOSOPE).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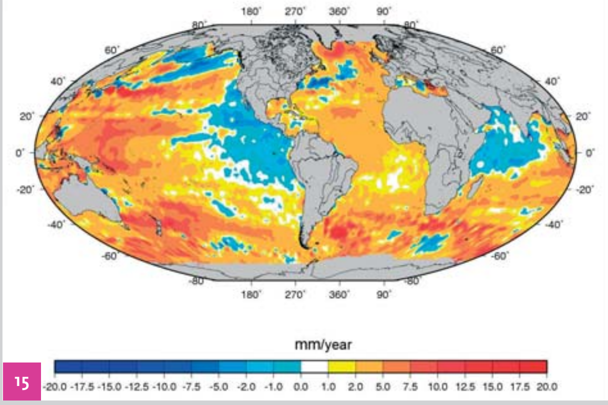
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Figure 15
Geographical distribution of the rate of sea level rise, averaged out from January 1993 to October 2005, from TOPEX-POSEIDON satellite data.
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Figure 14
Variations in global sea level between 65°S and 65°N from January 1993 to March 2006. The red dots are the estimations made by altimetry satellites (TOPEX-POSEIDON followed by JASON) every 10 days (time taken to complete one full orbit), while the blue line represents the average of the same signal.
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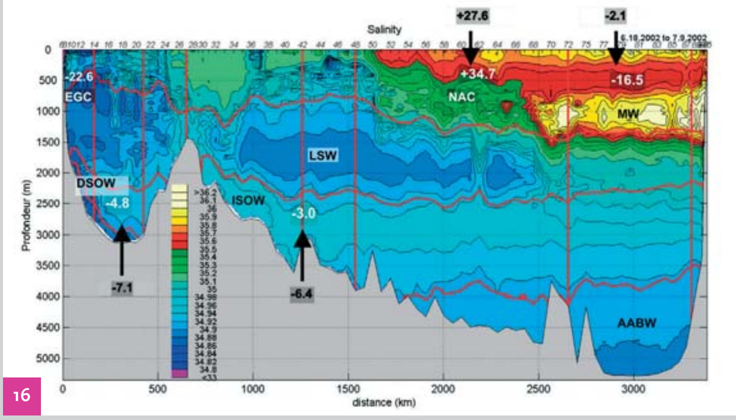
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Figure 16
Hydrographic section obtained in the North Atlantic sector between Greenland and Portugal during the 2002 OVIDE campaign and showing salinity as a marker of different water masses. Also shown are values for significantly differing flows of water masses, obtained in 1997 (in black) and in 2002 (in white).
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STUDIES ON CLIMATE VARIABILITY

Improving predictions of future climate trends also depends on a better understanding of the mechanisms driving the global climate system under natural conditions, including the major patterns of variability in both present-day and past climates.

The North Atlantic Region

European climate is largely determined by atmospheric conditions in the North Atlantic, which are predominantly influenced by four meteorological regimes (fig. 21, top), two of which represent phases of the North Atlantic Oscillation (NAO). Daily fluctuations in temperature and precipitation are due to the transition from one regime to another, while inter-seasonal to decadal climate variability depends on changes in the frequency of occurence. Analyses show that the four regimes have been remarkably stationary over the previous century as concerns their spatial structure. Meanwhile the positive NAO phases have clearly predominated in the last two decades (fig. 21, bottom), which accounts for a large fraction of the winter warming observed across Europe. Modelling studies and statistical analyses suggest that these regimes, in winter and in summer, are sensitive to variations in ocean temperatures in the northern tropical Atlantic, and that the occurrence of summer regimes that tend to produce heatwaves is linked, for instance, to atmospheric conditions in the tropical Atlantic.

The tropical climate

Field campaigns, satellite observations and modelling have significantly advanced knowledge on tropical climates. In the western equatorial Pacific, the haline front (of variation in salinity) has been tracked for several years, with results demonstrating its non-permanent nature. The characteristic structures of the frontal region have been specified, showing their links with El Niño-dominated decadal and interannual variability. Modelling experiments have also demonstrated the role of westerly wind bursts in these regions, especially as regards their impact on ocean structures, and the need to take these into account to improve statistical forecasts of El Niño events (fig. 22). Observations and simulations have also shown the active influence of Indian Ocean temperatures on the monsoon-El Niño system as a whole since the climatic discontinuity in 1976, as well as on climate variability in southern Africa.

The AMMA programme on African monsoons and their influence on the physical, chemical, hydrological and biosphere environment from local to regional scales was set up to find out why the Sahel experienced such a large rainfall deficit in the last century (fig. 23) and to forecast

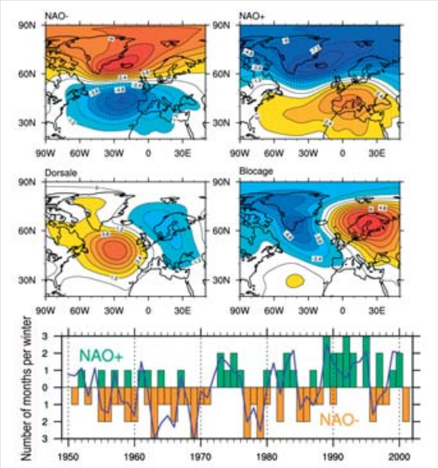

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Figure 21
Top: The four main meteorological regimes for surface pressure in the North Atlantic, estimated from NCEP re-analyses for the winter months (December to February) from 1950 to 2001.
Bottom: number of months in each winter when NAO regimes were present and conventional NAO index (blue curve) calculated as the difference in normalised pressure between Iceland and the Azores. In winter, the NAO+ regime (strengthened anticyclone from the Azores and deeper Icelandic depression) induces arid conditions in the Mediterranean and very mild weather in northern Europe, while the NAO- regime brings cold, dry weather to a large part of the European continent.
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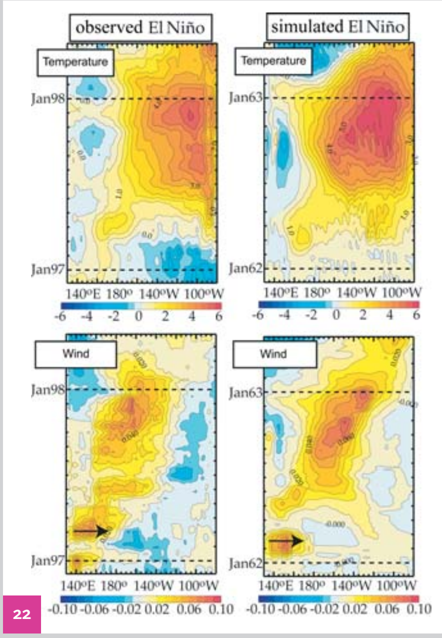

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Figure 22
Longitude versus time diagram in the Equatorial Pacific, showing anomalies in sea surface temperature (top) and in zonal wind stress (bottom) observed (left) during the 1997-1998 El Niño event, and simulated (right) with the HadOPA coupled ocean-atmosphere model into which a westerly wind burst was imposed (black arrow).
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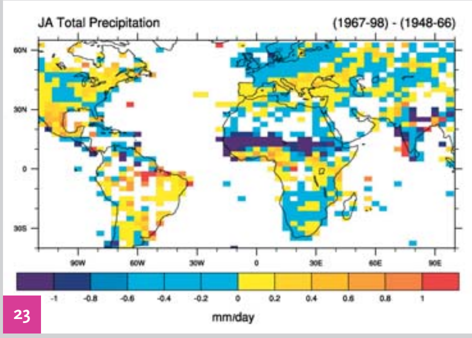

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Figure 23
Differences in precipitation averaged out over July and August in 1967-1998 and 1948-1966: the severe drought conditions in the Sahelian region (deficit of more than 0.8 mm per day) are clearly visible.
© CNRS/INSU, Météo-France, IRD

trends in its climate. Drawing on more than fifty institutions from many different countries and initiated by France, the programme conducted a phase of intensive operations during the summer of 2006 (fig. 24). A second major objective is to bring out the links between climate variability and health problems, water resources and food security in the countries concerned.

