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Can we be confident with climate models?*

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Resum. L'escalfament global, el canvi climàtic i els gasos d'efecte hivernacle són termes coneguts pel públic en general, ja que es mencionen freqüentment en els mitjans de comunicació, encara que sovint en un context incorrecte. Les percepcions actuals i les percepcions errònies sobre aquests termes es discuteixen en la primera part d'aquest treball. L'article continua amb una explicació sobre el funcionament dels models climàtics i els punts forts i febles que presenten. L'anàlisi conclou amb un breu resum d'altres aspectes importants referents a la ciència del canvi climàtic.

Paraules clau: Models climàtics · sistema climàtic · canvi climàtic antropogènic · Grup Intergovernamental d'Experts sobre el Canvi Climàtic (GIECC)

Abstract. Global warming, climate change, and greenhouse gases are terms familiar to the general public due to their frequent mention in the media, albeit often in an incorrect context. Current perceptions and misperceptions regarding these terms are discussed in the first part of this paper. This is followed by an explanation of how climate models work and the strengths and weaknesses of these models. The review concludes with a brief summary of several other important aspects of climate change science.

Keywords: Climate models · climate system · anthropogenic climate change · Intergovernmental Panel on Climate Change (IPCC)

Climate change as perceived by the general public

The public's knowledge of climate change ranges from the most basic level, with the recognition of phrases such as 'global warming' and 'greenhouse gases,' to an understanding of the simple causal relationships, personal contributions, timescales, and the detailed inter-relationships of natural processes. Overall, the current representation of climate change in the media, especially in the developed world, suggests that general awareness of the concept of climate change among the population has reached the near-saturation point. In fact, according to a survey carried out among 41 newspapers published in English all over the world, in the year 2006 almost 10,000 articles on climate change were published, compared with the ~5000 published in 2004. This increase in information has improved public recognition of the problem of global warming, its implications, and its causes. It has even become a marketing strategy for products ranging from clothing to oil and gasoline.

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But has the media's representation of climate change resulted in a better understanding of its causes and implications? A study published by the Department of Transport of the British Government [3] came to the following conclusions, which probably can be extrapolated to citizens of most of the developed countries:

- The vast majority of the public claim to believe that climate change is happening and around two-thirds are convinced that it is linked to human activity. They are, however, unclear about the details.
- Many people are well informed about some of the causes of climate change and the evidence suggests that knowledge is improving. Indeed, most people have a quite detailed, although often inconsistent, knowledge of the issue. For instance, the majority are able to identify the destruction of forests and the burning of fossil fuels as contributors to global warming, but at the same time not everybody recognizes the role played by power plant emissions, although quite a few are aware of the contribution of home use of gas and electricity. However, the prevalence of common misconceptions (such as the belief that the hole in the ozone layer is a cause) points to the varying degrees of uncertainty about the causes of climate change.
- Overall, it is not possible to conclude that people generally believe that climate change is caused only by large-scale

phenomena, but there does appear to be a disconnection between the recognition of primary contributors (e.g., fossil fuels) and the use of these fuels (e.g., in power stations or in the home).

- People more readily recognize the link between climate change and the use of fossil fuels for transportation than with their use in the home.
- Public concern regarding climate change is generally high.
- Although climate change generates concern, it is not the most critical issue. Public concern for climate change appears to be tempered by uncertainty about where and when it will occur, the extent of the change, and by competition from other issues of individual concern.
- The majority of citizens do not regard climate change as an immediate threat to themselves but rather to future generations and ‘faraway places.’ This is important, as evidence suggests that awareness of the environmental impact of human activities and feelings of personal obligation may be insufficient without concerns for the future. Nevertheless, an increasing numbers of people believe that the threat is more immediate and indeed may already be materializing.
- Although there are indications that people acknowledge their own contribution to climate change and their responsibility in its mitigation, responsibility for action is more likely to be relegated to regional, national, and global institutions. Even the majority of those already making changes in their behavior with respect to climate change believe that their own efforts make little difference.

In the author’s opinion, people’s awareness of global warming will emerge based on a concern about the future impact of climate change and on the technical tools that they have to assess impacts as projected in climate models. While currently there is a great deal of confidence about the projections of models describing global changes of climate, there are a paucity of models assessing the magnitude and time scale of local impacts. For this reason, climate change is considered as a distant reality. In the following sections, I describe what is meant by ‘the climate system’, present some of the recent climate models, and examine the capabilities of these models and our level of confidence about their projections. This review concludes with comments about the outlook for the future regarding the science and politics of climate change.

The climate system

The key to understanding global climate change is first to understand what global climate is and how it operates. At the planetary scale, global climate is regulated by how much energy the Earth receives from the sun. However, global climate is also affected by other energy flows that take place within the climate system itself. These include the atmosphere, the oceans, the cryosphere (ice sheets), the biosphere (living organisms and the soils), and the geosphere (sediments and

rocks), all of which, to a greater or lesser extent, affect the content and the movement of heat around the Earth’s surface.

