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# 1 Overview of climate variability and climate science

## 1.1 Climate dynamics, climate change and climate prediction

*Climate* is commonly thought of as the average condition of the atmosphere, ocean, land surfaces and the ecosystems that dwell in them. Every one knows what is meant by "Baja California has a desert climate" in terms of average temperature, average rainfall, average moisture in the air, and vegetation. Climate also includes the average wind direction and strength, average cloud cover, the temperature of the sea surface nearby, which affects the previous quantities, and the ocean currents that affect the sea surface temperature, and so on. While we might care most about the local climate in the land regions where we live, this interconnectedness of the climate system implies that we have to study it globally.

In contrast to climate, *weather* is the state of the atmosphere and ocean at a given moment in time. As the saying goes, "climate is what you expect, weather is what you get." However, climate includes not only average quantities, such as average precipitation, but also average measures of weather-related variability. These would include, for instance, the probability of a major rainfall event occurring in July in Baja, the range of variations of temperature that typically occur during January in Chicago, or the number of hurricanes that typically hit the US coast per year. Climate may thus be considered to include all quantities defined by averaging over the weather, i.e. over time scales of many weather events. Since the Earth has very strong changes with season, this means that an average must be taken, for instance, over January of many different years to obtain a climatological value for January, over many Februaries to obtain February climatology, and so on.

The importance of climate has increased with the realization that *climate change* is not restricted to past eons but is occurring on time scales that affect human activities. While climate is an average over weather events, the time period used in the average will affect the climate that one defines. For instance, the climate defined by an average from 1950–1970 will differ from the average from 1980–2000. We know that this average changes from one decade to another, and even more so between different centuries or millennia. These changes are referred to as *climate variability* – essentially all the variability that is not just weather. This includes ice ages and the long-term warm climate enjoyed by the dinosaurs, as well as events such as the drought that has plagued the Sahel region in Africa over the past decades, and *El Niño*, in which the tropical Pacific Ocean warms and cools every few years. Climate change has taken on a new dimension now that human activities can change the climate. This is referred to as *anthropogenic climate change* to distinguish it from natural climate variability such as El Niño. Examples of anthropogenic change include the ozone hole, acid rain and global warming.

Although climate has been of interest to humans since ancient times, the science that studies the processes that keep our climate in its current state, and cause climate changes, is new enough that there is not even agreement on what to call it. *Climate science* or *climate dynamics* are coming to be the preferred names. An older term, "climatology," is still also used but unfortunately has connotations of static, unchanging climate and old geographers poring over maps. The term *climatology* is now standardly used to refer to the average variables themselves, for instance "the January precipitation climatology." It can thus be confusing when it is used for the field of study. *Climate modeling* is a very important area of climate science, since much current work uses mathematical models. These *climate models* are mathematical representations of the climate system which typically consist of equations for temperature, winds, ocean currents and other climate variables, and which are almost always solved numerically on computers. Climate modeling necessarily interacts with the part of the field devoted to making and analyzing observations. Many climate scientists come from physics, mathematics, chemistry, engineering or biology, and bring the tools of their fields to bear on this rapidly developing area.

*Climate system* or *Earth system* are used to refer to the global, interlocking system of atmosphere, ocean, land surfaces, sea and land ice, and the parts of the biosphere and solid earth that are relevant for the problems of interest. The *biosphere* is the plant and animal component of the planet. Some jargon enthusiasts go so far as to call oceans, lakes, etc. the hydrosphere. Often the term *Earth system* is used to emphasize the simultaneous study of all parts of this system, including the important role of chemical reactions and biological contributions. The *physical climate system* is sometimes used to distinguish the parts of the system that can be studied while assuming that most of the chemistry and biology is unchanging. For instance, if one assumes that the composition of the atmosphere is roughly constant except for specified changes in carbon dioxide, one can examine the still very complex interplay of atmospheric circulation, heat balances, clouds, and oceanic circulation separately from the chemistry and biology of carbon dioxide uptake and release, and separately from other questions such as the ozone hole. A model that simulates a part, for instance, of the physical climate system is still termed a climate model, even if not all aspects are included. *Earth system model* is usually used for models that attempt to include physical, chemical and biological aspects at the same time.

