# The origin of climate changes

P. Delecluse

Centre National de Recherche Météorologique, Météo-France, 2 avenue Rapp, 75340 Paris Cedex 07, France

**Summary**

Investigation on climate change is coordinated by the Intergovernmental Panel on Climate Change (IPCC), which has the delicate task of collecting recent knowledge on climate change and the related impacts of the observed changes, and then developing a consensus statement from these findings. The IPCC's last review, published at the end of 2007, summarised major findings on the present climate situation. The observations show a clear increase in the temperature of the Earth's surface and the oceans, a reduction in the land snow cover, and melting of the sea ice and glaciers. Numerical modelling combined with statistical analysis has shown that this warming trend is very likely the signature of increasing emissions of greenhouse gases linked with human activities. Given the continuing social and economic development around the world, the IPCC emission scenarios forecast an increasing greenhouse effect, at least until 2050 according to the most optimistic models. The model ensemble predicts a rising temperature that will reach dangerous levels for the biosphere and ecosystems within this century. Hydrological systems and the potential significant impacts of these systems on the environment are also discussed. Facing this challenging future, societies must take measures to reduce emissions and work on adapting to an inexorably changing environment. Present knowledge is sufficient to start taking action, but a stronger foundation is needed to ensure that pertinent long-term choices are made that will meet the demands of an interactive and rapidly evolving world.

**Keywords**

Climate change – Emission scenario – Greenhouse gas – Modelling – Projection – Radiative balance.

## Introduction

The Earth has experienced very contrasted climates, from the 'Snowball Earth' 640 million years ago (when the mean temperature was about –50°C) to the very warm Cretaceous Period (when the mean temperature was above 20°C). The last million years have been marked by alternate cold glacial and warm climatic periods. This pattern of alternating cold and warm periods has been attributed to the variations in astronomical parameters which control the Earth's orbit around the Sun. Eight thousand years ago, the Earth entered a very stable warm period (with an average temperature of 15°C) which was expected to last quite a long time, given the Earth's very stable astronomical configuration. However, this stable equilibrium is presently challenged by the growing impact of human activities on climate. Observations show an increasing warming trend over the last century and this strong signature is likely to become a driving force for change for the whole living Earth for the next centuries.

Given the challenge facing the Earth's present climatic equilibrium, an international body was created to regularly produce a critical assessment of climate change, including scientific advancement, climate vulnerability, and mitigation strategies. The present paper reviews a few of the main results of this body's work on the physical science basis of climate change. After discussing some of the observations that have been made by research teams, the scientific basis of atmospheric warming due to greenhouse gases is explained and the contribution of emissions due to human activities is presented. A description of the present state of the climate is provided and is followed by a projection exercise for the 21st Century, where certainties and uncertainties about future climate are discussed.

## Intergovernmental Panel on Climate Change: the role of an international body

Scientific progress does not follow a straight line and knowledge often progresses by successive jumps. Observation is the essential foundation of scientific development and the last few decades have produced a large amount of new data that were quite disturbing, because they contradicted the assumption of a stable climate system and challenged currently held beliefs by proposing that the climate system is actually rapidly drifting. It took several years of sharp debates to accept the evidence that the Earth's climate was changing right under our noses. Given the severity of the problem, the United Nations Education Programme (UNEP) and the World Meteorological Organization (WMO) promoted the United Nations Framework Convention on Climate Change (UNFCCC). This body launched the Intergovernmental Panel on Climate Change (IPCC), which is in charge of preparing a regular report. This report gives an assessment of the scientific bases of climate change, the impacts of climate change on natural and human systems, the vulnerability of different systems to climate change, and the different options for mitigation and adaptation. It also provides recommendations to the UNFCCC.

The Fourth Assessment Report of the IPCC (AR4) was published at the end of 2007 and it summarises the results of thousands of research projects around the world. This international process is an interesting example of the advancement of ideas and science. Every four to five years, the IPCC is committed to writing a report which presents a worldwide consensus of independent research. All published results about human emissions of chemical trace gases and particles, atmospheric and oceanic states, the state of ice covered surfaces, and advances in climate change projections are critically compared and interpreted. The figures are thoroughly analysed and their accuracy is debated. For building scenarios for the projection of future climate change, a complex programme of modelling has been designed and only results which are published through the peer-review system are integrated into the discussion.

