INSTITUT DE FRANCE
Académie des sciences

CLIMATE CHANGE

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This report is a summary of the speeches and discussions which took place during the climate debate on 20 September 2010 at the Académie des Sciences, the written contributions that preceded it and the large number of subsequent discussions and comments.

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Climate change

26 October 2010

For thousands of years, the Earth's climate has changed with different periods and in different places. The observed changes have generally been spread over long periods, thereby lessening the perception that man might have of them at any given moment. In recent decades, however, climate change seems to have accelerated. It is therefore not surprising that the public questions the reality of these changes, their causes, their future and, more important, their immediate and longer-term consequences on living patterns, health, ecosystems and economy. Science may attempt to provide authoritative answers to these questions, even if they are only partial or temporary, inasmuch as they are guided by a concern for objectivity that must come foremost in any scientific approach. It is against this background that the Minister for Higher Education and Research called on the "Académie des sciences" to organise a scientific debate and provide an update on current knowledge of the subject.

The debate was open to some 120 French and foreign scientists, including specialists from outside the Academy, and was organised on the basis of written contributions followed by an oral debate, which took place on 20 September 2010. The variety of disciplines represented – mathematics, physics, mechanics, science of the universe, chemistry, biology and medical science – reflects the complex nature of the subject and the Academy's wish to make this event a multidisciplinary one. The debate – which was very full and of a high scientific calibre, focused on climate forecasting methods; it provided an opportunity to compare different points of view, pick out points of convergence and identify any remaining divergences and uncertainties. It was the starting point for a discussion that will be extended in the future.

Despite the new investigation resources that we have today, and despite the considerable volume of data gathered over the last twenty years, it should be emphasised that Science doesn't have an answer for everything, that it moves forward in stages and that it can only provide, at a given moment, an interpretation of proven facts and forecasts.

1. THE IMPORTANCE OF OBSERVATIONS FOR RECENT HISTORY

An analysis of climate change requires to have undertaken a global observation of every component of the climate system (atmosphere, oceans, land and ice) over long periods.

It is only since the mid-1970s that satellite observation programmes, backed up by *in situ* observation systems, have been able to collect sets of climate data that have been sampled regularly in space and time. For previous decades, the earlier partial data are being re-processed as part of an international coordination to make them coherent, taking account of changes in instrumentation or immediate environment.

Free data circulation is a unanimous recommendation, even though there is some debate about the form that this should take. The majority of researchers into climatology and other science of the universe disciplines recommend distributing the data after the specialists have standardised it and removed the effects of instruments or the environment. Some are also asking for access to raw data.

From all these data we can see the emergence of climate change indicators, the factors leading to change and the information we need as a basis for studying past climates.

1.1. CLIMATE CHANGE INDICATORS

1. **The increase in the Earth surface temperature** is 0.8 ± 0.2 °C since 1870[1]. It remains notably different for the two hemispheres: greater in the North and greater in the high latitudes. Variability between continents is also observed. Finally, a strong variation over annual and multi-decade periods is also observed, with two periods in which large increases are observed (approximately from 1910 to 1940 and 1975 to 2000) surrounded by periods of stagnation or decrease. Natural climate variations (El Niño, volcanic eruptions, North-Atlantic Oscillation) are visible.

2. **The temperature of the oceans,** which has been measured since the 1950s by commercial and oceanographic vessels (up to a depth of approximately 700 m) and more recently by the system of Argo profiling buoys, shows an average global increase over the last few decades. The thermal energy content of the ocean has therefore also increased, especially since the early 1980s. This warming is not uniform. It shows a significant regional variability with major oscillations over several years and even decades.

[1] An increase – smoothed over time – in the average temperature of the Earth's surface.

3. **The reduction in the surface area covered by Arctic sea ice.** The pack ice, the melting of which does not contribute towards raising the level of the oceans, is another strong indicator of the acceleration in climate change**:** from a stable 8.5 million km^2 between 1950 and 1975, the sea ice surface area has decreased very rapidly to 5.5 million km^2 in 2010.

4. **The retreat of the continental glaciers** has been observed almost everywhere in the last 3 or 4 decades, with a clear increase over the last 20 years.