*Global warming* is the predicted warming, and other associated changes in the climate system, that the vast majority of scientists in the field are convinced is beginning to occur in response to the increased amounts of *greenhouse gases* that are being emitted into the atmosphere by human activities. Greenhouse gases, such as carbon dioxide, methane and chlorofluorocarbons, are trace gases that absorb *infrared radiation* and thus affect the Earth's *energy budget* of incoming sunlight (solar radiation) and outgoing infrared radiation to space. This produces a warming tendency, known as the *greenhouse effect*. *Global change* more generally describes human-induced changes in the large-scale climate system, including the ozone hole. *Environmental change* is even more general, including air and water pollution, deforestation, soil erosion, and endangerment of individual species or ecosystems by loss or pollution of habitat. Some of these problems occur at *regional scales* such as the area of a few states, or even of a single city.

*Climate prediction*, on the other hand, includes the endeavor to predict not only human-induced changes in the global environment but also the natural variations of climate that affect us. El Niño is the most notable example of a phenomenon that was scarcely known two decades ago, and now is considered at least partly predictable because of advances over the past decade. Climate prediction relies heavily on physically based climate models, although for some purposes statistical models have also been used.

The current predictions of human-induced climate change are sufficiently grave that they demand decisions on response, mitigation strategies, government policy, international protocols and conventions. Predictions of natural climate variations raise questions of how the public interprets predictions, which climate variables (precipitation, temperature, etc.) are useful to which countries or interest groups, and what use will be made of the information. This is known as the *human dimension* of climate science.

## 1.2 The chemical and physical climate system

### 1.2.1 Chemical and physical aspects of the climate system

Changes in the chemical constituents of Earth's atmosphere and oceans are very important in environmental change from regional to global scales. This includes air pollution and the changes that human activities are creating in atmospheric concentrations of carbon dioxide, methane and other greenhouse gases that contribute to global warming.

The study of *environmental chemistry* includes the sources, reactions and pathways that contribute to setting the chemical composition of our atmosphere and ocean. It also includes the variations in chemical composition that have occurred during the history of the climate system.

Equally important are the many variations in the *dynamical* or *physical climate system*: the winds, the temperature, cloud amount, ice cover, ocean currents. Many of these variations do not depend on variations in the chemical composition of the atmosphere. There is no need, for instance, to model changes in ozone in a model aimed at predicting El Niño or in a weather prediction model. In studying a complex system, we need to make simplifications wherever this can be done without distorting the phenomenon of interest. So a conceptual separation is often made between these aspects of the Earth system. Examples of phenomena or topics of study associated with these subsystems include:

- Physical climate system: weather, El Niño, North Atlantic Oscillation, Asian monsoon variations, North American monsoon variations, droughts, floods, processes maintaining circulation of the atmosphere and oceans for current atmospheric composition, deep ocean circulation, ice ages…
- Environmental chemistry: the ozone hole, urban air pollution, aerosol formation, haze…

- Biosphere: evolution of the atmosphere, oxygen production, carbon cycle between biomass and carbon dioxide and other atmospheric and oceanic constituents, land surface processes, biodiversity…
- Linkages: the effects of the carbon cycle on carbon dioxide concentration and thus on the greenhouse effect, effects of dynamical processes on ozone hole formation (the stratospheric polar vortex, stratospheric ice clouds), vegetation effects on absorption of sunlight and evaporation from land surfaces…

Mathematical models of global climate can reproduce many aspects of the physical climate system without directly dealing with chemistry or biology. In this approach, the climatology of chemical and biological constituents is specified without going into the details of what maintains them. For instance, many models simulating the current state of ocean and atmospheric circulation take the current concentration of chemical constituents as given, such as oxygen, nitrogen, ozone and carbon dioxide. The total mass of the atmosphere and oceans is also taken as given, although early in Earth's history these were different.

Even in global warming, where changes in the concentration of carbon dioxide are crucial, it can be useful to *specify* an expected increase and study the response of the physical climate system. By specifying the carbon dioxide concentration as a function of time as an input to the physical climate system, one defers having to understand and correctly model the set of processes, involving chemistry and ecosystems feedbacks, that determine the concentration. While these processes are important, the burning question at the initial stage is what the physical climate system will do in response to the expected increases. Modeling and understanding this response can be extremely complex, as we shall see.