The atmosphere is a mixture of different gases and aerosols (suspended liquid and solid particles) and plays a crucial role in regulating the Earth’s climate. Air consists mostly of nitrogen (78%) and oxygen (21%). The so-called greenhouse gases, despite their relative scarcity, have a dramatic effect on the amount of energy stored within the atmosphere and consequently on the Earth’s climate. Greenhouse gases trap long-wave radiation within the lower atmosphere and in turn emit this radiation onto the Earth’s surface and into space, thus making the atmosphere and the surface of the Earth hotter. This heat trapping is a natural process, called the greenhouse effect, and it keeps the Earth about 33°C warmer than it would be otherwise.

The atmosphere, however, does not operate as an isolated system. The balance of radiation at the Earth’s surface depends on the latitude: being positive at lower latitudes and negative at higher latitudes. Therefore, energy flows take place through atmospheric and ocean currents but also between the atmosphere and other parts of the climate system, most significantly the world’s oceans. For example, ocean currents move heat from warm equatorial latitudes to colder polar latitudes. Another non-radiative component of the Earth’s energetic balance is the heat transferred by moisture. Water evaporating from the surface of the oceans stores heat, which is subsequently released when water vapor condenses to form clouds and rain. The significance of the oceans is that they store a much greater quantity of heat than the atmosphere. The top 100 m of the world’s oceans store much more energy than the entire atmosphere. Accordingly, flows of energy between the oceans and the atmosphere can have important effects on the global climate.

The world’s ice sheets, glaciers, and sea ice, collectively known as the cryosphere, have a significant impact on the Earth’s climate. The cryosphere is made up of Antarctica, Arctic Ocean, Greenland, Northern Canada, Northern Siberia and most of the high mountain ranges throughout the world, where sub-zero temperatures persist throughout the year. Snow and ice reflect a large quantity of sunlight instead of absorbing it and thus are very important for the global albedo [1] of Earth. Without the cryosphere, more energy would be absorbed at the Earth’s surface than reflected; consequently, the temperature of the atmosphere would be much higher.

All land plants synthesize energy from the photosynthesis of carbon dioxide and water in the presence of sunlight. Through this utilization of carbon dioxide in the atmosphere, plants have the ability to regulate the global climate. In the oceans, microscopic plankton process the carbon dioxide dissolved in seawater to carry out photosynthesis and to manufacture their tiny carbonate shells. The oceans replace the utilized carbon dioxide by drawing it down from the atmosphere. When the plankton die, their carbonate shells sink to the seafloor, effectively locking away the carbon dioxide from the atmosphere. This “biological pump” reduces by at least four-fold the atmospheric concentration of carbon dioxide, thereby reducing the Earth’s surface temperature.

The processes that link climate subsystems do not work along the same time scale—some are very fast while others are slow—such that their influence on the behavior of variables that determine the weather differs. Fast interactions characterize meteorology whereas slow ones are important for climate. But what is commonly understood as climate? In colloquial terms, it can be said that climate is the weather at some location averaged over long periods of time (>30 years), or the average pattern of weather variation at a certain location. Descriptions of regional climates are based on variables such as seasonal temperature or wind strength, the amount of rain or snowstorms and their intensity, and the severity of droughts.

What is a climate model?

A climate model is an attempt at reproducing climate or forecasting climatic conditions at a particular location or region or for the whole planet by means of simulations that take into account how climate works or by analyzing its regularities using statistical procedures. Climate models attempt to simulate climate behavior and thus to provide us with an understanding of the key physical, chemical, and biological processes that govern it. They give us a better understanding of the climate system, including past climates based on comparisons with records of instrumental and paleoclimatic observations. Climate models also help us to test our theories of many climate-relevant processes and to make predictions about climate in the future. They can be used to simulate climate on a wide range of geographical scales and over different lengths of time. The basic laws and other relationships necessary to model climate are expressed as a series of mathematical equations.

There are also statistical models of climate that, simply stated, seek to determine whether there is a relationship between certain observations. For example, the repeated occurrence of certain climate patterns may serve in the construction of seasonal climate forecasts (as in agricultural almanacs, for example). In other cases, the relationship between a change of temperature with time may be described by a linear regression line, or the seasonal cycle by a sinusoidal fit. More complicated relationships are also possible. These statistical models are very efficient at encapsulating existing information concisely and, assuming that things do not change much, they can provide reasonable predictions of future climate behavior. However, they are of little predictive value if the underlying system is subject to changes that might affect the interactions among the original variables.

Biophysics-based climate models, by contrast, try to capture the true physical causes of climate-related phenomena and therefore to incorporate the fundamental biological and chemical processes affecting the climate system. Since those processes, per definition, are not likely to change in the future, the likelihood of a successful prediction is greater. Climate models are essentially physics-based, but some of the small-scale components are only known empirically (for instance, the increase in evaporation as the wind strength increases). Thus, while statistical fits to the observed data are included within

climate model formulations, they are only used for process-level parameterizations, not for determining trends in time.