Past climates

Before the industrial age, our planet experienced climatic variations of various types that differed from current variations in their nature, duration and amplitude and which, thanks to paleoclimatic simulations, provide a unique opportunity to estimate the sensitivity of climate to forcing of various kinds, to assess model capacities and thus to improve climate prediction.

Through studies covering the last millennium, comparisons can be made between climate warming over the last century and earlier natural variations (fig. 25). The mid-Holocene, some 6,000 years ago, is also an extremely useful period for comparing models and observations because of the intense monsoons that occurred during that time. Studies under the international PMIP programme, coordinated by France, have shown that it is vital to take ocean-atmosphere-vegetation interactions into account to represent the complexity of changes in monsoon patterns. New high-resolution stratigraphic soundings (using boreholes) are being analysed to bring out climatic correlations between different regions. It has already been shown, for example, that the sudden cold events (known as “Heinrich” events) that occurred during glacial periods are correlated with arid episodes in the Mediterranean Basin. On the scale of these “rapid” events, marine core samples from the tropics also suggest links between deep-sea hydrology in the Atlantic and Antarctic climatology.

On a longer time-scale, studies on eight glacial-interglacial cycles using material from the EPICA project’s deep ice coring in the Antarctic have confirmed the link between CO_2 concentrations in the atmosphere and global temperatures (fig. 26), and also clearly show that CO_2 levels are now higher than at any time in the last 650,000 years. Studies of warm interglacial periods also provide an extremely useful framework to understand the mechanisms driving climatic conditions that were close to those of the present.

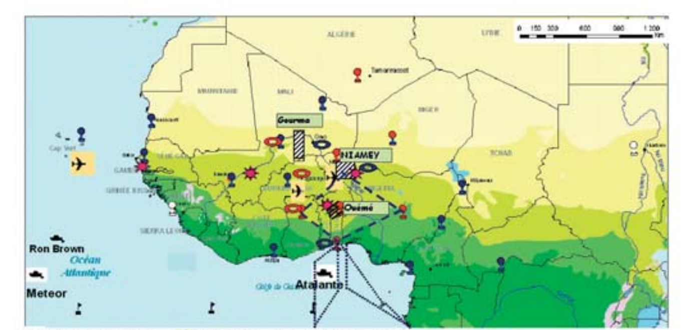

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Figure 24
System deployed for the AMMA campaigns (African Monsoon Multisciplinary Analyses) in the summer of 2006.
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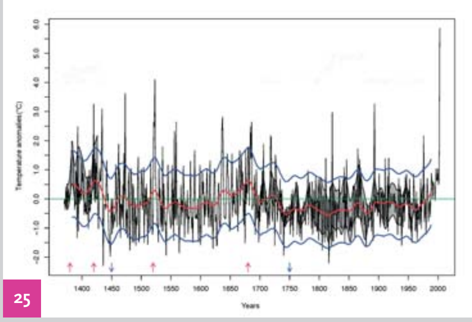

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Figure 25
Temperatures in Burgundy from the months of April to August from 1370 to 2003, reconstructed from grape harvesting dates and set against average observed temperatures from 1960 to 1989, taken as the reference (green line). Yearly anomalies (in black) are smoothed in red, and the confidence intervals due to differences between wine-growing areas are in blue. Red arrows indicate warm events and blue arrows cold events. These results demonstrate the totally exceptional nature of the 2003 heatwave.
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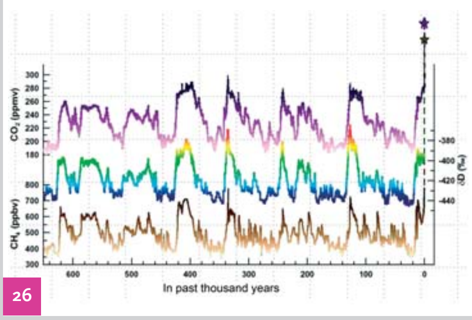

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Figure 26
Climate records during the last 8 climatic cycles as revealed by the ice core samples from the EPICA borehole in Antarctica. The profile for stable isotopes (deuterium) is a marker of air temperature. The air bubbles trapped in the ice are analysed to measure their CO_2 and methane content. Present-day concentrations have been added for comparison.
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MODELLING AND PREDICTING FUTURE

Preparatory work for the 4th IPCC report included the launch of a major international initiative to encourage modelling teams to carry out simulations of climate trend in accordance with a specific protocol. For the first time, all the required simulations were carried out by French teams, who thus made a stronger contribution to the preparation of the report.

French climate models

France has two climate models, one developed by Météo-France and CERFACS (referred to as CNRM), and the other by IPSL, which mainly differ in their atmospheric components. Since the previous IPCC report issued in 2001, improvements have been made to all the components in these climate models: atmosphere (representation of convection, clouds, aerosols and orography), oceans (free surface formulation), sea ice (rheology) and land (land use). Model resolution and coupling between components have also been improved. Finally, several studies have focused on coupling these climate models with models of chemistry, aerosols, biogeochemical cycles and vegetation dynamics.

Simulating climate trend

The simulations made for the IPCC report cover climate trend from 1860 to the present, as well as projections for the 21st century (fig. 31). For the 20th century, the trends simulated with the two French models are consistent with temperature observations, both at global scale and for France. Numerous studies have characterised and assessed their advantages and limitations in terms of both mean states and variability, by comparing their results with 20th century observations. Under the A2 scenario for continuously increasing emissions, simulations of future temperature trends are fairly similar in both models, showing average global warming of around 3.5°C by 2100 (fig. 32). While the CNRM and IPSL models both predict an overall increase in precipitation, respectively of 5% and 8%, their estimations differ at regional scale, particularly over continental areas.

Cloud feedbacks

Climate models in different countries differ as regards the scale of global warming they predict in response to an instantaneous twofold rise in atmospheric CO_2 (ranging from 1.5 to 4.5°C). It has been known for a long time that this uncertainty is primarily due to differences in the representation of the radiative response of clouds to climate change.

