GEORGE C. Marshall INSTITUTE

Climate Issues & Questions

Third Edition

The Marshall Institute – Science for Better Public Policy

The George C. Marshall Institute
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Climate Issues & Questions

The debate over the state of climate science and what it tells us about past and future climate has been going on for twenty years. It is not close to resolution, in spite of assertions to the contrary. What is often referred to as a "consensus" is anything but. In many cases, this consensus represents the "expert judgment" of a handful of Intergovernmental Panel on Climate Change (IPCC) authors, which other researchers can and do disagree with. For many, especially those engaged in advocacy, the claim of consensus is a device used to advance their agenda.

Although humanity has been interested in climate since prehistoric times, climate science is, in fact, a relatively new field. It is only since the 1970s, when models were developed to connect atmospheric and oceanic climate processes, that scientists have had the tools to study climate as a system. Also, it is only since the 1970s that satellites have been available to provide global climate data. While the 1970s may seem like a long time ago, it is too short a period to provide a comprehensive understanding of the climate system, which includes processes, such as the 60-80 year North Atlantic Oscillation, that occur over many decades. It can also take many years to detect and correct errors in the climate data base, such as the recently announced correction of NASA's surface temperature data for the U.S., and previous announcements of corrections to global satellite temperature data.

Concerns about either the potential impacts of climate change or the economic impact of ill-conceived policies result in some scientists entering the policy debate. Others, unfortunately, have entered the debate to advance political or economic agendas, gain funding for research, or enhance their personal reputations. To the extent that the debate is carried out in the public policy arena or media, the rigors of the scientific process are short-circuited.

This state of affairs creates misunderstandings and confusion over what we know about the climate system, past climate changes and their causes, human impacts on the climate system and how human activities may affect future climate. Policy needs are better served by clarity and accuracy.

The purpose of this document is to address a set of fundamental questions about climate change by summarizing the best available scientific information. The information provided is not intended to rebut claims about human impacts on climate or the potential for adverse impacts later this century. It is intended to separate fact from speculation and to demonstrate that, while concerns are legitimate, there is not a robust scientific basis for drawing definitive and objective conclusions about the extent of human influence on future climate. The presentation starts with a discussion of the IPCC and the processes by which it establishes consensus. It then discusses some of the aspects of climate science that are well established before moving to what is not certain, to what is unknown, and may be unknowable.

This is the third edition of *Climate Issues and Questions*. We have updated the 2006 edition with new information where available and responded to some of the claims made in the IPCC's Fourth Assessment Report (AR4). The Marshall Institute has published a more detailed critique of the claims in the IPCC's Fourth Assessment Report in a series of three *Policy Outlooks* released in 2007:

1. *Working Group (WG) I's Contribution to the IPCC's Fourth Assessment Report (AR4): A Critique*. ***www.marshall.org/pdf/materials/515.pdf***.
2. *Evaluating Working Group (WG) II's Contribution to the IPCC's Fourth Assessment Report (AR4)*. ***www.marshall.org/pdf/materials/526.pdf***.
3. *Working Group (WG) III's Contribution to the IPCC's Fourth Assessment Report (AR4): Be Sure to Read the Fine Print*. ***www.marshall.org/pdf/materials/530.pdf***.

The twenty-nine questions addressed in this report are listed below. Those marked with an * are new.

1. **How is the scientific consensus on climate change established and what does it mean?***
2. **How does the IPCC present statistical information?***
3. **How does the IPCC characterize the uncertainty in their expert judgment?***
4. **What are greenhouse gases and what is their concentration in the Earth's atmosphere?***
5. **What are past and current atmospheric concentrations of carbon dioxide (CO_2), how are they measured, and how accurate are the measurements?***
6. **Do we know why CO_2 concentrations are rising?**
7. **How is global average temperature determined, how accurate are the values and what do they mean?***
8. **What do we know about the relation between increases in the atmospheric concentrations of CO_2 and other greenhouse gases and temperature?**
9. **If temperature changes cannot be correlated with the increase in atmospheric concentrations of CO_2 and other greenhouse gases, what is causing them?**
10. **Do satellites and surface temperature measurements give different results?**
11. **Is the Arctic warming faster than the rest of the Earth?**

12. **Is evidence of increased ocean heat storage a "smoking gun" indicating climate change?**

13. **What influence does the Sun have on global climate?**

14. **What is known with a high degree of certainty about the climate system and human influence on it?**

15. **What major climate processes are uncertain and how important are these processes to understanding future climate?**

16. **What is the carbon cycle feedback and how might it affect the climate system?***

17. **What tools are available to separate the effects of the different drivers that contribute to climate change?**

18. **How accurate are climate models?**

19. **What is the basis for forecasts of large temperature increases and adverse climate impacts between 1990 and 2100?**

20. **How accurate are the parameters used in climate models?**

21. **How well have models done in "back-casting" past climate?**

22. **Is the global warming over the past century unique in the past 1,000 years or longer?**

23. **How much does the global climate vary naturally?**

24. **What do we know about the extent of human influence on climate? To what extent has the temperature increase since 1975 been the result of human activities?**

25. **Will climate change abruptly?**

26. **Will sea level rise abruptly?**

27. **Will the number of tropical cyclones (hurricanes, typhoons) increase and will they become more intense?**

28. **Will other extreme weather events, such as heat waves, increase?**

29. **How does the IPCC conduct climate change impact assessments?***

QUESTIONS & ANSWERS

1. **How is the scientific consensus on climate change established and what does it mean?**

The chief mechanism for establishing what is often referred to as a "scientific consensus" on climate change is the Intergovernmental Panel on Climate Change. For most questions, IPCC depends on the expert judgment of small teams of authors, often only a handful. Other experts can and do disagree with the judgment of these teams. However, there is a more fundamental problem with the IPCC approach. Science is not a consensus activity. The accuracy of a scientific statement does not depend on the agreement of experts; it depends on verification, either through experimentation or observation.

The chief mechanism for establishing consensus on climate change is the Intergovernmental Panel on Climate Change, which was established by the U.N. General Assembly in 1988 and given eighteen months to produce an assessment of the then state of knowledge on causes, impacts and control of climate change. The IPCC produced that assessment in 1990, but did not go out of business. Since 1990 it has produced a series of assessments, special reports and technical papers detailing the emerging state of knowledge about climate change. Its latest report, the Fourth Assessment Report (AR4), was released in four parts over the course of 2007.

AR4 consists of three underlying reports covering the science, impacts and mitigation of climate change, and a Synthesis Report covering the most politically sensitive results from the underlying reports. Each underlying report is made up of 10-20 chapters. Each chapter is written by a team of 10-12 Lead Authors chosen for their knowledge of the chapter's topic and to try to achieve geographic and gender balance. The team's size, and the desire for geographic and gender balance, limit the expertise on chapter teams. Additional input is obtained from Contributing Authors who are chosen by the Lead Authors to provide input on specific topics, and through the review procedure, which is open to all experts. However, all decisions on the content of the chapter are made by the author team, and especially by the two Convening Lead Authors who are team leaders for the chapter writing team.

Two other factors affect the quality of author teams. First, being an IPCC author is time- consuming. Many experts are not willing to devote the necessary time and will not volunteer to be IPCC authors, or in some cases, even reviewers. Second, each of the AR4 underlying reports contains a Summary for Policymakers (SPM), which is approved after a word-by-word review by more than 100 governments at an IPCC Plenary. Knowing that the summary of their work will be subject to government review affects the way IPCC authors present their work.

For some questions, e.g., how much has global average surface temperature risen over the past 100 years, sufficient data are available for a statistical analysis that will provide an average and an error band. For most questions, e.g., whether the temperature rise of the past century can be attributed to human activities, statistical analysis is not possible, and IPCC authors rely on expert judgment.

Many of the statements that the IPCC makes based on expert judgment are forecasts of future events, but the techniques that the IPCC uses violate the generally accepted principles of scientific forecasting. Green and Armstrong list five generalizations about forecasting that are particularly relevant to IPCC expert judgment:

1. Unaided (by the knowledge of well-established forecasting principles) judgmental forecasts by experts have no value.
2. Agreement among experts is weakly related to accuracy.
3. Complex models (those involving nonlinearities and interactions) harm accuracy because their errors multiply.
4. Given even modest uncertainty, predictions intervals are enormous.
5. When there is uncertainty in forecasting, forecasts should be conservative.[1]

The IPCC's approach violates each of these generalizations.

Green and Armstrong audited the IPCC AR4 chapter on climate models using Armstrong's Forecasting Audit, which evaluates forecasting practices against 140 principles.[2] The audit showed that IPCC violated seventy-two of the eighty-nine forecasting principles that could be evaluated. Two of these principles — Principle 9.3: Do not use fit to develop the model and Principle 13.26: Use out-of-sample data to test the forecast — address the way climate models are developed and their lack of scientific validation, a theme which will be discussed in the response to several questions below.

The IPCC likes to claim that thousands of experts are involved in the development of its Assessment Reports. This statement is true, but misleading. There are, in fact, thousands of authors and reviewers involved in the development of an Assessment Report, but it is the 10-12 Lead Authors for each chapter team who provide the expert judgment on any given question. Since chapters cover a broad range of topics, not all of the Lead Authors on a chapter team will have the necessary expertise to contribute to a given judgment. In many cases the IPCC's judgment is based on input from only a handful of experts. Since they are presenting their expert judgment, it is difficult, often impossible, for review comments to change that judgment. And it is these judgments from limited numbers of experts that are then presented as scientific consensus. Other experts can and will disagree with the IPCC's expert judgment, making the claim of consensus meaningless.[3] For example, the first draft the WG I (Science)'s contribution to AR4 generated almost 20,000 review comments. While some of these comments were editorial or supportive, most expressed some level of disagreement with the draft. WG I modified its draft to respond to some of these comments, but these changes generated a new set of disagreements.[4] The only consensus is between the Lead Authors or a subset of Lead Authors on a chapter writing team.

The IPCC misrepresents its work as consensus, but there is a more fundamental problem with the idea of scientific consensus. Science is not a consensus activity. The accuracy of a scientific statement does not depend on the agreement of experts; it depends on verification, either through experimentation or observation. Every scientific advance begins with one scientist challenging a prevailing point of view. Verification can take decades. Einstein's Theory of Relativity was proposed in 1905, but it took until 1919 for its observational verification. Alfred Wegner proposed plate tectonics in 1912, but it took until the 1950s for data supporting the theory to be generated.

2. How does the IPCC present statistical information?

When presenting statistical information, the IPCC uses a 90 percent confidence interval, not the 95 percent confidence interval that is standard scientific practice, making the results look more robust than they actually are.

Working Group I (WG I) (Science) is the only IPCC Working Group that routinely uses statistical analysis. However, it does not use the standard scientific approach to presenting this information. Instead, its results are reported as an average value and a 5-95 percent confidence interval (average [lower bound to upper bound]).[5] This is a 90 percent confidence interval, not the 95 percent confidence interval normally used in the scientific literature, and results in smaller uncertainty ranges than would be typically reported. For example, WG I reports the increase in global average surface temperature between 1906 and 2005 as 0.74°C [0.56°C to 0.92°C].[6] Had WG I used the 95 percent confidence interval, they would have reported this result as 0.74 ± 0.21°C, with the uncertainty range extending from 0.53 to 0.95°C. WG I's choice of the 90 percent confidence interval makes their results appear more robust than they actually are.

3. How does the IPCC characterize the uncertainty in their expert judgment?

Each of the IPCC Working Groups uses a different approach to characterizing the uncertainty in their subjective expert judgment. WG I and II use terms which are related to numerical values for likelihood and confidence, respectively. WG III uses qualitative terms that avoid the appearance of being based on statistical analysis.

Each IPCC Working Group uses a different approach to characterizing the uncertainty in its expert judgment. In most cases, Working Group I (Science) uses a likelihood scale. The terms used to characterize uncertainty and their meanings are:

<u>Likelihood of the occurrence/outcome</u>

Virtually Certain	>99% probability of occurrence
Extremely Likely	>95% probability
Very Likely	>90% probability
Likely	>66% probability
As Likely as Not	>50% probability
Medium Likelihood	33 – 66% probability
Unlikely	<33% probability
Very Unlikely	<10% probability
Extremely Unlikely	<5% probability[7]

In most cases, Working Group II (Impacts, Vulnerability and Adaptation) uses a confidence scale. The terms used to characterize uncertainty and their meaning are:

<u>Confidence Scale, chance of being correct</u>

Very High	At least	9 out of 10
High	About	8 out of 10
Medium	About	5 out of 10
Low	About	2 out of 10
Very Low	Less than	1 out of 10[8]

Finally, Working Group III (Mitigation) uses qualitative terminology, not the quantitative terminology used by WG I and II. The phrases used and their definitions are shown in the following Figure, copied from the approved version of WG III's Summary for Policymakers. This is a better approach than those used by WG I and WG II, where expert judgment is used to assign probabilities, creating a false impression that the authors conducted a statistical analysis.

Table SPM A.1: *Qualitative definition of uncertainty*[9]

Level of agreement (on a particular Finding) ↑			
	High agreement, limited evidence	High agreement, medium evidence	High agreement, much evidence
	Medium agreement, limited evidence	Medium agreement, medium evidence	Medium agreement, much evidence
	Low agreement, limited evidence	Low agreement, medium evidence	Low agreement, much evidence
	Amount of evidence (number and quality of independent sources) →		

4. What are greenhouse gases and what is their concentration in the Earth's atmosphere?

Greenhouse gases are trace gases in the atmosphere that have the ability to absorb heat radiated from the Earth surface. The amount of water vapor, the most important greenhouse gas in the atmosphere, depends on temperature and relative humidity, ranging from near zero in cold, dry polar air, to more than 6 percent in high humidity, tropical air. Other greenhouse gases, carbon dioxide, etc., account for less than a tenth of a percent of the atmosphere.