5. **The polar ice caps on Antarctica and Greenland** have shown a decrease of their total mass for the last ten years. Although a few of the higher regions in the interior of the ice caps, especially Antarctica, are thickening slightly as a result of increased snowfall, the dominant factor is mass loss. This is occurring in the coastal areas of Greenland and Western Antarctica through the very rapid run-off from certain glaciers towards the ocean and iceberg discharge. It is thought that the warming of ocean water in these regions is the major cause of the dynamic instabilities that have been observed.

6. **The average level of the oceans** is another indicator that integrates the effects of several components of the climate system (ocean, continental ice, continental waters). Prior to 1992, sea level was measured by tide gauges along the coasts of the continents and some islands: as an annual average for the whole planet, the level of the oceans rose at a rate of 0.7 mm per year between 1870 and 1930 and approximately 1.7 mm per year after 1930. Since 1992, these measurements have been taken by satellite: the rise in the average global level of the sea is approximately 3.4 mm per year. On this average rise are superimposed multi-year oscillations, which are linked to the natural variability of the climate system. Since the early 1990s, approximately a third of the climatic contributions to the rise are due to the dilatation of the ocean as a result of warming; the other two-thirds are due to continental ice – the melting of the polar ice caps in Greenland and Antarctica and the melting of the continental glaciers, in virtually equal proportions.

7. **Biological indicators**, such as the movement of land and marine animal populations and changes in the dates of seasonal agricultural activities, also point to the occurrence of global warming. Although difficult to quantify, these factors are important and have consequences in many areas of business, where they are widely taken into account.

To summarise: since the second half of the 19th century, several independent indicators show unambiguous evidence of global warming, post-Little Ice Age[2], modulated with time, with an increase between 1975 and 2003.

1-2. THE FACTORS LEADING TO CLIMATE CHANGE

We are seeing a change in certain factors likely to have a more or less significant effect on climate balance.

1. **The increase in atmospheric concentrations of greenhouse gases,** other than water vapour which is recycled rapidly and constantly, is a highly significant factor that needs to be carefully observed over several decades to achieve a reliable interpretation.

   Carbon dioxide (CO_2): its concentration has increased continuously since the mid-19th century, mainly as a result of industrial activity, rising from 280 ppm in 1870 to 388 ppm in 2009. The rate of increase measured since 1970 is approximately 500 times higher than the average over the last 5,000 years. Isotopic studies show that over half of the increase is due to the burning of fossil fuels and the rest to large-scale deforestation, with a low proportion ascribed to cement production.

   Methane (CH_4): due in particular to various forms of fermentation (wetlands, ruminants, domestic waste, biomass, etc.), natural gas leaks and the melting of the permafrost, its concentration has increased by 140 % over the same period. However, it seems to have stabilised since 2000.

   Nitrous oxide (N_2O): mainly due to agricultural activities (including the biological breakdown of agricultural nitrates in anoxic underground environments), its concentration has increased by 20 % over the same period.

   The increased greenhouse effect caused by these three components together is 2.3 W/m^2.

2. **The Sun's radiation** received by the Earth at a given latitude outside the atmosphere in summer or winter depends on the Sun's brightness, the distance between the Earth and the Sun, and the orientation of the Earth's rotation axis. The latter parameters vary on a scale of tens of thousands of years due to gravitational disturbances caused by the Moon and the other planets. The associated periods (20,000 years, 40,000 years, 100,000 years) are found in the glacial-interglacial cycles of the Quaternary period and in more ancient sediment data. The variations in seasonal radiation or in

[2] Little Ice Age : a cooling period that extended between 1300 and 1870.

latitude that they cause are significant, whereas the average annual variations calculated over the total surface of the Earth are small. The total energy radiated by the Sun is dominated by the visible part of the spectrum and has varied little during the 20th century if we take an average over the 11-year activity cycles. The relative variation in this energy during these cycles is approximately one-thousandth. The corresponding forcing[3], of approximately 0.2 W/m², is 10 times lower than that which is caused by the increased greenhouse effect linked to human activity.