Other aspects may be encapsulated in statistical approaches to future climate that differ slightly from those described above. For example, in the ‘initial condition ensemble’ a group of simulations are carried out using a single global climate model (GCM) but with slight perturbations in the initial conditions, e.g., the initial state of the climate system. This is done to average over chaotic behavior in the weather. A stronger and more extensively used methodology is the ‘multi-model ensemble,’ which consists of simulations from multiple models that invoke the same initial conditions and the same future scenarios. Surprisingly, when used to explain past climatological observations, this approach is a better match than those using a single model. Accordingly, it is also being used for climate projections.

The main question of interest concerning anthropogenic climate change is climate sensitivity. This is commonly viewed in the context of how climate will change when the atmospheric carbon dioxide concentration becomes double than that of the pre-industrial era. This is the atmospheric concentration of carbon dioxide most often used in current climate models. But to test these models, there must be experimental data for basic climate variables, such as obtained with direct instrumental measurements for basic climate variables. However, it should be taken into account that for the modern instrumental period the changes recorded for many aspects of climate have not been very large. Moreover, for surface temperature, instrument-based records are not longer than 250 years, except in a few places in the Northern Hemisphere. Therefore, modern observations do not enable proper assessment of climate sensitivity to future changes; instead, we must rely on indirect, or ‘proxy,’ data such as gathered by paleoclimatologists from natural records of climate variability, e.g., tree rings, ice cores, fossil pollen, ocean sediments, coral reefs, and historical data. An analysis of the records taken from these and other proxy sources extend our knowledge of climate evolution far beyond the instrumental record. Among the periods of most interest for testing climate sensitivities with respect to the uncertainties of climate projections are the mid-Holocene (for tropical rainfall, sea ice), the 8200 years event (for the ocean thermohaline circulation), the last two millennia (for decadal/multi-decadal variability), and the last interglacial period (for ice sheets/sea level).

At this point, we can examine the difference between weather forecasting models and climate models. Conceptually, they are very similar because both seek to reproduce the behavior of the same system, the atmosphere, but in practice the two types of models are used very differently. Weather models use as much data as are available to describe the current weather situation and then rely on physical principles to make predictions. Each six hours these models test whether their conclusions are different from the actual meteorological conditions, as measured at a set of predefined meteorological stations. This procedure, called data assimilation, ensures a high level of confidence in meteorological forecasting at least for a few days (generally not more than ten at present). Since they are run for short periods of time only, weather models tend to have a

much higher resolution and are described in more detailed physics than climate models. Moreover, the boundary conditions in a run of weather models are considered to be constant, whereas they are a dynamic aspect of climate models. Weather models develop in ways that improve short-term predictions, although the impact on long-term statistics or climatology needs to be assessed independently. Curiously, the best weather models often have a much worse climatology than the best climate models.

Global climate models are being used extensively to project global warming arising from increases in the atmospheric concentration of greenhouse gases. Estimates of future increases in greenhouse gases are applied as input in calculations that model how the global climate might evolve or respond in the future. In addition, natural changes must be taken into account, the most important being solar radiation, which changes with time. Variations in solar radiation in the past record are characterized by a high degree of uncertainty and complexity. Nonetheless, given a particular estimate of solar activity there are a number of modeled responses. First, the total amount of solar radiation can be easily varied within a particular model—this changes the total amount of energy entering the climatic system. Second, variations in the incoming energy over the solar cycle at different frequencies are not of the same amplitude; e.g., changes in UV radiation are about 10 times larger than changes in total irradiance. Since UV is mostly absorbed by ozone in the stratosphere, the inclusion of these changes increases the magnitude of the variability in the solar cycle in the stratosphere. Furthermore, the change in UV has an impact on the production of ozone itself (even down into the troposphere). This can be calculated with chemistry-climate models and is increasingly being incorporated into climate model scenarios. In addition, within the scientific community other aspects of solar activity on climate have been discussed, most notably the impact of galactic cosmic rays (which are modulated by the solar magnetic activity on solar-cycle timescales) on atmospheric ionization, which in turn has been linked to aerosol formation, and thus to cloud formation. Integrating those impacts within climate models remains a challenge and requires complete models of aerosol creation, growth, accretion and cloud nucleation—as yet, however, such models are lacking.

Although climate models can help to elucidate the processes that govern climate, the confidence placed in such models should always be questioned. Critically, it must be remembered that all climate models are simplifications of the climate system. Indeed, it may be that the climate system is too complex to be reproduced with sufficient accuracy. Climate models and their results must therefore be interpreted with due caution, and the margins of uncertainty reported with any model projection. Furthermore, results from climate models should always be validated or tested against real-world data, including instrumental and paleoclimatic records where available. Finally, projections of atmospheric concentrations of greenhouse gases are based on socioeconomic scenarios that include projections about economic, demographic, and technological developments, all of which are even more difficult to forecast than the behavior of the climate system.