Greenhouse gases are trace gases in the atmosphere that have the ability to absorb heat radiated from the Earth surface. This creates the Greenhouse Effect, which warms the Earth. Some greenhouse gases, e.g., water vapor and carbon dioxide (CO_2), are naturally occurring, but can also be generated by human activities. Other greenhouse gases, e.g., fluorinated compounds, are entirely the result of human activities. Naturally occurring greenhouse gases warm the Earth by about 30°C (54°F). Because of the complexities of the climate system, there is no accepted estimate of the amount of warming due to the human emissions of greenhouse gases.

Over 99.9 percent of the dry atmosphere is nitrogen, oxygen, and argon, which are not greenhouse gases. The amount of water vapor, the most important greenhouse gas in the atmosphere, depends on temperature and relative humidity, ranging from near zero in cold, dry polar air, to more than 6 percent, in high humidity, tropical air. Other greenhouse gases, carbon dioxide, etc., account for less than a tenth of a percent of the atmosphere. CO_2 accounts for the majority of human emissions of greenhouse gases.

5. What are past and current atmospheric concentrations of carbon dioxide (CO_2), how are they measured, and how accurate are the measurements?

Atmospheric concentration of CO_2 has varied greatly over time, from a high of as much as 4,000 parts-per-million (ppm) 200 million years ago to a low of about 180 ppm during several periods of glaciation over the past 400,000 years. It was relatively constant at about 280 ppm for 1,000 years before 1750. Since 1750, CO_2 concentration has risen, reaching 379 ppm in 2005.

Atmospheric concentrations of CO_2 have been measured directly on a routine basis since 1958. The CO_2 concentration in air bubbles trapped in ice sheets is used to determine atmospheric concentration for periods up to 700,000 years ago. For still earlier times a variety of techniques are available. The direct and ice core measurements are consistent and accurate; the techniques used for earlier times are more uncertain.

Direct, routine measurement of atmospheric CO_2 concentrations began in 1958 at Mauna Loa, Hawaii. Additional measurement points have been added since that time.[10] These measurements are extremely accurate and show a seasonal variation in CO_2 concentration, in part due to the growth and decay of plant matter over the course of the year. They also show that atmospheric CO_2 concentrations are essentially constant around the world. Prior to 1958, atmospheric CO_2 concentration was measured directly on a spot basis.[11] These results do not show a consistent pattern and their accuracy is unknown.

CO_2 is long-lived in the atmosphere and emissions during any single year are a small fraction of the total amount of atmospheric CO_2. As a result, CO_2 emissions are well mixed in the atmosphere and a ton of CO_2 emitted anywhere in the world has the same effect on atmospheric concentrations. This fact demonstrates the importance of focusing more attention on CO_2 emissions in developing countries where reducing their growth can be highly cost-effective.

The record of atmospheric CO_2 concentrations for periods before 1958 has been reconstructed using ice core data. The ice sheets that cover Antarctica, Greenland, the islands north of Canada and Russia, and the tops of some mountainous areas represent the accumulation of many thousands of years of snowfall. In very cold, dry areas, such as the interior of Greenland and Antarctica, the record is particularly good because there is little year-to-year evaporation or melt and snow compresses into annual layers of ice. These annual layers of ice contain small bubbles of air that were trapped when the snow fell. By carefully analyzing the air in these bubbles, it is possible to determine atmospheric composition over time. The longest time series of atmospheric CO_2 concentration, from the Vostok Station in Antarctica, is over 700,000 years long.[12] Ice core data on CO_2 concentration from Greenland and Antarctica are in good agreement, indicating that the measurements are accurate reflections of past conditions.

For still longer times in the past, atmospheric concentration of CO_2 is estimated by studying the balance among geochemical processes, including organic carbon burial in sediments, silicate rock weathering, and the effects of volcanic activity.[13] These studies provide estimates for atmospheric concentration of CO_2 for as far back as 400 million years. Data from geochemical studies are much less certain than data from ice cores or direct measurement.

In the far past, atmospheric concentrations of CO_2 were much higher than current levels, with one study indicating a peak of about 4000 ppm about 200 million years and a lesser peak of about 2000 ppm about 50 million years ago.[14] The ice-core data shows much lower levels, dropping to as low as 180 ppm during several periods of glaciation over the past 400,000 years. These drops were followed by rises to 300 ppm or more during inter-glacial periods.[15] Careful analyses of proxy temperature and proxy CO_2 concentration data indicates that the rise in CO_2 concentration followed the rise in temperature and was probably the result of increased plant growth and decreased ocean uptake of CO_2 during the warmer periods (See Question 16).

Ice core data show that atmospheric CO_2 concentration was constant at about 280 ppm from 1000 to about 1750. After that it began rising, very slowly at first, then somewhat more rapidly, reaching about 379 ppm in 2005.[16] Recently atmospheric CO_2 concentration has been rising at about 1.8 ppm per year or about 0.5 percent per year. This rate of increase would lead to doubling of atmospheric CO_2 concentration in about 140 years. Scenarios that reach a doubling of atmospheric CO_2 concentration in the latter half of this century are unrealistic. (This topic is discussed in more detail in Question 14.)

6. Do we know why CO_2 concentrations are rising?

There is little doubt that human activities have contributed to the recent increase in CO_2 concentration, though only about half of the CO_2 emissions that result from human activity accumulate in the atmosphere. The rest accumulates in the oceans or is stored in the biosphere.

Large amounts of CO_2 (about 700 billion metric tons per year) are continually exchanged between the atmosphere, oceans, and biosphere (the plants and animals of the world). This exchange is roughly in balance.[17] Human emissions from fossil fuel combustion, deforestation, and other land-use changes currently emit about 32 billion metric tons of CO_2 per year.[18] About half of this CO_2 is accumulating in the atmosphere. The rest accumulates in the oceans or is stored in the biosphere as enhanced plant growth. While deforestation and land-use changes result in the emission about 5.9 billion tons of CO_2 per year, the biosphere absorbs about 9.5 billion tons of CO_2 per year, a net absorption of about 3.7 billion tons of CO_2 per year.[19]

There is little doubt that humans have contributed to the recent increase in atmospheric CO_2 concentrations. Similar arguments can be made for the role of human activities in the increases observed in the atmospheric concentrations of other greenhouse gases, e.g., methane, nitrous oxide, and fluorinated compounds. However, as Question 8 examines, the relationship between these changes in the atmospheric concentrations and observed changes in climate is not simple. Many other factors affect climate and their roles must be considered in determining the effect of human emissions of greenhouse gases on climate.

7. How is global average temperature determined, how accurate are the values and what do they mean?

Global average surface temperature is the weighted average of data from thousands of weather stations around the world. Analysis indicates that this value could have total measurement errors of 0.2-0.3°C. Data analysis errors, such as the 0.15°C error NASA recently acknowledged in its U.S. temperature data for 2000-2006, can also occur. Together these errors could account for one-third to one-half of the reported increase in global average surface temperature during the past 100 years. The use of global average surface temperature as a measure

of climate change is questionable, since it tells us nothing about local and regional changes, or climate variability and extremes, which would be the cause of climate impacts.

Global average surface temperature is the area-weighted average of data from the thousands of land-based weather stations and ocean temperature measurements around the world. Developing this average is not as simple as it sounds. While weather station coverage is dense and well-maintained in the world's richer countries, it is sparse and poorly-maintained in many poorer countries, affecting the accuracy of information from these regions. In its Third Assessment Report in 2001, the IPCC expressed concern about the decline of the observational network in many parts of the world.[20] There are no indications that this decline has reversed. Also, as with any measurement, changes in the technique used to make the measurement and systematic errors affect the results. Balling (2003) estimated that these problems could lead to total errors of 0.2-0.3°C.[21]

In addition to measurement errors, reporting of global average temperature is subject to data analysis errors. For example, in August 2007, NASA reported that it was lowering the values in its data base of U.S. temperature from 2000 to 2006 by 0.15°C to correct for a data analysis error.[22]

While the combined effect of errors in measurement and data analysis has no impact on day-to-day weather reports, errors could account for a third to a half of the reported increase in global average surface temperature during the 20th century and are critical in judging the importance of these changes.

Even if we could accurately determine the change in global average temperature, there would still be questions about its value as a metric of climate change. The global average tells us nothing about regional and local changes or about climate variability and extremes that would be the causes of climate change impacts. For example, 1998 was the warmest year on record globally, but with the correction to NASA's temperature data, 1934 was the warmest year on record for the U.S. And, as will be discussed in Question 11, there is evidence that the Arctic was warmer in the 1930s than it is today. We use global average temperature rise as an indicator of climate change because, despite the uncertainties involved in its calculation, it is easier to understand than any other global climate variable and as is often the case, its political significance far exceeds its scientific merit.

8. What do we know about the relation between increases in the atmospheric concentrations of CO_2 and other greenhouse gases and temperature?

During the 20th century atmospheric concentrations of CO_2 and other greenhouse gases rose steadily, but global average surface temperature rose, then fell, then rose again in a pattern that showed no relationship to greenhouse gas concentration. There has been no significant

increase in global average surface temperature since 1998, despite a steady rise in greenhouse gas concentrations. CO_2 and other greenhouse gas concentrations were relatively constant from 1000 to 1750, but the Earth experienced a warm period from 800 to 1200, followed by a cold period from 1400 to about 1850.

Human emissions of CO_2 and other greenhouse gases rose steadily through the 20th century. These emissions resulted in increases in atmospheric concentrations of greenhouse gases. Global average temperature did not follow the same pattern. While there are problems in interpreting the surface temperature database, as shown in Figure 1,[23] global average surface temperature rose between 1910 and 1940, fell between 1940 and 1975, and has risen since 1975, until leveling off in recent years.[24]

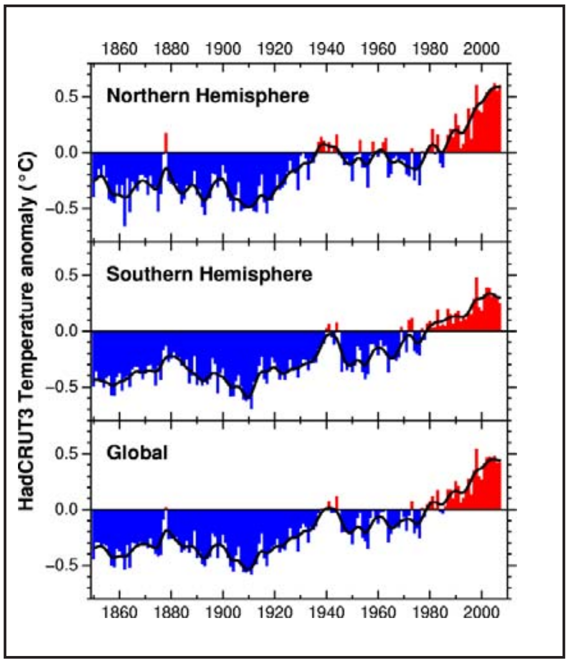

Figure 1 – Global Average Surface Temperature, 1850-2006

The fall in temperatures between 1940 and 1975 was sufficient to raise concerns in the scientific community about the start of a new ice age.[25] There has been no significant increase in global average surface temperature since 1998, despite a steady rise in greenhouse gas concentrations.

The observed pattern of surface temperature change cannot be explained by greenhouse gas emissions alone. The IPCC's Third Assessment Report concluded that the rise in temperature during the first half of the 20th century was due to solar variability,[26] while the Fourth Assessment Report was less certain, indicating disagreement on which factor was most important: solar variability, volcanic eruptions or natural variability.[27]

If greenhouse gases were the only factor affecting climate, temperature should have been stable between 1000 and 1750, followed by continual warming. Since there is insufficient direct temperature measurement data prior to 1850 to make an estimate of global temperature, climatologists use proxy measures, such as tree ring thickness, to estimate temperature.

Proxy measurements provide evidence that from about 800 to 1200, during a period called the Medieval Climate Optimum, substantial regions of the Earth were warmer than they are today. By 1400, a cold period, known as the Little Ice Age, had begun. This cold period lasted well into the 19th century. With their detailed analyses of well over 200 proxy climate studies from all parts of the world, Soon and his co-workers have shown that these two periods were global in nature and represented significant shifts in the Earth's climate.[28] These changes in climate are not explained by changes in the atmospheric concentrations of CO_2 and other greenhouse gases, since these concentrations were relatively constant during most of that period. The warming of the late 19th and early 20th century seems to be a natural recovery from the Little Ice Age.[29]

9. If temperature changes cannot be correlated with the increase in atmospheric concentrations of CO_2 and other greenhouse gases, what is causing them?

The climate system is a complex set of interactions between solar energy, clouds, particulates, water vapor and other greenhouse gases, and the absorption and reflection of solar radiation at the Earth's surface. The general nature of these interactions is understood by climate scientists, but their details are highly uncertain.