In studying such a complex system, what constitutes a good approximation depends on the question you are asking. It also depends on whether you are interested in understanding the overall behavior or if a highly accurate answer is required about particular details, and which set of interactions are key to the question being addressed. It is common to make one approximation to understand leading effects, and to improve on this in the next approximation. For instance, when first modeling global warming, initially approximations were used that amounted to specifying fixed ocean circulation. Current models applied to global warming typically include a full ocean model, but many specify carbon dioxide concentrations. Next-generation models now exist (and are being improved) that include interactive carbon cycles. At each stage the previous, simpler class of model remains valuable for understanding the results of the next class. Studying the components of the climate system separately is useful to make progress – as long as one never loses sight of the fact that there is one Earth system. Information from the chemists and biologists is essential to the dynamists and vice versa.

### 1.2.2 El Niño and global warming

El Niño is the largest *interannual* (year-to-year) climate variation. The source of the phenomenon involves an interaction between the tropical Pacific Ocean and the atmosphere above it. It can be reproduced in models in which the chemical composition is entirely fixed, i.e. it is a phenomenon of the physical climate system. In fact, the essential aspects of El Niño can be understood in models that include only the tropical Pacific region, although the impacts of what happens in this region are felt worldwide. As well as being a prime example of natural climate variability, El Niño was the first phenomenon for which the essential role of dynamical interaction between atmosphere and ocean was demonstrated. El Niño cannot be reproduced in an atmosphere model alone, nor in an ocean model alone – unless aspects of the observed El Niño evolution are specified in the other component. A coupled ocean–atmosphere model, on the other hand, can produce El Niño oscillations internally. Thus the study of El Niño has brought about an interdisciplinary interaction between atmospheric scientists and oceanographers.

In global warming, many of the complex effects created by an increase in greenhouse gases occur in the atmosphere. To a first approximation, these may be studied with relatively rudimentary effects of the ocean, although at the next level of understanding oceanic effects must be included. The number of subtle processes that must be modeled is daunting. These include, for example, the average on large scales of the effects of small-scale clouds, and how these change as the planet warms. These effects lie within the study of the physical climate system.

### Scope of this text

The causes of El Niño, and many of the most important uncertainties affecting our assessment of global warming, lie in the physical climate system. This text aims to provide an understanding of what these processes are, of the strengths and weaknesses of climate models, and of the extent of our ability to predict the climate system, including limits to accuracy at regional scales. The focus is on global-scale aspects of environmental change and variability, and on the physical, rather than chemical, components of the climate system. Other books are available that deal with air pollution and atmospheric chemistry and related topics. The task of linking the physical and chemical climate components to the biological and human dimensions of climate would require several courses. This book presents the basic science on the physical climate side, to provide a solid background for students in a wide range of science disciplines who may go on to work in these other areas. A knowledge of the capabilities and limitations of climate models can be useful background as society debates how (and whether) to limit the eventual magnitude of global warming and prepares to adapt to its impacts.

## 1.3 Climate models: a brief overview

The motions, temperature and other properties of the atmosphere and ocean are governed by basic laws of physics. These can be written as equations, which one can then attempt to solve. The results are too complex for a general solution to be written, but approximations to these equations can be solved numerically on computers. One common type of approximation is to divide the atmosphere and ocean into discrete grid boxes, writing the balance of forces, energy inputs etc. for each box as an equation that permits one to obtain the acceleration of the fluid in the box, its rate of change of temperature and so on. From this one computes the new velocity, temperature, etc. one *time step* – say, 20 minutes for the atmosphere or an hour for the ocean – later. The equations for each box depend on the values in neighboring boxes, so the computation is done for a million or so grid boxes over the globe. This is then repeated for the next time step, and so on until the desired length of simulation is obtained. Since it is common to simulate decades or even centuries in climate runs, *computational cost* is obviously a factor to be considered.

The basic method of solving for the motions of a gas or liquid described above has much in common with what one encounters in many fluid dynamics applications in engineering, such as flow over an aircraft wing. The atmospheric component of a climate model also has a close relationship to weather forecasting models. Major differences arise from the complexity of the climate system, and from the range of phenomena at different time scales that must be addressed, as will be discussed in Chapter 2. The climate system is “messier” than typical fluid dynamics problems since the impacts of such things as clouds, aerosols and even vegetation are important. Compared with a weather forecast model, a climate model must pay much more attention to processes that affect the long term. For instance, an error in calculation of infrared radiation emitted from the atmosphere might have little effect in a weather forecast that begins from observed initial conditions and runs for a week, but in a climate model that must simulate the global energy balance correctly, this effect would be important.