A climate model's core equations are derived from the laws of physics and are used to describe how temperature, pressure, winds (or currents), and other variables in the atmosphere and ocean change over time. Additional equations describe chemical and biological aspects of the climate system. In climate models, climate-related variables are represented on a three-dimensional grid representing the atmosphere and the oceans. The spacing between grid points in the atmosphere is crucial for evaluating the ability of a model to provide accurate climate projections for a specific region and the possible time scale of these projections. Typical grid spacing is 100 km horizontally and 500 m vertically. At present, this is too large for confident projections of the impacts of climate change at a regional scale. Researchers are therefore trying to develop models with greater resolution, a procedure generically known as downscaling.

The core of a climate model uses well-understood physical, chemical, and biological equations and principles that have provided insights into climatic changes of the past. Despite their limitations, current climate models are able to accurately represent key aspects of the climate system and are continually evaluated against datasets of real observations. This has confirmed their ability to reproduce many aspects of climate, including the overall strength and pattern of recent changes in key climate variables. However, while climate models successfully project climate globally, they cannot make projections regarding the climate in a specific region.

Climate models help us to understand climate

As noted above, the complexity of the climate system reflects the multiple interactions among its many parts as well as its numerous non-linear processes and complicated feedbacks, both of which are characterized by a dynamics that is very difficult to model. Climatic models can be used to generate insight into how the climate system works. We cannot explore climate mechanisms or test theories by experimenting on the climate system itself, nor is it possible to reproduce the full complexity of the climate system in a laboratory. Instead, climate models offer the best possible alternative by serving as a numerical laboratory where important questions can be addressed: How will the climate change in response to rising levels of greenhouse gases? What would happen to the climate if the ocean conveyor changes or slows down? Why did the Earth's climate change in the past?

Climate models take into account as many physical, chemical, and biological processes as possible but not all of them nor necessarily their dynamics. Instead, they use what are called parameterizations, that is, simplifications of certain processes, by using simpler mathematical representations in which a variable depends on other, more fundamental ones that have been determined experimentally. The current models are certainly good enough to simulate large-scale climate phenomena, and in this respect they are continually checked by researchers in order to identify the limitations of a particular model. This is an important aspect that stimulates further improvements and ultimately advances our understanding of the climate system.

Nonetheless, as noted above, general circulation models are unable to project temperature and precipitation for a specific place. There are often large statistical variations in both parameters over short distances because local climatic characteristics are affected by local geography. Global models are designed to describe the most important large-scale features of climate, such as energy flow, circulation, and temperature, in a grid-box volume (through physical laws of thermodynamics, the dynamics, and ideal gas laws). The shape of the landscape (details of mountains, coastline, etc.) used in the models reflects the spatial resolution; hence, at today's grid-box spacing, the model will not have sufficient detail to describe the local climate variation associated with local geographical features of lower spatial scale. For example, recent models are not capable of reproducing the topography of the Pyrenees, which has raised concern about the poor level of confidence in precipitation projections. However, through downscaling it is possible to use a GCM to derive some information about the local climate, as it is affected by local geography and large-scale atmospheric conditions. The results derived through downscaling can then be compared with local climate variables and applied to further assessments of the combination model-downscaling technique. This is, however, still an experimental approach.

The importance of downscaling is that if we know with certainty the impacts of climate change at a local level, then adaptation to change is easier. Unfortunately, the former is not the case and many people doubt that we will ever be able to make predictions that are detailed and certain enough such that 'predict and adapt' will be a viable option.

The majority of projections of future climate come from GCMs, which vary in the way they model the climate system and so produce different projections. These differences can be highly significant, for example, some models may show a region becoming wetter, while others show it becoming drier. This is what occurs with projections about precipitation in western Mediterranean regions: some models project small increases and others small reductions in the annual means. The advantages of GCMs are in large-scale processes of the climate system, as these models cannot make projections below the size of one grid cell (typically 300 km²) and perform best at much larger scales. Regional climate models (RCMs) and empirically downscaled data from GCMs allow projections to be made at a finer scale but they still have a high degree of uncertainty; RCM projections vary between models in the same way as GCMs and must be run within GCMs and so contain some of their larger biases as empirical downscaling does not attempt to correct any biases in the data obtained from the GCMs.

Much of the difference in output between GCMs is due to the way that they parameterize different variables. For some phenomena in the real world, knowledge of which is necessary for a climate model to work, the physics are only known empirically. Or it may be that the theory only truly applies at scales much smaller than the model's grid size. These physics needs to be 'parameterized' in a mathematical formulation that captures the phenomenology of the process and its sensitivity to change but avoids the very small-scale details. Parameterizations are approximations of the phenomena that we are trying to model, but

they work at scales that the models actually resolve. One example is how the models treat precipitation. Since they cannot represent the internal physics of rainfall, they instead define a relationship between, e.g., humidity in the atmosphere and rainfall. Another example is the radiation code; rather than using a line-by-line code, which would resolve the spectroscopic absorption at over 10,000 individual wavelengths, a GCM generally uses a broad-band approximation (with 30–50 bands), which gives nearly the same results as a full calculation. In some parameterizations, the functional form is reasonably well known, but the values of specific coefficients might not be. In these cases, the parameterizations are 'tuned' in order to reproduce the observed processes as much as possible.