Climate is the result of a complex set of interactions between natural, and more recently, human drivers. The most important natural driver is the intensity of solar radiation reaching the Earth, which is determined by changes in the Sun itself and by shifts in the Earth's orbit and tilt. Satellite measurements indicate that the intensity of solar radiation reaching the Earth changes over the 11-year sunspot cycle. Astronomers have also determined that the Earth's orbit and tilt change in cycles that last up to 100,000 years. These cycles appear to be the cause of ice ages and interglacial periods, but are not of concern when discussing climate on short time-scales.

Solar energy reaches the Earth as short-wave energy. Not all of it penetrates the atmosphere to the surface. Atmospheric gases are essentially transparent to short-wave energy, but about one-third of solar energy is reflected by clouds and particulate material in the atmosphere. However, not all clouds and particulates reflect solar radiation; some absorb it. The two-thirds of solar energy that reaches the surface can either be absorbed by the surface or reflected. Bright surfaces, such as ice or snow, reflect a large portion of the energy that hits them; dark surfaces, such as bare soil, absorb most of the energy that hits them.

A second important natural driver of climate is the Greenhouse Effect. The Earth has to have a mechanism for getting rid of the energy that it absorbs, or else it would heat up and eventually melt. It gets rid of energy by emitting long-wave, or thermal, radiation. The oxygen, nitrogen and argon that make up 99.9 percent of the dry atmosphere are transparent to this long-wave radiation. Water vapor and some trace gases in atmosphere, such as carbon dioxide and methane, absorb long-wave radiation, heating the atmosphere. This process is known as the Greenhouse Effect[30] and the water vapor and the trace gases that can absorb long-wave radiation are known as greenhouse gases.

While the Greenhouse Effect is important, the simplistic model presented for this process may be incorrect. Particularly in the tropics, the large amount of water vapor in the atmosphere prevents thermal radiation from escaping. Heat from the surface is transported away by wind and updrafts of warm air. When this heat rises to a level where the concentration of water vapor is lower, further cooling can occur by thermal radiation.[31] This implies that we will not be able to separate the greenhouse gas contribution to warming from other factors until we can model the vertical temperature of the tropical atmosphere. Climate models do a poor job of simulating the tropical atmosphere.[32]

A third natural driver is the presence of particulate matter in the atmosphere. Some particulates, such as sulfate aerosols, reflect incoming solar radiation and have a cooling effect. Others, such as the black carbon resulting from fossil fuel combustion, absorb incoming solar radiation and have a warming effect. These effects are referred to as the direct effects of particulates. Particulates also can have indirect effects. Fine particulates act as nuclei for cloud formation. Low-level clouds reflect solar radiation and thus have a cooling effect. Some high level clouds can absorb solar radiation and have a warming effect. Understanding the role of particulates in the climate system is a major research priority because of the high level of uncertainty about their effects.

Volcanic eruptions can change the level of natural climate drivers by adding both greenhouse gases and particulates to the atmosphere. Eruptions that throw large amounts of sulfate particulate into the lower stratosphere have the largest effect. One such eruption, Mt. Pinatubo in 1992, lowered global average temperature by about 0.5°C (about 0.9°F) in the following year and affected global climate for up to three years.[33]

Human activities can also affect the climate system by adding both greenhouse gases and particulates to the atmosphere and by changing the Earth's surface, which in turn changes the amount of incoming solar radiation reflected by that surface. Combustion of both fossil and biomass fuels is the biggest human source of greenhouse gas emissions, but other activities also contribute. Cement manufacture emits CO_2. Agriculture and landfills are sources of methane emissions. Fertilizer use and nylon manufacture are sources of nitrous oxide emissions, and air conditioners and refrigerators can emit fluorine-containing greenhouse gases. Land-use changes also can affect the climate system. Clearing land for agricultural use increases the amount of dark surface that absorbs rather than reflects incoming solar energy; it also removes trees and plants that absorb and store CO_2.

The drivers that affect the climate system are not independent; they are connected by a complex set of feedbacks, the most important of which is the water vapor feedback. If the Earth warms, more water will evaporate and the atmospheric concentration of water vapor will increase. Water vapor is a greenhouse gas, so increasing its atmospheric concentration will further increase warming. However, higher atmospheric concentrations of water vapor will also result in more cloud formation, which can lead either to cooling or warming. Another feedback is the sea ice effect. If the Earth warms, some sea ice will melt. Sea ice reflects most of the incoming solar radiation that falls on it, but the ocean that is exposed when sea ice melts absorbs most of the radiation that falls on it. Shrinking sea ice creates further warming.

If there were no other changes in the climate system, climate sensitivity, which is the change in equilibrium global average temperature in response to a doubling of atmospheric concentration of CO_2, is estimated to be 1.2°C (2.2°F).[34] When feedbacks are taken into account, a high level of uncertainty is created. The IPCC now estimates climate sensitivity as lying between 2 and 4.5°C (3.6 – 8.1°F).[35]

A further complication to our understanding of the climate system is the cyclic behavior that it exhibits. One of the quickest of these cyclical behaviors, ENSO (El Niño – Southern Oscillation), which occurs on a 3-7 year period, is well known, but not well understood or predictable.

On a longer time scale, the Interdecadal Pacific Oscillation (IPO) warms the sea surface in the Pacific during its positive periods and cools it during its negative period. The IPO was negative from 1947 to 1976, roughly corresponding to the 20th century period of decrease in global average surface temperature, and positive from 1977 to at least 2005, corresponding to a period of rising global average surface temperature.[36] The IPO appears to be superimposed on the shorter ENSO cycle, which causes changes in sea surface temperatures in the tropical Pacific, but the relationship between the two is not understood. To further complicate relationships, the Pacific Decadal Oscillation affects sea surface temperatures in the northern Pacific, but it is unclear whether this is an independent cycle or merely the northern Pacific part of the IPO.

The Atlantic Ocean also exhibits cyclic behavior. The North Atlantic Oscillation (NAO) has a positive phase, which is: "… associated with cold winters over the north-west Atlantic and warm winters over Europe, Siberia and eastern Asia as well as wet conditions from Iceland to Scandinavia and dry winters over southern Europe."[37]

The NAO turned positive in about 1970 and has been strongly positive since 1985. The IPCC's AR4 added that from 1968 to 1997, the NAO accounted for 1.6° of the 3.0°C of warming observed over the Eurasian land mass during the months of January, February and March.[38] As will be discussed below, climate models do not project or back-cast these cyclical behaviors.

10. Do satellites and surface temperature measurements give different results?

Differences between temperature trends in the lower atmosphere measured by satellites and temperature trends from surface weather stations have been narrowed, but still exist. There are several estimates of both satellite and surface temperature trends. Most temperature trends measured by satellites still show less warming than most temperature trends measured at the surface, but the estimates overlap. In addition, the range of model projections of temperature trends overlaps both sets of measurements. This led the U.S. Climate Change Science Program to conclude that there was no inconsistency between the two data sets.

While there is "no inconsistency" between model results and observations, there is still no agreement. This lack of agreement is important, since it provides an empirical test of climate models, which the models fail. Climate models predict more warming in the lower atmosphere than at the surface. However, the University of Alabama at Huntsville's set of satellite data, the only set of satellite data that is fully consistent with balloon measurements, shows less warming than surface measurements.

Satellite measurements of microwave radiation from the lowest five miles of the atmosphere can be used as a proxy for surface temperature. Satellite measurements have an advantage over surface measurements in that they provide equal coverage over a very high percentage of the Earth's surface. They have the disadvantage of being indirect measurements that have to be calibrated. In addition, satellite orbits decay with time, complicating the calibration problem. And since the satellites used for these measurements have limited lifetimes, the series of satellites used to generate temperature history for several decades have to be calibrated against each other.

As has been well publicized, for many years there was a significant disagreement between surface and satellite measurements of temperature trends. Satellite measurements first showed cooling, then much less warming than surface measurements. In 2000, the National Research Council of the National Academy of Sciences concluded that the difference between the two sets of measurements was real and could not be explained.[39] A more recent paper explores the reasons for uncertainty in temperature measurements and concludes that reducing uncertainty requires a minimum of three independent data sets.[40]

Additional data and data analysis since 2000 has narrowed the difference between satellite and surface estimates of temperature change. Both sets of data have been subjected to multiple analyses and there are a range of estimates for each, which overlap. However, most analyses still show less warming in the lower atmosphere than at the surface. There is also a range of model estimates of temperature trends, which overlaps both data sets. This situation has led the U.S. Climate Change Science Program to conclude: "There is no fundamental inconsistency between … model results and observations at the global scale."[41]

While there is "no inconsistency" between model results and observations, there is still no agreement. This lack of agreement is important, since it provides an empirical test of climate models, which the models fail. Climate models predict more warming in the lower atmosphere than at the surface.[42] The University of Alabama at Huntsville's set of satellite data, the only set of satellite data that is fully consistent with balloon measurements, shows less warming than surface measurements.[43]

As a result of its reanalysis of the satellite and surface temperature data, the U.S. Climate Change Science Program concluded that further data and analyses are needed to resolve these remaining difference and to improve our understanding of the dynamics of the climate system.[44] This is an important conclusion, which unfortunately is often overlooked in the rush to proclaim the success of climate models.

11. Is the Arctic warming faster than the rest of the Earth?

Like the rest of the Earth, the Arctic is warming. The best available evidence suggests that over the 20th century, it warmed at a somewhat faster rate than the global average, but less than would be projected by climate models. Understanding temperature trends in the Arctic is complicated by limited data and the fact that conditions in the Arctic can change much more rapidly than over the rest of the Earth.

Independent of temperature measurements, there is much evidence that, along with the rest of the Earth, the Arctic has warmed over the past few decades. Satellite measurements since 1978 indicate that the area covered by sea ice at the summer minimum has declined by 7.4 [5.0 to 9.8] percent per decade[45] and there are many reports of warming and increased melting of permafrost.[46] The questions are whether this warming is unusual, and if so, can it be attributed to human emissions of greenhouse gases?

A recent study by Peter Chylek *et al*. (2006) analyzing the Greenland temperature records offers important context for evaluating concerns about the Arctic:

> Although there has been a considerable temperature increase during the last decade (1995 to 2005) a similar increase and at a faster rate occurred during the early part of the 20th century (1920 to 1930) when carbon dioxide or other greenhouse gases could not be a cause. The Greenland warming of 1920 to 1930 demonstrates that a high concentration of carbon dioxide and other greenhouse gases is not a necessary condition for period of warming to arise. The observed 1995–2005 temperature increase seems to be within a natural variability of Greenland climate.[47]

A widely quoted source for statements indicating unusual warming of the Arctic is the *Arctic Climate Impact Assessment* (ACIA)[48] published in 2004 by the Arctic Council, an intergovernmental group of the eight countries, including the U.S., with territory above the Arctic Circle. A key figure in the ACIA report shows the five-year running average for land-based weather station above 60°N. This choice of weather stations includes a large area which is south of the Arctic Circle (66.5°N), the usual boundary of the Arctic, but more importantly includes data from Siberian weather stations of questionable accuracy. Nevertheless, the pattern of average temperature rise and fall in the Arctic mimics that of the global average with a slight offset in time. Average temperature rose from about 1915 to about 1935, then fell until about 1965, then rose through the rest of the century. The changes in temperature are more abrupt, during both the rising and falling periods, than for the Earth as a whole. As discussed above in Question 8, neither the rise in temperature for the early part of the century nor the fall in temperature during the middle of the century can be explained by human activities.

ACIA makes much of the fact that for 1966-2002, the average temperature at land-based weather stations above 60°N rose 0.38°C per decade, four times the global average. 1966 represents the temperature low after three decades of cooling, so any trend based on that starting year would be exaggerated. Had one looked at a five-year running average from 1934 to 2002 for land-based weather stations above 70°N, the true Arctic, the trend line would have shown a small decline in temperature.[49]

In his testimony to the Senate Committee on Commerce Science and Transportation Subcommittee on Global Climate Change and Impacts, Dr. S.-I. Akasofu, Director of the International Arctic Research Center at the University of Alaska Fairbanks, pointed out that warming in parts of the Arctic has been occurring since the early 18th century. Dr. Akasofu's testimony also highlighted the importance of separating natural and human-induced climate change before attempting to project future climate.[50] While he focused on the Arctic, his area of expertise, this advice is equally valid for the rest of the globe.

Paleoclimatic data show that the Arctic has experienced wide swings in temperature over short periods of time independent of any possible human influence. As discussed below in Question 23, about 11,500 years ago the average temperature in Central Greenland rose 7°C in a few decades. Such rapid changes have also occurred more recently. During the decade of the 1920s, average annual temperature for coastal stations in Greenland rose 2-4°C, with peak temperatures occurring in the 1930s.[51] Paleoclimatic data from the Taimyr Peninsula above 70°N in Siberia indicates that both the 3rd and the 10th to 12th centuries were warmer than the 20th, and the warmest period of the 20th century was around 1940.[52] Taken together, these results show that the recent warming in the Arctic is not unusual, nor can it be attributed solely to human activities.

12. Is evidence of increased ocean heat storage a "smoking gun" indicating climate change?

Claims that "smoking gun" evidence for climate change was found in the oceans' increased storage of heat are surprising, since there can be no doubt that climate has been changing. While there is a debate over the amount of change and an even greater debate over the causes of that change, there is no debate about the world as a being warmer than it was a century ago. In light of this warming, the conclusions that the Earth is absorbing more energy than it is emitting and that the oceans are storing more heat are obvious.