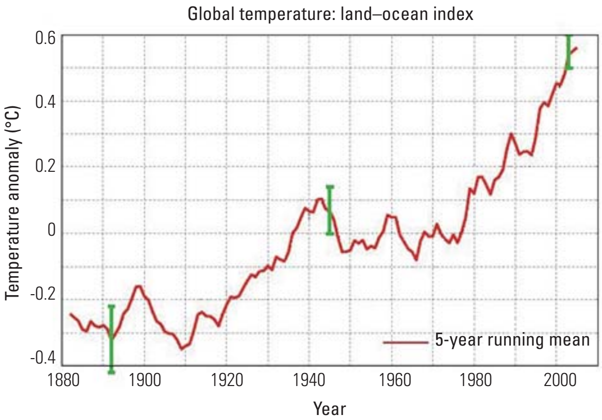
Sometimes the results are straightforward and a rapid agreement is obtained, but this is not always the case and ensuing debates can result in new research questions. A debate can reach the limit of present knowledge and new research is needed to interpret some of the data. The status of the Antarctic ice sheet is a good example of such a debate. The growth of an ice sheet is controlled by ablation–precipitation budget and by temperature. Most glaciers are more sensitive to temperature than to precipitation. In the Antarctic, where precipitation is minimal, a higher temperature should cause melting of the ice sheet. However, a higher temperature also favours an increase in precipitation, which should promote growth of the ice sheet. Thus, the state of the Antarctic ice sheet is influenced by two competing processes. A specific observation effort was launched to carefully specify the regional evolution of this large ice sheet and the AR4 concluded that the whole Antarctic ice sheet is indeed shrinking.

Questions, such as the one posed above, speed up research in order to get a better understanding of the underlying mechanisms and the expected evolution of climate change. Science is thus strongly stimulated by the questions raised by the IPCC and little by little the establishment of a firm basis of knowledge raises confidence. Most of the results discussed hereafter come from the consensus analysis presented in the IPCC AR4.

## Observing the climate system

Global long-term time series of combined land surface air temperature and sea surface temperature have been developed and maintained by the Climatic Research Unit in the United Kingdom (UK), in association with the UK Met Office Hadley Centre (2), the National Climatic Data Centre in the United States of America (16) and the NASA Goddard Institute for Space Studies (8). These temperature series have been homogenised in order to take into account instrumental ruptures, extension of urban environment and sampling scarcity, and have recently been combined with space observations in order to deliver a consistent picture of the climate evolution since the pre-industrial era.

The conclusion from the IPCC AR4 is that the global air temperature from the pre-industrial era (1850 to 1899) to the present time has increased by 0.76°C (+/–0.19°C) and the growth rate has progressively accelerated: the linear rate in the last 50 years is double the centennial rate, and 11 of the last 12 years rank among the 12 warmest years since 1850 (Fig. 1). This global signature erases many local climatic features and the natural climate variability. The regional distribution of this warming shows a strong signal in high latitude continental regions and a moderate but




The green bars measure the range of uncertainty around the mean value

**Fig. 1**
**Graph of surface temperature anomalies (land and ocean temperatures are averaged [°C]) with a 5-year running mean**

significant warming signal in the Southern Hemisphere. One direct consequence of this warming is the reduction of areas covered by snow and the retreat of the major glaciers of the world in both high and low latitudes. Analysis of satellite observations (following the method of Brown [3]) shows a marked decrease of the snow covered area in the Northern Hemisphere. The sea ice is also observed to be rapidly melting in the summer season. The year 2007 showed a record decrease in the sea ice extent. At the end of the melting season in September the sea ice extent was 39% below the long-term average from 1979 to 2000 (12).

The global ocean is also warming (9). The signal, originally observed in the upper sea levels, is slowly penetrating downwards into the deep ocean and is now observed extending to a depth of 3,000 m (11). The distribution of the signal is far from being homogeneous and reflects the global oceanic circulation, with penetration being more active in the convection and subduction regions, like that seen in the sub-Arctic regions.

### Interpreting the recent evolution of the climate system

The Earth's climate is far from being stable and the history revealed by sediment analyses shows a complex evolution, with changes at multiple scales. Many factors shape the Earth's climate and are associated with different timescales. The present location of the continents, with two large land masses in the Northern Hemisphere, three in the mid latitude of the Southern Hemisphere, and a continent directly over the South Pole, is associated with a very different climate from that which was observed when the whole land mass was assembled at the equator 1,100 million years ago as the supercontinent Rodinia. The atmospheric composition of trace gases and particles is also important: strong and continuous volcanic activity could be associated with a cool atmosphere, while exuberant vegetation with a high carbon dioxide ($CO_2$) level could be linked with a warm climate, such as that seen three to five million years ago during the Pliocene period. Polar ice and ocean sediments can also tell us a lot about the climatic history of the last million years and show the importance of the orbital parameters. Milankovitch's theory suggests that glacial–interglacial cycles occurred in response to orbital forcing, with a strong positive amplification of this forcing caused by several components of the Earth's system (ice sheets, oceanic circulation, biophysical feedbacks, aerosols, and the concentration of greenhouse gases). The last million years have been characterised by a glacial cycle interrupted by warm periods, with a dominant periodicity of 125,000 years. These strong variations in the Earth's climate were accompanied by large modifications of the ice caps and thus of the sea level. Bubbles from ice cores were analysed and showed that the air composition was also variable: high levels of $CO_2$, methane ($CH_4$) and nitrous oxide ($N_20$) were measured during warm periods and low levels during cold periods, although the signals were not exactly in phase. Moreover, the sediments also show that the present-day levels of $CH_4$ (1,774 ppb) and $CO_2$ (379 ppm) have not been observed in the last million years, suggesting that the present situation has no analogue in the last million years.

