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FROM RESEARCH  
TO INDUSTRY

# 15 → The climate

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**PREDICTING THE CLIMATE: MODELING**  
**THE GREENHOUSE EFFECT**  
**STUDYING PAST CLIMATES**  
**MONITORING CHANGES TO CLIMATE AND THE ENVIRONMENT**



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# The climate

## THE CLIMATE MACHINE 4

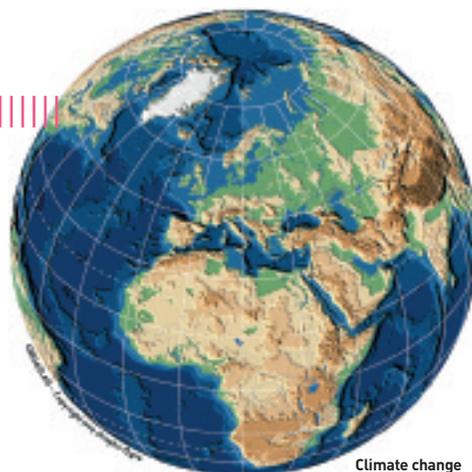
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Climate change impacts on the entire planet.

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Today, various technologies help us to understand climate function.

"Climate involves changes in meteorological conditions considered over the entire planet."

# climatology and meteorology

Before we begin, we need to define the difference between meteorology and climatology. Meteorology is the study and forecasting of atmospheric phenomena over short periods of time, for specific geographic areas. The information dealt with is, therefore, temporary. Climatology investigates sets of meteorological conditions which are likely to affect different regions over long periods of time. The subject is built upon the foundations of various natural sciences: geography, geology, physics, chemistry...

The word "climate" is used to refer to two distinct ideas. The more traditional meaning, which we learnt in our geography classes, is a property of a given location: the Earth is divided into climatic areas as a function of the meteorological conditions which dominate the various seasons in those regions. The second meaning of the word "climate" refers to a global approach with respect to time: in this case, we are interested in changes in meteorological conditions considered over the entire planet and over long time periods (at least 30 years). It is this second meaning of the word that forms the subject of this leaflet, a leaflet which aims to explain how the global climate functions.

TO UNDERSTAND THE CLIMATE ON EARTH, WE NEED TO DEFINE THE "CLIMATE MACHINE", STARTING BY IDENTIFYING THE SIGNIFICANT PARAMETERS AND THEIR INTERACTIONS.

# The climate machine

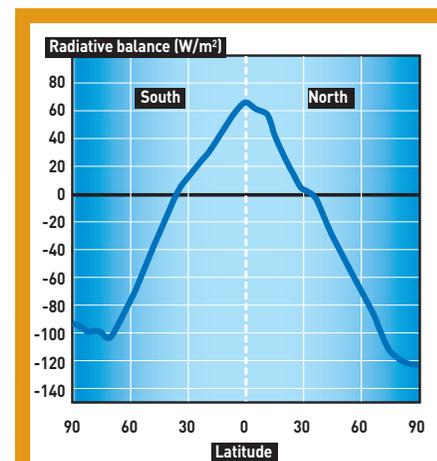


## THE EARTH AND THE SUN

The Earth is a solid rotating ball, enveloped in gas, and covered with water over 70% of its surface. The 30% of the surface that projects above this water is very unevenly distributed over the globe, and has a varied topography. The planet receives its energy from the Sun with a mean power of  $1,368 \text{ W/m}^2$  incident at the top of the atmosphere, measured perpendicular to the Sun's rays. Since the Earth is a sphere, and only half of it can be illuminated by the sun at any one time, the mean energy received at the surface of the Earth is  $342 \text{ W/m}^2$ . There is a large disparity between the equatorial regions where, in the middle of the day, the Sun's rays meet the surface almost perpendicularly, and the polar regions, where the glancing impact of the illumination provides only a weak energy per unit surface area (the word climate comes from the Greek klima which means inclination).

The spectrum of radiation originating from the sun consists mainly of wavelengths between  $0.2 \mu\text{m}$ , in the ultra-violet region, and  $4 \mu\text{m}$  in the infrared. The Earth emits energy back into space, in the form of infrared rays (from 4 to  $100 \mu\text{m}$ ).

The climate is said to be in "radiative equilibrium" when the amount of (solar) energy it receives is equal to the amount of energy re-emitted by the Earth in the form of infrared radiation (see the chapter below on "The greenhouse effect"). Such a radiative equilibrium is achieved on the global level. In contrast, there is a strong variation between different latitudes: at



## THE MEAN ANNUAL RADIATIVE BALANCE

The radiative balance is the difference between the energy received from the Sun and that emitted back into space, as a function of latitude. This curve comes from the results of the ERBE (Earth Radiation Budget Experiment, see box on page 6) which since 1984 has used satellite measurements of the radiation sent from the Earth into space (reflected solar radiation and radiation from the ground).

the lowest latitudes, the energy received exceeds energy radiated back into space. Above latitude  $35^\circ$ , the inverse is true. Hence, the surface of the Earth is in a radiative disequilibrium at any individual location. If no heat transport was taking place, temperatures would be very much higher than we know them to be in the Tropics, and would be lower above latitude  $40^\circ$ ; i.e. it would be warmer in most of Africa and cooler in France, for example.

The current average meteorological conditions exist because of the climate machine, which transports excess heat from lower latitudes to higher latitudes.

The atmosphere and the oceans transport comparable amount of energy. According to current estimates (see diagram p.6), oceanic heat-transport dominates at lower latitudes, via the water

cycle and atmospheric heat transport takes over as we move towards the poles.

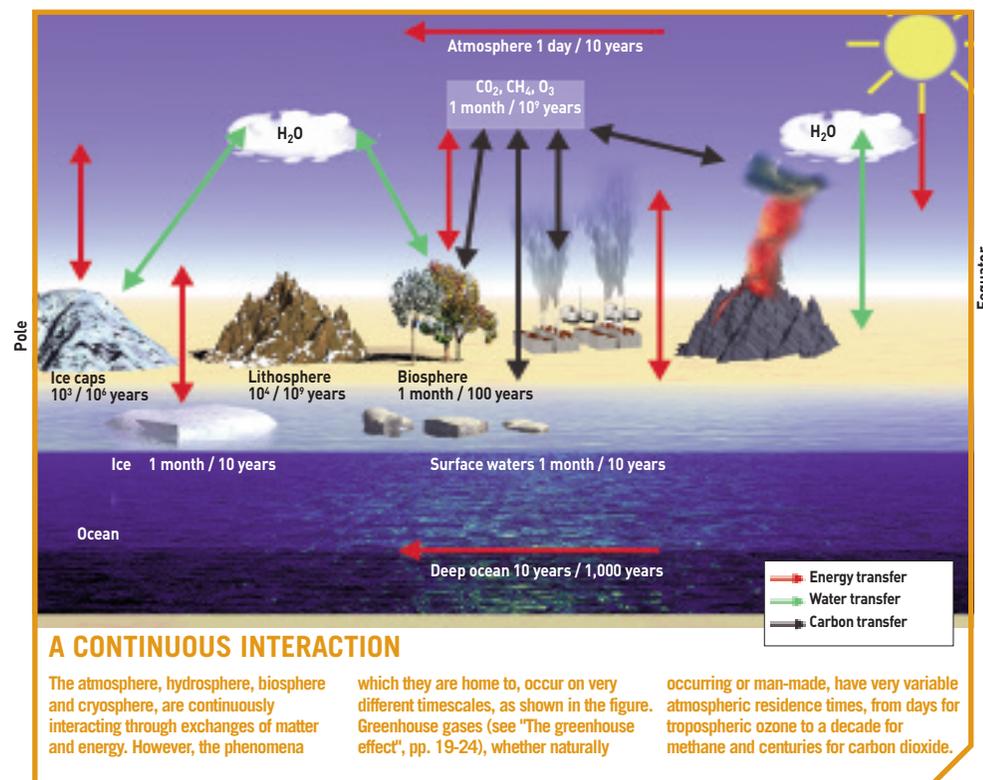
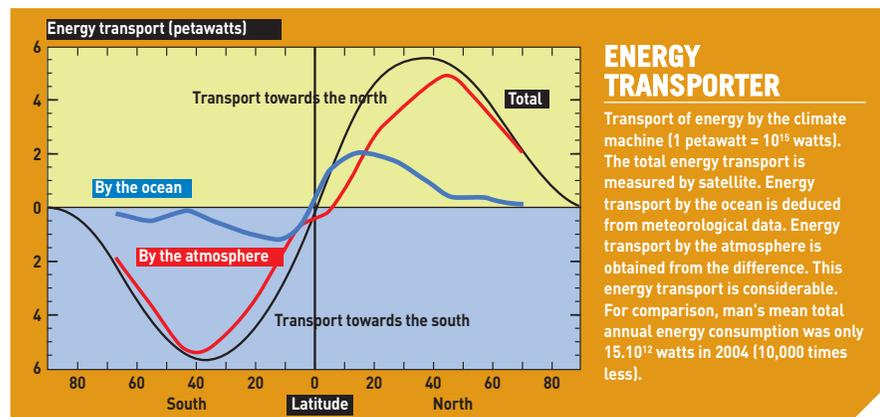
## THE MULTIPLE ASPECTS

The function of the climate machine is regulated by the laws of physics (thermodynamics, fluid mechanics, radiative transfer...), as well as chemistry and biology. It relies on the various phenomena which occur within the fluid layers that envelop the surface of the Earth:

- the two fluid dynamic, of the atmosphere and the waters of the oceans (hydrosphere);
- the physical and chemical processes of the compounds they contain, and their interactions with the biosphere (continental vegetation, aquatic microorganisms on the ocean surface), in particular, but not uniquely, for the role of photosynthesis;

• the formation, thawing, and behavior of ice (cryosphere), both marine (pack ice) and continental (especially, the large ice caps of Greenland and Antarctica). The phenomena governing the function of the various components of the climatic system have very different response times. Hence, mixing in the lower stratosphere occurs on a timescale of a day; mixing of oceanic surface waters requires one month; one year is needed for dispersal of atmospheric aerosols; decades are required to eliminate certain greenhouse gases; it takes a millennium for water to complete a deep oceanic circulation loop and several tens of thousands of years for the continents to achieve isostatic equilibration.

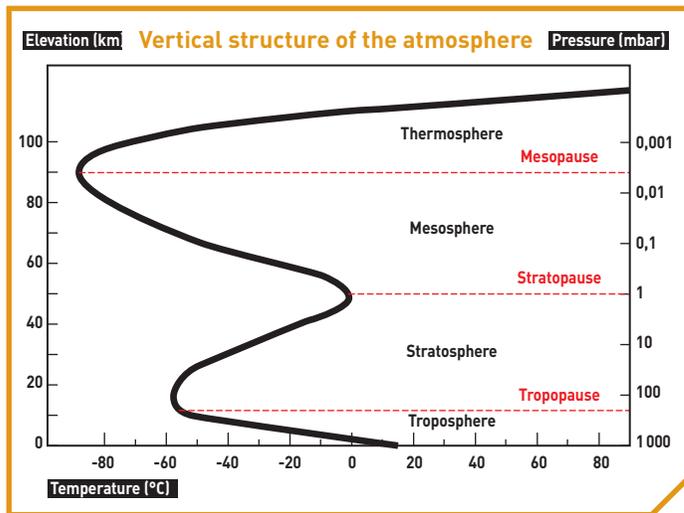
The continents are floating to varying degrees on the terrestrial magma, as a function of their weight. They rise slowly as this weight diminishes through erosion or large scale thawing of glacial masses.