The Sun's activity cycles[4] mainly affect the ultraviolet part of the solar spectrum, along with the solar wind and cosmic rays, which undergo strong variations in their mean range during the solar cycle and over periods of several decades. One of these variations was observed in the "Maunder Minimum", which, over a period of more than 50 years, saw a very low level of solar activity revealed by the virtually total absence of sunspots (*c.* 1645-1715). This observation coincides approximately with the most marked phases of the Little Ice Age. It is of interest to note that the recent solar minimum is the longest for 40 years. For several indicators, the solar activity over this period shows a diminution in both the minima and the maxima, the current minimum corresponding to an absence of sunspots for 266 days, a situation that has not occurred for over 40 years. Irradiance measured from space fell by 0.02 % between the penultimate and most recent solar cycle, whereas climate indicators have shown a warming over this 40-year period.

The Sun's activity cannot therefore be the dominant factor in this warming, even though correlations between solar activity and certain *short-term* variations in the Earth's temperature have been highlighted, which could be the sign of a coupling. None of the mechanisms for transferring and amplifying solar forcing, and particularly solar activity, are as yet fully

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3 Forcing: a disruption to the Earth's energy balance, caused, for example, by changes in the amount of energy received from the Sun, changes in the quantity or nature of the greenhouse gases or particles, or a change in the nature of the Earth's surface. Forcing is expressed in watts per square metre (W/m²), and may be of natural or anthropic origin. Radiative forcing varies virtually on a periodic basis according to the life of the Sun-Earth pairing. On the other hand, anthropic forcing has increased in line with the Earth's population.

4 By « Sun's activity » we mean the phenomena associated with the Sun's magnetic field and the expulsion of high-energy matter and particles (e.g. sunspots, eruptions and solar wind). The sun's activity varies periodically, with cycles of approximately 11 years and 23 years. Certain quantities linked to the activity cycle (eruptions, high-energy particles) vary in considerable proportions (from a few units to over a hundred for sunspots). The range in variation over the cycle itself shows long-term variability with spectacular minima. The total energy radiated by the Sun in the form of electromagnetic radiation (mainly visible, but also infra-red and ultraviolet light) is called "irradiance". There is a very small variation in irradiance (approximately one-thousandth) associated with the activity cycle.

understood. If the 11-year cycle of the Sun's activity tended to reduce in intensity, as has been the case in the past, a gradual slowdown in global warming could occur.

1-3. STUDYING THE CLIMATES OF THE PAST

We can study the climates of the past by looking at a range of indicators, such as:

- geological indicators (geochronology, paleotemperatures, sediments, carbons, fossils);
- the direct observation and very precise chemical analysis of air bubbles from the atmosphere of the past trapped in ice core samples taken from the Greenland and Antarctic ice caps: these indicators cover 800,000 years in Antarctica and 123,000 years in Greenland;
- the observation of isotopic tracers, which are temperature indicators;
- the observation, statistical analysis and isotopic geochemistry of sediments and marine microfauna.

This type of study shows us, for example, the Earth largely covered in ice around 700 million years ago, or the existence of an overall but non-linear cooling for the last 60 million years, with the appearance of the Antarctic ice cap 35 million years ago and the Northern hemisphere ice caps approximately 4 million years ago. Current climate change is placed in relation to the natural global warming that has occurred since the last ice age.

Observations of ice core samples provide invaluable information about temperature and the content of CO_2 and other greenhouse gases (CH_4) in the atmosphere; this can be combined with geological analyses of marine sediments on the extension to the ice caps over the glaciation/deglaciation cycles during the Quaternary period. These observations can help towards the modelling of climate mechanisms and the definition of tests that may be used to validate climate models. The changes associated with deglaciation show complex effects: warming in Antarctica precedes an increase in CO_2 by 800 years; this is then followed, 4,000 years later, by a shrinking of the ice caps in the Northern hemisphere, which may reduce albedo[5] and cause further warming. These complex transitions constitute a range of observed situations that may be used to test the models. Analysis of the ice in the polar ice caps shows that CO_2, CH_4 and N_2O concentrations have probably not been so high for 800,000 years[6].

2- CLIMATE MECHANISMS

Through the energy that the Earth receives from it, **the Sun** is the driving force behind the climate machine. Observation of the energy radiated by the Sun has become increasingly accurate as a result of the data provided by satellites.