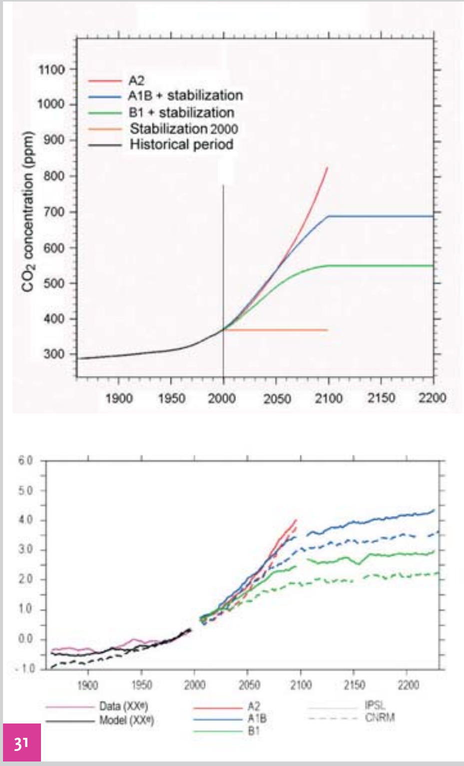

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Figure 31
Top: trends in atmospheric CO_2 concentrations observed from 1850 to 2000 and estimated for the 21st century according to three socio-economic scenarios proposed by the IPCC: the A2 scenario with continually increasing CO_2 emissions; the A1B scenario with emissions increasing and then stabilising; and the B1 scenario with emissions increasing and then decreasing. To study the inertia of the climate system, simulations were made with CO_2 concentrations remaining constant from the year 2000 and 2100 for the A1B and B1 scenarios.
Bottom: trends in average global surface temperatures (°C) observed and compiled by the CRU from 1860 to 2004 (in black) and simulated with the CNRM and IPSL models, using the IPCC scenarios from 2000 onwards.
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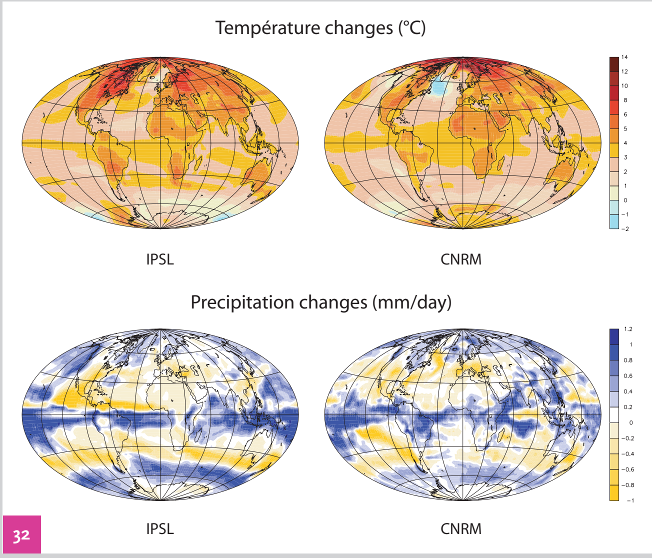

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Figure 32
Geographic distribution of differences in temperature and precipitation between the end of the 21st and 20th centuries, calculated with the IPSL and CNRM models for the A2 scenario.
© IPSL, CNRM

With the development of new methodologies to analyse simulation results in terms of physical feedback mechanisms, it is now clear that these uncertainties lie mainly in the response of boundary-layer clouds (stratus, stratocumulus and cumulus) (fig. 33). This finding opens up the way for new strategies to evaluate the role of these clouds and their sensitivity in the models.

Feedbacks between climate and the carbon cycle

The possibility of positive feedback between human-induced climate change and the carbon cycle has recently come to light: changes in physical parameters (temperature, water vapour) could in fact significantly affect the efficiency of natural sinks (the continental biosphere and oceans) in absorbing CO_2 emissions from human activity. This would accelerate the rate of CO_2 increase and therefore boost climate change even further. Ongoing studies under the international C4MIP project, which is coordinated by France, to compare results from coupled climate-carbon models with CO_2 emission forcing, all show CO_2 increasing at a faster rate, resulting in a 20 to 200 ppm increase in concentrations by 2100 (fig. 34, top). This accelerating pace in turn induces additional warming of some 1.5°C compared to the estimations produced by traditional models (fig. 34, bottom).

The cryosphere

The models indicate that by the end of the 21st century, the Greenland ice cap will be melting at a significantly faster rate. However, the resulting rise in sea level should be mitigated by increasing snowfall over Antarctica as a result of higher temperatures in the region. Although the volume of meltwater flowing from Greenland into the ocean is still low compared to freshwater inflows from precipitation and rivers, a rapid increase in meltwater inflows would weaken thermohaline ocean circulation still further, as the sensitivity tests conducted with the IPSL model appear to suggest. Sea ice is currently shrinking rapidly, and the most recent models are indicating that the trend will continue to point where the Arctic Ocean may become entirely ice-free by the end of the 21st century (fig. 35).

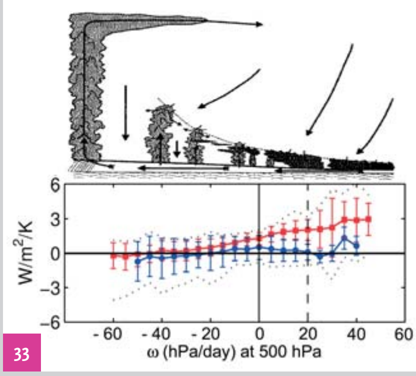

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Figure 33
Responses of sensitive climate models (in red, average simulation results from models predicting severe climate warming) and less sensitive models (in blue, models predicting less severe warming) to radiative forcing from tropical cloud cover under different atmospheric circulation regimes. Positive responses correspond to lower cloud reflectivity of solar radiation. The largest differences between the two model categories concerning radiative responses of clouds to climate warming are found under atmospheric subsidence regimes (right), which are characterised by the presence of low stratus, stratocumulus or small cumulus clouds.
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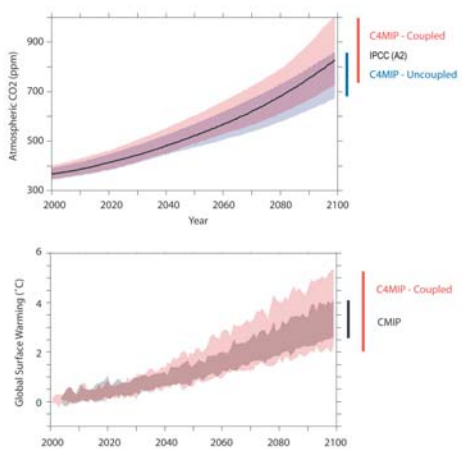

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Figure 34
Simulations for the A2 scenario. Top: dispersion of CO_2 concentrations in C4MIP simulations with and without climate-carbon coupling. Bottom: global temperature set against the reference temperature (year 2000), with coupled C4MIP simulations and IPCC simulations forced with CO_2 concentrations (A2 scenario, black curve) without climate-carbon coupling.
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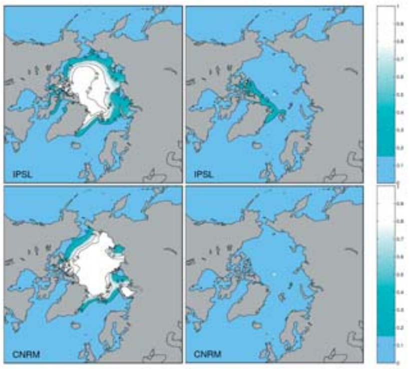

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Figure 35
Fraction of average Arctic sea ice in September (minimum extent), simulated with the IPSL model (top) and the CNRM model (bottom). On the left, results for 1960-1989, which are very close to satellite observations. On the right, results for 2070-2099 with scenario A2. Even though the two models do not produce identical results, both clearly show the underlying regression of sea ice.
© IPSL, CNRM

CLIMATE CHANGE IN FRANCE

Detecting and attributing man-made causes

Studies within the French research community were the first to suggest that it should be possible to detect, from observations of minimum summer temperatures in France, the spatial fingerprint of human-induced climate change at sub-regional scales (fig. 41). Studies to attribute causes are showing that the largest share of human-induced climate warming is due to the combined action of greenhouse gases and sulphate aerosols. The analyses made indicate that spatial patterns of warming mainly result from changes in evapotranspiration. Furthermore, studies on precipitation show that it is also possible to detect an anthropic signal in winter weather trend for recent decades, which mainly stem from changes in the occurrence of different weather regimes. On the other hand, there is no discernible trend for the last fifty years indicating an increase in the number and intensity of storms, or any significant increase in the number of episodes of torrential rain in south-eastern France.