The most complex climate models, described above, are known for historical reasons as *general circulation models* or GCMs (some authors reinterpret GCM as *global climate model*, except that one also uses the term “ocean GCM” to describe an ocean model of the same level of complexity). Even once a phenomena has been simulated in a GCM, it is not necessarily easy to understand the underlying physical mechanism, since a GCM includes so many effects. *Intermediate complexity* climate models are also used, in which the aim is to construct a model that is based on the same physical principles as a GCM and is also directly comparable to observations, but in which only the aspects of the system important to the target phenomenon are retained. Usually approximations are made that further simplify the solution of the equations. Intermediate complexity models are used for analyzing phenomena and also for exploring new phenomena. Intermediate complexity ocean–atmosphere models of the tropical Pacific region, for instance, were first used to simulate, understand and predict El Niño, while GCMs were still struggling with the difficulty of accurately simulating all aspects of the climate in the region. Part of our discussion of El Niño in Chapter 4 will be based on such a model, after the equations that govern the balances of the climate system are introduced in Chapter 3. Chapter 5 elaborates in more detail how climate models are constructed and the flavors of model used for different applications. It also addresses issues of model accuracy. In Chapter 6 we use a very simple climate model, a globally averaged energy balance model, to understand essential aspects of the greenhouse effect. We then return to simulations of global warming in the most complex climate models in Chapter 7.

## 1.4 Global change in recent history

### 1.4.1 Trace gas concentrations

Although we will concentrate on the physical climate system, we need to begin with some atmospheric chemistry. *Trace gases* form a tiny fraction of the atmosphere's mass, but that makes their concentration more susceptible to variation. In particular, human activities can significantly change the trace gas composition of the atmosphere. Table 1.1 gives recent typical concentrations of some of the trace gases that are susceptible to such variations. The units, parts per million (ppm) by volume, indicate what fraction of the molecules in air each gas constitutes. For instance, carbon dioxide, at about 370 ppm early in this decade, accounts for 0.037% of air molecules. The major components of air are nitrogen ($N_2$) at 78.08% and oxygen ($O_2$) at 20.95% (for dry air). Some trace gases, such as argon (0.93%), are essentially unchanging on our time scales, so are less important to global change. Water vapor, at typical concentrations of 1 to 20 parts per thousand, is an extremely important constituent in all aspects of Earth's climate. Because its concentration varies strongly in time and space, and because it changes phase to produce clouds, rain and snow, water is treated separately from other chemical constituents in climate models. All of the trace gases can have variations in time and space. Gases that have long residence time in the atmosphere tend to be mixed by atmospheric motions, so the variations are much smaller than the mean concentration. For instance, annual average carbon dioxide concentrations in northern and southern hemispheres differ by less than 1%, even though sources and sinks of $CO_2$ differ between the hemispheres. Gases with short residence times, such as ozone, are much more closely tied to the location of sources or sinks and can vary strongly in the vertical and horizontal.

**Table 1.1** Typical concentrations (and chemical formulae) of some of the trace gases that are important to global change.

| Trace gas name | Formula | Concentration |
|---|---|---|
| Carbon dioxide | $CO_2$ | 377 ppm |
| Methane | $CH_4$ | 1.8 ppm |
| Nitrous oxide | $N_2O$ | 0.32 ppm |
| Ozone | $O_3$ | 0.000 251 ppm (average; max 10 ppm in stratosphere) |
| CFC-11 (Freon) | CFC3 | 0.000 254 ppm |

*Note:* Units are parts per million by volume. CFC denotes chlorofluorocarbon. Values are for 2004 from Clerbaux and Cunnold (2006); for magnitude of stratospheric maximum values see Randall *et al*. (2005).