A part of the sun's energy (mainly contained in the visible part of the electromagnetic spectrum) is reflected straight back into space by the clouds and the Earth's surface (albedo); the other part is absorbed by the ground and the oceans. In a balanced situation, the latter send all this energy back into space as infrared radiation. But the atmosphere[7], in its turn, absorbs a part of this terrestrial radiation and re-emits it into space and towards the ground. The Earth's surface is therefore warmer than it would be without an atmosphere: this is known as the ***greenhouse effect***.
The molecules responsible for this effect are water vapour, carbon dioxide and other gases such as methane and nitrous oxide.

When conditions change — due either to the energy received from the Sun or to the greenhouse gas content — the climate system evolves towards a new state of balance. This is what climatologists call a response to ***forcing***. In this evolution, a change in one parameter leads to changes in other parameters: for example, a rise in temperature increases the amount of water vapour and carbon dioxide in the atmosphere, modifies cloud cover, reduces the volume of continental ice, etc. The increased temperature of the ocean could lead to the ocean becoming less effective in absorbing part of the carbon produced by man's activities. These feedbacks may be positive, reinforcing the effect of the initial forcing, or negative when they reduce it. Depending on the parameters involved, these effects, which may be quantitatively significant, become evident over short periods, of a few

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[5] Albedo: fraction of solar energy reflected back into space.
[6] However, CO_2 concentration may have been significantly higher than the current concentration during geological times; for example, it is estimated at approximately 4,000 ppm at the beginning of the Tertiary period (60 to 50 million years ago).
[7] The atmosphere is made up of a number of superimposed layers; two of these, the ones closest to the Earth's surface, intervene in climate: the troposphere, which extends from the Earth's surface to an altitude of 8 to 16 km, and the stratosphere, which extends from 16 to 50 km.

days for changes in the atmosphere, or on the other hand, very long periods for the ocean.

The potential effects of the solar activity cycle on the climate are the subject of speculation but have given rise to active research. Certain mechanisms invoked concern the effect of galactic cosmic radiation, heavily altered by the solar wind which could affect cloud formation; other couplings between the stratosphere and the troposphere, combined with electric currents, are also mentioned. These effects, which are secondary compared to the effect of atmospheric conditions such as water vapour content, the overall stability and circulation of the atmosphere, etc., are related to a subjacent area of physics that is currently the subject of experimental research at CERN. Other mechanisms, which involve a major change in the UV component during the cycle and modify the ozone distribution in the stratosphere, are currently under study.

The ocean is an essential component of the climate system due to its dynamics and thermal inertia, which mean that it evolves much more slowly than the atmosphere. It thus plays an important role as a long-term regulator of the system, delaying the return to balance by several centuries and even thousands of years after major climate disturbances. Couplings between the ocean and the atmosphere are still insufficiently understood, but are the result of major natural climate disturbances, such as El Niño or the North-Atlantic Oscillation, which are observed over a timescale of a few years to a few decades.

The ice caps and climates of the Quaternary period are known as a result of the analysis of ice core samples, which have shown an oscillation between glacial and interglacial periods and a global stability over the last few thousand years, pointing to the existence of at least one effective negative feedback, the foremost being the emission of infrared radiation from the Earth. The most rapid variations in the switches between glacial and interglacial periods seem to have been affected by strong positive feedbacks between temperature, CO_2 content and the surfaces of the ice caps in the Northern hemisphere.

Greenhouse gases

The direct effect on the atmosphere of a change in CO_2 concentration is clearly understood. It is illustrated by an increase in the infrared radiation emitted by the ground, evaluated at 3.7 ± 0.1 W/m2 for a doubling of CO_2 in the atmosphere, equivalent to an average surface warming of 1.1 ± 0.2 °C.

Approximately half of the CO_2 produced by human activity at a given moment and discharged into the atmosphere stays there. The other half is currently absorbed by the ocean[8] and continental vegetation: it takes approximately a century for the proportion sent into the atmosphere to be reduced by half. We have made great progress in our knowledge of the ocean-atmosphere and continent-atmosphere exchange mechanisms, but uncertainty still remains about more accurate predictions on the scale of a century. This knowledge depends on a description of the deep-ocean circulation and the complex nature of photosynthesis.