As well as this large non-uniformity in the timescales of the phenomena involved, there is also a large variety in the range of their characteristic distances: aerosol particles have sub-micron dimensions, ice crystals and water droplets in clouds have micrometer dimensions (which determine their radiative heat transfer behavior); the mixed layer at the surface of the oceans is around 100 meters thick, the ice-caps cover millions of square kilometers and have heights of several kilometers; and ocean currents cover distances measured in thousands of kilometers.



Almost all the atmospheric phenomena which affect climate occur in the troposphere.



## THE ATMOSPHERE

The Earth is surrounded by a gaseous envelope, the atmosphere. The main atmospheric phenomena which affect the climate, take place in the troposphere. The stratosphere also plays a role through its involvement in the **radiative balance** in normal conditions through absorption of UV by **ozone**, but also

A powerful greenhouse gas, formed naturally in the stratosphere and present in the troposphere due to the effects of pollution.

The balance of the quantity of energy received (from the Sun) in comparison to the quantity of energy re-emitted (into space).

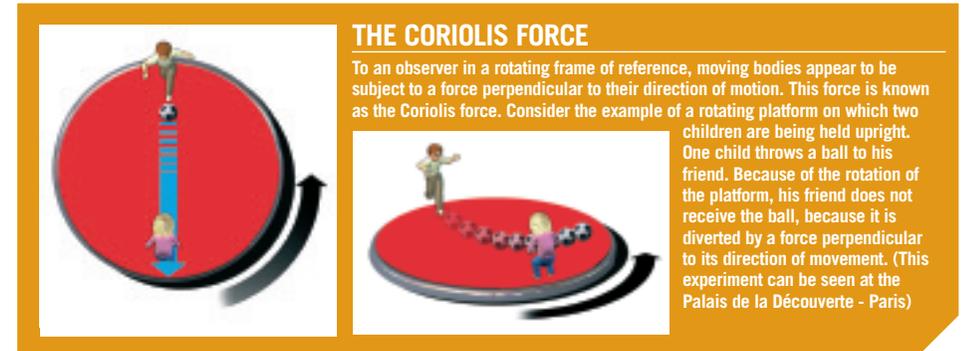
in the presence of sulfate aerosols (injected into the stratosphere during major volcanic eruptions). These aerosols act as a parasol, reflecting part of the Sun's light back into space. The stratosphere is stratified in temperature, from which it gets its name.

The troposphere is characterized by a steep vertical temperature gradient, due to the fact that most of the heat which supplies it, is transmitted from the Earth's surface:

- either directly by conduction and turbulence - referred to as sensible heat;
- or in the form of infrared radiation, a large fraction of which is absorbed by components of the troposphere;
- or in the form of latent heat, through evaporation of water from the surface. This heat is returned when the vapor condenses. The troposphere is moved around by a system of winds whose "engine" is powered by heat. The operation of this engine is strongly influenced by the rotation of the Earth, and notably by its topography.

## Circulation of the atmosphere

The trade winds are very regular winds coming from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere. Very warm and very dry at the outset, these winds pick up moisture as they move along their oceanic route. They converge in the equatorial region, where their burden of momentum, heat



## THE CORIOLIS FORCE

To an observer in a rotating frame of reference, moving bodies appear to be subject to a force perpendicular to their direction of motion. This force is known as the Coriolis force. Consider the example of a rotating platform on which two children are being held upright. One child throws a ball to his friend. Because of the rotation of the platform, his friend does not receive the ball, because it is diverted by a force perpendicular to its direction of movement. (This experiment can be seen at the Palais de la Découverte - Paris)

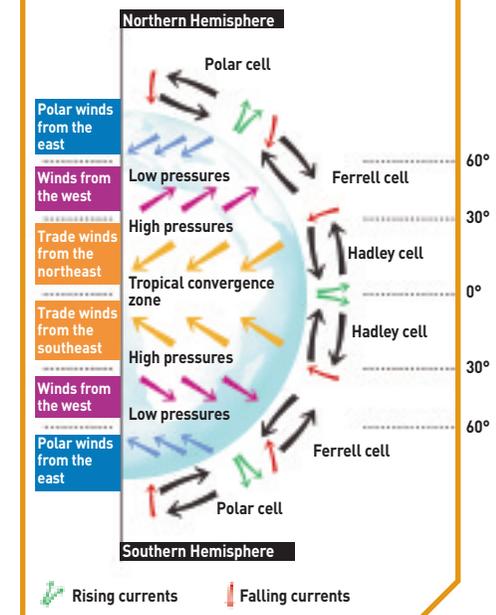
and humidity, provides the equatorial air with the necessary energy to rise up by **humid convection** to the troposphere at an altitude of 15 km, generating intense **precipitation**. At an altitude of 15 km, these air masses, largely drained of moisture, diverge moving north and south to end up at around latitude 30°. Here they descend again, becoming reheated and strongly reducing their relative humidity. This explains the presence of the great deserts in the two hemispheres. The trade winds are pushed towards the West by the "Coriolis force" (see box above), a manifestation of the fact that the movement is taking place on a rotating body.

Convection cells are also found at other latitudes (see diagram opposite): Ferrell cells at intermediate latitudes and polar cells at high latitudes. At intermediate latitudes, these diverse cells lead to westerly winds at the surface and the jet streams at high altitude. The circulation is strongly modulated by Rossby waves, which are a consequence of the variation of the Coriolis force

Vertical movement of the air due to inhomogeneity in its temperature and hence its density.

Liquid: rain and fog.  
Solid: snow and hail.

## Typical behavior of the atmospheric circulation



as a function of latitude. These atmospheric instabilities generate the succession of depressions which sweep across the Atlantic and Western Europe.

The diverse meteorological phenomena produced within the atmosphere (wind, transport mechanisms, precipitation, cloud...) are clearly actors on the climatic stage. Clouds, which are able to absorb and reflect solar radiation and radiation from the ground, play a fundamental role as either regulators or amplifiers of the greenhouse effect, depending on their structure and altitude.

The various components of the system interact continuously. Hence, the winds drive the large ocean currents, whose characteristics are also refined by the topography of the oceanic basin and by the rotation of the Earth.

## THE OCEANS

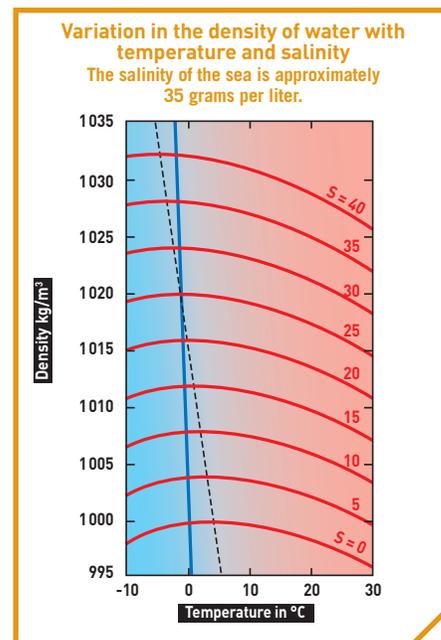
The Oceans are a large, salt-water reservoir, whose surface covers 70% of the Earth to a mean depth of 3.7 km.

### Ocean circulation

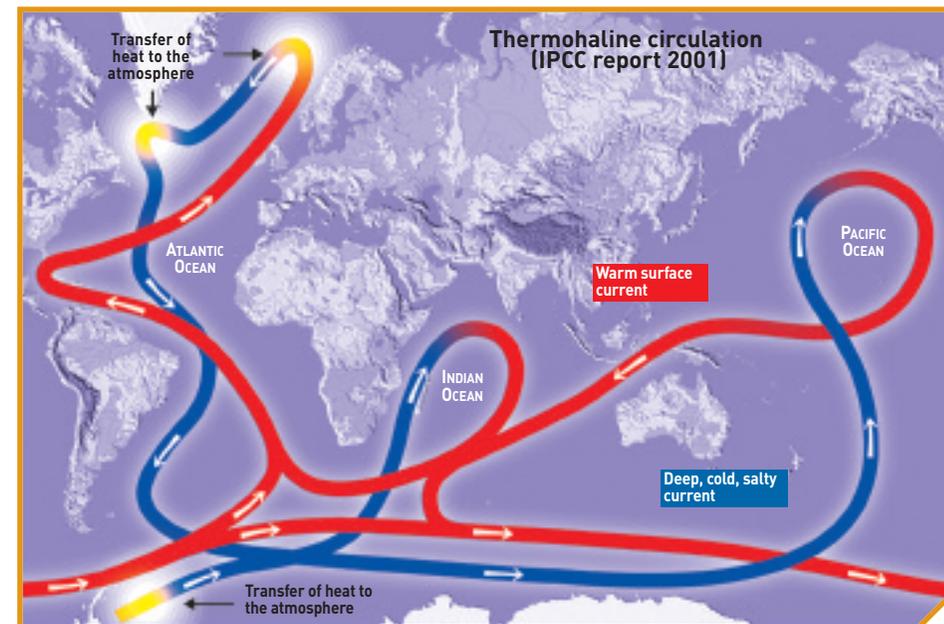
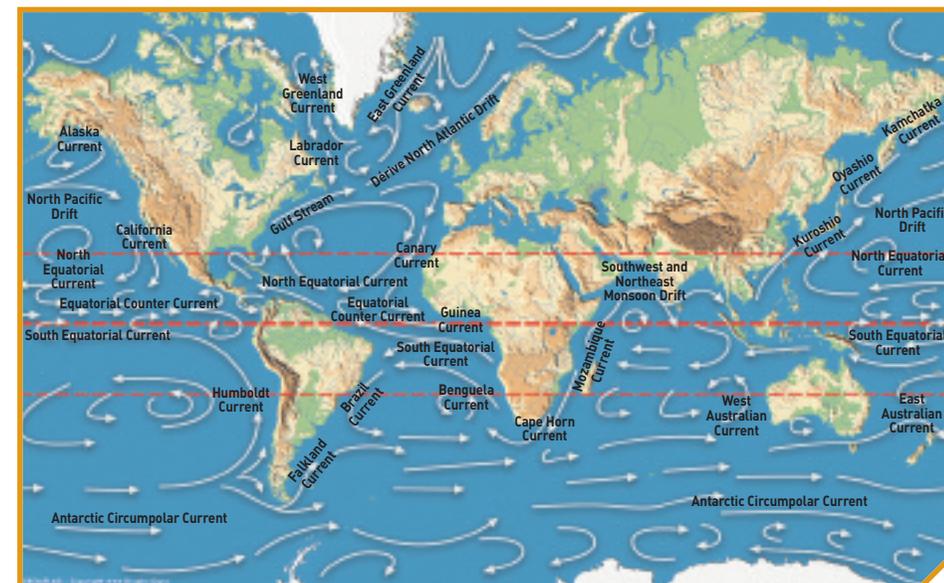
Salinity and water temperature vary from one point to another. The water masses circulating in the world's oceans only mix very slowly with each other. Because of this, their temperature and salinity changes very slowly and this allow oceanographers to trace the origins of these water masses.