## Radiative balance of the Earth and the effect of greenhouse gases

Revolving around the Sun, the Earth's temperature is in a delicate balance between the energy it receives from the Sun and the energy it radiates into space. Paleoclimatologists have long been interested in the variation in this balance, which is assumed to be responsible for most of the variability of the Earth's climate in the last million years. This variability was interpreted as being a function of the slight variation in the distribution of the incoming solar radiation due to the modification of the Earth's orbit.

The Sun, which has a very high average temperature of about 6,000 K, emits energy in the X-ray and visible light regions of the electromagnetic spectrum. The Earth, which has a much lower average temperature (radiative temperature) of 255 K (–18°C), emits mostly in the infrared region (long-wave radiation) following the Stefan-Boltzmann's Law on blackbody emission (18). Saying that the Earth is in radiative balance means that the incoming solar irradiance is equal to the emitted long-wave radiation and this balance leads to an average radiative Earth temperature of 255 K (–18°C), which is much lower than the observed average temperature of the Earth's surface (15°C). The difference in temperature is due to the greenhouse effect caused by the presence of tiny traces of gases in the Earth's atmosphere. The most important gas responsible for this effect is the water vapour present in the lowest layer of the Earth's atmosphere (the troposphere). The Earth's surface emits energy in the infrared wavelengths to outer space, but several wavelengths of this irradiance are trapped by the water molecules, which absorb the incoming rays and re-emit the energy into the surrounding atmosphere. The global effect of absorption/emission of the Earth's irradiance by the water vapour is that a huge part of the infrared radiation is trapped in the troposphere, thus contributing to an increase in the Earth's surface temperature. Water vapour accounts for 60% of the greenhouse effect, while other trace gases, like the long-life greenhouse gases ($CO_2$, $CH_4$, $N_20$), make variable contributions to the greenhouse effect depending on their radiative properties and concentration in the atmosphere.

### The role of greenhouse gases

The development of human activities, from land use and agriculture to industry and transport, is based on an expanding exploitation of natural resources. The industrial era was built on the production of energy from coal, and progressively other fossil reservoirs were exploited. The consumption of fossil energy, forest burning, and intensive agriculture have produced many atmospheric trace gases, some of which are very volatile, while others have a very long lifespan in the atmosphere. For instance, $CH_4$ has a mean residence time of 12 years and $N_20$ of 114 years (13). This means that once these gases are emitted from the Earth's surface they remain in the atmosphere long enough to be well mixed and to have a global impact on the radiative energy budget of the Earth. This can be seen clearly in very isolated areas such as the Kerguelen Islands in the South Indian Ocean, where 'long-life' greenhouse gases have had time to mix with atmospheric winds, unaffected by human activity: emissions in these areas reflect the background atmospheric composition rather than the local variability found in populated areas.

Greenhouse gases are classified as a function of their radiative forcing. Radiative forcing is a measure of how the energy present in the global Earth-atmosphere system will change due to the presence of various factors, such as greenhouse gases, which alter the balance between incoming solar radiation and outgoing infrared radiation. Each gas has a radiative forcing value which is defined as the change in net irradiance (solar plus long-wave) at the top of the low level atmosphere after allowing for upper atmosphere temperatures to readjust to radiative equilibrium, with surface and tropospheric temperatures and state held fixed at the unperturbed values (14). The radiative forcing value is used to assess and compare the anthropogenic drivers to the natural drivers of climate change: additional $CO_2$ is the most important driver (1.66 $Wm^{-2}$), $CH_4$ the second (0.48 $Wm^{-2}$), followed by $N_20$ (0.16 $Wm^{-2}$) as the third.

The concentration of $CO_2$, observed through a global network (10), has increased 36% from 280 ppm in the pre-industrial era to 379 ppm in 2006 (a concentration that has not been reached in the last 600,000 years, as recorded in the Dome C ice core [Antarctic]). However, $CO_2$ is slowly absorbed by the Earth's biosphere (vegetation, soil, and marine biosphere) and, therefore, the observed concentration only reflects about half the total emission level. Furthermore, the absorption capacity of the land surface and marine biosphere is limited and if $CO_2$ concentrations continue to increase this could, in the short term, speed up the growth of some plants and, in the long term, affect the resilience of some ecosystems.