Frequency of extreme weather events

An assessment has been made of the impact of human-induced climate change on the frequency of extreme winds, temperatures and precipitation in metropolitan France. High-resolution simulations across Europe were produced with the IPSL and CNRM models for the A2 scenario, with an emphasis on the frequency of heatwaves, storms, torrential rains and drought. The results show a substantial increase in heatwaves (fig. 42), moderately increasing risks of heavy winter rains and an almost negligible impact on high winds. The impact on the frequency of tropical cyclones in the North Atlantic was also investigated. It was found that cyclone frequency depends on the scenarios used for ocean temperature trend, but that associated precipitation is increasing.

Impacts on snow cover and glaciers

In the last few decades, observations at medium altitude (1,000-1,500 m) have shown a decline in snow cover (fig. 43), in terms of both height and duration. The decline is not so marked at higher altitudes. Glacier shrinkage has also increased in recent years in the Alps, as well as in the tropical glaciers of the Andes (fig. 44).

The evidence indicates that these trends will continue: snow cover will decline in terms of duration (by several weeks at around 1,500 m), extent and thickness. Whatever the climate scenario used, glaciers will continue to shrink, since their mass budgets will no longer be in equilibrium with

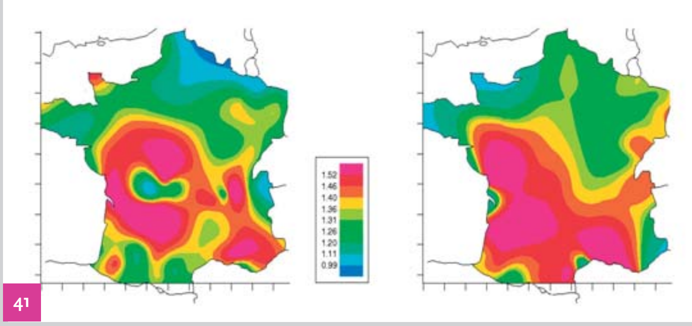

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Figure 41
Left: rate of change in minimum daily summer temperatures observed from 1971 to 2000 (in 1/10°C per decade). Right: fingerprint (technically "guess-pattern") of expected climate warming by the end of this century, calculated from the average of three simulations forced with increasing greenhouse gases and sulphate aerosols and run with the CNRM model zoomed in over France (arbitrary values on a scale increasing from blue to pink).
© CNRM

Figure 42
Average number of heatwave days in summer, a heatwave being defined as a series of at least six consecutive days in which maximum daytime temperatures are at least 5°C higher than the climatic norm (for 1961-1990): reference climate (a), average climate around 2050 simulated with the IPSL model (b) and the CNRM model (c) for the A2 scenario.
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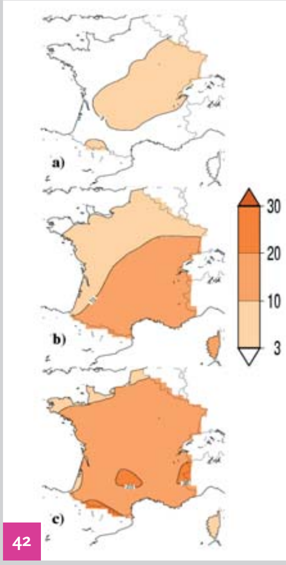

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Figure 43
Interannual variability in snow-cover mean thickness from 11 to 20 February (a) and snow-cover duration (b) at the col de Porte (at 1,320 m in the Chartreuse Massif in Isère).
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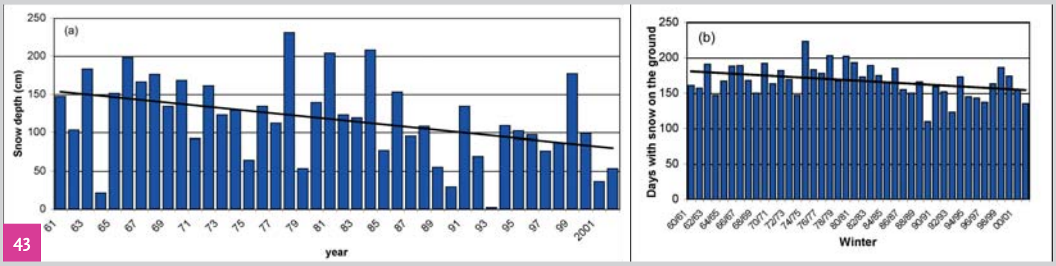

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the climatic conditions forecast for the 21st century. A 3°C rise in temperature will cause every glacier in France to disappear, with the exception of those in the highest regions of the Mont-Blanc range.

Hydrology and water resources

Studies since 2001 on the major river basins in France (mainly the Rhone, Seine and Adour-Garonne) show that estimating the impact of climate change on water resources in the second half of the 21st century is a complex matter. This is because water regimes are shaped not only by climate filtering in the receiving environment, but also by the extensive artificialisation of water flow transfers brought about by hydraulic and agricultural engineering works. In winter and spring, northern France is likely to experience an increase in the volume of water discharge generated by rainfall (fig. 45), but it is likely to remain stable or drop slightly in the southern regions. In mountain areas, rivers floods caused by the spring thaw will appear about a month earlier than at present (fig. 46). Throughout the country, minimum water levels will drop further in summer and autumn, mainly because of an overall increase in evapotranspiration. Winter floods in the lowlands and flash floods in the Mediterranean basin are likely to increase in frequency.

Initial studies carried out in the Seine basin downstream from Paris show that in terms of water quality, mainly during low water periods, the positive impacts of technical improvements in wastewater treatment and of stricter regulations on agricultural inputs should begin to offset the negative impacts of reduced discharge volumes.

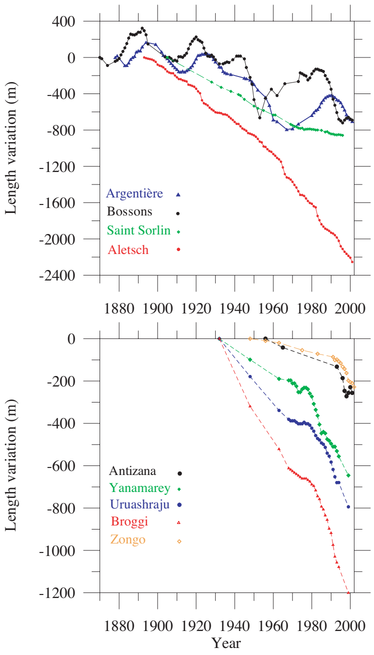

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Figure 44
Variations in length of 4 Alpine glaciers (France and Switzerland) since the end of the 19th century (top), and of five Andean glaciers (Bolivia,Pérou, Equator) since the middle of the 20th century (bottom).
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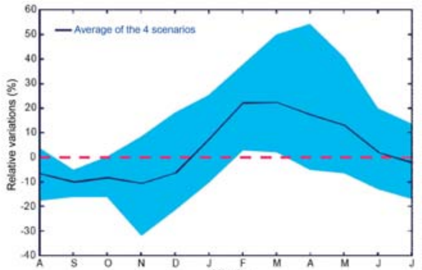