Ocean water is entrained in great currents which bring considerable kinetic energy into play. Most of this energy is carried in surface currents (gene-

rally less than a kilometer thick), which are driven by the wind. A rotating current (caused by the Coriolis force) can be found around the circumference of each of the great Ocean basins, running clockwise in the Northern Hemisphere and anticlockwise in the Southern Hemisphere. Another important current, also caused by the wind, encircles the Antarctic continent. Because of their differences in temperature and salinity, these water masses also have different densities. These differences cause another deep



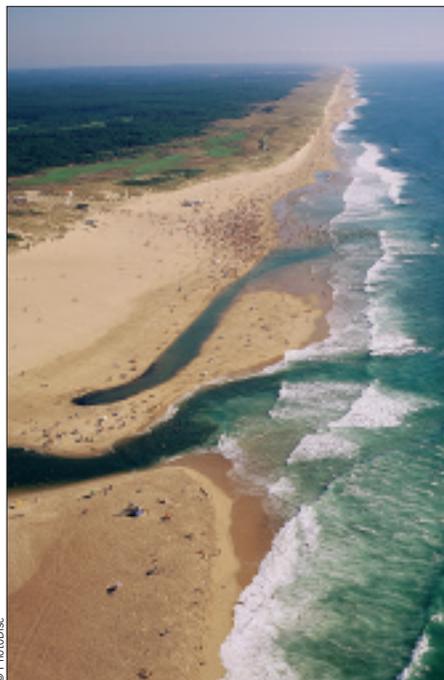
### Surface ocean currents



## “The winds are responsible for surface ocean currents.”

circulation, called **thermohaline circulation**. In the Norwegian Sea, and also around the Antarctic, the waters become very cold. Part of the water freezes (at approximately  $-1.8\text{ }^{\circ}\text{C}$ ) to give sea ice (pack ice) and, in so doing, expels its salt which duly increases the salinity of the surrounding

Because of its origin: temperature and salinity; thermohaline comes from the Greek *thermos* = heat and *halos* = salts.



The large oceanic water currents bring into play considerable kinetic energy, mostly concentrated at the surface.

unfrozen water. The result is to form very salty and very cold water, which is therefore very dense, and sinks towards the ocean floor.

This water then begins to travel a great loop along the bottom of this worldwide ocean. Effects which favor the rising of this cold water from the deep, produced by diffusion towards warmer masses and by winds along certain coasts or in the equatorial zone, will eventually return these waters to the surface, where they will be heated. They will then be carried by surface circulation and will finally return to the area of deep water formation, after a tour which could last 1,000 years.

### OCEAN-ATMOSPHERE INTERACTIONS

The atmosphere and the oceans transport approximately equal amounts of energy. According to the estimates in the diagram on page 6, oceanic heat transport dominates at lower latitudes via the water cycle, whereas atmospheric heat transport takes over towards the poles. The winds are responsible for surface ocean currents, which induce a significant change in the relative momentum between the two fluids. One fundamental exchange, is the exchange of water, first in the “ocean to atmosphere” direction, in the form of water vapor, and then in the “atmosphere to the ocean” direction by precipitation and a flow back to the sea of water which falls on the continents. Water vapor plays an essential role in the atmosphere’s transport of heat towards higher latitudes.

The existence of a warm ocean surface (temperature  $> 27\text{ }^{\circ}\text{C}$ ) is a requirement for formation of tropical cyclones.

The Ocean plays an important role in the carbon cycle: it currently absorbs around 1/4 of all carbon dioxide emitted by man. Note that because of the acidification that it causes in the water, this absorption could have significant consequences on the biological equilibrium of the ocean and its biodiversity.

Plankton emit sulfur compounds, which move into the atmosphere in the form of sulfur oxides. These oxides gather in aerosols and play a fundamental role in the condensation of vapor within clouds.

Through its large heat capacity and its inertia, due to the time of circulation and equilibration, the Ocean smoothes out these phenomena in the short term and delays longer term changes.

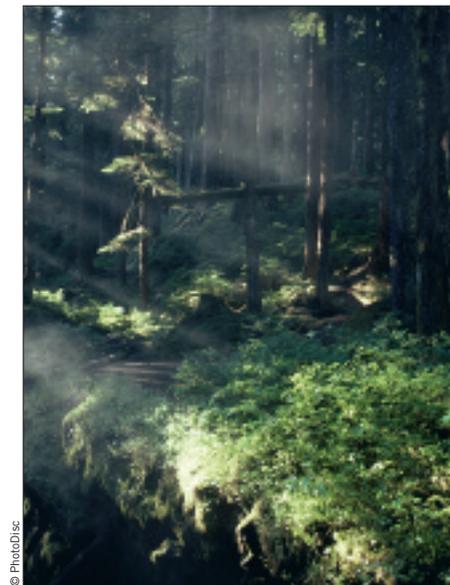
### THE ROLE OF THE CONTINENTAL BIOSPHERE

Vegetation plays several roles in the climate machine.

Firstly it has a radiative role: a surface covered with vegetation absorbs much more solar radiation than bare soil. This role will be more or less significant, depending on the type of vegetation and the season.

Vegetation also plays a significant role in the water cycle, absorbing water in order to grow, and then rejecting it through evapotranspiration. Local cave paintings reveal that, six thousand years ago, the Saharan population was practicing farming

Vegetation absorbs water to grow and rejects it by evapotranspiration.



© PhotoDisc

and fishing. It has been shown that the level of rainfall experienced during this green Saharan period could not have occurred without the presence of local vegetation.

The annual cycle has vegetation as a consumer of carbon dioxide in its active period (photosynthesis) and as an emitter of carbon dioxide, by respiration, in vegetative rest periods. At present,  $\text{CO}_2$  absorption exceeds its emission: vegetation is one of a number of phenomena that specialists refer to as **carbon sinks**.

Under the effect of climate warming, the role of this sink could be counterbalanced by the decomposition of rotting vegetation. Moreover, its capacity to absorb  $\text{CO}_2$  reduces in hot and dry climatic conditions, such as during the 2003 heat wave in Europe.

Substances are emitted into the ambient environment by sources and removed by sinks.



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The formation of sea-ice is responsible for thermohaline circulation of the ocean.

Vegetation can then become, at least locally, a CO<sub>2</sub> source.

Finally, vegetation also plays a role in the nitrogen cycle and in the emission of various reactive components and greenhouse gases. Nitrogen oxides are greenhouse gases, or their precursors.

### THE ROLE OF THE CRYOSPHERE

In the liquid state, water can absorb nearly all the solar radiation **incident** upon it. In the solid state **Which reaches its surface.** (snow or ice), it becomes a very good reflector and returns radiation to space.

Furthermore, during crystallization seawater ejects the salt that was dissolved in it. Hence, the formation of sea-ice is an essential part of the process that causes the great thermohaline circulation loop in the ocean.

With the warming that is now occurring, there is a risk that the **permafrost** will melt, releasing into the atmosphere large quantities of methane, a gas with a significant greenhouse warming potential. Furthermore, the polar ice-caps risk being destabilized and released into the sea in the form of icebergs containing massive quantities of fresh water. These could sufficiently alter

**Permanently frozen ground, which occupies a significant fraction of the continental surface area of the northern hemisphere, particularly around 70°N.**

the density of seawater to cause significant disturbances to the thermohaline circulation.

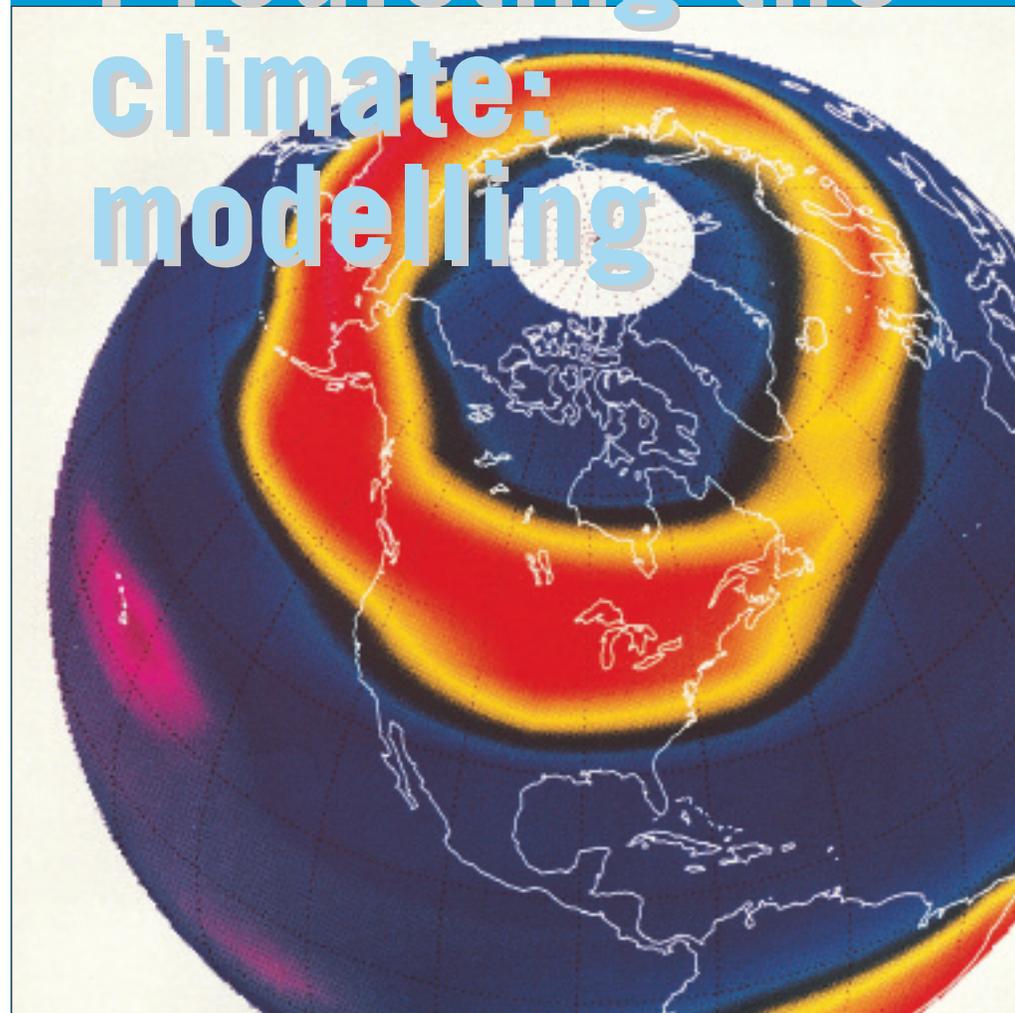
### THE ROLE OF THE LITHOSPHERE

The time constants of the lithosphere are such that their variations do not have any significant effect on the climate on human timescales. On the geological timescale, however, the lithosphere plays a role. The movements of tectonic plates, which change the layout of the continents and oceans, are important for circulation of the atmosphere and of the ocean. The formation of massive mountains also modifies atmospheric circulation and the accumulation of snow at high altitudes strongly increases the **albedo** of the surface. Accumulation or degradation of large rock layers **Reflective efficiency.**

(basalts) leads to major changes in the composition of the atmosphere and hence in the natural greenhouse effect. These various effects have caused the Earth to experience episodes (600 to 700 million years ago, in the Neoproterozoic Era), when its surface was completely covered in ice on the single continent that existed at that time, Rodinia, and probably also over the entire ocean.

FORECASTING WHAT THE WEATHER WILL DO IS ONE THING... DEFINING THE CLIMATE AND PREDICTING HOW IT WILL CHANGE IS QUITE ANOTHER. TO ACHIEVE THIS REQUIRES THE USE OF MODELS.

# Predicting the climate: modelling



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## “A small variation in initial atmospheric conditions can modify subsequent developments”

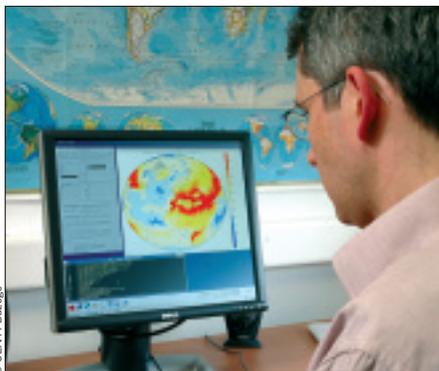
### LONG-TERM FORECASTS

The task addressed by meteorologists is to know what the weather will do at a given time and place. Owing to the chaotic character of the atmosphere (the equations which described its function are a long way from being linear; a small change in initial conditions can have a considerable effect on the subsequent developments), beyond a few days, it is only possible to determine the weather in a rather unreliable way. Given this situation, it is not necessary to take account of more slowly changing phenomena when compiling meteorological forecasts: current, longest-term aims relate to seasonal forecasting.