## Climate of the 21st Century

Conducting an assessment of the present climate state is only a first step, it should be followed rapidly by the question 'What future are we building?' Due to the impact of human activities on climate change, the Earth's future will be strongly influenced by the way in which societies choose to develop. Projections of greenhouse gas emissions are made with integrated models, accounting for demography, economic development, technological changes, capacity building, social and cultural interactions and energy markets. Several scenarios have been proposed with subsequent estimates of $CO_2$ emissions for the 21st Century. They are described in detail in the IPCC Special Report on Emission Scenarios (SRES).

For a given SRES scenario, coupled ocean–atmosphere models of different complexity are used to compute climate projections for the 21st Century. A limited number of SRES scenarios have been selected from the report and are described below. The SRES B1 scenario forecasts a convergent world that is rapidly evolving toward a service and information economy and is focused on global solutions for social, economic and environmental sustainability. The SRES A2 scenario describes a very heterogeneous world that is focused on regional economic growth. The SRES A1F1 scenario describes a world that is experiencing rapid economic growth as a result of technological development based on intensive fossil energy utilisation.

The model ensemble forecasts a mean temperature rise ranging from 1.7°C (range 1.0°C to 2.7°C) for the SRES B1 scenario to 4.0°C (range 2.4°C to 6.3°C) for the SRES A1F1 scenario. Despite the temperature range in the projections, spatial patterns are very coherent among the ensemble, with warming increasing with latitude and intensified in continental regions. As an example of IPCC projections, three distributions of the projected temperatures are presented in Figs. 2a, 2b and 2c. These maps show the temperature anomalies, averaged from 2070 to 2099 minus the averaged temperature from 1970 to 1999, for the SRES scenarios A2 and B1 using the two French models included in the IPCC ensemble (CNRM-CM3 and IPSL-CM4). The amplitude of the temperature anomalies is clearly dependent on the scenario (i.e. using the CNRM-CM3 model, temperature anomalies over France range from 1°C to 3°C for the SRES B1 scenario to 3°C to 5°C for the SRES A2 scenario), while the spatial patterns are very consistent (i.e. each of the maps shows an amplified signal on the continents and in the northern latitudes). Note that the CNRM-CM3 model shows maximum warming in the Arctic while the IPSL-CM4 model shows maximum warming just north of Canada. This difference in distribution demonstrates the critical impact of representing the ice covered regions, which have a strong positive feedback on climate. It also shows that the projected temperatures are very dependent on small differences between models.