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Figure 45
Variation in discharge of the River Seine at Pose for 2070-2099 (MODCOU model) compared to the current reference period (1985-1991): in light blue, the graph envelope obtained for 4 climate change scenarios, with their average shown as a dark blue curve. This lowland water regime is slightly influenced by snow.
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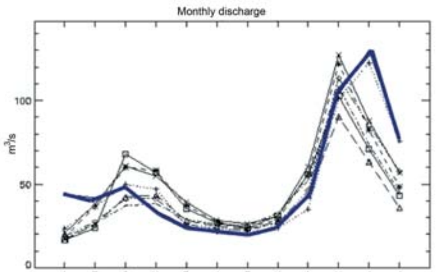

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Figure 46
Average annual discharge for the river Durance at La Clapière in the Hautes Alpes (size of the hydrological basin: 2,170 km²) for 2050-2060 (Safran/Crocus/Isba/MODCOU model): in blue, water discharge in the current reference period (1981-1994); in black, simulated discharge for 6 climate change scenarios (corresponding to a doubling of CO_2 level). The water regime here is strongly influenced by snow coverage modifications: early spring flood, more marked low water in summer.
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IMPACTS OF CLIMATE CHANGE ON THE

Acidification of ocean waters

A major consequence of increasing CO_2 level is the acidification of ocean waters. Since the beginning of the industrial age, there has been an observed decrease of 0.1 in pH values for seawater. It is estimated that in the sensitive waters of the Southern Ocean, with the scenario for continuously increasing emissions (formerly known as IS92a), acidification could cause a drop of about 56% in carbonate concentrations by 2100 (fig. 51), which would affect the skeletons of certain animal species (fig. 52). However, these results depend on the quality of model representations of species physiology and physical ocean circulation. France has therefore devoted an important effort to international OCMIP coordination, in order to compare the quality of representations of transport in ocean circulation models.

Biological freshwater and marine systems

In recent years, a large number of studies in the French research community have focused on the impact of climate warming on key biological processes in flagship marine species, such as fin whales, king penguins, bluefin tuna, sole and anchovy. Each of these studies has shown that climate change is significantly affecting capacities for reproduction and/or survival and/or migration in these species.

Another research field is focusing on the mechanisms of interaction between fisheries and climate variability. A Franco-British team has shown, based on long-term monitoring of zooplankton in the north-east Atlantic, that recruitment (which is the fraction of juveniles having survived the first phases in the life cycle) among cod stocks in the North Sea is significantly correlated with the zooplankton community. Cold periods are favourable to the production of the zooplankton that nourishes cod larvae, and it is clear that the collapse of cod stocks was thus ultimately caused by a combination of overfishing and climate warming. A high priority is being given at international level to improve knowledge on the processes that enable living organisms to adapt to change, the objective being to understand the limits of adaptation and therefore improve predictions of climate change impacts on biodiversity, since available information on this topic is very inadequate at present. A French team has shown that brooding king penguins are capable of storing fish intact in their stomachs for nearly 3 weeks, despite a body temperature of 37°C. This form of adaptation enables them to feed their newly hatched chicks for 10 days, at times when the other parent has to travel further afield to reach increasingly distant marine food sources, a trend which, as another French team has shown, is linked to El Niño. The maximum time that these penguins can conserve food thus determines their ability to adapt to this kind of interannual climate variation.

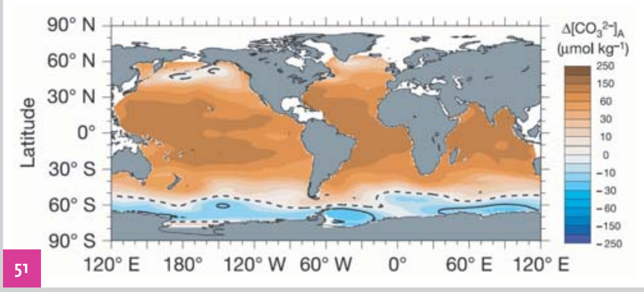

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Figure 51
Deviation from aragonite saturation point in oceans in 2099, obtained by averaging results from 10 ocean models. Aragonite and calcite are the two forms of calcium carbonate, aragonite being the more soluble form and therefore soonest affected by acidification (supersaturated waters in orange, under-saturated waters in blue).
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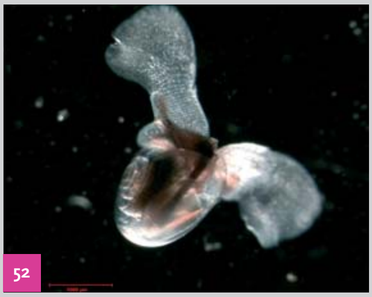

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Figure 52
Limacina helicina, or sea butterfly, the dominant pteropod in polar waters. Pteropods are gastropod molluscs with two fin-shaped locomotor organs
© Russ Hopcroft, NOAA

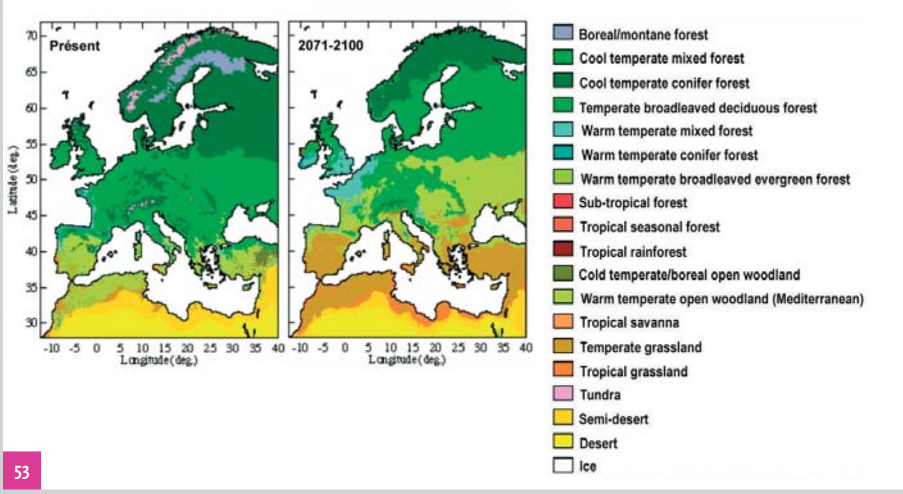

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Figure 53
Distribution of vegetation in Europe and North Africa, observed (left) and simulated (right) with the CARAIB model forced with the ARPEGE climate model, after running the A2 scenario for the period from 2071 to 2100.
© CEFE, University of Liège

Biological systems in terrestrial environments, agriculture and forests

The impact of climate change on the mechanisms driving biological systems in terrestrial environments, agriculture and forests is being studied through research work that combines experimentation and modelling. Specific research programmes have been undertaken to assess impacts on biodiversity.

Biodiversity is affected by climate change because of its impacts on distribution ranges, life cycles and phenology (growth, winter mortality, resting phases, reproductive ages and so on), interactions (parasitism, symbiosis, pollination, etc.) and the responses of organisms (weakened defence mechanisms, increased stress, etc.).

At present, the effects of climate change are well documented for species ranges and phenology. Current research programmes are producing simulations in the form of maps of projected plant distributions, based on the climatic determinism of plant species or on species phenology (fig. 53).