On average, the Earth receives about 342 watts per square meter of incoming solar radiation. About a third of this radiation (107 watts per square meter) is reflected by clouds and aerosols in the atmosphere, the balance (235 watts per square meter) penetrates to the surface, where some of it is reflected and the rest absorbed.[53] All of the solar energy that reaches the surface must be emitted back into space. If not, the Earth would heat up and eventually melt. On a short term basis, the Earth can absorb more or less energy than it emits. If it absorbs more, the Earth will warm; if it absorbs less, the Earth will cool. Since the Earth has been warming for most of the past century, it is reasonable to assume that the Earth has been absorbing more solar energy than it is emitting. The fact that the oceans are warming, and their heat content increasing is not surprising. The atmosphere has been warming, on average, for a century and since the oceans exchange heat with the atmosphere, they, too, should be warming. Nor is it surprising that the Earth is committed to additional warming. The climate system has inertia and continues either warming or cooling for a period of time after the driver has been removed. This topic was discussed in the IPCC's First Assessment Report,[54] published in 1990, and well understood before that.

13. What influence does the Sun have on global climate?

The Sun provides the energy that drives the climate system. Long-term variations in the intensity of solar energy reaching the Earth are believed to cause climate change on geological time-scales. New

studies indicate that changes in the Sun's magnetic field may be responsible for shorter-term changes in climate, including much of the climate of the 20th century. Also, at least one indirect effect of solar variability, the effect that changes in the amount of UV radiation emitted by the Sun have on the warming effect of the ozone layer, has been established. A second indirect effect, the effect that changes in solar radiation have on cosmic-ray induced cloudiness, has been hypothesized, but not proven. This suggested effect is being studied both by observations and in laboratory simulations.

The Sun provides the energy that drives the climate system, but as described above, solar energy interacts with the other components of the climate system in complex ways. Clouds, particulates, and the Earth's surface can either absorb or reflect solar energy. Absorption of solar energy has a warming effect, while reflection of solar energy has a cooling effect. The climate system is further complicated by the effects of greenhouse gases which absorb solar energy that was earlier absorbed and then re-radiated by the Earth's surface. While the climate system is complex, it is certain that any change in the amount of solar energy reaching the Earth will have an effect on climate.

The brightness of the Sun, a measure of the amount of solar energy being emitted, varies with the Sun's magnetism over the 11-year sunspot cycle. In 2001, the IPCC cited satellite measurements that indicate that changes in the intensity of solar energy are too small, about $\pm$ 0.08 percent,[55] to account for climate change. Recent research, however, challenges that conclusion. In 2003, two researchers from Columbia University challenged the then consensus view that there had been no upward trend in solar irradiance in the past few decades. Their data, using a different set of satellite measurements than had been used by IPCC, showed an upward trend in the amount of energy being emitted by the Sun.[56] In 2005, two Duke University researchers,[57] using the Columbia University data, concluded that changes in solar intensity could have accounted for a minimum of 10-30 percent of the surface warming observed between 1980 and 2002. These findings are important not only in explaining recent warming, but in estimating the potential of greenhouse gases to create future warming. If recent increases in greenhouse gas concentrations have led to a smaller amount of the observed warming than calculated by climate models, future increases in greenhouse gas concentrations will also lead to less warming than calculated by climate models.

In 2004, two NASA researchers, Hathaway and Wilson, used historical data on sunspots to predict that the next solar cycle, which should peak in 2010, would have a higher than average number of sunspots, while the following cycle, which should peaks in 2023, would have a significantly lower number of sunspots.[58] Since more sunspots means a brighter sun, this would indicate increased warming due to solar intensity through 2010, followed a decrease to 2023.

About 1 percent of the energy from the Sun reaching the Earth is in the form of UV radiation. This UV radiation creates the ozone layer in the stratosphere.

Ozone is a greenhouse gas, and as a result, the ozone layer is warmer than the layers of atmosphere immediately above or below it. Since it is warmer, it radiates energy, including downward to the troposphere, thus affecting climate. Over the course of the 11-year solar cycle, the UV portion of the Sun's energy varies significantly more than total solar energy, but too little is known about the effect of this variation to quantify its impact on global average temperature.[59]

Some researchers have studied potential feedbacks that would allow small changes in solar irradiance to be amplified into larger changes in climate. One proposed mechanism involves the affect that variations in the Sun's magnetic field have on cosmic rays, which in turn affect cloudiness.

The strength of the Sun's magnetic field varies through the 11-year solar cycle. When the Sun's magnetic field is strong, it reduces the number of cosmic rays hitting the Earth. Laboratory experiments have shown that cosmic rays are one of the factors causing the formation of water droplets and clouds in the atmosphere; more cosmic rays translate to more clouds.[60] In 1997, two Danish researchers, Svensmark and Friis-Christiansen, showed that from 1983 to 1994, there was a high degree of correlation between total cloud cover and the number of cosmic rays striking the Earth, which in turn is correlated with the intensity of the Sun's magnetic field.[61] The changes in cloud cover, 3-4 percent, were large enough to explain much of climate change. Additional observational studies aimed at determining whether there is a correlation between solar intensity and cloudiness are underway, and CERN, the European Organization for Nuclear Research, will be conducting laboratory experiments to determine whether simulated cosmic rays can, in fact, create the conditions for cloud formation.[62]

14. What is known with a high degree of certainty about the climate system and human influence on it?

We know, with a high degree of certainty, that:

- **the surface of the Earth has warmed over the past century;**
- **increases in the atmospheric concentrations of CO_2 and other greenhouse gases have a warming effect;**
- **human emissions of CO_2 and other greenhouse gases are responsible for much of the increase in atmospheric concentrations of these gases; and**
- **economic growth trends, particularly in the developing nations, will increase human emissions of CO_2, at least over the next few decades because economic growth requires energy use and the dominant source of energy will remain fossil fuels.**

These facts are the basis for concern about potential human impacts on the climate system.

15. What major climate processes are uncertain and how important are these processes to understanding future climate?

Key uncertainties in our understanding of the climate system include the details of ocean circulation, the hydrological (water) cycle including clouds, and the properties of aerosols. The cumulative effect of these and other uncertainties in our understanding of the climate system is an inability to accurately model the climate system. Since models are the only way to project future climate, our lack of understanding of key climate processes means we lack the ability to accurately project future climate.

Many important climate processes are highly uncertain, including roles of:

- ocean currents,
- clouds and water vapor feedbacks, and
- aerosols

in the climate system. As a result of these deficiencies in our understanding, we lack the ability to accurately model the climate system or project its future behavior.

We know that over 90 percent of the energy in the climate system is in the ocean currents, which play an important role in distributing this energy around the globe. There is a high level of uncertainty about the mechanisms by which this occurs. In the past, ocean circulation was often referred to as thermohaline circulation. It is now referred to as meridional overturning circulation (MOC). Some scientists argue that MOC is driven by differences in the temperature and salinity of different regions of the ocean. If this is the case, then changes in global surface temperature could disrupt ocean circulation patterns, bringing climate changes to various parts of the globe.[63] However, other scientists argue that ocean circulation is driven by tidal forces.[64] This argument is supported by satellite measurements that show the Moon slowly moving away from the Earth, creating enough energy to drive the ocean currents.[65] If this argument is correct, warming will have no effect on the ocean currents.

Whichever mechanism drives ocean currents, we lack detailed understanding of their operation. The Strategic Plan of the U.S. Climate Change Science Program (CCSP), which was reviewed and endorsed by the National Research Council, documents this by stating that:

> All major U.S. climate models fail to adequately simulate several climate processes and their associated feedbacks in response to natural or anthropogenic perturbations. The oceans store and transport energy, carbon, nutrients, salt, and freshwater on multiple time scales and help to regulate and determine climate changes on a continuum of time

> scales. Yet some critical ocean phenomena, including ocean mixing and large-scale circulation features that determine the rate of storage and transport, remain as key challenges to understand, assess, and model.[66]

The CCSP Strategic Plan does not include a specific focus on ocean circulation, but treats the area as one of the uncertainties that need to be resolved. *Our Changing Planet 2007*, the CCSP's report supporting its FY 2007 budget request, includes the following statement about research in this area:

> Ocean mixing processes that are too small to be explicitly included in current climate models are an important area of research, since these processes largely determine the rate of heat uptake by the ocean.[67]

The report goes on to detail CCSP research in this area.

We know that the hydrological (water) cycle, including cloud formation and dynamics, plays an important role in the climate system, but again we lack detailed understanding of its operation. The CCSP Strategic Plan states:

> Other critical processes that are inadequately represented in climate models include atmospheric convection, the hydrological cycle, and cloud radiative forcing processes.[68]

The Strategic Plan devotes a full chapter to the water cycle and lists a number of research questions aimed at elucidating the role of clouds in the climate system.[69]

Aerosols are a third major area of uncertainty in our understanding of the climate system. Again quoting the CCSP Strategic Plan:

> Research has demonstrated that atmospheric particles (aerosols) can cause a net cooling or warming tendency within the climate system, depending on their physical and chemical characteristics. Sulfate-based aerosols, for example, tend to cool, whereas black carbon (soot) tends to warm the system. In addition to these direct effects, aerosols can also have indirect effects on radiative forcing (e.g., changes in cloud properties). When climate models include the effects of sulfate aerosols, the simulation of global mean temperature is improved. One of the largest uncertainties about the net impacts of aerosols on climate is the diverse warming and cooling influences of very complex mixtures of aerosol types and their spatial distribution. Further, the poorly understood impact of aerosols on the formation of both water droplets and ice crystals in clouds also results in large uncertainties in the ability to project climate changes. More detail is needed globally to describe the scattering and absorbing optical properties of aerosols from regional sources and how these aerosols impact on other regions of the globe.[70]

The Strategic Plan calls for addressing a number of research questions to reduce these uncertainties.

Clouds and aerosols remain major areas of uncertainty in our understanding of the climate system. *Our Changing Planet 2007* states:

> One of the largest uncertainties in the projection of future climate change is the role of aerosols.[71]

and

> Advances have also been made in understanding of the effects of aerosols on cloud formation and precipitation, although significant uncertainties remain. … A priority for this program is to continue to improve understanding of these and other cloud processes and to incorporate these improvements into climate models.[72]

The significance of clouds is illustrated by recent research suggesting that climate researchers may have incorrectly stated the temperature-cloud relationship. Clouds typically are viewed as a positive feedback, meaning that rising temperatures produce more clouds which trap more heat, and indeed this relationship carries over into most leading climate models. An examination of precipitation and cloud patterns in the tropics indicates the existence of a negative feedback mechanism instead.[73]

The cumulative effect of these and other uncertainties in our understanding of the climate system is an inability to accurately model the climate system. As the National Academies of Science observed:

> … climate models are imperfect. Their simulation skill is limited by uncertainties in their formulation, the limited size of their calculations, and the difficulty in interpreting their answers that exhibit almost as much complexity as in nature.[74]

Our Changing Planet 2007 documents the improvement made in climate models since the NAS assessment, but in describing research to improve these models stated:

> A multi-institutional project will continue in FY 2007 to attempt to reduce errors in the tropics in coupled ocean-atmosphere general circulation models. These errors affect the average SST (sea surface temperature) and precipitation as well as the structure and distribution of climate variability throughout the tropics, and *must be significantly reduced* [emphasis added] for coupled general circulation models to realize their potential for climate prediction.[75]

Since models are the only way to project future climate, our lack of understanding of key climate processes means we lack the ability to accurately project future climate.

16. What is the carbon cycle feedback and how might it affect the climate system?

The carbon cycle is the circulation of CO_2 from the atmosphere to the oceans and the biosphere (plants and animals), then back to the atmosphere. Currently, all of the CO_2 from natural sources and about half of the CO_2 from human emissions that reach the atmosphere are absorbed either by the biosphere or the oceans. Concern has been raised that the climate change will reduce the ability of the biosphere and oceans to absorb CO_2, leaving more of it in the atmosphere and creating a positive feedback between the carbon cycle and climate. Climate model projections including carbon cycle effects show atmospheric CO_2 levels in 2100 that are from 20 to 224 ppm higher than models without the carbon cycle.

The Marshall Institute questions whether the processes involved are sufficiently well-understood to make such projections. The oceans have a large additional capacity to store CO_2, but questions have been raised about the effect that climate change might have on the rate of transfer of CO_2 from the atmosphere to the oceans. The IPCC lists understanding of the processes involved as key uncertainties. Concerns have also been raised about the ability of biomass and soils to continue to absorb a constant share of an increasing level of human CO_2 emissions. The IPCC rightly warns that projections of future rates of soil and biomass CO_2 storage should be considered cautiously.

The carbon cycle is the circulation of CO_2 from the atmosphere to the oceans and the biosphere (plants and animals), then back to the atmosphere. This process is shown schematically in the following figure from WG I, Chapter 7.[76]

Currently, all of the CO_2 from natural sources and about half of the CO_2 from human emissions that reach the atmosphere are absorbed either by the biosphere or the oceans. Concern has been raised that climate change will reduce the ability of the biosphere and oceans to absorb CO_2, leaving more of it in the atmosphere and creating a positive feedback between the carbon cycle and climate. Climate model projections including carbon cycle effects show atmospheric CO_2 levels in 2100 that are from 20 to 224 ppm higher than models without the carbon cycle.[77] This large range indicates a high level of uncertainty about the processes involved. The Marshall Institute questions whether they are sufficiently well-understood to make such projections.