Climate can be defined as the distribution of possible meteorological conditions, over a possibly very long period of time, in a given region. This is a question of not only knowing what the weather actually will do, but also what the weather could do, with what probability and what changes are possible. The laws which govern the functioning of the climate machine are the same, but in this case it is no longer possible to ignore the long timescale components of the system. This is the first major difference between meteorological models and climate models. The limited power of computers causes a second difference. Meteorological models, which only consider a restricted number of phenomena over a rather short period of time, can work on a large number of points in space with a short time step. In contrast, climate models must

Divisions of time on the order of an hour, a week, a year...

include all phenomena

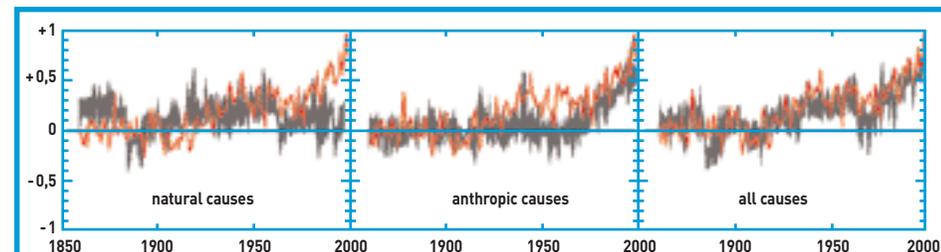


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There are large differences between meteorological models and climate models.

and run calculations over long time periods. Hence, even with the most powerful computer configurations (such as the Earth Simulator in Japan), climate models are limited to calculations using longer time steps and lower spatial resolution (typically 100 km) than meteorological models.

From a more conceptual point of view, the way in which the models operate is also different: meteorological models start from observations and go on to calculate the development, over a short period of time, of the meteorological situation in comparison to these observations. The chaotic nature of the climate means that, after a certain number of time steps, the model has lost any memory of the initial conditions. It cannot describe the real world from day-to-day, rather, it provides a statistical view which



### WHAT CAUSES WHICH TEMPERATURES?

Temperature changes, recorded since the middle of the 19th century, are shown in red, with the results from the model in grey. The models are not able to reproduce the observed variation if they only take into account natural causes: volcanic activity, solar activity (left-hand figure): or if they

only consider those causes resulting from human activity: greenhouse gas effect, aerosols, soil usage (centre figure). By contrast, it can reproduce the observations well if we take into account of both natural causes and human activity at the same time (right-hand figure).

This is a good indication that we understand the climate machine but also demonstrates that man is genuinely en route to derailing the climate. (Figure extracted from the IPCC report 2001, see box "International political action", p. 39).



© PhotoDisc

The task is not only to know what the weather will do, but what the weather could do, and with what probability.

is representative of the real world when subject to the conditions imposed in the model (amount of sunshine, atmospheric composition, etc.). This is the mode of operation for climate models.

### QUESTIONS OF HIERARCHY

For the climatologist, models typically have two very different kinds of use, with various degrees of complexity, which leads to construction of a hierarchy of models:

- first they act as a way of testing hypotheses on the mechanisms involved in climatic phenomena, such as the abrupt variations in past climates discovered by drilling experi-

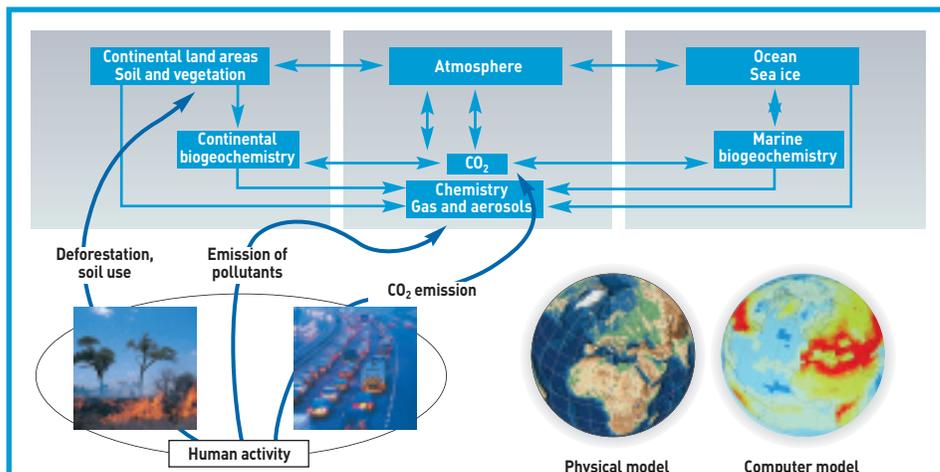
ments in the glacial ice caps of Greenland and through sampling marine sediments in the North Atlantic. We would like to simulate the dynamic processes of climate variation and the **threshold effects**. We can easily understand that

Phenomena which only occur when certain quantities exceed a particular value.

a complex model, with very long calculation times, will not be suitable for this type of study. We need to use simplified models, which are nevertheless

suitable for determining the impact of particular processes on the climate.

- Three-dimensional general circulation models are used for long duration simulations. These are intended either to test the model's capacity to reproduce a climate state which is very different from the current one, or to forecast what the climate might be in an altered environment.

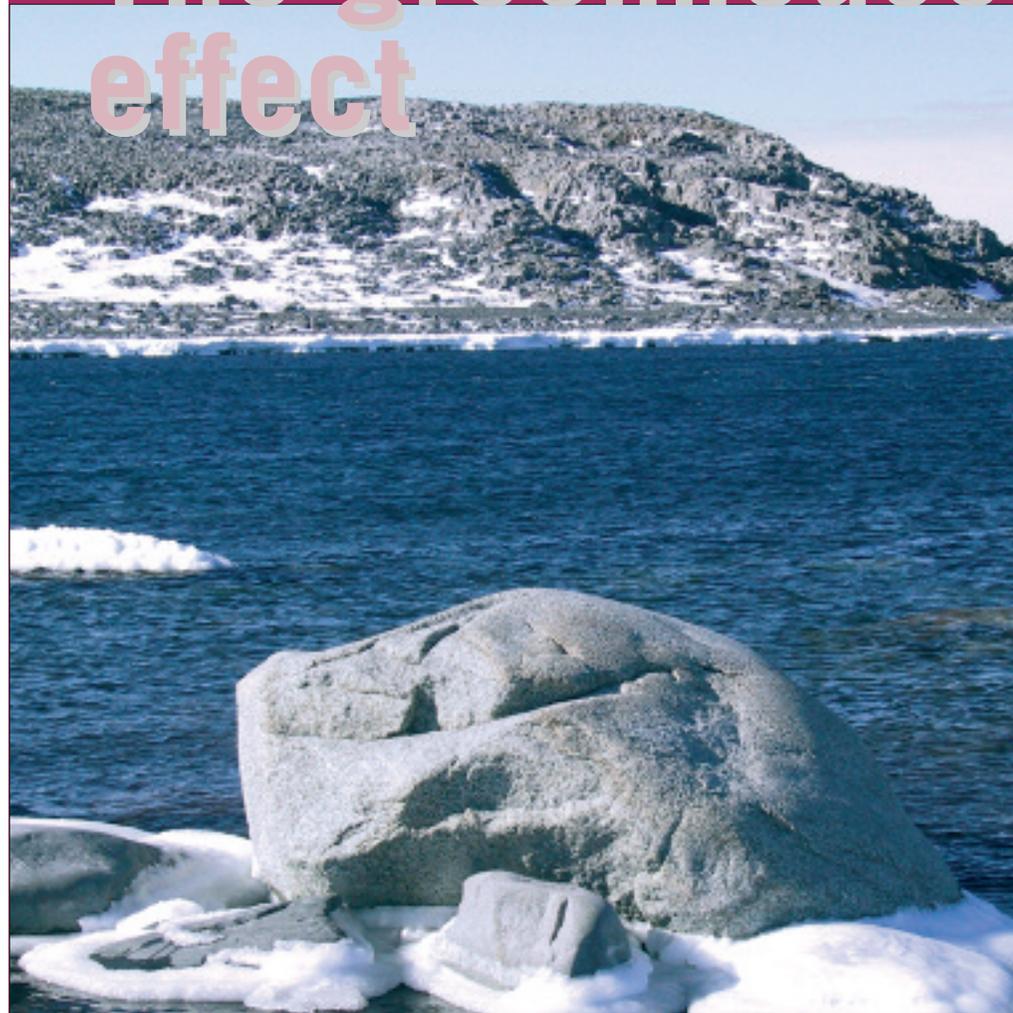


### CLIMATE EQUATIONS

A climate model is composed of a flat physical model on a horizontal and vertical grid, suitable for numerical resolution of the climate-system equations. It must take account of all the environmental compartments: the atmosphere, oceans and continents, and their respective components. It needs to describe the perturbations caused by human activity and it allows all these elements to interact.

A NATURAL PHENOMENA, ESSENTIAL FOR LIFE, THE GREENHOUSE EFFECT IS BEING AMPLIFIED BY HUMAN ACTIVITIES. IT HAS BEGUN TO CHANGE THE CLIMATE.

# The greenhouse effect



## 1824 1860's

The greenhouse effect is discovered by Jean Baptiste Joseph Fourier, a French mathematician.

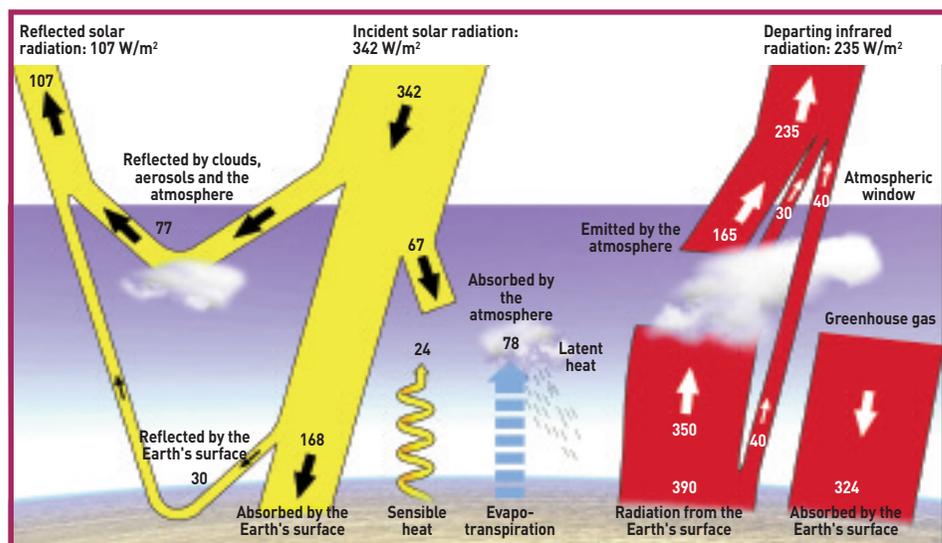
The Irish physicist John Tyndall attributes the greenhouse effect to water vapor and carbon dioxide.