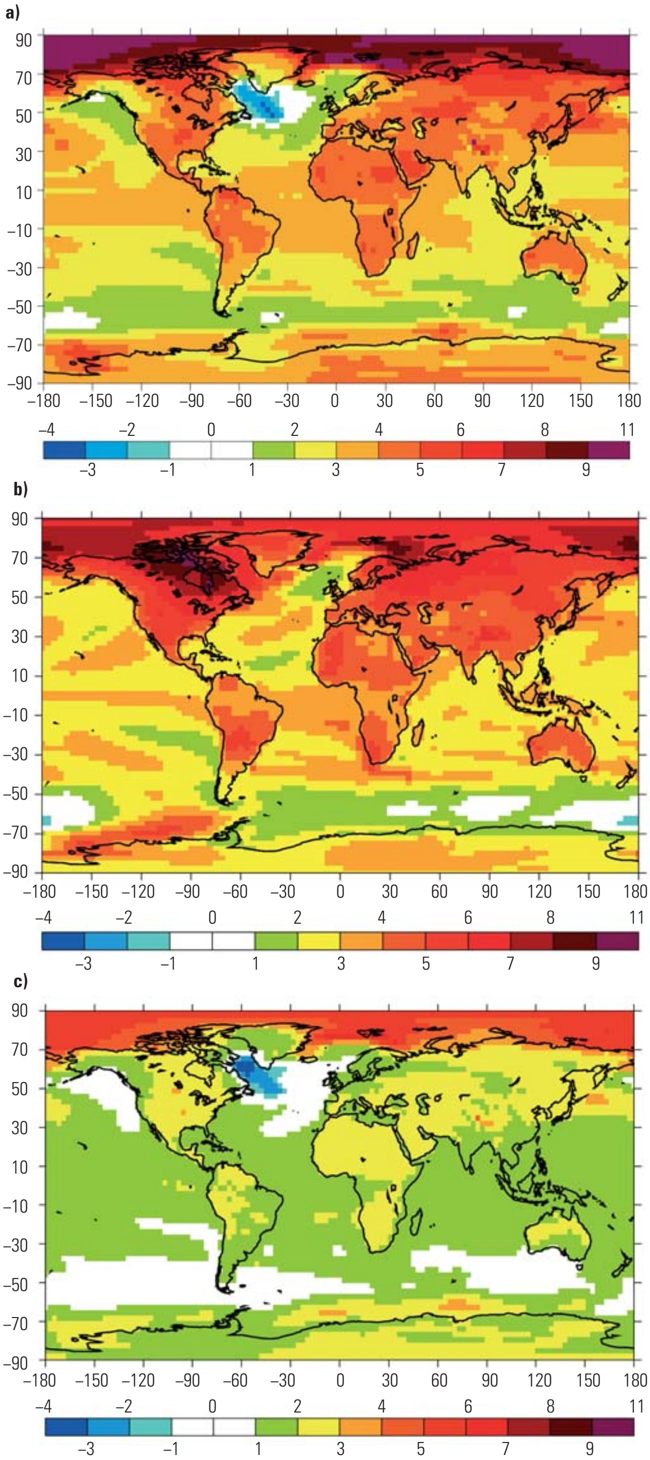



**Fig. 2**
**Temperature anomalies (°C) averaged from 2070 to 2099, minus the averaged temperature from 1970 to 1999, computed for the SRES A2 scenario using the CNRM-CM3 model (a) and the IPSL-CM4 model (b), and for the SRES B1 scenario using the CNRM-CM3 model (c)**

In terms of precipitation, which is a very important climatic parameter but very variable in its temporal and spatial structure, it is more difficult to reach a consensus among models, although some similarities exist among the different maps. The precipitation anomalies computed by the French models CNRM-CM3 and IPSL-CM4 are presented in Figs. 3a, 3b and 3c. There is a trend of increased precipitation in already wet regions, like the InterTropical Convergence Zones, and a trend of reduced precipitation in already dry regions. The signal, for instance, is very consistent over Europe, with northern Europe being wetter and the Mediterranean region being drier. Divergence between models appears in some areas, such as India or the core of South America, where the intensity of the Monsoon regime is dependent on the land surface representation. The precipitation projections indicate an intensification of the hydrological cycle associated with an increased water-holding capacity of the atmosphere, as the mean atmospheric residence time of the water vapour is actually increased (4).

There is no substitute for knowledge and our present capacity to model the trajectory for the Earth's global climate is limited by many uncertainties that must be addressed with coordinated research programmes. The physical models that are used to compute climate change still suffer from biases due to the difficulty in correctly representing oceanic, atmospheric and ice behaviour. For instance, the representation of clouds in the atmosphere remains the largest source of uncertainty between atmospheric models and this leads to differences in the prediction of the future climate (1, 19). In the ocean, convective regions remain very far from being adequately represented and this could affect predictions about the future of the Atlantic thermohaline circulation (6, 15, 17). The differences between models in representing the air–sea–ice feedbacks in the regions of deep water