However, its effects on interactions and co-adaptation between organisms are little known as yet, despite the importance of this topic, particularly in terms of plant (fig. 54), animal and human health.

More recently, research work has focused on analyses of observed trends linked to recent warming, drawing on databases and particularly on the phenological calendar of natural and cultivated plant species, which has advanced by an estimated two to three weeks for fruit trees (fig. 55) and vines (fig. 56), for example.

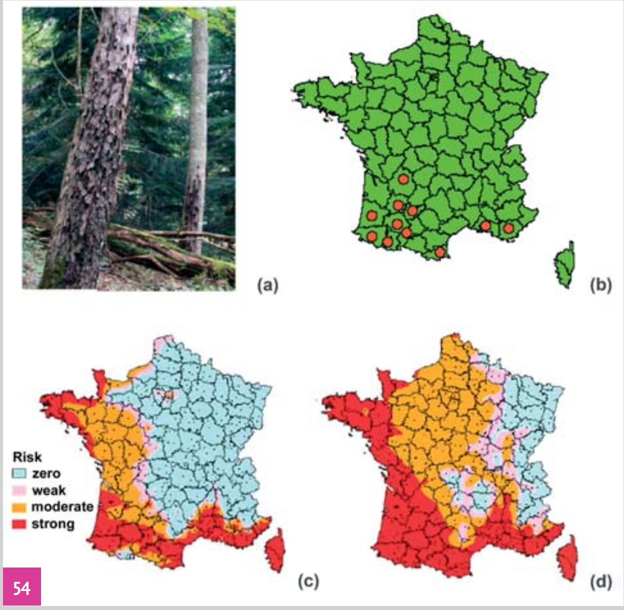

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Figure 54
a) Symptoms of bleeding canker on red oak in response to cortical tissue infection; (b) current distribution of the disease in different oak species; (c) map of disease risks in pedunculate oaks based on climate data observed from 1968 to 1998; (d) map of disease risks in pedunculate oaks based on climate data simulations for 2069 to 2099.
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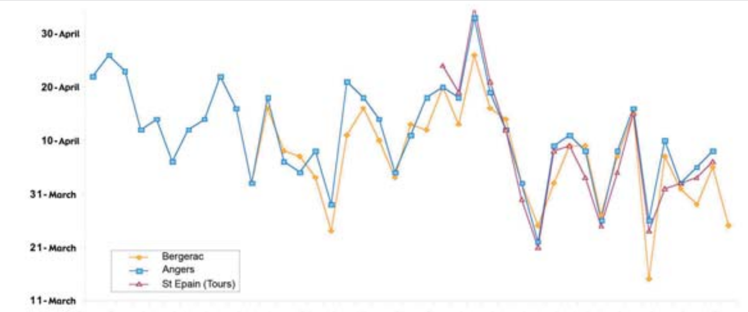

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Figure 55
Changes in the blossoming period for William pears since 1962 in Bergerac, Angers and Saint-Épain (Tours).
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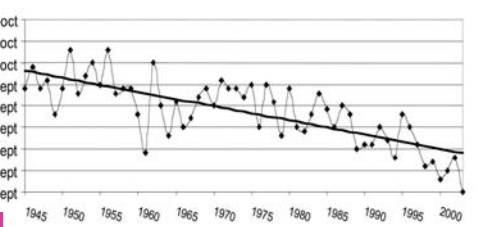

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Figure 56
Changes in grape harvesting dates at Châteauneuf-du-Pape (southern Côtes-du-Rhône) from 1945 to 2000.
© Institut Rhodanien

CLIMATE-RELATED RISKS AND PUBLIC

Socio-economic research on climate change focuses on the assessment and the costs of greenhouse gases (GHG) abatement, i.e., of reducing emission costs, and climate impacts. These topics, which are at the heart of public debates, are centered on the possible types of action and the time frame of their implementation.

Energy scenarios, development scenarios and greenhouse gas emissions

In order to design development and GHG emissions scenarios, it has been necessary to develop a series of models that couple sectoral expertise in energy, and agriculture with macroeconomic models involving the other dimensions of economic policies, such as employment, taxation and competitiveness. This work has especially highlighted the fact that uncertainties for macroeconomic parameters (higher growth in developing countries, market fragmentation, trends in saving rates and active population figures) are at least as high as those for trends in technology. It has also allowed to explain that, ultimately, the actual final costs of policies will not be the same as their apparent direct costs. For example, a given cost of emission reduction may translate into a higher or lower social cost depending on the kind of economic tools used (linkage between both climate and tax policies). Because of the complex interdependence between sectors and between economic agents, those who initially and apparently bear the costs of these policies may not be the same as those who bear the real economic consequences.

Economic analyses of CO_2 emission reduction strategies

Studies in this area have essentially focused on the implementation conditions of the Kyoto protocol and on the impact of the different mechanisms introduced to reduce GHG emissions (fig.61). The “tradable emission permits” (TEP) mechanism has been assessed, confirming the findings in the international literature that indicates that a TEP system could more than halve the costs involved in implementing the Protocol. Research on the conditions required to extend such a system to the developing countries after 2012, when the first Kyoto protocol commitment period expires, has shown that the positive nature of the system is sensitive to the conditions under which initial quotas are allocated. It is also sensitive to the use of export revenues. If this is inadequate, trading gains could be cancelled out by the international energy price rise’s regressive effects for low income populations. The “clean development mechanism” (CDM), which has been set up to support emission reduction projects conducted in developing countries, has also been investigated, particularly with regard to the reality and the measurement of the achieved reductions , and also in order to assess

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Figure 61
Industry, together with electricity and transports, are the major sources of CO_2 emission.
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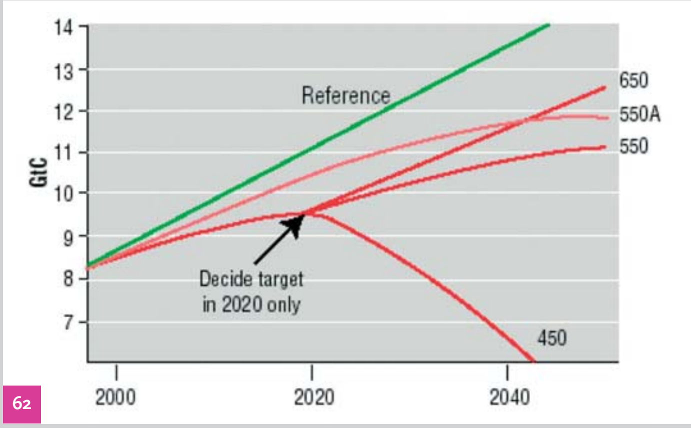

62

Figure 62
Optimum pathway for CO_2 emissions (in red) allowing to wait until 2020 to decide upon the stabilisation concentration level (450, 550 or 650 ppm). This simulation shows that a first reduction of emissions is necessary right now to be ready in case of surprises in 2020 which would need strong reductions.
Following on the present-day trend of emissions (in green) or from a weak reduction (light red, 550A), would induce a very high cost if a change of target is required in 2020.
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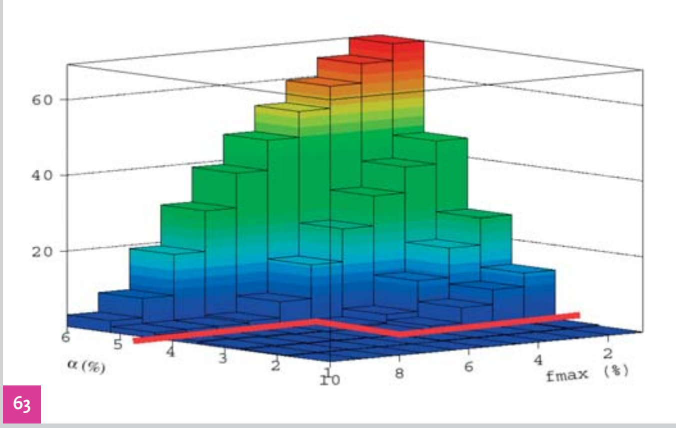
synergies between these projects and the development policies of the host countries. A leveraging effect on development has been revealed, whereby one Euro in revenue from carbon trading can lead to an income that is 1.3 to 4 times higher for the host country's economy, depending on initial assumptions.