One of the most decisive and important parameterizations is that of clouds. Models do indeed consider clouds and allow for cloud changes in response to changes in atmospheric composition, for example, regarding aerosols and water-vapor content. There are certainly questions about how realistic these modeled clouds are and whether they have the right sensitivity concerning the albedo, but all models do include them. In general, models suggest that clouds exert a positive feedback, i.e., there is a relative increase in high clouds (which warm more than they cool) compared to low clouds (which cool more than they warm), but this is quite variable among models and not very well constrained by the data. Cloud parameterizations are amongst the most complex component of the models. The large differences in mechanisms for cloud formation (convection, fronts, continental and marine) are reflected in the formation of different cloud types. Clouds have important microphysics that determine their properties (such as cloud particle size and phase) and they interact strongly with aerosols. Standard GCMs include most of these physics, and some models resolve clouds in each grid box. In such cases, much of the parameterization is omitted but at the cost of a considerable increase in complexity and, at present, uncertainty and therefore of computation time. Improvements in clouds representation by the GCMs would imply considerable progress in GCMs and other models of climate change.

Uncertainty and differences between the models also arise because the small differences in the starting conditions from which the models begin their runs vary the output and the projections that they produce. Interestingly, a comparison of the outputs of models shows that they make similar projections regarding greenhouse gas concentrations in the atmosphere. For this reason, the Intergovernmental Panel on Climate Change (IPCC) [2] carried out a prospective analysis to postulate a series of future scenarios [7] describing how the world will evolve politically, economically, demographically, and technologically until the end of 21st century, as this, in turn, will influence the emissions of greenhouse gases and therefore atmospheric composition.

In attempts to identify the full range of possible future climates, scientists are conducting experiments in which for many thousands of model runs the values of parameters and initial conditions are changed slightly, yielding a range of plausible projections. These experiments are the previously mentioned multi-ensemble model runs, and those changing the

parameters of the models are referred to as perturbed physics experiments. The greater the number of simulations, the more confidence there should be if the full range of uncertainty in the system has been taken into account, although it may be that more models are needed in order to achieve the desired completeness.

Given the differences between models, it is important to look at the range of projections resulting from many if not all of them rather than simply relying on one outcome chosen from many possibilities. Reliance on a projection from one model likely ignores the fact that other models project different changes. If an adaptation option is based only on one projection, it may be unsuitable if that projection turns out to be incorrect. Some areas of uncertainty are likely to decrease, but some may not. For example, as the range of projections of change in temperature for 2050 has shifted very little since initial calculations were made over 20 years ago, it is important to recognize that we need to work with this uncertainty.

The important point in the context of adaptation is how to deal with this uncertainty and make decisions that are robust against a range of future possibilities. One approach is to look at the range of projections from the different models to see which results are consistent. We can be confident that if all models say it will get wetter in June then this is likely to indeed be the case. If the relevant results are uncertain, then it is important to choose adaptation options that will be effective regardless of which change occurs, i.e., that are robust against a range of future changes. This might involve the construction of resilient systems with a large adaptive capacity rather than choosing options that rely on a single direction of change.

What do the models predict for the future?

Climate models successfully reproduce the main features of the present climate, such as rainfall, as well as the temperature changes over the last 100 years, the Holocene (6000 years ago), and Last Glacial Maximum (21,000 years ago). Current models enable us to attribute the causes of past climate change and to predict the main features of climate in the future, with a high degree of confidence. As noted above, researchers are developing new models to provide more regional details of the impacts of climate change, and a more complete analysis of extreme events. But what are the main predictions of the most frequently used models?

The climate projections documented in the Fourth Assessment Report (AR4) of the IPCC [9] are based on a large set of climate simulations involving 23 global climate models. These simulations were carried out not only for the future but also to describe the recent past (1860–2000), thus enabling evaluation of their reliability in reproducing the climate trends of the 20th century. The concentrations of the major greenhouse gases (carbon dioxide, methane, nitrous oxide, ozone, and chlorofluorocarbons) as well as aerosol concentrations were consistent with observations. Future projections according to emission scenarios B1, A1B, and A2 [7] were based on different socioeconomic assumptions, including population growth, en-

ergy consumption, use of fossil fuels, renewable energy sources etc. The models project that, compared to the time period 1980–1999, global warming by 1.8°C (range 1.1°C–2.9°C) for B1, 2.8°C (1.7°C–4.4°C) for A1B, and 3.4°C (2.0°C–5.4°C) for A2 will occur at the end of the 21st century. In the most extreme (fossil intensive) scenario, A1FI, global warming may even exceed 6°C.