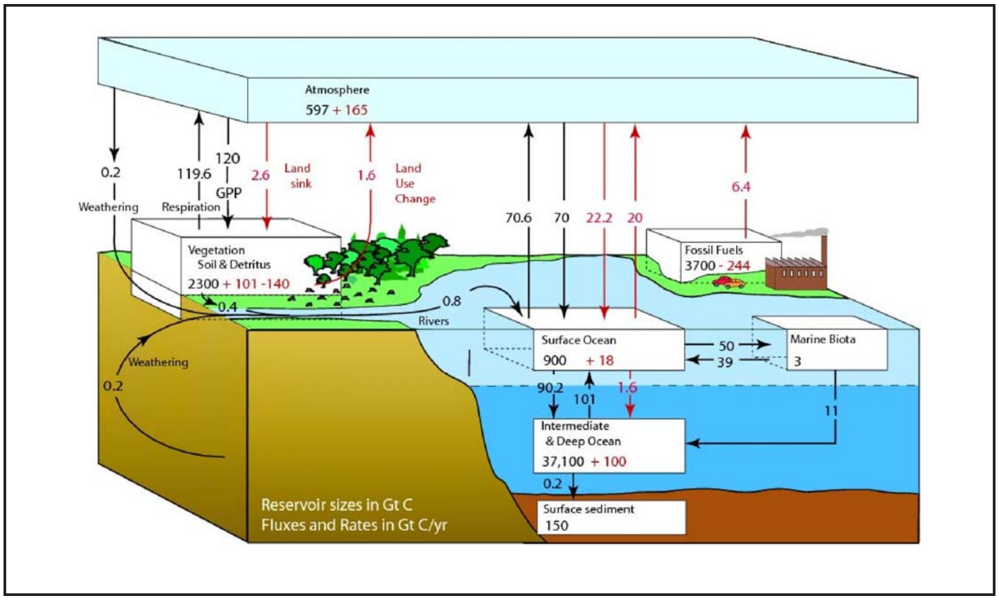

Figure 7.3. The global carbon (dioxide) cycle for the 1990s, showing main annual fluxes in GtC yr^{-1}: Pre-industrial 'natural' fluxes in black and 'anthropogenic' fluxes in red. Modified from Sarmiento and Gruber (2006), with changes in pool-sizes from Sabine et al. (2004a). The net terrestrial loss of −39 GtC is inferred from cumulative (fossil fuel emissions − atmospheric increase − ocean storage). The loss of −140 GtC from the 'Vegetation, Soil & detritus' compartment represents the cumulative emissions from land use change (Houghton, 2003), and requires a terrestrial biosphere sink of 101 GtC (in Sabine et al., given only as ranges of −140 to −80 GtC and 61 to 141 GtC respectively; other uncertainties given in their Table 1). Net anthropogenic exchanges with the atmosphere are taken from Column 5 'AR4' in Table 7.1. Gross fluxes generally have uncertainties of more than ±20 percent but fractional amounts have been retained to achieve overall balance when including estimates in fractions of GtC yr^{-1} for riverine transport, weathering, deep ocean burial, etc. 'GPP' is annual gross (terrestrial) primary production.

CO_2 reacts with sea water to create carbonate ions, which make the oceans slightly acidic and creates the carbonate needed by marine organisms for their shells. This allows the oceans to store much more CO_2 than they would be able to through simple solubility. As the oceans become more acidic through increased formation of carbonate ion, the total amount of CO_2 that can be stored in the oceans deceases. At present, the oceans are not saturated with CO_2 and have a large additional capacity to absorb CO_2.[78]

Also of concern is the rate at which CO_2 can be transferred from the atmosphere to the oceans. This is a function of ocean circulation rate and density stratification, since they affect the rate of mixing in the ocean. Wind speed over the ocean also affects transfer rate, since it determines the rate of mixing between air and water at the ocean surface. WG I concludes: "A potential slowing down of the ocean circulation and the decrease of seawater buffering with rising CO_2 concentration will suppress oceanic uptake of anthropogenic CO_2."[79]

WG I's listing of key uncertainties calls this conclusion into question:

> Future changes in ocean circulation and density stratification are still highly uncertain. Both the physical uptake of CO_2 by the oceans and changes in the biological cycling of carbon depend on these factors.

and

> The overall reaction of marine biological carbon cycling to a warm and high-CO_2 world is not yet well understood. Several small feedback mechanisms may add up to a significant one.[80]

The potential impact of climate change on the biosphere's ability to store CO_2 is also poorly understood. Plants absorb CO_2 from the atmosphere and via photo-synthesis convert that CO_2 into biomass. When plants die, most of the carbon they contain is oxidized back to CO_2 and emitted to the atmosphere. A small amount, mostly from plant roots, is stored in the ground as soil carbon. An even smaller amount, from the bodies of sea animals, is stored in the ocean floor as carbonates. Both soil carbon and carbonates can release CO_2 if they are exposed to the atmosphere.

Deforestation, forest fires, and other events that kill trees can result in an extra release of CO_2 to the atmosphere. Reforestation, either natural or managed, absorbs CO_2 from the atmosphere. Over the past century there has been extensive reforestation in Northern Hemisphere. For example, prior to 1930, most of New England, the Catskill Mountains area of New York State and much of the Southern Appalachians, including Shenandoah and the Great Smokey Mountains National Parks, had been cleared. These areas are now forest-covered. It has long been recognized that increasing atmospheric concentrations of CO_2 enhances plant growth rates through what is referred to as CO_2 fertilization, even in face of other environmental constraints.[81] This stores, at least temporarily, more CO_2. Data on deforestation, reforestation, and CO_2 fertilization rates are inexact, but WG I estimates that the net effect has been removal of 3.3 ± 2.2 billion metric tons of CO_2 per year over the 2000-2005 period.[82]

Several concerns have been about the ability of the biosphere to continue absorbing CO_2. Some researchers claim that the benefits of CO_2 fertilization decrease and eventually disappear as atmospheric CO_2 levels increase. Other researchers assert that the ability of soils to absorb carbon is similarly limited. Finally, concern has been expressed that climate change will lead to shifts in the type of vegetation covering large areas of the Earth. Of particular concern are the conversion of forests to savanna or grassland and the large scale loss of trees. While all of these effects are possible, they are poorly understood and WG I concludes:

> …projections of changes in land carbon storage are tied not only to ecosystem responses, but also to modeled projections of climate change itself. As there are strong feedbacks between these components of the Earth system, future projections should be considered cautiously.[83]

The Marshall Institute agrees with WG I's caution and believes that too little is known about the potential effects of climate change on CO_2 storage in either the oceans or the biosphere to justify the projections being made about increases in atmospheric CO_2 concentration. Better definition of the processes involved is needed before incorporating them into climate models.

17. What tools are available to separate the effects of the different drivers that contribute to climate change?

Climate scientists use coupled atmosphere-ocean general circulation models (AOGCMs or just GCMs) to try to separate the effects of the different drivers that affect the climate system. These models use mathematical equations to describe the different processes known to occur in the climate system. AOGCMs are extremely complex because they must try to model all of the processes occurring in both the atmosphere and the oceans, neither of which are homogeneous, by dividing them into small grid boxes, then modeling change in small time increments. The resulting computational demand exceeds the capacity of even the best supercomputers.

Scientists have two general sets of tools for separating the effects of variables in a complex system: statistical analysis and modeling. The climate system is too complex and climate data too limited for statistical approaches to work. This leaves modeling.

Climate models are an attempt to develop mathematical equations to describe the individual processes that are known to occur in the climate system, and then solve all of these equations simultaneously to obtain a description of the overall behavior of the system. For example, we know that the climate system must obey the fundamental laws of physics, e.g., that mass and energy must be conserved. We also know that many processes such as the reflection of radiation from the Earth's surface and the warming effect of greenhouse gases will occur. Climate models attempt to express all of these phenomena as a set of mathematical equations.

While climate models are relatively simple in concept, their use is extraordinarily complex for several reasons:

a. The climate system consists of two inter-connected sub-systems, the atmosphere and the oceans. While the importance of the atmosphere in the climate system is obvious, it is the oceans that contain the overwhelming share of the energy in the system. Change in the atmosphere can be rapid, but change in the oceans is slow. Any calculation of future climate must take this slow change in the oceans into account.

The physical processes taking place in the atmosphere and the oceans are different. The most advanced climate models, called coupled atmosphere-ocean general circulation models (abbreviated AOGCMs, or just GCMs), attempt to model all the major climate processes in both the atmosphere and the oceans.

b. Neither the atmosphere nor the oceans are homogeneous. To deal with the complexity of the real world, many climate models use a Cartesian grid approach, dividing both the atmosphere and oceans into a set of boxes or cells.[84] The most advanced climate models use a three-dimensional (3-D) approach in which the atmosphere is divided into cells that are about 100 miles square and vary in height from a few thousand feet close to the surface to several miles in the stratosphere. The oceans are also divided into cells, though the size of ocean cells need not be the same as the size of atmospheric cells.

   Conditions within a single cell are assumed to be uniform, but we know from practical experience that both the weather and climate can be very different over a distance of 100 miles, particularly in mountainous or coastal regions. Computer simulations have shown that for areas with highly diverse climate, such as Britain, it is necessary to reduce cell size by a factor of about four, to about twenty-five miles on a side, to accurately simulate some aspects of climate.[85] Reducing the length and width of cells by a factor of four increases the computing requirement by a factor of sixteen, assuming that no reduction is made in the height of the cells. This is beyond the current capacity of even the best supercomputers.

c. Running a climate model also requires a set of initial conditions, i.e., the weather conditions around the globe at a specific time. Climate is a chaotic system, which means that small changes in initial conditions can result in large changes in output conditions. One of the ways of handling this problem is to run the model using an ensemble of varying initial conditions. Output results which are relatively independent of the initial conditions are probably more robust and believable than output results which are dependent on initial conditions. While there is agreement among climate modelers that using the ensemble approach is highly desirable, the practicalities of computer capacity and availability mean that it is rarely used.

d. The climate model is run by calculating the changes indicated by the model's equations over a short increment of time – 20 minutes in the most advanced AOGCMs – for one cell, then using the output of that cell as inputs for its neighboring cells. The process is repeated until the change in each cell around the globe has been calculated. In a perfect model, results for the initial cell at the end of the calculation would be the same as those determined at the start of the calculation. However, climate models are far from perfect, so the whole process must be repeated and smoothed using standard numerical calculation techniques. Eventually, a consistent set of results is determined for the first time step. The whole process is repeated for the next time step until the model has been run for the desired amount of time.

18. How accurate are climate models?

Current climate models have many shortcomings. They cannot accurately model tropical climate or the atmosphere's vertical temperature profile. Their estimates of natural climate variability are highly uncertain, and there are large differences in the response of different models to the same forcing. No climate model has been scientifically validated.

A model's output is only as good as its equations and inputs. There is general agreement among climate scientists on the shortcomings of current climate models and their outputs. After listing recent improvement in climate modeling, the IPCC's AR4 contains the following frank assessment of the shortcomings of models:

> Nevertheless, models still show significant errors. Although these are generally greater at smaller scales, important large-scale problems also remain. For example, deficiencies remain in the simulation of tropical precipitation, the El Niño-Southern Oscillation and Madden-Julian Oscillation (an observed variation in tropical winds and rainfall with a scale of 30 to 90 days). The ultimate source of most such errors is that many important small-scale processes cannot be represented explicitly in models, and so must be included in approximate form as they interact with large-scale features. This is partly due to limitations in computing power, but also the results from limitation in scientific understanding or in the availability of detailed observations of some physical processes. Significant uncertainties, in particular are associated with the representation of clouds, and in the resulting cloud response to climate change. Consequently, models continue to display a substantial range of global temperature change in response to specified greenhouse gas forcing.[86]

The IPCC's comment about the significant differences in the response of different models to the same forcing is perhaps the most indicative of the limitations of current climate models. These differences occur because different climate models use very different mathematical representations of the same climate processes. They do this because there still is no agreement among climate scientists about the physics of some key climate processes, such as cloud formation. The quality of climate models cannot improve until there is a better understanding of these key climate processes.

Because of these shortcomings, most climate model outputs do not closely simulate conditions observed in the real world.[87] However, some climate models have been adjusted, or calibrated, to where they provide a reasonable simulation of some aspects of climate. Advocates use these simulations to claim that the models are valid representations of the climate system. They are not.

The difference between *calibration* and *validation* of models is critical. Climate models are routinely calibrated, or adjusted, to make their output look more like the real world. However, calibrating a model to produce a realistic simulation of current climate conditions does not ensure that it will provide realistic projections of future climate conditions. Realistic representations of current climate or projections of future climate require a model that has been validated and an accurate set of inputs. Validation requires that the model be developed using one set of data, then its output shown to match an independent set of data. At this time, no climate model has been validated.

The effects of model calibration can be seen in the results of research being carried out at MIT, where an on-going project is testing climate models against real world observations. Rather than trying to compare model projections of temperature and precipitation, which has to be done on a point-by-point basis around the globe, the MIT researchers have looked at some of the internal parameters which can be derived from model calculations. One such internal parameter is the rate of heat transfer to the deep ocean. This parameter is important because the faster heat is transferred to the deep ocean, the slower the surface will warm. The MIT researchers found that almost all commonly used climate models have higher rates of heat transfer to the deep ocean than seen in observations.[88] Since the models have been calibrated to match the surface temperature record of the past century, they must also contain other, compensating errors. These compensating errors will not necessarily have the same impact on projections of future climate, raising questions about the validity of those projections. See Question 1 above for an analysis of the shortcomings of climate models as scientific forecasting tools.