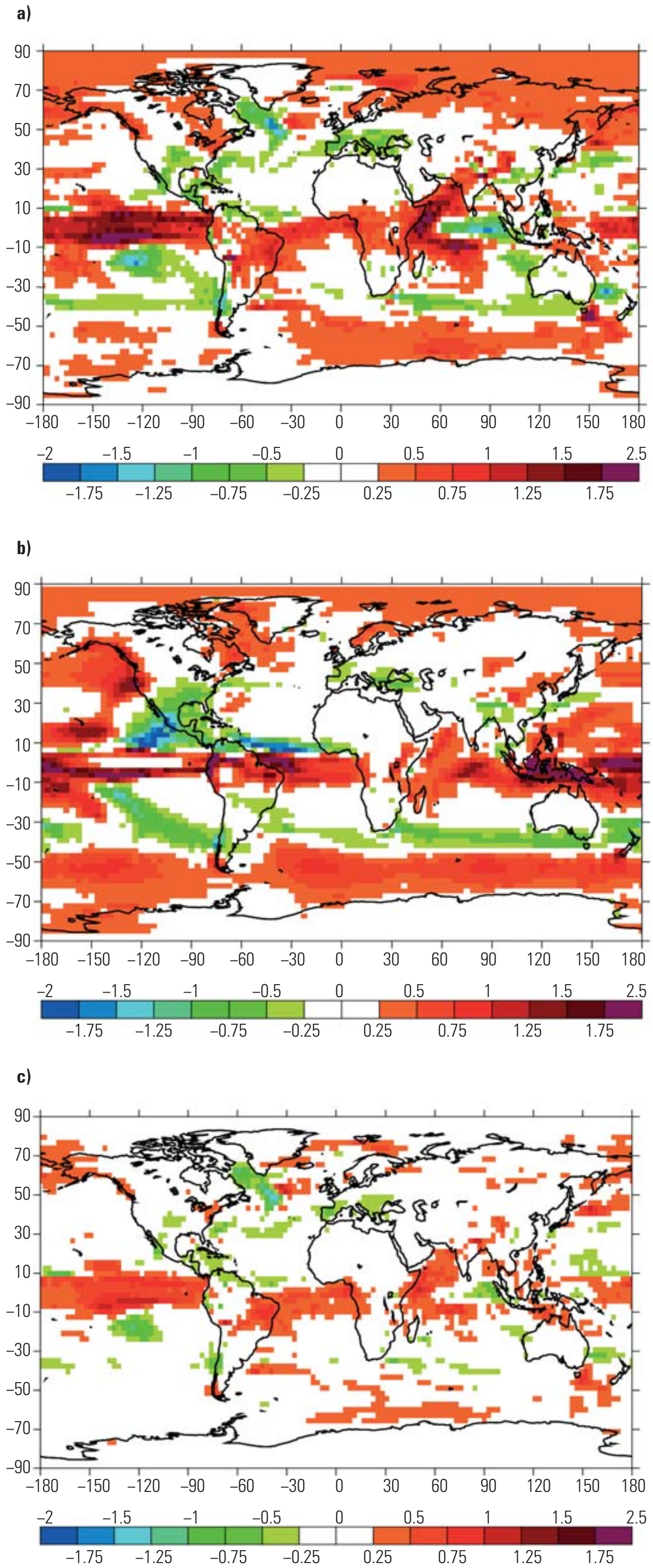



**Fig. 3**
**Precipitation anomalies (mm/day) averaged from 2070 to 2099, minus the averaged precipitation from 1970 to 1999, computed for the SRES A2 scenario using the CNRM-CM3 model (a) and the IPSL-CM4 model (b), and for the SRES B1 scenario using the CNRM-CM3 model (c)**

formation are reflected in the regional climate projections for the North Atlantic (see the temperature patterns in the North Atlantic in Fig. 2). For the polar caps, most models do not account for the ice dynamics, as the behaviour of the large ice shelves over the ocean remains a difficult process to represent. All climate models are still run with coarse resolution, which severely constrains the choice of model parameters.

Besides the limitations already present in the coupled models, some components are not yet fully represented. For instance, future concentration of greenhouse gases is specified in the SRES scenarios, but it is not taken into account that greenhouse gases interact with the climate: the biosphere fixes $CO_2$ to produce chlorophyll and respiration produces $CO_2$. It would be more correct to specify human emissions of greenhouse gases and model the biosphere in dynamic interaction with climate. A few groups have already introduced the explicit coupling between $CO_2$ and the climate into their models, and they have indeed shown that this coupling influences future climate change (5). New components that contribute to the climate system need to be studied and evaluated.

As the future strongly depends on the amount of greenhouse gases that are emitted, a large source of uncertainty in projecting these emissions lies in determining the demography of developing countries and the social and economic development that will take place in these countries in the future. Technological advances are needed to provide energy in ways that are efficient and more ecological and are adapted for underdeveloped and developing countries, which are desperately in need of low cost, efficient and ecological technology. Reducing emissions is a challenge that should be addressed with equity by all countries and all generations. The possible evolutions need to be modelled in full interaction with climate change because climate change will alter our life style and energy consumption.

Finally, let us remember that the nature of the climate system is chaotic, which means that a slight difference (the famous butterfly fluttering…) can alter the future climate for many decades. It is thus necessary to develop an ensemble approach employing large coordinated programmes in order to increase confidence in the projections for the future.

# Conclusion

The latest scientific results on climate change have clearly demonstrated that human societies will face an inexorable warming in future centuries, even if we are able to reduce greenhouse gas emissions to the levels that were observed in the year 2000. This persistent warming is linked to the complex nature of the climate, whereby perturbation that affects components of the climate with a very slow adjustment time, such as the oceans, will continue to have an impact for centuries to come (e.g. $CO_2$ that is absorbed deep into the ocean today will resurface in the future). Model ensembles were designed to detect the signature of the ongoing climate change, which is now attributed with confidence to increasing greenhouse gas emissions due to the development of human activities. Although they have not been discussed here, this warming trend has already had severe impacts on our environment. But the worst is yet to come as a result of the social and economic development that will take place in different countries in the future (7). According to the SRES scenarios, temperature and precipitation will modify the regional climates that have sustained our present development. Moreover, this evolution in climate change will be marked by extreme events to which the environment and societies are particularly vulnerable, such as storms, heat waves or flash floods. Even if a reduction in emissions is made a priority and policies are adapted to cope with the unavoidable changes in our environment, there are still huge gaps in our knowledge on how climate is changing, at what speed the changes will occur, the impacts of this change, which regions will be affected, etc. Strengthening basic knowledge on our changing environment is a priority in order to preserve the Earth for future generations.

## Acknowledgements

The author would like to thank all of the contributors to the IPCC Fourth Assessment Report and particularly the CNRM-Météo-France and IPSL modelling teams who produced the projections discussed in this paper. Special thanks also to David Salas y Melia who drew the figures from the model outputs.