But, what does the range of simulations look like? Figure 1 shows the plots for the global mean temperature anomaly for 55 individual realizations of the 20th century and their continuation for the 21st century following the A1B scenario. Since this scenario is close enough to the actual forcing over recent years, it seems, in principle, to be a valid approximation for the simulations up to the present and for the probable future. It is clear from Fig. 1 that there is no doubt about the long-term trend (the global warming signal), but it is also obvious that the short-term behavior of any individual realization is uncertain. This is the impact of the uncorrelated stochastic variability (weather!) in the models that is associated with their interannual and interdecadal modes.

Another consequence of global warming is the increase of atmospheric water vapor and increased water-vapor transport from the ocean to the continents, resulting in enhanced precipitation over the respective land masses. There are, however, large regional differences in the precipitation changes. In most models, precipitation is projected to increase at high latitudes, as already observed, and in parts of the tropics, whereas the subtropics will suffer from precipitation deficits. Models projections, overall, for the Mediterranean regions are not conclusive, but most of them include an increase in the annual water deficit. The seasonal behavior of these changes is not homogeneous. In the summer, the models describe reductions in total rainfall of >50%. Thus, the differences between humid and arid climate zones will be enhanced in a warmer climate.

Similarly, a rise in the sea level is projected. Normally, sea-level variations occur on different time scales: rapid variations

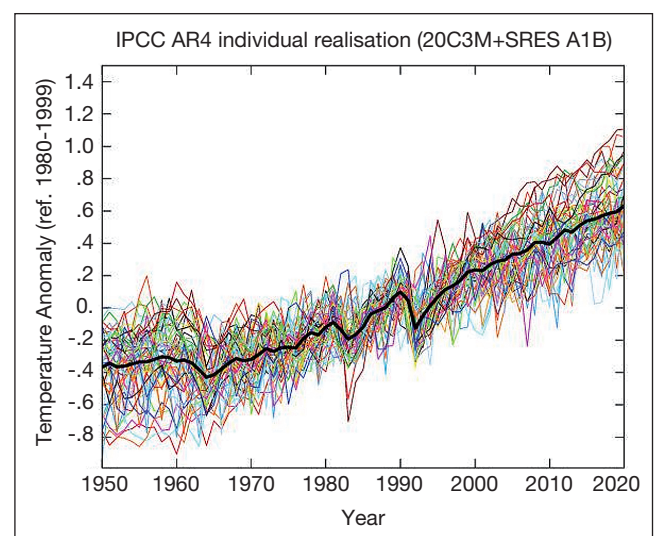


Fig. 1. Fifty-five individual simulations of temperature anomaly compared with the mean temperature from 1980–1999. The projections for a future warming are robust but in a short term there is still a big dispersion among the different models.

(hours to days) are caused by winds and tides, whereas longer-term changes are related to large-scale climate processes. Additionally, tectonic uplift or the sinking of land masses can change the water level locally. Sea-level changes also vary in space on longer time-scales, depending on the distribution of temperature, wind stress, and circulation changes. Therefore, local sea-level variations can be larger (or smaller) than the global average value. In the 20th century, tide gauge records predicted a global mean sea-level rise of 1.7 ± 0.5 mm per year. The observations have been corrected with geological models to account for tectonic uplift or sinking. Nonetheless, the uncertainty of this global mean value is still relatively large, because only very few long-term tide gauge observations exist, and the corrections that need to be applied also exhibit uncertainties. In principle, the observed rise should be equal to the sum of its contributions. Since the collection of satellite altimetry data, starting in 1993, much more accurate observations of global sea-level variations have been obtained. Indeed, recent data show that between 1993 and 2003 global mean sea level rose by approximately 3.1 mm per year, which represents a considerable acceleration over previous periods.

The increased concentrations of greenhouse gases in the atmosphere cause the oceans to warm—since warm water occupies more volume than cold water, the water column expands and the sea level rises (thermal expansion). Sea-level changes due to density variations are termed *steric sea-level variations*. If the entire water column (a depth of up to 4000 m) were warmed by 1°C , the sea level would rise by approximately 50 cm. However, a homogeneous warming within a short time period is unrealistic, because waters comprising the deep-ocean layers exchange very slowly with those of the ocean surface (the number given is only meant to provide an order of magnitude). Therefore, deep-ocean layers warm very gradually, which on the one hand slows the thermal sea-level rise, but on the other hand also causes the sea level to rise much longer into the future, even when atmospheric warming has long come to a halt. Temperature observations in the second half of the 20th century show a warming of all ocean basins, which has led to a thermal expansion of these waters. Since about 1990, this expansion has been accelerating and has contributed significantly to the observed total sea-level rise.