Climate change impacts and decisions

A series of studies focused on the costs of climate change impacts in order to identify and rank the main uncertainties so as to allow short term decisions (danger thresholds for GHG concentrations, maximum temperature level, sensitivity of climate responses), and for the adoption an of an optimal response to emission reductions in view of long-term risks.

Discussions have been lead in two ways: compliance with emission caps (in accordance with the Climate Convention) and cost-benefit analyses. In the first case, studies have allowed to calculate optimal strategies to achieve different goals for the stabilisation of CO_2 concentrations (450 to 650 ppm), given that we do not know at present the concentration that will not cause irreversible damage. Until it is possible to decrease these uncertainties, the optimal strategy involves adopting an emission pathway that leaves possibilities for branching into more drastic reduction strategies if it becomes necessary to do so, without imposing immediate costs that could ultimately prove to have been too high (fig. 62). The second case is a context of cost-benefit analyses in which climate impacts are treated in monetary terms: threshold effect and non-linearity are more important factors than the absolute amount of damage costs in the very long term. The rate of change thus becomes the leading parameter since it determines adaptation capacities. It can be shown that even in the case of severe impacts, the economic cost will be low if they appear gradually enough to allow timely implementation of adaptation measures. This is no longer the case when impacts appear at a faster pace than economic adaptation. For example, a succession of extreme events may give rise to very high costs if reconstruction needs exceed economic capacities (fig. 63).

An additional contribution concerns the tempo of carbon sequestration activities. Carbon cycle models that include changes in fluxes linked to land use changes have been used to quantify the non-equivalence between carbon emissions from fossil fuels and those stemming from deforestation which reduces the capacity of potential carbon sinks. This study has shown that it is important to slow down deforestation and to increase carbon sequestration in biomass (fig. 64).



63

Figure 63
Decline in GDP due to extreme climate events after 100 years. The red line shows the limit below which GDP would decline by less than 1%; *alpha* is a composite index of the increase in the frequency and destructive power of extreme events; *fmax* is a measure of the maximum amount of investment and potentially usable human resources available for reconstruction over a given period of time.
© CIRED

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Figure 64
Deforestation emits CO_2 and reduces the capacity of the land biosphere to absorb anthropogenic CO_2. Photo from Brazil.
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IMPACTS ON HUMAN HEALTH

Climate change is likely to affect human health in several ways: extreme temperatures may affect vulnerable people and epidemics may develop as a result of changes in the distribution range of disease vectors.

A survey of mortality in France during the 2003 heatwave established climate thresholds that are life-threatening for the French population. Simulations for the end of this century, carried out for the IPCC scenarios, have predicted that maximum mortality will shift from winter to summer (fig. 71).

The 30-year drought being experienced in West Africa has resulted in the emergence of tick-borne borrelia infection. This is due to the increased range of the disease vector, which has been shown to be massively present north of the 750 mm/year isohyet (isoprecipitation) in the entire western half of the region.

Three other projects now under way are looking into the impact of climate change on cholera in the Mediterranean and dengue fever in South America, as well as on thermoregulation among vulnerable people during heatwaves.

THE 2003 HEATWAVE

The 2003 heatwave, when temperatures in France were at least 4°C higher than average, and the severe drought conditions that prevailed as from the month of June, was exceptional. The analysis of grape harvest in dates in Burgundy since 1370 has confirmed its historic nature (see fig. 25 p.7). However, climate simulations made for the A2 scenario show that conditions like these will become common by the end of the century, and even considerably worse (fig. 72).

The heatwave had major consequences for the population, with excess mortality estimated at 15,000 people, for agriculture, with production losses of up to 20 or 30% for some annual crops and up to 50% for fodder crops, and for forests and natural environments under long-term monitoring programmes. The consequences for biomass have been assessed by combining models of biosphere mechanisms and satellite data (fig. 73). A European project has succeeded in quantifying the loss in terms of carbon storage at around four years (fig. 74), thus demonstrating high positive retroaction of climate warming on the overall carbon budget.

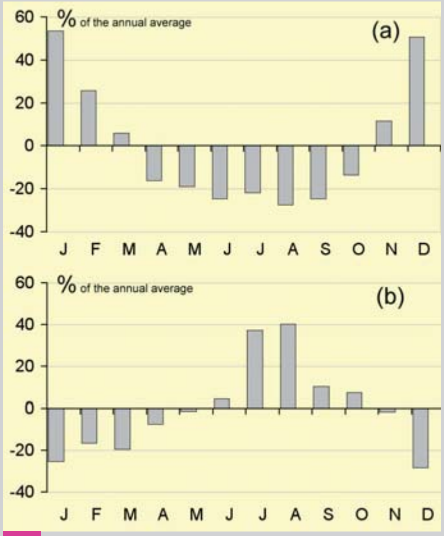

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Figure 71
Trends in the seasonal rhythm of mortality in France observed from 1991 to 1995 (a) and stimulated for 3°C of warming (b).
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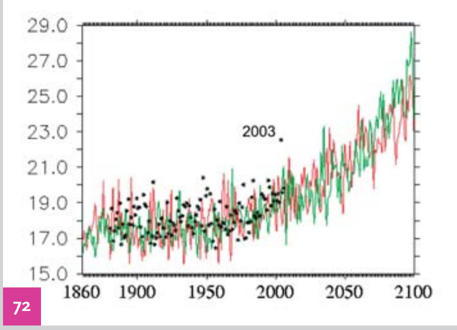

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Figure 72
Trends in average temperatures (°C) from June to August in metropolitan France observed from 1880 to 2005 (in black) and simulated with the CNRM model (in red) and the IPSL model (in green) beyond the year 2000 for the A2 scenario. The highest temperatures in the summer of 2003 will become common by the end of the 21st century.
© LMD/IPSL, CNRM

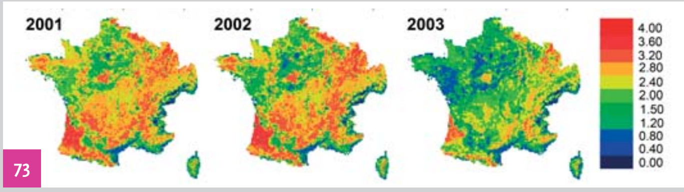

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Figure 73
Leaf index observed in mid-August across France (ECOCLIMAP2).
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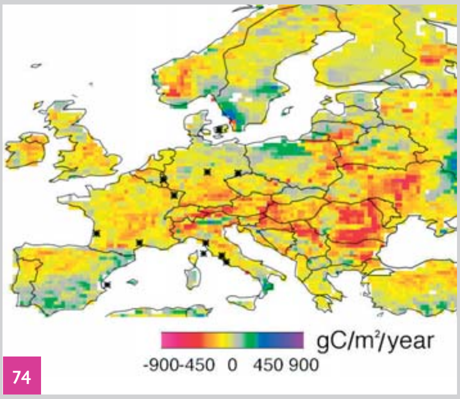

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Figure 74
Deviation of plant productivity associated with the 2003 heatwave from average productivity between 1998 and 2005.
© LSCE/IPSL

RESEARCH INFRASTRUCTURES

Climate studies require an approach that combines field campaigns, observations on the ground and from space and modelling. Oceanographic vessels, research planes, balloons, satellites and computation facilities are made available to the community by the different national research organisations. These research organisations are also developing a policy for long-term *in-situ* observation systems, with additional experimentation facilities in the area of biosphere responses. France is contributing in this way to the implementation of a Global Earth Observation System of Systems (GEOSS).