Some dates relating to the greenhouse effect... Some dates relating to the greenhouse effect... Some dates relating to the green

### SOLAR ENERGY...

Climatic equilibrium (the stationary state) is obtained when the global energy balance is, on average, zero: i.e. the quantity of energy received (from the Sun) is equal to the quantity of energy lost (emitted into space). Energy coming from the Sun: currently 1,368 W/m<sup>2</sup>

reaches the "top of the atmosphere", which corresponds to a mean global energy of 342 W/m<sup>2</sup> on the ground. Taking account of the Earth's mean albedo (around 30 %), it can be calculated that, in the absence of other phenomena, this equates to 239 W/m<sup>2</sup> being absorbed by the Earth. The Earth behaves as a black body



### ENERGY FLOW WITHIN THE CLIMATE SYSTEM

The atmosphere is highly transparent to sunlight: in spite of the presence of clouds, nearly 60% of the luminous energy arriving at the Earth reaches the surface of the globe, which only reflects a small fraction. Overall, half the solar

energy arriving at the Earth is absorbed by the continents and oceans, which it warms. Part of this heat is re-emitted, mainly in the form of infrared radiation. Certain gases, present in small quantities in the atmosphere (water vapor,

carbon dioxide, methane), absorb infrared radiation: Only 10% of the radiation emitted by the surface of the Earth escapes directly into space. (Source: IPCC report 2001)

## 1896

The Swedish physicist and chemist, Svante Arrhenius, gives the greenhouse effect its current description. He also suggests that burning fossil

fuels to increase the concentration of carbon dioxide in the atmosphere would have beneficial consequences: a more uniform terrestrial climate,

stimulated plant growth and hence increased production of nutrition for a growing population. Such optimism was possible in an era when there was

only a very basic understanding of the operation of the climate machine.

which radiates energy, in the form of electromagnetic waves, with an intensity that depends very strongly on its temperature (Stefan-Boltzmann law). To radiate 239 W/m<sup>2</sup>, the surface of the Earth would need a mean global temperature of -18 °C, which would not be very favorable to life as we know it.

The actual mean temperature of the surface is +15 °C, which is, in itself, experimental proof of the existence of a natural greenhouse effect. At 15 °C (288 K), the Earth is emitting infrared radiation with peak intensity at a wavelength of 10 μm. There are a number of trace gases present in the atmosphere which are able to absorb radiation at the wavelengths of this infrared radiation emitted from the ground. The atmosphere, which is transparent to almost all of the incident solar radiation, therefore behaves as an absorber which traps a significant fraction of the radiation from the ground. The atmosphere, warmed by this absorbed radiation, also behaves as a black body and will itself emit energy in the form of infrared radiation. Because of its lower temperature, the atmosphere will radiate less energy than the surface. Since it radiates in an isotropic fashion, half of this re-emitted radiation will travel in a direction towards the surface of the Earth. Hence, energy is being trapped between the atmosphere and the surface and this will lead to surface warming. This behavior reminds us of a greenhouse: where the glass allows incident solar radia-

tion to enter, but then traps the energy inside the greenhouse. This similarity led to the name "greenhouse gas" being applied to atmospheric gases which absorb infrared radiation coming from the ground.

The basic composition of the atmosphere, which varies slightly from place to place, is given in the table below:

The composition of the atmosphere near the Earth's surface (0 to 25 km)  
Greenhouse gases are in blue italics\*

GAZ	CHEMICAL FORMULA	ABUNDANCE (by volume)
Nitrogen	N <sub>2</sub>	78,08%
Oxygen	O <sub>2</sub>	20,95%
Water vapor	H <sub>2</sub> O	0 to 4%
Argon	Ar	0,93%
Carbon dioxide	CO <sub>2</sub>	0,0370%
Neon	Ne	0,0018%
Helium	He	0,0005%
Methane	CH <sub>4</sub>	0,00017%
Hydrogen	H <sub>2</sub>	0,00005%
Nitrous oxide	N <sub>2</sub> O	0,00003
Ozone	O <sub>3</sub>	0,000004%

\* In reality, it is not the quite genuine, opacity of glass to infrared radiation which is responsible for trapping energy in a greenhouse, but the obstacle provided by the roof to the escape of any hot air by convection. It is now common to see plastic greenhouses which are transparent to infrared.

**“In the past century and a half, man has re-injected 300 billion tons of carbon into the atmosphere, in the form of CO<sub>2</sub>.”**

In nature, the main greenhouse gas is water vapor, which is directly responsible for around 60% of the natural greenhouse effect. The rest comes from clouds and various gases (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, O<sub>3</sub>) and ranked first among these is carbon dioxide. Although present in very low quantities, ozone is a very effective greenhouse gas and contributes 8% of the global greenhouse effect.

Since the beginning of the industrial era, man has re-injected 300 billion tons of carbon, in the form of CO<sub>2</sub>, into the atmosphere. Natural processes had taken millions of years to hide this carbon under the ground in the form of coal, oil and gas. Although half of this carbon dioxide has been recaptured by vegetation, the soil and the oceans, 150 billion tonnes remains in the atmosphere where the

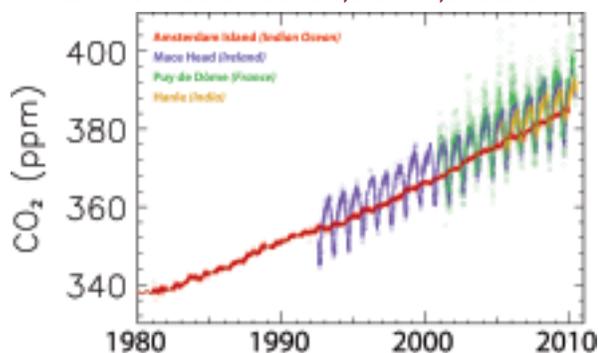
carbon concentration has increased by 30% since 1800, rising from 280 to 387 ppm today (parts per million).

More than 50% of the additional greenhouse effect due to human activity comes from CO<sub>2</sub>. The other contributors are methane, nitrous oxide, tropospheric ozone, carbon halides (CFCs or their current substitutes)...

The effect of a greenhouse gas on the climate depends not only on its opacity to infrared radiation, but also on the time that it remains in the atmosphere before being eliminated, either by a chemical reaction or by absorption into another section of the environment. Tropospheric ozone, which is eliminated by chemical reactions, has a very variable residence time depending

A product of anaerobic decomposition of cellulose, in particular on rice plantations or in the paunches of ruminants.

Evolution of the atmospheric concentration of CO<sub>2</sub> since 1980 on Amsterdam Island and, since 1992, at Mace Head



### CONCENTRATED ATMOSPHERE

In Ireland, an oscillation is superimposed on top of the continuous mean increase. This is due to the seasonal activity of vegetation which is very significant in these northern hemisphere latitudes.

At Mace Head, when the wind comes from the continent, it carries an increased concentration of CO<sub>2</sub>, resulting directly from local human activities.

### AEROSOLS

The term “aerosols” refers to suspensions of fine particles in the atmosphere. They can be natural or anthropic in origin (produced by man).

Some natural aerosols come from the ocean: sea-salt produced by evaporation of spray, sulfates coming from the oxidation of sulfur compounds (dimethyl sulfide) emitted by plankton.

Others come from the continents: dust originating on land picked up by

Dust of mineral origin, lifted from the ground.

wind erosion, carbon in mineral or organic form (soot particles)

produced by forest fires or savanna struck by lightning, volcanic dust and sulfates.



© PhotoDisc

Human activity contributes to the generation of certain types of aerosols: stripping vegetation from the soil enhances its erosion by the wind; various types of industrial combustion processes, transport and fires set for agricultural practices (particularly savanna or forest fires) produce carbon aerosols, whereas atmospheric emissions of sulfur produce sulfate aerosols.

The majority of aerosols remain in

the troposphere for a short period only; their duration is less than a week. They can be transported over several thousand kilometers. They return to Earth under the effect of gravity or are washed out of the atmosphere by rain. Their geographical distribution is very variable; their effect is therefore essentially local.



© PhotoDisc

Stratospheric sulfate aerosols are produced by major volcanic eruptions (e.g. Mt St-Helen, Pinatubo). These can remain in the stratosphere for more than a year. They therefore have time to equilibrate their concentration which, after several months, has become homogeneous at any given latitude.

The climatic role of aerosols is complex and not yet fully established. It depends on the nature of the aerosol, on its size and altitude, and on the local albedo of the surface.

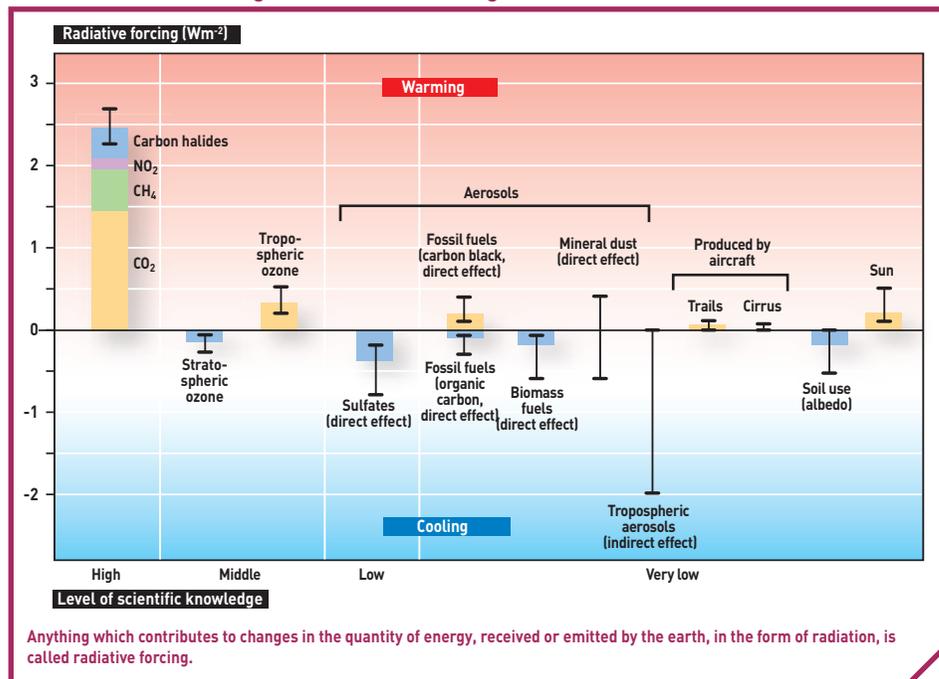
They act directly like a parasol against solar radiation, which they can absorb or reflect. Hence, stratospheric aerosols coming from the eruption of Pinatubo caused a reduction in global temperature of half a degree, during the two years following the eruption. However, certain aerosols contribute to the greenhouse effect by absorbing infrared radiation emitted from the ground.



© CEA

Aerosols also have several indirect effects on climate: they act as nuclei for water vapor condensation during cloud formation; their concentration will influence droplet size and this size then has an effect on the reflective efficiency (albedo) and residence time of the clouds. Through absorbing radiation coming from the ground, they heat the atmosphere locally, altering its vertical stability. Through complex chemical reactions in which they participate, they influence the concentration of greenhouse gas compounds or their precursors. Finally, they affect photosynthesis because they supply essential nutrients to phytoplankton, both in the open ocean and also in the Amazonian forest.

## Changes in radiative forcing between 1750 and 2000



on atmospheric conditions. It is, however, not more than several weeks. Methane has a residence time of 10 years, carbon dioxide of more than 100 years, nitrous oxide and CFCs have residence times on the order of a century. Indeed, many of the compounds injected into the atmosphere contribute to the greenhouse effect, even if they are not themselves greenhouse gases. Aerosols (see box on page 23) contribute directly to the greenhouse effect as a function of their composition, their altitude and their reflectivity from the ground.