The ocean volume changes also because of the addition of water from external water reservoirs. The world's largest freshwater reservoir is the Antarctic ice sheet, with a volume currently estimated as 24.7 km^3 ; thus, melting of the entire ice sheet would raise the sea level by approximately 56.6 m. Melting of the second largest water reservoir, the 2.9 km^3 Greenland ice sheet, would raise the sea level by approximately 7.3 m. Until recently, estimates of the Antarctic and Greenland mass balances were highly uncertain, but new satellite-based observations show a retreat at least of the Greenland ice sheet. Whether or not these observations represent long-term changes is not clear due to the relatively short observational time. Similarly, it is currently not resolved whether the Antarctic ice sheet is also shrinking (the mean of all Antarctic observations points to a net melting, but the associated uncertainties are so large that even a growing ice sheet cannot be ruled out).

Since 1850, many mountain glaciers and ice caps have retreated. This melting directly causes a rise in sea level, as the melt water enters the oceans through continental runoff. Melting of the entire volume would raise the sea level by between 15 and 37 cm. In the 20th century, the retreat of mountain glaciers has substantially contributed to the observed sea-level rise.

Projections for the ocean level rise in the next century depend on the global warming scenario considered. However, since the oceans exchange relatively slowly with the atmosphere, thermal expansion over the next 20–30 years is more or less independent of the global warming scenario. Based on different greenhouse emission estimates for the future, climate models project a global sea-level rise of 18–59 cm for 2090–2099 relative to the period 1980–1990 (Fig. 2). The largest contribution comes from thermal expansion, followed by the melting of mountain glaciers and ice caps. A large uncertainty in predictions of future sea-level rise is associated with the development of the Greenland and Antarctic ice sheets under global warming. If the currently observed melting trend of the Greenland ice sheet continues or accelerates with rising atmospheric temperatures, the rise in sea level would be more than predicted. For the Antarctic ice sheet, the uncertainty is, as noted above, even greater.

Facing the future

The scientific debate continues and will continue in the following years. There are still numerous aspects very important for climate science that need more research and a better understanding of how natural systems behave. Some of them have been mentioned in this work, including downscaling, parameterizations, and ice-sheet melting. In the following paragraphs, some others are mentioned [11].

Methane. The amount of methane in the Earth's atmosphere shot up in 2007, bringing to an end a period of about a decade in which atmospheric levels of this potent greenhouse gas were essentially stable. Methane levels in the atmosphere have more than doubled since pre-industrial times, accounting for around one-fifth of the human contribution to greenhouse-gas-driven global warming. Until recently, the leveling off of methane levels suggested that its rate of emission from the Earth's surface was approximately balanced by its rate of destruction in the atmosphere. This was refuted by the enormous increase in 2007. Methane is released from wetlands and wildfires as well as from human activities, such as fossil fuel use and farming, but in the atmosphere it reacts with a compound known as the hydroxyl radical and disappears. A recent work [13] examined the change in global emissions of methane over a 10-year period. Atmospheric measurements of methane and other chemical compounds were obtained from two monitoring networks comprising 12 worldwide locations. Methane levels were found to have risen simultaneously across all global sites beginning in early 2007. The increase was proposed to have been caused, at least in part, by a slight decline in the atmospheric levels of the hydroxyl radical, but changes in hydroxyl chemistry alone are insufficient to account for the entire rise in methane concentrations.

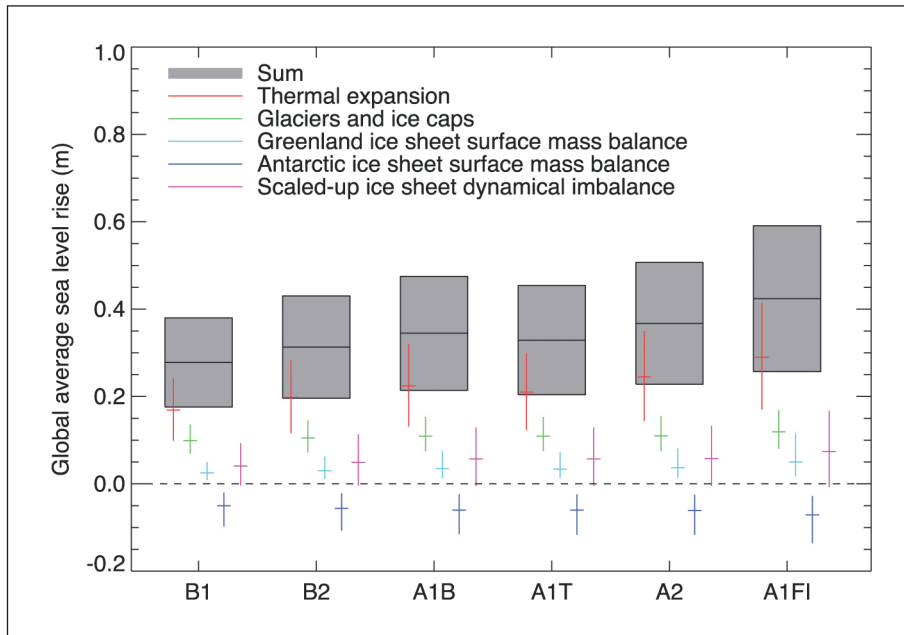


Fig. 2. Projections and uncertainties (5 to 95% ranges) of global average sea level rise and its components in 2090 to 2099 (relative to 1980 to 1999) for the six Special Report on Emissions Scenarios (SRES). Source: IPCC 2007.