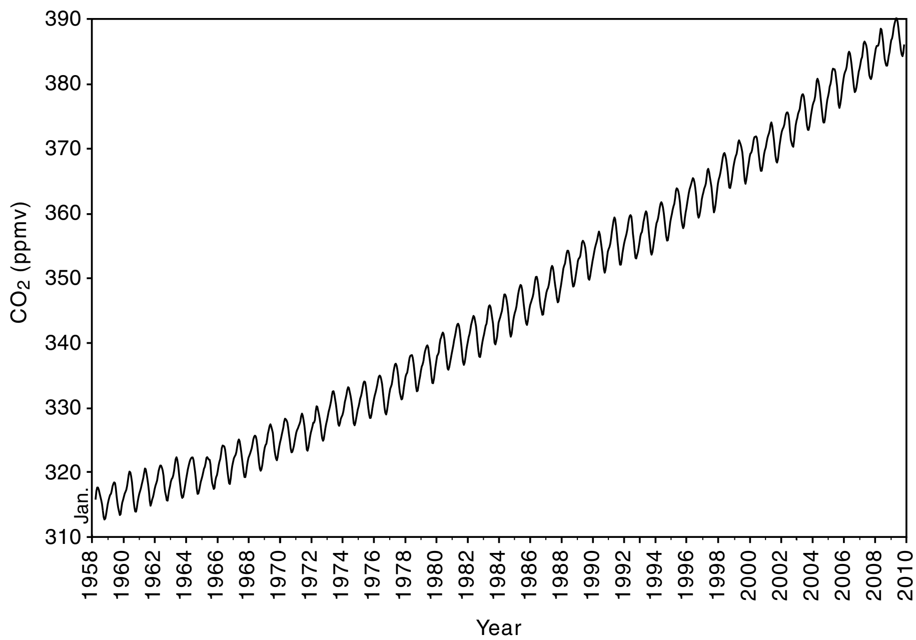


**Fig. 1.1** Carbon dioxide concentrations (monthly mean) since 1958, measured at Mauna Loa, Hawaii. Units are parts per million by volume, and tick marks occur at January of the indicated year. From the National Oceanographic and Atmospheric Administration (NOAA) Climate Monitoring and Diagnostics Laboratory. Data prior to 1974 are from Keeling *et al*. (1976).

Figure 1.1 shows a measurement that has helped launch much of the current concern over global warming. The concentration of carbon dioxide has been consistently measured at a point far from continental effects, Mauna Loa, Hawaii, since 1958. It shows a dramatic, continued increase throughout the time series, evidence that the emissions of carbon dioxide from human use of fossil fuels is indeed having the expected effect of increasing atmospheric concentrations of carbon dioxide. Subsequent measurements have borne out that this holds on a global scale. The yearly variations in concentration are due to the seasonal cycle and biological effects. In summer, there is more sunlight available for photosynthesis, so there is more carbon dioxide fixed into plant biomass in the summer hemisphere. Since there is asymmetry between the amount of land and ocean in the northern and southern hemisphere, seasonal effects also occur in the global average, not just in the individual hemispheres. These small spatial and seasonal or interannual variations can give clues to the biological contributions to the *carbon cycle*. In Figure 1.1, smaller interannual variations may also be seen. These occur because of interannual climate variations, especially El Niño, affecting the biological systems.

Figure 1.2 shows how selected trace gases have varied over a longer time period, namely the last centuries, since industrialization made it possible for humans to release them in substantial quantities into the atmosphere. The concentrations may be taken as typical of global average values, but are estimated from various sources. These include direct atmospheric measurements at particular locations, for parts of the record, and measurements