19. What is the basis for forecasts of large temperature increases and adverse climate impacts between 1990 and 2100?

Forecasts of large temperature increases and adverse climate impacts between 1990 and 2100 are based on the output of climate models using the IPCC SRES (*Special Report on Emissions Scenarios*) Scenarios as input. Concerns about the quality of climate model output have been discussed above. Large increases in temperature depend on three assumptions, none of which are likely:

a. No overt action is taken to control greenhouse gas emissions. However, a variety of actions, some voluntary, some mandatory, are currently being taken to control greenhouse gas emissions.

b. **Greenhouse gas emissions grow at the high end of the range of the IPCC emissions scenarios, i.e., CO_2 emissions in 2100 that were over five times current CO_2 emissions. These high emission scenarios have been broadly criticized as unrealistic.**[89]

c. **The climate system shows a high sensitivity to changes in greenhouse gas concentrations. Reports from a recent IPCC workshop indicate that while there is still a great deal of uncertainty, climate modelers now believe that the climate system is less responsive to greenhouse gas concentrations than would be required for the 6.4°C temperature rise, the upper end of projections in the IPCC Fourth Assessment Report.** [90]

Forecasts of large temperature increases and adverse climate impacts between 1990 and 2100 are based on the output of climate models. The output of a climate model is only as good as the model's ability to accurately represent the climate system and the quality of inputs used. As discussed above, climate models have many shortcomings and none has been scientifically validated. Equally critical, some of the inputs needed to project climate for the next 100 years, e.g., human emissions of greenhouse gases and aerosols, are unknowable. These will be determined by the rates of population and economic growth and technological change. Neither of these is predictable for more than a short period into the future.

Faced with an inability to predict future human emissions, climate scientists use the scenario approach. The IPCC defines a scenario as "an image of the future" and a set of scenarios as alternate images of the future.[91] Currently, the most widely used set of emissions scenarios for projecting future climate are the so-called SRES scenarios published by the IPCC in 2000 in its *Special Report on Emissions Scenarios.* This report presents emissions projections for thirty-five scenarios and recommended that climate modelers use a sub-set of six "marker" scenarios for climate projections. These marker scenarios vary dramatically in their projections of future emissions. Cumulative CO_2 emissions between 1990 and 2100, which will determine atmospheric concentration of CO_2, vary by a factor of more than two. Sulfur emissions in 2100, which will determine sulfate aerosol concentration in 2100, vary by a factor of three.[92] If all forty scenarios are considered the range of variability is much greater, a factor of more than three in cumulative CO_2 emissions and a factor of nearly eight in sulfate emissions in 2100.

In AR4, WG III defends the SRES by comparing the six SRES maker scenarios to an array of emission scenarios published after SRES. However, this comparison shows that the two highest emission SRES marker scenarios, A2 and A1FI, projected emissions in 2100 substantially above the 75 percentile of the post-SRES scenarios, adding further support to the argument that these high emission scenarios were unrealistic.[93]

In AR4 the IPCC used the full range of emissions scenarios and seven different climate models to project temperature in 2100. This exercise yielded a projection of a 1.1 – 6.4°C (2.0 – 11.5°F) temperature rise between 1990 and 2100.[94] This range of uncertainty is larger than reported by IPCC in its Third Assessment Report because a wider range of models was used and because a significant new source of uncertainty was added, climate-carbon feedback. This feedback was discussed in Question 16.

Most of the attention paid to these projections has focused on the upper end of the temperature range, since it would result in the most dramatic impacts. The upper end of the range depends on the three assumptions described at the beginning of this question, none of which are likely.

Climate models are not currently capable of accurately projecting future climate and furthermore it is clear that the upper end of their climate change projections is unrealistic.

20. How accurate are the parameters used in climate models?

The scientific level of understanding of the direct effects of greenhouse gases is high, but the scientific understanding of most other drivers of the climate system is low. Many other input parameters, e.g., carbon emissions from land-use change, are not known accurately.

The figure below from WG I[95] summarizes the effects of various drivers on the climate system. Radiative forcing is defined as the change in the amount of energy radiated downward at the top of the troposphere as a result of a change in one of the drivers of climate change. The IPCC reports change since 1750, meaning that the 100 ppm change in CO_2 concentration between 1750 and 2005 (from 280 ppm to 380 ppm) has resulted in an increase of about 1.66 Watts per square meter in the amount of energy radiated downward.

Figure SPM 2 represents a change from previous IPCC statements on radiative forcing in two ways. First, the level of scientific understanding (LOSU) for almost all drivers has been raised, though the basis for the increase is not obvious. Second, for the first time, the IPCC has been willing to sum the components of radiative forcing and come up with an overall value; a best estimate of 1.6 Watts per square meter with a 5-95 percent confidence interval of 0.6 to 2.4 Watts per square meter. Given that the LOSU for direct aerosol effects is medium-to-low and the LOSU for indirect aerosol effects is low, and that the uncertainty bands for these two effects are large relative to their best estimate values, the validity of adding radiative forcing estimates is questionable at best.

Radiative Forcing Components

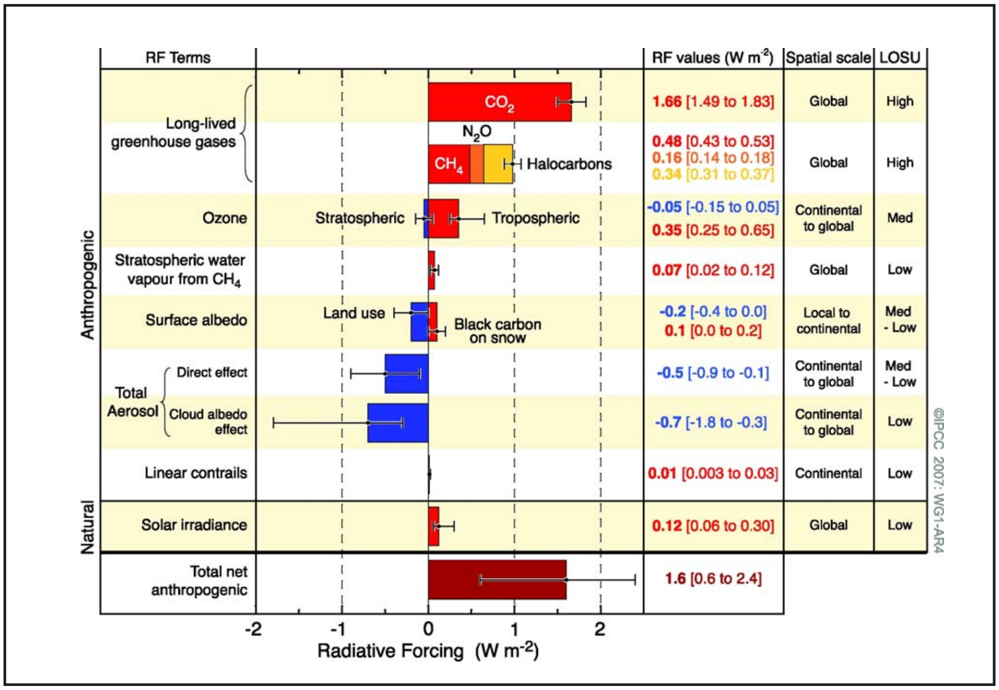

Figure SPM.2. Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. These require summing asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. The range for linear contrails does not include other possible effects of aviation on cloudiness.

21. How well have models done in "back-casting" past climate?

Model results that match global average surface temperature for the past 140 years have been published, but they are suspect because of: (1) the quality of the surface temperature data used to determine global average surface temperature; and (2) the quality of the models themselves.

In its Third Assessment Report, IPCC concluded: "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."[96] Much of the underpinning for this conclusion was found in a climate model study that attempted to "back-cast" the global average surface temperature of the past 140 years using only natural forcings (solar variability and volcanic eruptions), only anthropogenic or man-made forcings (greenhouse gas and sulfate emissions), or a combination of both natural and man-made forcings.

This approach as updated in AR4 using an average of results from multiple climate models. The key results are shown in Figure TS. 23, reproduced below.[97] The figure purports to show that natural forcings alone cannot explain the rise in global average surface temperature over the last fifty years, but when both anthropogenic and natural forcing are taken into account, the models provides a good fit to the observations. Goodness of fit is an expert judgment, and the modelers making this judgment have a bias towards saying that the models are doing a good job. Taking a somewhat more skeptical view, it appears that no individual model does a good job of backcasting global average temperature, but that by averaging a large number of model results it is possible to be closer to the observations. It is also clear that the model averages smooth the year-to-year variations in global average temperature, e.g., for the period 1915-1960. Finally, the model averages overestimate the effects of volcanic eruptions, e.g., for El Chichon and Pinatubo.

The reasons that climate models cannot do a better job of backcasting temperature are:

- the quality of the data used to determine the global average surface temperature; and
- the models used to simulate that surface temperature.

The surface temperature data base has several limitations, including:

- uneven geographic coverage – most of the data are for industrialized nations, with sparse coverage over much of the developing world;[98]
- sea surface temperature measurements that are more scattered and require more adjustment than the land-based measurements;[99] and
- numerous possible errors created by instrument calibration and siting problems.[100]

Concerns about the accuracy and meaning of climate model results were discussed above in Questions 19 and 20.

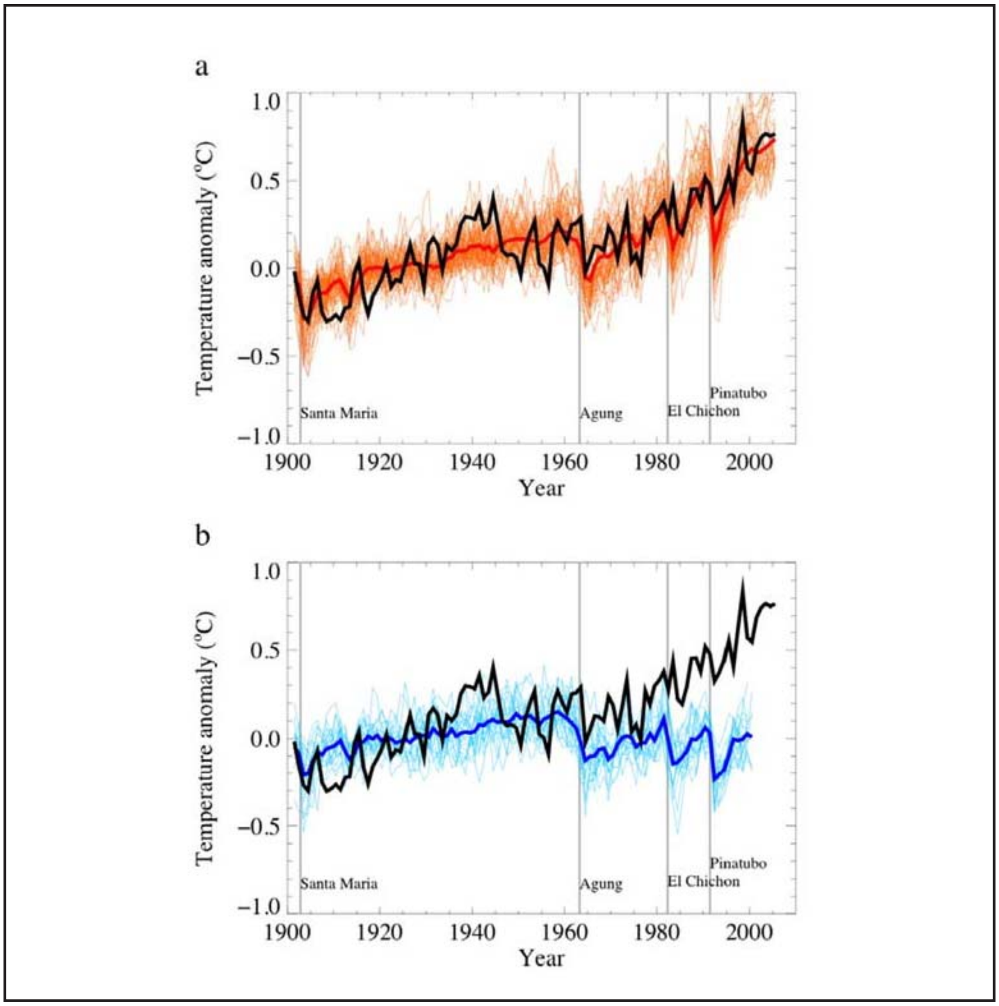

Figure TS-23. (a) Global mean surface temperature anomalies relative to the period 1901-1950, as observed (black line) and as obtained from simulations with both anthropogenic and natural forcings. The multimodel ensemble mean is shown as a thick red curve and individual simulations are shown as thin red curves. Vertical grey lines indicate the timing of major volcanic events. (b) As (a), except that the simulated global mean temperature anomalies are for natural forcings only. The multimodel ensemble mean is shown as a thick blue curve and individual simulations are shown as thin blue curves. The simulations are selected as for Figure TS-22. Each simulation was sampled so that coverage corresponds to that of the observations. Further details of the methodology for producing this figure are given in the supplementary information for chapter 9. {Figure 9.5}

22. Is the global warming over the past century unique in the past 1,000 years or longer?

The IPCC's AR4 concludes:

> **Average Northern Hemisphere temperatures during the second half of the 20th century were *very likely* higher than during any other 50-year period in the last 500 years and *likely* the highest in at least the past 1,300 years.**

***Likely* indicates a professional judgment that there is 66-90 percent chance of the statement being true; *very likely*, a greater than 90 percent chance of being true.**

The IPCC claims that this conclusion is supported by the results of twelve reconstructions of past temperature based on proxy measures such as tree rings. However, a committee of statisticians found that most studies used the same proxy data and therefore were not independent. They also criticized the paleoclimatic community for not making use of independent statistical expertise and for allowing its work to become politicized.