Fusion of the permafrost was proposed as an important source of methane. Therefore some of the newly added methane could have originated in regions of high latitude; however, these hypotheses remain to be verified.

A new greenhouse gas? The importance of nitrogen trifluoride (NF_3) as a greenhouse gas was not evaluated until the Third Assessment Report [8]. Current publications report a long lifetime for NF_3 —between 500 and 700 years or more—with a high global warming potential, which according to the Kyoto criteria would be second only to that of sulfur hexafluoride (SF_6). The atmospheric concentration of NF_3 has increased 20-fold over the past three decades and has a potential greenhouse impact larger than that of the SF_6 emissions of industrialized nations, or even of the world's largest coal-fired power plants. Like other chemicals, NF_3 began as a niche product, in this case for rocket fuel and lasers. Now, it is marketed as a plasma etchant and equipment cleaning gas in the semiconductor industry. With the surge in demand for flat panel displays, the market for NF_3 has grown enormously [12].

How much warming, when, and at what concentration we should try to stabilize atmospheric greenhouse gases? There is wide agreement that we are already experiencing a warming trend in atmospheric and sea surface temperatures, such that it is reasonable to wonder how climate will change in the short-term and what will be the consequences. Independent of the long term, climate is subject to internal fluctuations, which produce internal climate variability. Over the next decade, it could be that the current Atlantic meridional overturning circulation will weaken to its long-term mean, such that the North Atlantic sea-surface temperature and European and North American surface temperatures will cool slightly [10]. If this occurs, the global surface temperature may not increase over the next decade, because natural climate variations in the North Atlantic and tropical Pacific will temporarily offset the

projected anthropogenic warming. These findings do not imply that global warming is not happening, but rather that natural oscillations in the climate system could lead to short-term changes that temporarily eclipse human-induced warming. However, this last statement is questionable to climate experts not convinced that falling temperatures in some regions will cause a slight slowdown in global warming.

A long-unresolved point is the concentration at which atmospheric greenhouse gases should be stabilized to avert a dangerous degree of change. Atmospheric CO_2 concentrations today are around 385 parts per million (ppm), with 400–450 ppm as the upper limit to keep warming below 2°C above pre-industrial levels. However, James Hansen [6], a prestigious NASA scientist, has stated that more stringent limits will probably be necessary to avoid irreversible catastrophic effects. His work is in agreement with other studies (e.g., [14]) concluding that the severity of human-induced climate change depends not only on the magnitude of the change but also on its potential irreversibility. Models have been used to show that climate change arising from increases in the carbon dioxide concentration is largely irreversible, even after emissions cease. Therefore, the period between when the emissions stop until the atmosphere recovers its former greenhouse gases concentrations will be quite long. Other scientists are more optimistic and recommend [5] stabilization of the atmospheric CO_2 concentration at up to 550 ppm, a limit that is used as a reference in international mitigation conferences. Scientific uncertainty remains about just how much CO_2 is too much, but, based on the current state of affairs, reaching a final consensual figure will also be a question of what is politically achievable.

Will storms be more frequent in the future? There has been much speculation as to whether storms and hurricanes will increase in intensity, frequency, or duration as a result of global warming. Globally, the number of major hurricanes has shot up by 75% since 1970, but the role of human activity in

this rise has remained contentious. Using a specific model designed for hurricanes, Kerry Emmanuel [4] showed that warming should reduce the frequency of hurricanes globally, although hurricane intensity may increase in some locations. At present, there is no definite consensus among scientists because the relationship between sea-surface temperature and storm formation, on local or global scales, has yet to be elucidated. The same could be said concerning Mediterranean storms. Some models predict that global warming will produce more frequent and more intense storms but until now there is no evidence supporting this claim.

Final remarks

Although there has been a great progress in climate modeling during the last 15 years, confident projections of future climate await the resolution of certain problems, as discussed in this review. For example, missing processes in the models affect the size and iteration time. In addition, natural climate variability is superimposed on anthropogenic trends, which contributes to the vagueness of current models. Perhaps the biggest uncertainty is future emissions of greenhouse gases, because this will depend on the evolution of society. This is further complicated by the fact that in the absence of a political consensus it will be difficult to achieve substantial mitigation of greenhouse gases emissions. The problem will persist as long as there is no scientific agreement, which is needed in order to send a certain and precise message about the future consequences of increasing greenhouse gas emissions for the Earth's climate and the global impacts of the changing climate.

Notes and references

Notes

1. The Earth's albedo is the amount of radiation reflected by Earth (clouds, surface) to the space and is expressed as

a percentage. The most important processes that determine the albedo are the reflection onto clouds and the surface of ocean, and the type of land cover.

2. The Intergovernmental Panel for Climate Change (IPCC) is an international panel of experts in climate change. It was created in 1988 by the World Meteorological Organization and the United Nations Environmental Program.

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