Compounds which alter the oxidative capacity of the atmosphere will make an indirect contribution to the greenhouse effect, through their effects on the production of gases such as ozone or by modifying the elimination of gases such as methane. For example, carbon monoxide CO destroys hydroxyl radicals OH which are destructive agents to methane. Hence, injecting CO into the atmosphere inhibits the elimination of methane whose greenhouse effect will, therefore, endure for a longer time.

THE HISTORY OF THE EARTH'S CLIMATE HAS SEEN ALTERNATE PERIODS OF WARM AND COLD. THE REASONS FOR THESE CHANGES AND THEIR IMPACT REMAIN TO BE DETERMINED.

# Studying past climates



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**“By comparing the dates of past wine harvests, it could be seen that the heat wave of 2003 was unprecedented over the previous six centuries.”**

Climate varies naturally. The history of the Earth's climate is peppered, with hot episodes and cold episodes. Climatologists are regularly asked how they can tell that the increase in temperature observed over the last century is really due to man and not a manifestation of natural climatic variation. For climatologists it is, therefore, important to know the details of past climates and to understand why and how climate can vary.

It was known in the 19th century, through the work of Swiss naturalist Louis Agassiz, that the Earth had been subject to periods of glaciation. We now know that, over the course of the last million years, it has been subject to a succession of glacial episodes interspaced with generally rather short, warm periods, as at present. During the long glaciations, the high latitude continents of the northern hemisphere were covered with ice several kilometers thick. The history of these episodes is itself rather



Layers of ice accumulated, year after year, in Greenland and Antarctica are also indicators of the history of the climate.

variable with local temperature changes, in Greenland, as high as 15 °C over several decades. It is important for climatologists to understand these various changes. It is very useful for modelers to have well documented information on such episodes which they can use to test the ability of their models to reproduce real climates that are very different from the present day.

### NATURE AND ITS INDICATORS

Systematic measurement of meteorological conditions only began in the second half of the 19th century. To gain knowledge of past climates, climatologists must, therefore, find indices which testify to the climate which prevailed at the time. Some indicators exist for historical time periods, for example the dates of agricultural work (it has been determined from the dates of the grape harvest, that the heat wave of 2003 was unprecedented over the previous six centuries). But most indicators must be searched for on the ground, in regions where nature has been able to preserve them. This will depend on the time period and scale of the phenomena which are of interest:

- in marine sediments, for very long time scales;
- in lake sediments;
- in coral skeletons;
- in concretions (stalagmites) slowly deposited in caves;
- in the ice building, year by year, on the continents at high latitudes (Greenland, Antarctica);
- in the highest mountain ranges (Andes),



### A CORE FOR THE CLIMATE

In the cellar of the castle, on the CNRS site at Gif-sur-Yvette, thousands of cores of marine sediment are stored. Climatologists want to take samples of these cores at different depths in the sediment (in the lower left photograph, the core is placed in a container, graduated by depth of sediment). The isotopic composition of the Foraminifera skeletons which the core contains, tell us about the climate which governed the lives of the foraminifera measured.

where the ice does not melt in the summer. For the most recent time periods, the growth of trees can be analyzed using the characteristics recorded in the annual rings. Climatologists find the information that has been deposited in these natural archives.

- in sediments this comes from the debris (shells, skeletons, etc., of aquatic animals), pollen grains and insoluble minerals;
- in the continental glaciers (polar or alpine), apart from the ice, we also find deposited particles and trapped air;
- concretions in caves contain the minerals precipitated at the time of their formation... A deposit needs to be decoded like a book, page by page, i.e. layer by layer.

The growth of these deposits is sometimes affected by the weather, displaying a marked seasonality. This is the case for ice, coral and sometimes concretions.

As long as the marks left by this seasonal variation are clear, it allows the signals recorded at different depths to be precisely dated. Beyond this, more indirect methods are required to establish the chronology of measured events at different sites around the globe.

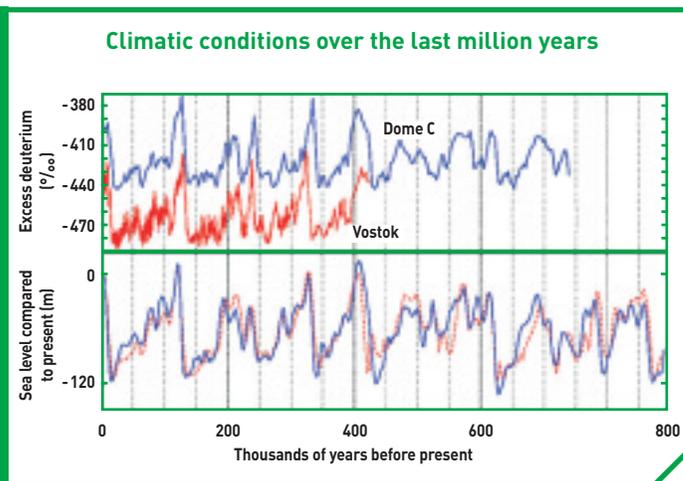
### BETWEEN HOT AND COLD

From deep drilling of cores in Greenland and Antarctica, as well as many measurements on marine sediments, it has been possible to almost entirely rediscover the climatic conditions

The upper curves, representing the isotopic thermometers [see box on page opposite], give the temperatures measured using the ice cores from Vostok (in red) and from Dome C (in blue).

The lower curves show the sea level determined from the isotopic composition in 180 of the benthic foraminifera from marine sediments.

Two sets of different measurements are shown (in blue and red dots) to show the uncertainty in these values.

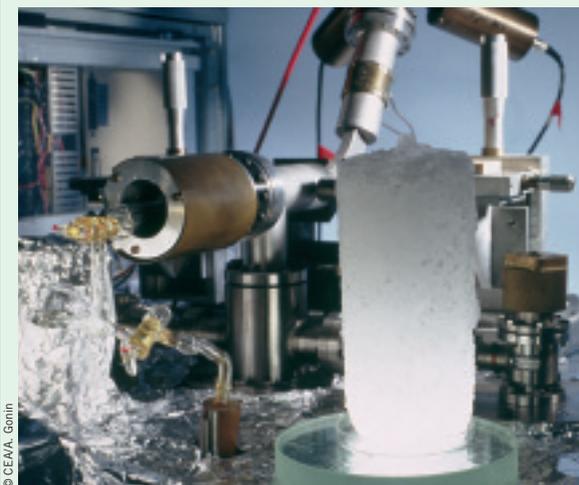


over the last million years. The isotopic paleothermometer shows us that the climate has oscillated between two states, with a periodicity of around 100,000 years: a cold state, corresponding to large-scale glaciation, the last of which reached its height 21,000 years ago, - and a warm state, like the present one, generally of short duration. The last warm period to last as long as the present one occurred 400,000 years ago; this was a comparable time, in terms of the orbital cycle of the Earth, to the present situation. The primary cause of large scale glaciation was the geographic distribution and intensity of solar illumination throughout the year. This variation is however far from sufficient to produce the large changes observed. Feedback phenomena, particularly due to the strong albedo or greenhouse gases associated with snow-covered ice caps and pack ice, have a considerable ampli-

fying effect. It is remarkable to see, as was discovered from the bubbles of air imprisoned in the ice cores from Vostok, these measurements demonstrate that the greenhouse gases  $\text{CO}_2$  and  $\text{CH}_4$  and the Earth temperature are tightly linked, although it is not a demonstration that  $\text{CO}_2$  drives the climate. The current understanding is that orbital forcing has driven the temperature changes and that  $\text{CO}_2$  has a strong positive feedback to the initial temperature changes.

But none of these periods, warm and cold, was calm. Analysis of glacial ice cores and oceanic cores has highlighted rapid changes in the climate at high latitudes. The interpretation which has been given to these events is that large flows of icebergs deposited enormous quantities of fresh water into the North Atlantic, seriously disturbing the oceanic circulation. Similar events could arise in the future if global warming,

## ISOTOPES AS CLIMATIC INDICATORS



An icicle fragment is unveiled in front of the spectrometer in order to determine its isotopic composition.

A water molecule is formed from two atoms of hydrogen and one atom of oxygen  $\text{H}_2\text{O}$ . On average, in 0.015% of cases, one or other of the hydrogen atoms will be in the form of the stable, heavy isotope of hydrogen, deuterium. Similarly, in 0.2% of cases, the oxygen atom will be the heavy isotope,  $^{18}\text{O}$ . But physical and chemical processes can enrich or impoverish water in these heavy isotopes. In the cases of interest to us, the processes involved are phase changes: evaporation or condensation, which results in a

small, but measurable, fractionation. During the phase change, the denser phase is enriched in the heavier isotope to the detriment of the lighter phase. Already impoverished of heavy isotopes by its evaporation in the tropical regions, water vapor will become increasingly impoverished all along its path towards the poles. This is because of the successive partial condensations to which it is subject, due to progressive reduction in its temperature. The more marked the cooling the more impoverished will be the snow.

By measuring the isotopic composition of the ice, the temperature of the cloud from which it came can be determined. Polar ice is hence impoverished in deuterium as well as in  $^{18}\text{O}$ . The excess  $^{18}\text{O}$  will be found in the water and in indicators in the oceans where the water is hence enriched. Hence an excess of  $^{18}\text{O}$  can be found in the carbonate residues of the **foraminifera** which have been **Planktonic animals**, sedimented-out on the floor of the ocean.

By combining measurements of the isotopic composition of polar ice and of marine foraminifera, it is possible to deduce how much water had been taken out of the sea to form ice. Hence, the total volume of ice and the sea level at that time can be determined. This made it possible to show that sea level was around 120 meters lower than at present during the major ice ages, which allowed, for example, our ancestors to enter the Cosquer cave, whose entrance is currently situated at a depth of 37 meters in the calanque near to Marseille.

Phase changes are not the only processes that lead to fractionation. Diffusion, certain biological reactions, etc., lead to fractionations, measurement of which provides an indication of the quantity and occurrence of these processes and hence the natural or anthropic, biological or mineral, origin of the element measured.



Hendrick Avercamp (1585–1634), *A Winter Scene with Skaters* (Rijksmuseum, Amsterdam). Cold winters where skaters could enjoy the frozen rivers provided a great deal of inspiration for painters during the Little Ice Age.

© alg-images



### LIFE AND DEATH OF A FORAMINIFERA

Foraminifera live and die in the waters of the oceans. Their shells are found in sediments on the ocean floor. During the periods of abrupt cooling which have punctuated the warmer phases, conditions (temperature and salinity) have caused the Foraminifera to disappear completely. In their place, the sediments contain rocky debris, scoured from the continents by the glaciers. It is the dropping into the ocean of gigantic pieces of these glaciers which, by releasing the massive amounts of fresh water which they contain, has modified oceanic circulation and provoked the cooling.

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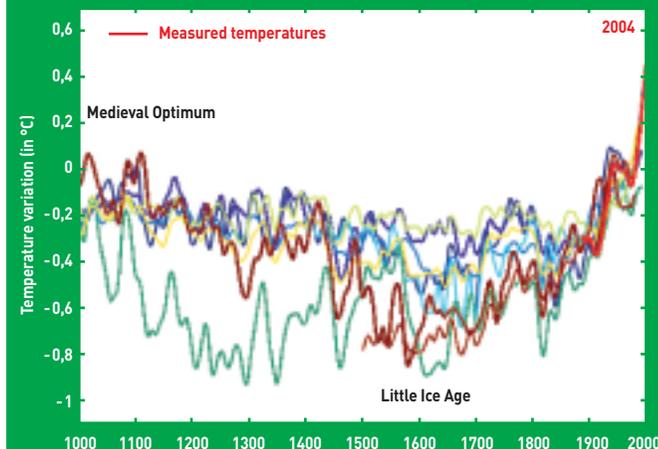
accompanied by significant precipitation or abrupt melting of the glacial ice caps, occurs. The possibility cannot be ruled out, that this could sufficiently disturb oceanic circulation, by moving the northern limit of the North Atlantic Drift to the south, (see chart of surface ocean currents, page 11), so as to remove the warm waters of the Gulf Stream from the coast of Europe and hence limit future warming of Western Europe.