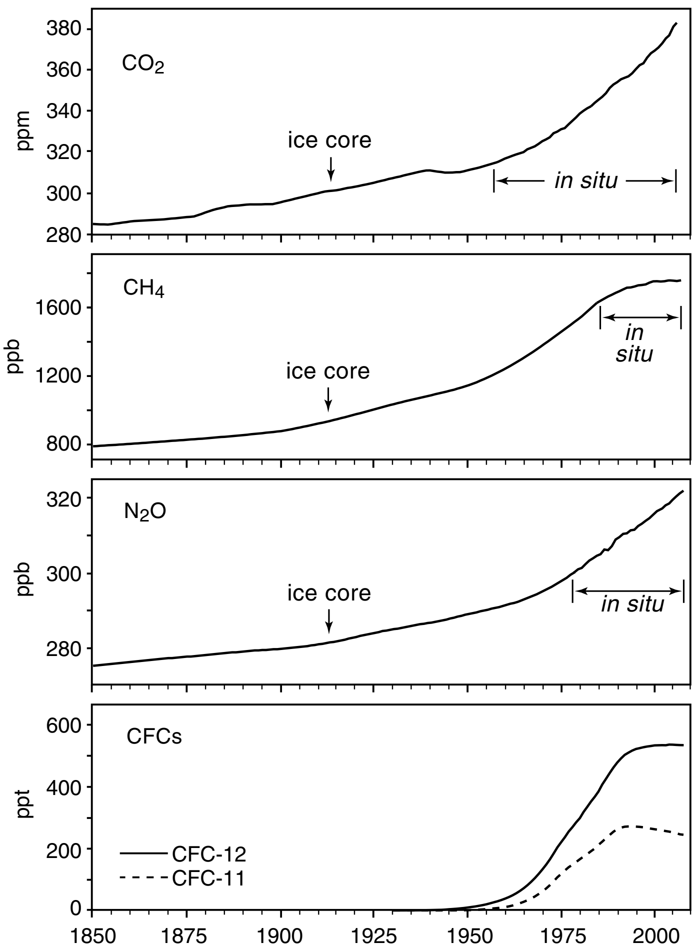


**Fig. 1.2** Concentration of various trace gases, carbon dioxide, methane, nitrous oxide and two chlorofluorocarbons, respectively, estimated since 1850. The part of the record from direct atmospheric measurements is marked "*in situ*." Data from Goddard Institute for Space Studies following Hansen *et al*. (1998).

of concentrations in air bubbles trapped in ice cores taken from the Greenland and Antarctic ice caps.[1] These permit the atmospheric concentrations to be estimated for times before measurements were being recorded for the atmosphere. Overall, they show increases in concentration, with a greater rate of increase in recent times, following rising population and industrialization. The CFCs are man-made compounds, so their concentration is zero before about 1950. All the gases shown contribute to the greenhouse effect, while the CFCs have an additional effect – stratospheric ozone loss. The human sources of nitrous oxide are imperfectly measured, but biomass burning and fertilizer use are believed to contribute. Methane is produced by cattle, sheep, rice paddies and waste disposal and as a by-product of fossil fuel use, which are all increasing with human population. Natural sources of methane include wetlands and termites.

### 1.4.2 A word on the ozone hole

The role of CFCs in ozone destruction was predicted by Sherwood Rowland and Mario Molina in 1974. In 1985, J. C. Farman and coworkers published observations of Antarctic ozone depletion in southern spring – that has since grown into what we all know as the *ozone hole*. The Montreal Protocol in 1987 set a timetable (since revised) for phase-out of CFC emissions.[2] CFC concentrations have indeed leveled out or begun to decrease slowly in recent years. Because of the reservoir effect of existing CFCs in the atmosphere, it may be 50 years before ozone levels recover. This is a relative success story compared with the discussions that the world is embroiled in regarding responses to the threat of global warming. It was aided by the ground work laid by the "spray-can ban" in the late 1970s, in which such countries as Canada, Sweden and the United States limited non-essential uses of CFCs, and by the development of alternative products. It is also worth noting that the prediction of ozone destruction involving CFCs was correct overall, but that nature still held a twist. The degree of ozone destruction producing the Antarctic hole turned out to be enhanced by the presence of polar stratospheric clouds whose ice crystals provide a surface on which the reactions occur more rapidly.

The ozone hole and global warming are separate environmental threats, in the sense that one can occur without the other, and they have different causes. Although there can be some small, hypothesized modifications of each by the other, we should not confuse the two. The ozone hole is essentially a chemical effect, and so is not treated further here. However, it provides a potent example of human impacts on our climate.

### 1.4.3 Some history of global warming studies

The threat of global warming by the greenhouse effect has been postulated since the beginning of the century. In contrast to the ozone hole, definitive identification of anthropogenic warming is not something that can occur in one step, but rather is a matter of slowly amassing evidence of a gradual warming. The quantification of future potential warming is a task that involves many climate scientists slowly pushing back the frontiers of what is known of the climate system. Table 1.2 gives a few of the events in the timeline of global warming.

Beginning in 1990, a concerted effort was made by climate scientists and others to summarize the current state of knowledge. The resulting Intergovernmental Panel on Climate Change (IPCC) Reports are consensus documents that capture the "center of gravity" of scientists' current understanding.[3] They are intended to make available to world leaders and decision makers the best estimates of how large global warming might become. At the same time, these reports, and other statements by climate scientists, must convey some sense of the uncertainty, often given as a range of possible outcomes, that remains. Chapters 6 and 7 examine in detail this consensus of what is known, what is uncertain, and why. Taking action to mitigate global warming entails enormous economic efforts and, therefore, political implications. The IPCC reports have therefore been the subject of considerable debate in both media and government.