Uncertainties over the indirect global effect of a change in CO_2 concentration, with all the feedbacks considered, is the subject of debate within the climatologist community. The complex nature of feedbacks has led most scientists to conclude that models are essential in accurately evaluating this indirect effect.

3. CLIMATE MODELS

Climate models have considerably improved over the last 30 years and now include many mechanisms that were ignored in the early models. However, the evaluation of uncertainties is central to the debate.

3-1. TWO TYPES OF PROCESS DESCRIPTIONS

Process modelling needs to consider two types of mechanisms: firstly, those for which the physical-chemical processes are well understood and may be translated into equations, and the others, too complex, which can only currently be described via phenomenological relationships based on observation.

In the first group are:

- the three-dimensional circulation of the atmosphere and its evolution;
- radiative forcing, which is the subject of a physical modelling of the transfer of radiation through the gaseous atmosphere, taking account of its chemical composition, temperature stratification and the presence of aerosols;
- hydrodynamic ocean circulation models.

[8] An increase in the temperature of the ocean could reduce its capacity to absorb CO_2. In addition, an increase in CO_2 concentration in the ocean leads to its acidification, which has major negative consequences on ocean plant and animal life.

For these mechanisms, the limitations tof the space and time resolutions in modelling are linked to the power of the computers and the performance of the algorithms used.

The second process group requires a proportion of empirical modelling.

Forcing feedbacks that emerge from models depend on two types of processes.

The radiative feedback of **water vapour** produced by a doubling of CO_2 at a temperature rise of 1.1 ± 0.2 °C leads, in all models, to increase the direct effect from 0.5 to 1 °C. Research is continuing into other possible effects that may be induced.

The effect of the clouds — liquid water droplets or ice particles — may vary considerably according to the models: the description of a change in cloud cover is unanimously acknowledged as being the most uncertain part. Clouds have two antagonistic effects: an "umbrella" effect that reflects the solar flux back into space (negative feedback caused by low cloud) and a greenhouse effect (positive feedback caused by high cloud). The least "sensitive" models predict an approximately neutral global cloud effect, while the more "sensitive" models lead to a further warming of approximately 2 °C for a doubling of CO_2 concentration.

Current climate models have a spatial resolution of several tens and even hundreds of kilometres, which does not allow us to describe the clouds individually but only statistically through empirical models.

The geographical distribution of water vapour content given by some of the more recent models is very similar to what is being observed, which gives support to modelling.

Multi-decade variations in the ocean (North-Atlantic Oscillations, El Niño, etc.) are still difficult to model.

The melting of the ice caused by climate warming is a mechanism that acts over the long term. The effects of polar ice cap dynamics are beginning to be included in coupled climate models.

The effects of vegetation or marine biology, which directly affect the albedo on continental or marine surfaces, cannot be modelled using basic biological processes. The albedo is described by empirical relationships that are deduced from a combination of observations from satellites and on the ground.

3-2. VALIDATION TESTS

The current approach to validate climate models is to work with a test hierarchy. The model is developed from process studies, such as campaigns to observe a type of cloud or vegetation. Once the formulation has been defined, it is run in "meteorological mode" (short term) or as a simulation of natural multi-year instabilities, or in relation to the seasonal cycle or ancient climates. Comparisons are made with observational data over a large number of parameters. They are the only way of testing these models and comparing the amplitude of feedbacks revealed by the models with reality.

The ability of climate models to reproduce the past changes in climate on a multi-decade scale is limited by the fact that consistent data did not appear until the 1970s.

Some very significant results have been obtained: greater warming on the surface of the continents than on the surface of the oceans, and even greater in the Arctic regions, reduction in extremes of cold, an increase in the frequency of extreme hot events, global reduction in the cryosphere[9], a greater warming of the tropical atmosphere at altitude than on the surface, natural variability on a ten-year scale of global trends towards warming during the 20th century, the decrease in the surface area of Arctic sea ice from 1975-80.

The validity of forecasts for the coming decades and their uncertainties are a central issue. A comparison of the results of these forecasts gives an indication of the uncertainties caused by differences in the modelling of certain mechanisms. In addition, some still unidentified mechanisms are obviously not included in the models.