■

# L'origine des changements climatiques

P. Delecluse

**Résumé**

La recherche sur le changement climatique est coordonnée par le Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC), qui a la délicate mission de recueillir les informations les plus récentes sur le changement climatique et sur l'incidence des changements constatés, et d'en dégager un consensus. Le dernier rapport du GIEC, qui date de 2007, résume les principales observations quant à la situation actuelle du climat. Ces observations indiquent une nette augmentation de la température de l'atmosphère et des océans, une réduction de la couverture neigeuse et une fonte massive de la banquise et des glaciers. L'analyse statistique de modélisations numériques montre que cette tendance au réchauffement est très probablement la conséquence d'une augmentation des émissions de gaz à effet de serre liées aux activités humaines. Compte tenu de l'évolution continue du développement social et économique dans le monde, les scénarios d'émission du GIEC prévoient que l'incidence des gaz à effet de serre ne devrait pas cesser d'augmenter et ce, d'après les modèles les plus optimistes, jusqu'en 2050 au moins. Les différents modèles s'accordent à prédire une augmentation des températures tout au long du 21$^{e}$ siècle jusqu'à atteindre des niveaux dangereux pour la biosphère et les écosystèmes. Les systèmes hydrologiques et les incidences potentielles de ces systèmes sur l'environnement sont également discutés. Pour faire face aux enjeux du futur, les sociétés doivent prendre des mesures pour réduire les émissions et pour s'adapter à un environnement dont le changement est inexorable. Les connaissances actuelles offrent déjà quelques pistes d'actions à suivre, mais des fondations plus solides sont nécessaires pour prendre les bonnes décisions sur le long terme et répondre ainsi aux mutations rapides et aux interactions du monde de demain.

**Mots-clés**

Changement climatique – Équilibre radiatif – Gaz à effet de serre – Modèle – Projection – Scénario d'émission.

■

# Origen de los cambios climáticos

P. Delecluse

**Resumen**

El Grupo Intergubernamental de Expertos sobre el Cambio Climático (IPCC) es el órgano que coordina las investigaciones sobre el cambio climático y tiene a su cargo la delicada tarea de centralizar los más recientes conocimientos sobre el tema y las consecuencias de los cambios observados y de elaborar acto seguido un informe consensuado a partir de esa información. En el último informe del IPCC, que se publicó a finales de 2007, se resumían los principales datos empíricos sobre la actual situación del clima. Estos datos revelan un claro aumento de la temperatura de los océanos y la superficie terrestre, una reducción de la superficie recubierta por la nieve y la fusión de hielos marinos y glaciares. La combinación de modelos numéricos y análisis estadísticos ha dejado patente que esta tendencia al calentamiento lleva la firma del creciente volumen de emisiones de gases de efecto invernadero vinculadas a la actividad humana. Teniendo en cuenta el incesante desarrollo social y económico que se registra en todo el mundo, las hipótesis de emisiones con que trabaja el IPCC prevén un efecto invernadero cada vez más acusado hasta por lo menos 2050, según los modelos más optimistas. El uso combinado de varios modelos permite anticipar que en el curso de este siglo las temperaturas subirán hasta niveles peligrosos para la biosfera y los ecosistemas. También se examinan las consecuencias del fenómeno para los sistemas hidrológicos y sus posibles efectos sobre el medio ambiente. Ante perspectivas tan poco halagüeñas, es indispensable que las sociedades tomen medidas para reducir las emisiones y trabajen para adaptarse a los inexorables cambios que sufrirá el entorno. Ya se sabe lo bastante como para poner en marcha una serie de actuaciones, pero se requiere una base más sólida para tener la seguridad de que se eligen soluciones pertinentes a largo plazo y de que éstas servirán para satisfacer las necesidades de un mundo interactivo y sujeto a rápidas transformaciones.

**Palabras clave**

Cambio climático – Elaboración de modelos – Equilibrio radiativo – Gas de efecto invernadero – Hipótesis de emisiones – Proyección.

■

# References

1. Bony S. & Dufresne J.-L. (2005). – Marine boundary layer clouds at the heart of cloud feedback uncertainties in climate models. *Geophys. Res. Lett.*, **32**, L20806, DOI:10.1029/2005GL023851.

2. Brohan P., Kennedy J.J., Harris I., Tett S.F.B. & Jones P.D. (2006). – Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. *J. Geophys. Res.*, **111**, D12106, DOI:10.1029/2005JD006548.

3. Brown R.D. (2000). – Northern hemisphere snow cover variability and change, 1915-97. *J. Climate*, **13**, 2339-2355.

4. Douville H., Chauvin F., Planton S., Royer J.-F., Salas-Mélia D. & Tyteca S. (2002). – Sensitivity of the hydrological cycle to increasing amounts of greenhouse gases and aerosols. *Clim. Dyn.*, **20**, 45-68.