### THE ONCE GREEN SAHARA...

Climatic variability is not limited to ice ages. Six thousand years ago, the Sahara was not the desert we know today, but a verdant region with lakes, where farming and fishing were practiced. There are many cave paintings which testify to this. Europe experienced a climate optimum in the Middle Ages, which, among other things, allowed colonization of Greenland by the Vikings.

After this, a notable cooling marked the period 1400-1850: the Little Ice Age saw tempera-

### Mean temperature evolution of the Northern Hemisphere since the year 1000



The values shown are the mean temperature variations over the period 1961–1990. The red curve is the instrumental value measured with various thermometers since 1902. The other curves are values presented by various authors. Their dispersion indicates the uncertainty in these estimates. The Mediaeval Climate Optimum and the low temperatures of the Little Ice Age can be clearly distinguished. However, the most striking feature is the rapid and significant increase in temperature since the start of the 20th century and in particular since 1970. (Figure taken from Wikipedia).

### ISOTOPES EMPLOYED IN CHRONOLOGY

A major problem for climatologists is to correlate the dates obtained from different indicators measured at different locations around the globe. This is an indispensable requirement if we are to establish the chronology of diverse events.

The majority of the "clocks" employed are based on radioactive decay. One of the best-known is carbon-14 (<sup>14</sup>C) measurement. During its life, a biological organism continuously balances the isotopic composition of its carbon with that of the surrounding environment - i.e. with the atmosphere in the case of vegetation.

Biological tissues, therefore, mirror the ambient ratio of carbon-14. After its death (at a time referred to as  $t_0$ ), exchange with the environment ceases; the carbon-14 continues to decay with a radioactive half-life of 5,730 years. The ratio in the present-day sample makes it possible to determine how long it has been dead, provided one knows what the ambient ratio was at the time of death. Many other radioactive families are used such as the pairs: uranium 234 and thorium 230; potassium 40 and argon 40, etc. Some minerals accumulate received

radiation. Under certain conditions, they will emit light proportional to the quantity of this accumulated radiation. Researchers use this property for dating. The great difficulty is to find sufficient sensitive phenomena to cover all of the time ranges to be considered and samples for which it is significant to define  $t_0$ . Dating can also take advantage of other techniques, such as intensity measurements of the Earth's magnetic field, recorded by magnetic minerals, which have the advantage of been able to study synchronous variations over the whole planet.



© CEA/P. Bazoge

In carbon-14 dating, samples are chemically treated to extract the carbon which is purified in the form of  $\text{CO}_2$ . This carbon dioxide is then reduced and transformed to graphite. Isotopic analysis of the graphite is performed using a particle accelerator (tandem) coupled to a magnetic spectrometer. This technique makes it possible to process very small samples (mg of carbon). Processing benches make it possible to prepare a large number of samples simultaneously.

## “El Niño can cause heavy rainfall on the western side of South America and severe droughts in Indonesia.”

tures lowered throughout Europe (frozen winter scenes inspired many artists) and more or less affected the whole of the northern hemisphere, with a notable advance of glaciers. Since 1850, man has been assisting in a warming process which has seen the end of the Little Ice Age.

But we have also entered into the industrial era, and it is necessary to separate what is natural and what is due to human activity.

### THE EL NIÑO EXAMPLE

This involves a short-term variability in the climate, which is located primarily in the equatorial Pacific but which, through its most violent events, affects all of the tropics as far up as 40° south in the Indian and Pacific oceans and the Western border of the Atlantic.

It is characterized by an anomalous coupling of the atmosphere and the ocean. In the normal situation (when El Niño is not present), the trade winds push the surface waters from the Americas towards Indonesia. This results, in the West Pacific, in high humidity over Indonesia and a sea level that is higher than in the East Pacific. In the East, along the Peruvian coast, deep cold waters rise up, rich in nutrients, leading to cool temperatures and a marine productivity which is very favorable for fishing.

Approximately every three or four years, the trade winds are weaker and the ocean flows back towards Peru. This blocks the rising deep water and hence the fish. It can lead to torrential rain along the west coast of South America and serious drought, sometimes generating fires, in Indonesia. This phenomenon which lasts several months has been christened El Niño (the child, implying: Jesus) by the Peruvian population, who appreciate the warm water that it brings to their cold coasts around Christmas.

Between two El Niño type events, the opposite phenomena can occur which, by analogy, has been named La Niña.

Given the violence of recent El Niño, the question has been asked as to what influence global warming is having on the frequency and intensity of this phenomenon.

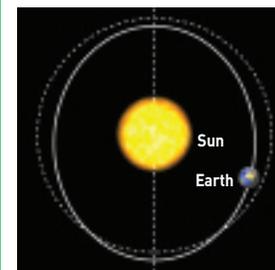
El Niño is not the only example of climatic variability. For example, the North-Atlantic Oscillation (NAO), modulates the position and intensity of westerly winds over the ocean, and strongly affects climate conditions (temperature, precipitation, storms, etc.) in the North Atlantic and Europe.

### ASTRONOMICAL GLACIATION THEORY

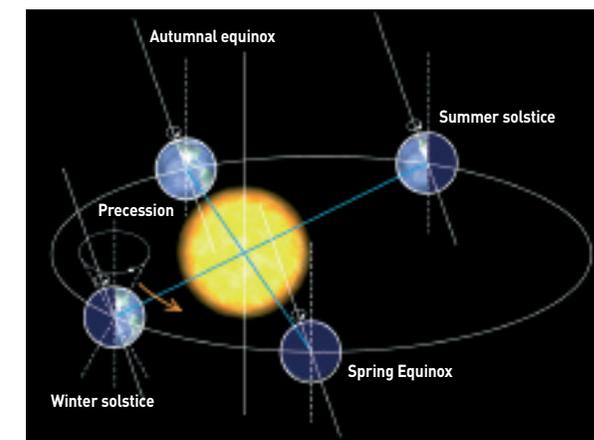
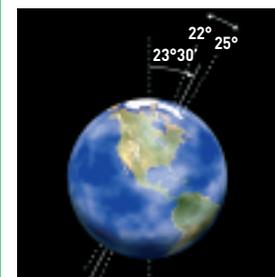
In the Northern Hemisphere, continental landmasses predominate in comparison to the oceans (though the pole is in an ocean). In the Southern Hemisphere, the continents only occupy a very small fraction of the surface area (though here the Pole is at the centre of a continent). An

ice age will clearly start on the continents, where the thermal inertia is lower than that of the ocean, and hence will start in the Northern Hemisphere (Antarctica remains covered by ice in any event). If precipitation and sunlight conditions are such that the snow falling in winter does not melt in

summer, then snow will accumulate and be transformed into ice. Such conditions require a seasonality that does not exhibit large contrasts, having humid winters, which are not too cold and cool summers. This is where the position of the Earth with respect to the Sun plays a role.



▲ The motion of the Earth describes an ellipse with the Sun at one of the focal points. The Earth is subject to the attraction of the Sun, but also of attraction by the other planets in the solar system. This has the effect of deforming its trajectory, causing the seasonal distribution of radiation from the sun to vary.



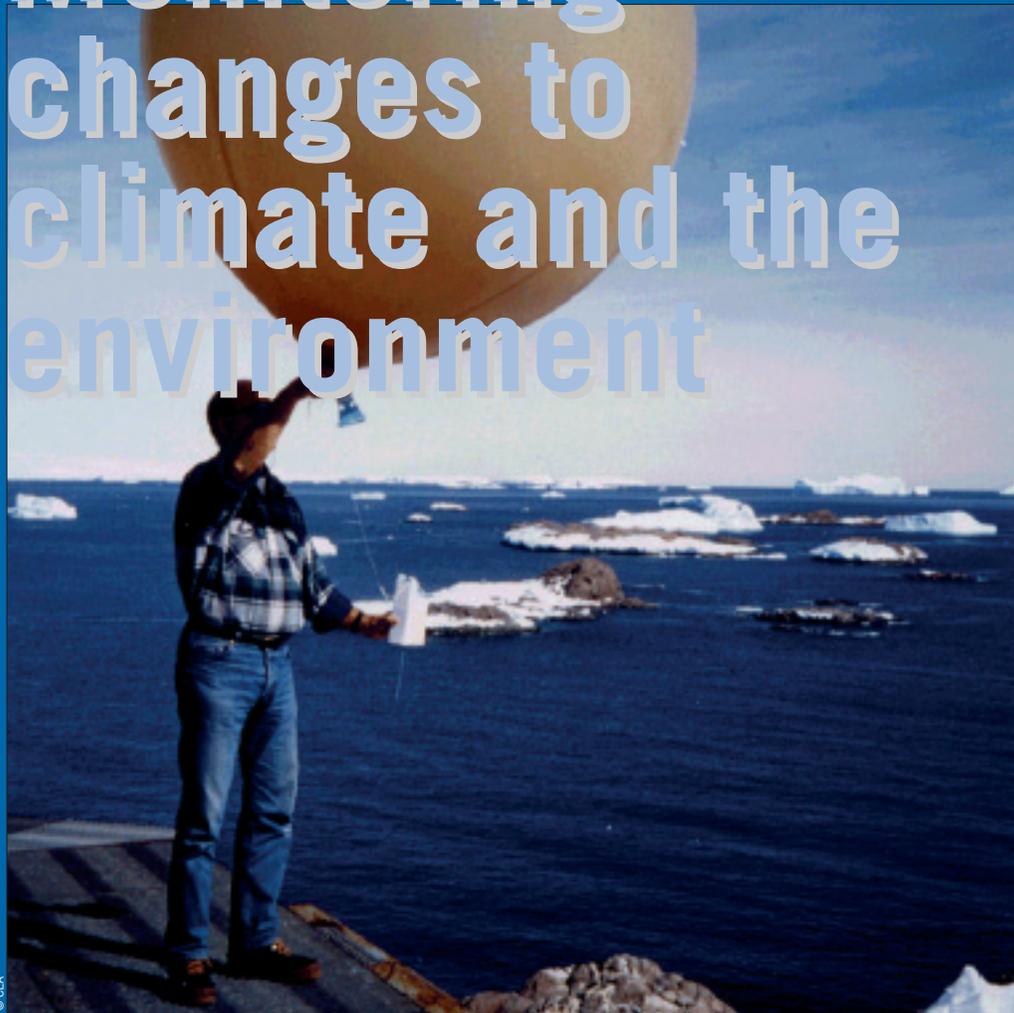
◀ Three types of pseudo-periodic changes affect the position of the Earth with respect to the Sun:

- the eccentricity of the ellipse which varies with two pseudo-periods of 100,000 and 413,000 years,
- the inclination of the Earth's axes of rotation to the plane of the ecliptic, which varies between 22 and 25° with a period of 41,000 years;

▲ – finally, the rotation of the Earth also has a precession movement (with periods of 19,000 and 23,000 years), on a cone, the peak of which is located at the centre of the Earth. The axis perpendicular to the ecliptic plane leads to a shift of the position of the equinoxes and solstices on the ellipse. These diverse frequencies are the dominant frequencies of climate variation over the course of the last million years.

REGULAR MEASUREMENT OF CLIMATIC CHANGES HELPS US TO UNDERSTAND THE CONSEQUENCES OF OUR BEHAVIOR.