The best evidence indicates that the Earth experienced a warmer than average period, known as the Medieval Warm Period, between 800 and 1200, then a colder than average period, known as the Little Ice Age, between 1400 and 1850. It is highly likely that current global average temperature is warmer than it was during the Little Ice Age, and may be as warm as or warmer than it was during the Medieval Warm Period. Lacking direct measurement of temperature during either of these periods, it is unreasonable to make categorical statements about current temperatures being warmer than the past.

In its Third Assessment Report, the IPCC took a stronger position about the 20th century being warmer than the past when it concluded:

> … the increase in temperature in the 20th century is *likely* to have been the largest of any century during the past 1,000 years. It is also *likely* that, in the Northern Hemisphere, the 1990s was the warmest decade and 1998 the warmest year.[101]

The IPCC defines *likely* as having a 66-90 percent chance of being true in the expert judgment of the authors who drew the conclusion. The aforementioned adjustment to the U.S. temperature record, which resulted in 1934 once again becoming the warmest year, offers apt illustration of the caution that should be taken when considering conclusions derived from expert judgment.

Nevertheless, the main support for this conclusion was a proxy study published by Mann, *et al.*, purporting to show slowly declining surface temperature for the Northern Hemisphere between 1000 and 1900, followed by a sharp rise in temperature during the 20th century.[102] Their curve has been referred to as the "hockey stick." Subsequent scientific work has shown the Mann, *et al.* study to be deeply flawed and its conclusions unjustified.[103]

In 2003, McIntyre and McKitrick published a reanalysis of the data used by Mann, *et al.*, which showed that the "hockey stick" was based on four categories of error: collation errors, unjustified truncation and extrapolation, use of obsolete data, and calculation mistakes.[104] Correcting for these errors, they found that the proxy data showed higher temperatures for the early 15th century than for the 20th century.

Also in 2003, Soon and his co-workers published a detailed analysis of over 200 proxy studies from all parts of the world that demonstrated the existence of both a warm period (the Medieval Climate Optimum) from about 800 to about 1200 and a cool period (the Little Ice Age) from about 1400 to about 1850.[105] Data providing evidence of these warm and cool periods argues strongly again the slowly declining temperature from 1000 to 1900 shown by Mann, *et al.* The proxy data also show that many parts of the world have experienced higher temperatures at some point in the last 1,000 years than they experienced during the second half of the 20th century. Soon, *et al.* did not believe that the proxy data they collected was of sufficient quality to construct a global average temperature history for the last 1,000 years.

In 2004, von Storch, *et al.* published the results of a climate modeling study which showed that the empirical methods used by Mann, *et al*. systematically underestimated the variability of climate.[106] Von Storch, *et al*. concluded that "variations may have been at least a factor of two larger than indicated by empirical reconstructions."

In 2006, a National Academy of Science report concluded that data for the period before 1600 were too sparse to reach definitive conclusions about temperature tends. The NAS also had "less confidence" in the Mann, *et al*. conclusion than expressed by the IPCC Third Assessment Report.[107]

In AR4, WG I defended Mann's work, but also used a total of twelve studies to come to the following conclusion:

> Average Northern Hemisphere temperatures during the second half of the 20th century were *very likely* higher than during any other 50-year period in the last 500 years and *likely* the highest in at least the past 1,300 years. Some recent studies indicate greater variability in Northern Hemisphere temperatures than suggested in the TAR, particularly finding that cooler periods existed in the 12th to 14th, 17th and 19th centuries. Warmer periods prior to the 20th century are within the uncertainty range given in the TAR.[108]

Likely indicates a 66-90 percent chance of being true in the view of the authors; *very likely*, a greater than 90 percent chance of being true.

In 2006, while WG I was in the final stages of preparing its report, an *ad hoc* committee of statisticians chaired by Edward Wegman, Professor of Information Technology and Applied Statistics at George Mason University, prepared a report for the U.S. House Committee on Energy and Commerce evaluating the methodology used in developing the "hockey stick" and similar temperature reconstructions.[109] The ad hoc committee found:

> It is clear that many of the proxies are re-used in most of the papers. It is not surprising that the papers would obtain similar results and so cannot be claimed to be independent verifications.

WG I does not discuss the degree to which the twelve studies it cites use the same proxy data. However, given the scarcity of this type of information, there must be considerable re-use of the available proxies.

The ad hoc committee also found:

> As statisticians, we are struck by the isolation of communities such as the paleoclimate community that rely on statistical methods, yet do not seem to be interacting with the mainstream statistical community. The public policy implications of this debate are financially staggering and yet apparently no independent statistical expertise was sought or used.

This criticism is important, since it supports the evaluation of McIntyre and McKitrick,[110] two of the most vocal critics of the hockey stick, who found that Mann, *et al*. improperly used standard statistical techniques.

Finally, the ad hoc committee found: "… the work (of Mann, *et al*.) has become sufficiently politicized that this community can hardly reassess their public positions without losing credibility." While this explains WG I's strong defense of Mann, *et al*. in the face of the legitimate criticism of this study, it casts doubt on the scientific objectivity of WG I's assessment.

The three studies (McIntyre and McKitrick, 2003; Soon, *et al*., 2003; and von Storch, *et al*., 2004), all of which were published in the peer-reviewed literature, raise serious questions about the Mann, *et al.* study and the IPCC conclusion that was based on it. They also offer a practical example of both the scientific process and the risks of short-circuiting it. The scientific process worked as it should in the debate over the temperature history of the last 1,000 years. One group of scientists, Mann, *et al.*, published their data and analysis. The analysis had flaws and those flaws were identified by other scientists who published corrections. Scientists have long recognized that "it isn't science until it's been done twice," that is, scientific results should not be considered valid until they have been replicated or until they have been tested the way Mann, *et al.*'s results were tested.

In the case of Mann, *et al.*, the correction process took 5-6 years. For most scientific questions this would have caused no problem. However, during that time the IPCC chose to highlight the Mann, *et al.* findings, *before they had been validated through the normal scientific process*, and some policymakers made the conclusions from Mann, *et al.* a key part of the policy debate. What should have been an ordinary scientific question became a political one, to the detriment of the scientific process.

The best evidence indicates that the Earth experienced a warmer than average period, known as the Medieval Warm Period, between 800 and 1200, then a colder than average period, known as the Little Ice Age, between 1400 and 1850. It is highly likely that current global average temperature is warmer than it were during the Little Ice Age, and may be as warm or warmer than it were during the Medieval Warm Period. However, lacking direct measurement of temperature during either of these periods, it is unreasonable to make categorical statements about current temperatures being warmer than the past.

23. How much does the global climate vary naturally?

Climate scientists don't know the answer to this question, but the available data suggest that there is considerable natural variation on a time-scale of decades to centuries.

Climate varies naturally on timescales ranging from seasons to tens of thousands of years between ice ages. Knowledge of the natural variability of the climate system is needed to assess the extent of human impact on the climate system. At present there are no robust estimates for climate variability on the decades-to-centuries timescale that is essential for evaluating the extent to which human activities have already affected the climate system, and to provide the baseline of knowledge needed to assess how they might affect it in the future.

During the last 10,000 years the climate has remained relatively warm and stable, allowing humans to advance and prosper. But even during this generally warm period temperature has fluctuated significantly. About 6,500 years ago, during a period known as the Holocene Climate Optimum, the climate was warmer than it is today. There is also evidence that roughly a thousand years ago, during a period called the Medieval Climate Optimum, some regions of the Earth were substantially warmer than they are today. By 1400 A.D., a cold period, known as the Little Ice Age, had begun. This cold period lasted well into the 19th century. The warming of the late 19th and early 20th century seems to be a natural recovery from the Little Ice Age.[111]

Climate scientists do not have a good estimate of natural climate variability on a decade- or century-long timescale. In 1999, the National Research Council identified obtaining such an estimate as one of the major challenges in climate science.[112] That challenge is likely to remain unmet for a considerable period into the future. In 2006, the CCSP identified understanding of natural climate variability over periods of several years, a simpler task than understanding it on a decade- or century-long timescale, as a major challenge.[113] Yet having a good estimate of natural variability is critical in evaluating whether projected changes in future climate are significant.

The climate system varies naturally as the result of four factors:

- mathematically, the climate system exhibits "chaotic" (i.e., complex and non-linear) behavior, which means that it has limited predictability;
- important parts of the climate system exhibit oscillating behavior, e.g., the El Niño-Southern Oscillation (ENSO) cycle that repeats every 3-7 years in the tropical Pacific, and the North Atlantic Oscillation that has a cycle length of 60-80 years;
- variability in solar intensity, a key driver of the climate system, which occurs in cycles varying in length form the familiar 11-year sunspot cycle to shifts in the Earth's orbit that occur in cycles of 100,000 years; and
- the random nature of volcanic eruptions, which emit both greenhouse gases and aerosols, both of which impact the climate system.

Two approaches have been used to estimate natural climate variability, climate models and analysis of paleoclimatic data. To date, neither has provided an adequate estimate of decadal to centennial variability. Comparisons of estimates of temperature variability, calculated from climate model simulations with the actual variability observed in temperature measurements for periods of up to forty years, show that that the climate models do a poor job of simulating actual variability.[114] This poor performance is probably the result of problems in both the ocean and land-surface components of the models, including their inability to accurately simulate the ENSO cycle. Furthermore, the currently available climate models do not provide the independent evaluation needed to estimate variability. Paleoclimatic data derived from proxies such as tree rings and coral reefs are subject to error and uncertainties that limit their precision. However, the few attempts that have been made to estimate the natural variability of surface temperature on decadal to centennial timescales from paleoclimatic data indicate that natural variability is significantly greater than the changes observed during the 20th century.

More detail on research on the causes and magnitude of natural climate variability can be found in the Marshall Institute report *Natural Climate Variability.*[115]

24. What do we know about the extent of human influence on climate? To what extent has the temperature increase since 1975 been the result of human activities?

The best answer to these questions is "We don't know." Human activities have a number of potential impacts on climate. Greenhouse gas emissions contribute to warming, as do some particulate emissions. Other particulate emissions produce cooling. Land-use changes can produce either warming or cooling, depending on the change. The direct effects of greenhouse gas emissions are relatively easy to determine, but their indirect effects, through water vapor and other feedbacks, are poorly understood. The impacts of other human activities, such as particulate emissions and land-use changes, are poorly understood.

25. Will climate change abruptly?

While climate has changed abruptly in the past, meaning over decades or centuries, there is no evidence that it is likely to do so during the 21st century.

Over the last million years, the Earth's climate has shifted dramatically between ice ages and warmer periods like the present one. The glacial periods, with major advances of ice sheets, have generally lasted about 100,000 years, while the interglacial periods have lasted about 10,000 years. The transition between glacial and interglacial conditions can take place in less than a thousand years—sometimes in as little as decades. Such dramatic climatic shifts occurred near the end of the last major ice age, about 15,000 years ago. First, a brief warming occurred, and then the ice age returned for roughly a thousand years. Finally, by 11,500 years ago, the climate quickly warmed again.[116] Ice core data indicate that temperatures in central Greenland rose by 7°C or more in a few decades. Other proxy measurements indicate that broad regions of the world warmed in thirty years or less.[117]

Recently attention has focused on the potential for climate to change abruptly as the result of human activities. A common scenario is the onset of an ice age as the result of human greenhouse gas emissions.

It is now generally agreed that changes in the Earth's orbit, which result in changes in the amount of solar energy reaching the Earth's surface, are responsible for both ice ages and the warm interglacial periods between them. This theory was first popularized in the 1920s by Milutin Milankovitch, a Serbian astrophysicist. He theorized that three factors controlled the amount of solar energy reaching the Earth's surface:

- the eccentricity, or shape, of the Earth's orbit, which varies on a cycle of about 100,000 years;
- the tilt of the Earth's axis, which varies on a cycle of about 41,000 years; and
- the precession of the equinoxes, which varies on a cycle of about 22,000 years.

Milankovitch's theory was largely ignored for fifty years until a study of deep-sea sediment cores published in 1976 showed that his cycles did explain large-scale climate changes.[118] Subsequent studies of ice core samples from Greenland and Antarctica showed that in some cases over the past 250,000 years, changes in atmospheric levels of carbon dioxide followed, rather than preceded, changes in temperature.[119]

Since increases in greenhouse gases concentrations should cause warming rather than cooling, the obvious question is how could warming trigger an ice age? In response to this question, climate disaster theorists have come up with the following scenario. Warming will lead to melting of glaciers and ice sheets in Greenland and Antarctica, which, in turn, will lead to the release of large amounts of fresh water into northern and southern oceans. These releases of fresh water will shut down the thermohaline circulation (such as the Gulf Stream) that currently carries large amounts of heat from the semi-tropics to higher latitudes. Deprived of this transfer of heat, the higher latitudes will cool, triggering the next ice age. Thermohaline circulation is now referred to as meridional overturning circulation (MOC).