5. Friedlingstein P., Cox P., Betts R., Bopp L., von Bloh W., Brovkin V., Cadule P., Doney S., Eby M., Fung I., Govindasamy B., John J., Jones C., Joos F., Kato T., Kawamiya M., Knorr W., Lindsay K., Matthews H.D., Raddatz T., Rayner P., Reick C., Roeckner E., Schnitzler K.G., Schnur R., Strassmann K., Weaver A.J., Yoshikawa C. & Zeng N. (2006). – Climate-carbon cycle feedback analysis, results from the C4MIP model intercomparison. *J. Climate*, **19**, 3337-3353.

6. Gregory J.M., Dixon K.W., Stouffer R.J., Weaver A.J., Driesschaert E., Eby M., Fichefet T., Hasumi H., Hu A., Jungclaus J.H., Kamenkovich I.V., Levermann A., Montoya M., Murakami S., Nawrath S., Oka A., Sokolov A.P. & Thorpe R.B. (2005). – A model intercomparison of changes in the Atlantic thermohaline circulation in response to increasing atmospheric $CO_2$ concentration. *Geophys. Res. Lett.,* **32**, L12703, DOI:10.1029/2005GL023209.

7. Hansen J. (2006). – The threat to the planet. *New York Rev. Books*, **53** (12), 12-16.

8. Hansen J., Gregory J.M., Dixon K.W., Stouffer R.J., Weaver A.J., Driesschaert E., Eby M., Fichefet T., Hasumi H., Hu A., Jungclaus J.H., Kamenkovich I.V., Levermann A., Montoya M., Murakami S., Nawrath S., Oka A., Sokolov A.P. & Thorpe R.B. (2001). – A closer look at United States and global surface temperature change. *J. Geophys. Res*., **106**, 23947-23963.

9. Ishii M., Kimoto M., Sakamoto K. & Iwasaki S.I. (2006). – Steric sea level changes estimated from historical ocean subsurface temperature and salinity analyses. *J. Oceanogr.*, **62** (2), 155-170.

10. Keeling C.D. & Whorf T.P. (2005). – Atmospheric $CO_2$ records from sites in the SIO air sampling network. *In* Trends: a compendium of data on global change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, Tennessee. Available at: http://cdiac.esd.ornl.gov/trends/co2/sio-keel-flask/sio-keel-flask.html.

11. Levitus S., Antonov J.I. & Boyer T.P. (2005). – Warming of the world ocean, 1955-2003. *Geophys. Res. Lett.*, **32**, L02604, DOI:10.1029/2004GL021592.

12. National Snow and Ice Data Center (2007). – Press Release: Arctic sea ice shatters all previous record lows, 1 October 2007. Available at: http://www.nsidc.org/news/press/2007_seaiceminimum/20071001_pressrelease.html.

13. Prather M.J. & Ehhalt D. (2001). – Atmospheric chemistry and greenhouse gases. *In* Climate change 2001: the physical science basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden & D. Xiaosu, eds). Cambridge University Press, Cambridge, United Kingdom, 239-287.

14. Ramaswamy V., Boucher O., Ghan S. & Smith S.J. (2001). – Radiative forcing of climate change. *In* Climate change 2001: the physical science basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden & D. Xiaosu, eds). Cambridge University Press, Cambridge, United Kingdom, 349-416.

15. Schmittner A., Latif M. & Schneider B. (2005). – Model projections of the North Atlantic thermohaline circulation for the 21st century assessed by observations. *Geophys. Res. Lett.*, **32**, L23710, DOI:10.1029/2005GL024368.

16. Smith T.M., Peterson T.C., Lawrimore J.H. & Reynolds R.W. (2005). – New surface temperature analyses for climate monitoring. *Geophys. Res. Lett*., **32**, L14712, DOI:10.1029/2005GL023402.

17. Swingedouw D., Braconnot P., Delecluse P., Guilyardi E. & Marti O. (2007). – The impact of global freshwater forcing on the thermohaline circulation: adjustment of North Atlantic convection sites in a CGCM. *Climate Dyn*., **28**, 291-305, DOI:10.1007/s00382-006-0171-3.

18. Trenberth K.E. (1992). – Climate system modeling. Cambridge University Press, Cambridge, United Kingdom, 788 pp.

19. Webb M.J., Senior C.A., Sexton D.M.H., Ingram W.J., Williams K.D., Ringer M.A., McAvaney B.J., Colman R., Soden B.J., Gudgel R., Knutson T., Emori S., Ogura T., Tsushima Y., Andronova N., Li B., Musat I., Bony S. & Taylor K.E. (2006). – On the contribution of local feedback mechanisms to the range of climate sensitivity in two GCM ensembles. *Climate Dyn.*, **27** (1), 17-38.