# Monitoring changes to climate and the environment



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**“A single geostationary, meteorological satellite can continuously monitor around one third of the surface of the globe”**

## METEOROLOGICAL SATELLITES

Meteorological variability is very large in the short term. In our region, it is very much greater than the worst variations predicted for average climatic conditions. A large number of measurements over a long period of time will be necessary to detect climate change and the environmental parameters which depend upon it.

The geographic separation of measurements, and their frequency, will depend on the spatial and temporal variability of the phenomena which are to be monitored.

For measurements which require daily monitoring on a large spatial and temporal scale, a satellite is the ideal observatory, provided it has instruments capable of resolving the phenomena to be studied. Geostationary meteorological satellites can monitor a third of the surface of the globe, and can do this several times per hour. Satellites in polar orbit can make daily observation of almost the entire surface of the globe. To observe phenomena which are limited to a given geographical region (for example: the monsoon), satellites require specific orbits. Apart from meteorological satellites, satellites dedicated to observation of the environment and to monitoring climate components (clouds, solar radiation, radiation from the ground, aerosols, greenhouse gases, etc.) have been launched for the scientific community.

Although a large amount of meteorological data can be measured by satellite, there is nevertheless the problem of vertical variation, which can only be resolved for a limited number of para-

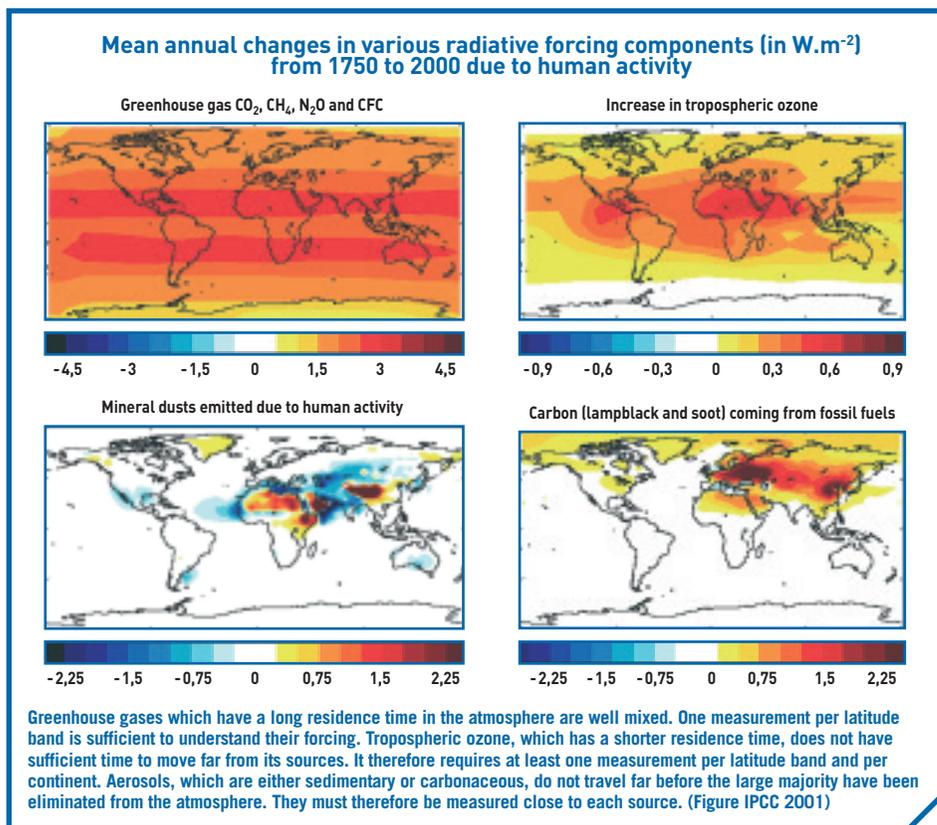
eters. Moreover, the satellite cannot record a large number of parameters with a high spatial resolution, without risking saturating data transmission and processing.

Finally, once launched, a satellite is inaccessible and its correct operation can only be verified and corrected through measurements taken from the ground. These are an indispensable complement to satellite measurements. Long-term, high frequency monitoring will be made by automatic stations, judiciously distributed over the surface of the globe to ensure good coverage and to prevent the required signal being perturbed. These will include meteorological stations, automatic buoys, stations for analysis of atmosphere composition and automatic spectrometers, etc.



© PhotoDisc

A satellite is an ideal observatory for daily monitoring on a large spatial and temporal scale.



Moreover meteorologists make daily measurements using balloon based probes, to attain vertical distributions of weather parameters.

As an indication, the World Meteorological Organization uses some 10,000 stations on land, 7,000 stations on board ships and 800 drifting buoys in the sea, more than 800 radiosonde stations and 14 satellites, of which 8 are geostationary.

For a geographically limited, detailed understanding, there are programs of recurrent measurements which, if necessary, use existing transport: temperature measurements of the sea are car-

ried out daily by numerous merchant ships and atmospheric measurements are installed on board airliners.

Finally, study of particular phenomena may require multi-instrument programs, the most important of which have been set up on the international scale. Consider for example the INDOEX campaign in 1999, which studied aerosols emitted by India. This program simultaneously put in place measurements on the ground, on board ships, at airports and by satellite. Another example of a program dedicated to climate is AMMA, which



Atmospheric measurements on board an aircraft for gathering geographically limited, but detailed information.

was a program studying African monsoons, for which the majority of observations took place in 2005.

## THE CLIMATE OF THE FUTURE

Measurements carried out directly in the atmosphere show that the concentration of greenhouse gases in the atmosphere has been increasing at a speed unknown in the geological history of the Earth and to a level without precedent in the course of the last million years.

Changes to the climate and the environment have been clearly observed over the course of the 20<sup>th</sup> century:

- there has been a mean temperature increase of 0.7 °C, and the nocturnal maximum temperature has increased more than the diurnal maximum temperature;
- sea level has risen by 17 cm;
- over the last 30 years the volume of pack ice

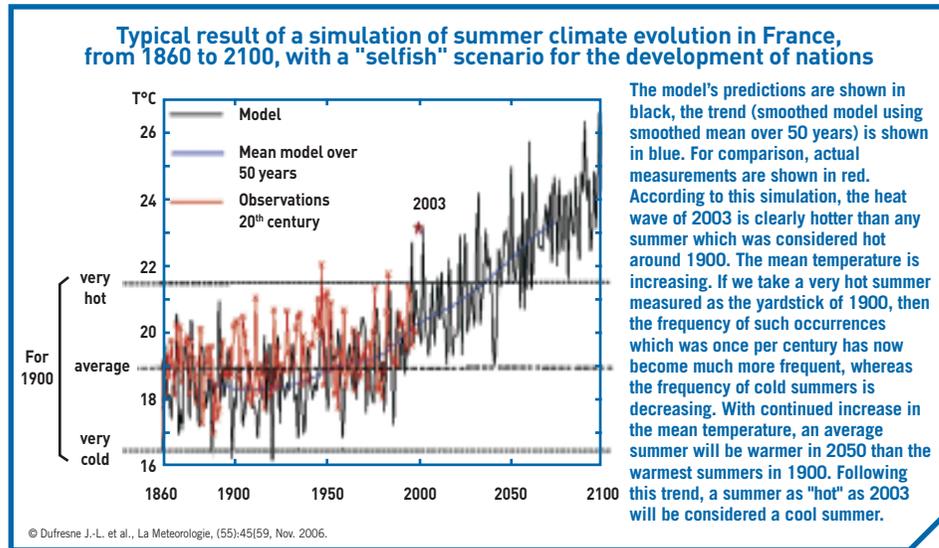


Analyses on the ground are an indispensable complement to satellite measurements.

in the Arctic Ocean has sharply decreased; its minimum surface area in summer has decreased by 40%, with, in consequence, a notable warming of the seawater in the whole region.

Considering the quantities of gas which have already been injected into the atmosphere and the inertia of the system, warming of the climate should be expected in the coming century, even if concentrations of greenhouse gas do not increase further. However, even the most optimistic estimates of changes in the world's society and its behavior, predicts a strong increase in this concentration.

In order to estimate how the climate will change over the course of the 21<sup>st</sup> century and beyond, it is not possible to simply extrapolate from past climates, since we do not know of an analogous set of astronomical and environmental characteristics sufficiently close to those of the present day. We must therefore rely on modeling.



As we have seen, climate modeling is an imperfect science: the climate machine is complex and the phenomena in play are often still poorly understood and difficult to model in a realistic fashion. The unavoidable limits on calculation resources require to use simplified approaches, which cannot take into account the full and fine details of certain phenomena. Each model seeks to bring its own solutions to these diverse problems. This leads to a disparity in results, which climatologists investigate under large international inter-comparison programs.

A certain number of results are robust and are found in all the models: hence, it is certain that warming will be the greatest at high latitudes, as has already been observed in the Arctic, with the consequence of massive thawing of the **permafrost** and the out-gassing of the methane that it holds. In the case of

Ground frozen all year round.

rainfall, the whole of the Mediterranean basin is threatened by increased aridification. However, the amplitude of these phenomena and their geographic distribution will depend greatly on the way in which humanity manages the accumulation of greenhouse gases. Simulations of future climate are necessarily based on scenarios of society's development and its emissions of greenhouse gases. The environmental impacts of future climate change often result in pessimistic predictions. However, without a sufficient understanding of the feedback actions of the system, it is currently difficult to predict the severity and frequency of the events which are likely to be produced. Increased awareness of the possible consequences of the disturbances that mankind is bringing to the global environment have resulted in an enormous research effort over the last few

**“The "ecological" awakening has advanced our capacity to model the climate.”**

decades and considerable progress has been made in our understanding and our ability to model the climate, in particular thanks to studies of past climates. However, our understanding of the mechanisms of change and stabilization of the climate, which have been used to model its history, are still very limited. They must be improved in order to allow a reliable forecast of the changes in climate, particularly in extreme cases, for which the impact on society may be major.



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Maximum warming could provoke a massive thaw.

## INTERNATIONAL POLITICAL ACTION

Climate change and changes to the global environment have led to the organization of some important conferences.

At the request of the G7 and under auspices of the United Nations, a group of international scientists, the IPCC (Intergovernmental Panel on Climate Change), was set in place in 1988. This intergovernmental group of experts on climate change produces a report every five or six years on the current state of knowledge concerning climate change (<http://www.ipcc.ch>). The most recent is dated 2007.

Under the impetus of the United Nations Environment Program, the problems posed by substances which deplete the atmospheric ozone layer were discussed in Vienna (1985) and notably in Montréal (September 1987) where a

protocol was signed imposing reductions in the production and use of chlorofluorocarbons (CFC).

The protocol has been subject to amendments in London (1990), which imposed a ban on CFC's from 1<sup>st</sup> January 2000 and extended the regulation to other products, in Copenhagen (1992), Montreal (1997) and Beijing (1999).

At the Earth Summit in Rio de Janeiro (June 1992), a framework United Nations Framework Convention was signed on climate change, which adopted the objective of stabilizing greenhouse gas emissions (coming into force on 21<sup>st</sup> March 1994).

At the Kyoto conference (December 1997) a protocol was signed on global reduction of emissions of these gases, by 5.2% on average, in 2008-2012, compared with the

1990 baseline, for OECD countries and the countries of Eastern Europe (including Russia). The reduction targets for the European Union and France were 8% and 0% respectively. In spite of the conference keeping to an intensive pace, it was necessary to wait until 2005 before Russia finally rejoined and the protocol could be ratified. For the subsequent period (starting from 2013), the Bali conference (December 2007) has begun the process to define the reductions in greenhouse gas emission and the terms and methods of these reductions. It has also begun actions for adapting to climate change.

In 2007, the Nobel Peace Prize was awarded, jointly, to Al Gore and to the IPCC for their activity in raising awareness of the risks linked to climate change.