Earth observation from space

Numerous satellite programmes, piloted by the French Space Agency, CNES, or in cooperation with other space agencies, are contributing to climate studies. They include, for instance, studies of clouds, aerosols and ocean colour (POLDER instrument on board the PARASOL microsatellite), ocean altimetry (TOPEX-POSEIDON, JASON), studies on the microphysical properties of clouds and aerosols (CALIPSO mission) and stratospheric chemistry (ODIN, ENVISAT) (fig. 81). Other projects are currently being developed to measure soil humidity and ocean salinity (SMOS microsatellite), tropical cloud cover (Megha-tropiques) and Sun-Earth relationships (PICARD microsatellite).

Field campaigns

Oceanographic, coastal and deep-sea vessels and research aircraft are all national facilities that are essential to implement intensive *in-situ* measurement campaigns, usually under international campaigns. These facilities also include ground instruments such as radar, lidar, sensors, and so on. The AMMA programme is using the two French research aircraft (fig. 82) as well as the Atalante research ship in the Atlantic Ocean (fig. 83). The instruments implemented on these ships and aircraft are made available from the national stock.

Polar research

The Paul Émile Victor Polar Research Institute runs facilities, such as the Franco-Italian Concordia station in Antarctica (fig. 84), for research in remote polar regions. It also uses the Marion Dufresne (fig. 85), a vessel which was specially designed for research in the Southern Ocean and for taking core samples from marine sediment. Its public service mission enables the French research community to take an active part in international projects, such as the EPICA ice coring project at Concordia or the IMAGES core sampling campaigns.

81

Figure 81
The A-TRAIN, a satellite series used to study the role of interactions between aerosols, clouds, water vapour and radiation, in which France is participating with its PARASOL and CALIPSO satellites.

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Figure 82
The Falcon 20 (CNRS/INSU, CNES), one of the two French research aircraft used for high-altitude measurements, landing at Niamey airport during the AMMA campaign.
© AMMA,
Photo TABURET

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Figure 84
The Concordia Station in Antarctica.
© IPEV

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Figure 83
The Atalante research ship (AMMA).
© IFREMER

Figure 85
The Marion Dufresne.
© IPEV

Long-term observation systems

To ensure that a large number of parameters can be monitored over the long term – for at least ten years – France has set up a system of long-term observation systems. These are monitoring atmosphere composition, sea level, ocean parameters and Alpine and Andean glaciers, as well as taking measurements used to study processes in the different environments. The data acquired are being used to build up mainly international research databases. France is also contributing to worldwide ocean research with deployments of ARGO floats under the Coriolis project (fig. 86).

Biosphere research

For studies on how the biosphere is likely to be affected by changes in physical or biogeochemical parameters, the research community uses a range of experiment systems designed to test the environmental parameters of the ecosystems concerned (fig. 87).

Computation facilities

Climate modelling requires powerful computational facilities that are made available to the research community by national computing centres (fig. 88). In France, producing the simulations for the 4th IPCC report required some 80,000 hours of calculations over six months.

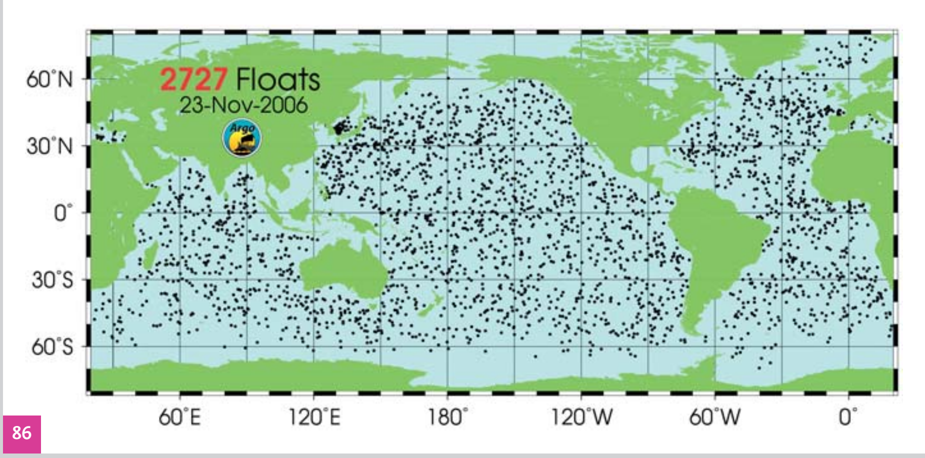

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Figure 86
Distribution of ARGO floats.
© ARGO

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Figure 88
The NEC computer at the CNRS computing centre.
© IDRIS

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Figure 87
System for studies on the consequences for natural ecosystem mechanisms of changes in climate variables.
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Climate research necessarily requires a multidisciplinary approach, which in France is organised around national programmes that are managed by Institut National des Sciences de l'Univers, the Ministry for Research, the Ministry for Ecology and Sustainable Development (GICC programme), and, more recently, by the National Research Agency.
These different programmes involve a large number of research organisations and contribute to major international programmes, mainly the World Climate Research Programme and the International Geosphere-Biosphere Programme.

http://www.insu.cnrs.fr
http://medias.obs-mip.fr/gicc

French research organisations

CEA > Commissariat à l'énergie atomique (*French Atomic Energy Commission*)
CEMAGREF > Institut de recherche pour l'ingénierie de l'agriculture et de l'environnement (*French Institute of Agricultural and Environmental Engineering Research*)
CNRS > Centre national de la recherche scientifique (*National Centre for Scientific Research*)
IFREMER > Institut français de recherche pour l'exploitation de la mer (*French Institute for Research on Marine Resource Use*)
INRA > Institut national de la recherche agronomique (*National Institute for Agronomic Research*)
IRD > Institut de recherche pour le développement (*French Development Research Institute*)
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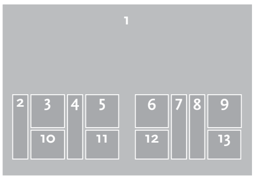

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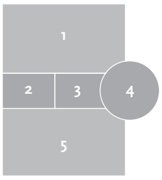

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Facilities and programming agencies

ANR > Agence nationale de la recherche (*National Research Agency*)
CNES > Centre national d'études spatiales (*French Space Agency*)
INSU > Institut national des sciences de l'Univers (*National Institute for Earth and Astronomical sciences*)
IPEV > Institut polaire français Paul Émile Victor (*Paul Émile Victor Polar Research Institute*)

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