Direct, purely statistical correlations between two quantities are useful in highlighting couplings that are not modelled or are poorly represented, but not for accurately testing the mechanisms internal to the models and their relevance in simulating climate variations. This forms part of the current debate between scientists.

The possible highly unstable or chaotic behaviour of the atmosphere-ocean-cryosphere-continental landmass system is another major factor leading to uncertainty.

The nature of such chaotic behaviour or of bifurcations between clearly separate climate system conditions remain open and are the subject of intensive international research.

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[9] The word "cryosphere" is used to describe all the ice on Earth (large ice caps in Antarctica and Greenland, mountain glaciers, pack ice).

CONCLUSIONS

- A number of independent indicators point to an increase in global warming from 1975 to 2003.
- This increase is mainly due to the increased concentration of CO_2 in the atmosphere.
- The increase in CO_2 and, to a lesser degree, in the other greenhouse gases, is without doubt due to human activity.
- It constitutes a threat to the climate, and also to the oceans due to the acidification process that it causes.
- This increase leads to feedbacks in the global climate system; their complexity requires the use of models and tests to validate them.
- We still do not fully understand the mechanisms that may play a role in transferring and amplifying solar forcing, and particularly solar activity. Solar activity has slightly decreased on average since 1975 and cannot have played a dominant role in the warming that has been observed over this period.
- Major uncertainties remain about the modelling of clouds, the evolution in sea ice and the polar ice caps, the ocean-atmosphere coupling, the evolution of the biosphere and the carbon cycle process.
- Climate evolution forecasts for the next 30 to 50 years are little affected by uncertainties over the modelling of slowly-evolving processes. These forecasts are particularly useful in responding to the current concerns in our societies, aggravated by the predictable increase in populations.
- Climate evolution can only be analysed by using long, large-scale, consistent, continuous series of data. The major international terrestrial and space observation programmes must be maintained and developed, and their results made freely available to the international scientific community.
- The interdisciplinary nature of the problems we have encountered means that we need to further involve the various scientific communities in order to continue the progress already achieved in the field of climatology and open up new opportunities for future research.

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

MINISTÈRE
DE L'ENSEIGNEMENT SUPÉRIEUR
ET DE LA RECHERCHE

La Ministre

OP/DBX

Paris, le - 1 AVR. 2010

Cher Monsieur le Président,

Des voix s'élèvent aujourd'hui pour remettre en cause l'existence d'un large consensus parmi les chercheurs sur les causes et les conséquences du changement climatique.

Pour ma part, je constate que les travaux, les conclusions et les méthodes des climatologues français font depuis des années l'objet d'une indiscutable reconnaissance dans la communauté scientifique nationale et internationale. Cette reconnaissance unanime fonde la confiance que le Gouvernement leur porte.

L'engagement personnel du Président de la République dans les négociations internationales sur le changement climatique, tout comme le Grenelle de l'environnement ou la place qu'a tenue la question du climat dans l'élaboration de notre stratégie nationale de recherche et d'innovation sont là pour en témoigner.

C'est en effet en s'appuyant sur les travaux scientifiques qui portent sur les évolutions actuelles du climat que le Gouvernement a fait une priorité absolue de la lutte contre le changement climatique.

Il ne revient bien évidemment pas aux responsables politiques, mais à la communauté scientifique de trancher des différends portant sur des travaux de recherche. C'est pourquoi je souhaiterais que l'Académie des sciences organise, dans les meilleurs délais, un débat scientifique approfondi pour permettre la confrontation sereine des points de vue et des méthodes et établir l'état actuel des connaissances scientifiques sur le changement climatique.

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Ce débat se déroulera en parallèle du processus lancé par le Secrétaire général de l'Organisation des Nations Unies, qui a saisi l'*InterAcademy Council* afin que celui-ci procède à une analyse scientifique approfondie et indépendante des méthodes et conclusions du Groupe intergouvernemental d'experts sur l'évolution du climat.

L'Académie des Sciences étant membre de l'*InterAcademy Council*, je souhaite que ces deux débats n'interfèrent pas l'un avec l'autre.

Je vous prie d'agréer, Monsieur le Président, l'expression de ma meilleure considération.

Bien à vous,

Valérie PECRESSE

INSTITUT DE FRANCE
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