While this scenario may sound convincing, it is not supported by scientific fact. Carl Wunsch, an oceanographer at MIT, points out, the term thermohaline circulation, which implies that currents like the Gulf Stream are driven by differences in the temperature and salinity of sea water through the ocean, is a misnomer. These differences are not strong enough. What drives ocean currents is the tidal force exerted by the Moon.[120] Wunsch's argument is supported by satellite data indicating that the Moon is slowly moving away from the Earth creating the tidal energy necessary to drive ocean currents.[121]

Even climate scientists who disagree with Wunsch and argue that warming could weaken MOC reject the disaster scenario. In a letter to *Science*, Wallace Broecker of Lamont-Doherty Earth Observatory, who first raised concerns about the effect of warming on MOC, rejected both the speed and the severity of the disaster scenario.[122]

MOC has been studied both by observations and models. The observations do not show a recent trend in the MOC despite the warming of the last thirty years.[123] The models used have significant shortcomings, and their output should be viewed cautiously, but they indicate that it is very unlikely (<5 percent chance of being true) that the MOC will undergo an abrupt change during the 21st century.[124]

In summary, all available evidence indicates that ice ages are the result of changes in the amount of solar energy reaching the Earth's surface, not changes in greenhouse gas concentrations.

Another "abrupt" climate change scenario involves massive species extinctions as a result of climate change. For example, a paper by Thomas, *et al.* studied 1,100 species with limited geographic range and concluded that a temperature rise of 0.8-1.7°C by 2050 would commit 18 percent of them to extinction.[125] However, Thomas and his co-authors also report that climate change was implicated in the extinction of only one species during the 20th century, when according to the IPCC, global average temperature rose by 0.6°C. Is it reasonable to assume that if a 0.6°C temperature rise caused the extinction of only one species, that a 0.8-1.7°C temperature rise will cause the extinction of 18 percent of the millions of species on Earth?[126] We think not.

26. Will sea level rise abruptly?

There currently is no scientific evidence to support concern about rapid sea level rise during this century. Longer term, the dynamics of glacier and ice sheet melting are too poorly understood to make reasonable projections.

In a warming climate sea level will rise for two reasons: (1) melting glaciers and ice sheets will add more water to the oceans, and (2) the water in the oceans will expand as it warms. However, as with all parts of the climate system, there are complicating factors. Sea level also rises and falls due to geological shifts in the land underlying the ocean and the coast. The polar regions are very dry. However, if they warm, more moisture can fall as snow and result in more, not less, accumulation of ice. Finally, the amount of water that is stored in reservoirs and not allowed to flow to the ocean has to be subtracted from potential sea level rise.

In AR4, the IPCC estimates that total sea level rise was 0.17 meters (6.6 inches) during the 20th century.[127] It projects a rise of 0.18-0.59 meters (7-23 inches) between 1990 and 2100. This is a narrower range with a lower upper end that than the 0.09-0.88 meters (4-35 inches) projected in IPCC's Third Assessment Report.[128] The IPCC claims better modeling of ocean heat transfer has led to the reduced uncertainty range. The upper end of both projection ranges is based on the high emission SRES scenarios, which are dependent on three assumptions, none of which is likely (See Question 19).

Larger increases in sea level rise would require rapid melting of either the Greenland or Antarctic ice sheets. Modeling studies indicate that the Antarctic ice sheets may gain mass because of increased precipitation, contributing to a decline in sea level, during the next century. The Greenland ice sheet is projected to lose mass, but not sufficiently to cause a rapid increase in sea level. Both the increase in mass of the Antarctic ice sheet and loss of mass of the Greenland ice sheet are included in the IPCC's estimate of sea level rise to 2100.[129]

Some observations indicate faster glacier flow in parts of both Greenland and Antarctica. This would lead to more icebergs and more rapid melting of ice. The IPCC concluded that there was insufficient evidence to include this phenomenon in its sea level calculations. As indicated in Question 11, at least the Arctic underwent a period of warming between about 1920 and about 1940 equal to recent warming. This period of warming did not lead to significant sea level rise.

27. Will the number of tropical cyclones (hurricanes, typhoons) increase and will they become more intense?

It is well established that tropical cyclones will not form unless the sea surface temperature in 26°C (79°F) or higher. However, tropical cyclone formation depends on a parameter known as Convective

Available Potential Energy (CAPE), which is a function of both sea surface temperature and atmospheric circulation. The atmosphere can either collect the energy available from the warm ocean, leading to cyclone formation, or dissipate it, in which case a cyclone will not form. Since sea surface temperatures are often above 26°C, but tropical cyclones are relatively rare events, dissipative conditions predominate. The same parameter controls tropical cyclone intensity.

Projections that tropical cyclone intensity will increase in the future are based on regional climate models embedded in global climate models. This technique creates general problems, based on the mathematical approach it uses. It application to prediction of future tropical cyclones is even more problematic because the global climate models that provide the boundary conditions for the regional models do a poor job of simulating tropical climate (see Question 18).

The large number of hurricanes and weaker tropical cyclones in the North Atlantic during the 2004 and 2005 hurricane seasons has been attributed by some to an effect of human-induced climate change, but those claims are now known to have overstated the linkage (or something similar). The atmospheric conditions that lead to cyclone formation are controlled by the cyclic conditions in the various ocean basins. The positive phase of the North Atlantic Oscillation (NAO), which began in 1995, leads to more hurricane formation (See Question 9 for more detail on the NAO and other cyclic climate phenomena). El Niño also has an impact, suppressing hurricane formation in the North Atlantic. Compared with the 1970 – 1995 period, which was the negative phase of the NAO, all years between 1995 and 2005 have had above average Atlantic hurricane activity except for 1997 and 2002, which were years with strong El Niños.

Interestingly, there is a strong negative correlation between hurricane activity in the North Atlantic and typhoon activity in the North Pacific; years with high hurricane activity tend to be years with low typhoon activity, and globally the number of tropical cyclones tends to be fairly constant. This, too, argues that atmospheric circulation is a far more important factor in tropical cyclone formation that sea surface temperature.[130] The year 1997, which had strong El Niño activity and weak hurricane activity in the North Atlantic, saw the highest ever recorded number of typhoons in the North Pacific.[131] While this was "the highest ever recorded number of typhoons," care must be taken in interpreting this and other statistics for tropical cyclones. Prior to the satellite era, observation of these storms was incomplete. They were reported only if they hit land or a ship encountered them and reported their occurrence.

Another concern is that even if the number of tropical cyclones does not increase, the ones that are formed will become more intense. The IPCC's conclusion on the intensity of recent hurricanes reads:

> There is observational evidence for an increase of intense tropical cyclone activity in the North Atlantic since about 1970, correlated with increases of tropical sea surface temperatures. There are also suggestions of increased intense tropical cyclone activity in some other regions where concerns over data quality are greater. Multi-decadal variability and the quality of the tropical cyclone records prior to routine satellite observations in about 1970 complicate the detection of long-term trends in tropical cyclone activity.[132]

As WG I's text indicates, it does not have a strong basis for its conclusion. WG I depends heavily on the work of Emanuel,[133] who found that the total power dissipation of hurricanes in the North Atlantic and typhoons in the North Pacific increased beginning in the mid-1970s. However, because the total power dissipation index depends on the cube of wind speed, it is very sensitive to data quality. In fact, after first publishing his results, Emanuel had to adjust them downward to reflect this problem. Emanuel's work was challenged by other scientists, including Landsea[134] of NOAA, who resigned as an IPCC author because he felt that his views were not adequately reflected in early drafts of WG I's report. More recently, Kossin, *et al.*[135] found no upward trend in hurricane intensity in any ocean basin other than the North Atlantic. These authors note that the North Atlantic accounts for only 15 percent of global hurricane activity, calling into question the underlying assumption in Emmanuel's work that increasing sea surface temperature leads to more intense hurricanes.

William M. Gray, Professor Emeritus of Atmospheric Science at Colorado State University, is widely recognized for having developed the best predictive model for hurricane formation in the North Atlantic. Sea surface temperature is a factor in Gray's model, but not the controlling factor. Gray compares two fifty-year periods: 1900-1949 and 1956-2005. Global average surface temperature rose 0.4°C (0.7°F) between these two periods, an amount similar to the temperature rise since the 1970s, but there were fewer named storms, hurricanes, or intense hurricanes making landfall on the U.S. during the 1956-2005 period than during the earlier period. The explanation for this apparent contradiction lies in the complex way that heat is distributed in the North Atlantic Ocean. Based in his analysis of the climate system, Gray predicts that the warming of the last thirty years will come to an end in the next five to ten years and that global average surface temperatures will be *lower* twenty years from now than they are today.[136, 137]

There is also evidence of an approximately sixty-year cycle in the frequency of hurricanes in the North Atlantic, thirty years of above average storm frequency followed by thirty years of below average storm frequency. On average, the 1930s to 1960s had more hurricanes per year than the 1960s to early 1990s. Indications are that North Atlantic hurricane frequency increased starting in 1995.[138] If projections of the cycle are correct, we can expect another ten to fifteen years of higher than average numbers of hurricanes in the North Atlantic. This potential cycle raises further questions about WG I's conclusion, since what appears to be a change in hurricane intensity could simply be part of a naturally occurring cycle.

Given the questions that have been raised about Emmanuel's work, the IPCC's conclusion on hurricanes appears unjustified.

The IPCC also concludes that future hurricanes will be more intense: "… it is likely that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and heavier precipitation …"[139] These studies are based on using high resolution regional climate models (RCMs) imbedded in lower resolution global climate models. The conditions generated by the lower resolution global models are the lateral boundary conditions (LBCs) for the high resolution models. There are general problems with this approach. As the IPCC notes:

> The difficulties associated with implementation of LBCs in nested models are well documented. As time progresses in a climate simulation, the RCM solution gradually turns from an initial-value problem more into a boundary value problem. The mathematical interpretation is that nested models represent a fundamentally ill-posed boundary value problem.[140]

There are more specific problems with applying this approach in the tropics. As noted in Question 18, climate models do a poor job of simulating tropical precipitation, the El Niño-Southern Oscillation cycle and other aspects of tropical climate. Since hurricanes and typhoons are tropical phenomena, these problems are critical to the ability of climate models to accurately simulate them. The IPCC notes this problem as follows:

> The ability of RCMs to simulate regional climate depends strongly on the realism of the large-scale circulation that is provided by LBCs. Latif *et al*. (2001) and Davey *et al*. (2002) show that strong biases in the tropical climatology of AOGCMs can negatively affect downscaling studies for several regions of the world.[141]

Given these acknowledged problems, the Marshall Institute questions the validity for projections of future hurricane and typhoon intensities.

28. Will other extreme weather events, such as heat waves, increase?

If the Earth warms, some types of extreme weather events will increase, others will decrease, and still others will remain unchanged. The occurrence of what is now defined as extreme heat will increase, while extreme cold will decrease.

If the Earth warms, some types of extreme weather events will increase, others will decrease, and still others will remain unchanged. The frequency of extreme temperature events will change. What constitutes a "heat wave" is a function of location; 90°F is an extreme temperature for Boston, but not an unusual summer event in Dallas or Phoenix. If average temperature increases, the likelihood of surpassing the local definition of extreme heat will also increase. Conversely, the likelihood of surpassing the local definition of extreme cold will decrease. In time, it is likely that these definitions would be changed to reflect the change in long-term climate.

If the Earth warms, precipitation patterns will change, which will lead to a change in the frequency of floods and droughts. Some areas will see increases in either floods or droughts, other will see decreases. Since climate models do an even poorer job of projecting precipitation changes than they do for temperature changes, it is not possible to say whether the net change will be positive or negative.[142]

The last class of weather extremes is small-scale (on a global basis) events, such as tornadoes, hail and thunderstorms. The IPCC finds insufficient evidence to determine whether there has been a change in the frequency of these events,[143] and makes no projections about their future frequency.

29. How does the IPCC conduct climate change impact assessments?

IPCC WG II's projections of future impacts of climate change are based on the use of the SRES scenarios, which do not take actions to control greenhouse gas emissions into account, in unvalidated climate models to predict future climate. This projection of future climate is then used in empirical impact models, whose accuracy for extreme conditions is unknown. Impacts are assessed without taking into account that global capacity to respond to climate change will grow over the next century as a result of economic growth, adaptation and improved technology.

The projection of future impacts of climate change is presented in WG II's contribution to the IPCC Fourth Assessment report, and is based on assumptions about future climate change. Some of these findings are qualitative, based on simple logic, and relatively robust. For example, if it gets warmer, there will be a continuation in the changes in natural systems that have been observed over the last century. However, other qualitative findings, and all of the quantitative findings, are based on modeling. These findings are derived from a four step approach:

1. The IPCC's SRES scenarios were used as input to a climate model.
2. The output from the climate model was used as a prediction of future climate.
3. The predicted future climate was used as input to an empirical impact model, e.g., river run-off as a function of rainfall and temperature.
4. The difference between the output of the impact model and current conditions was assumed to be the impact of climate change.

Each of these steps is so fraught with uncertainty or unrealistic assumptions that the outputs of the exercise are meaningless.

- The SRES scenarios are baseline scenarios, i.e., they assume that no overt action is taken to control greenhouse gas emissions. This is an unrealistic assumption, since a variety of actions are currently being taken to control greenhouse gas emissions, some voluntary, some mandatory, and those in the future will be shaped by new knowledge.
- None of the climate models used by the IPCC has been independently validated. In fact, in its contribution to AR4, WG I does not discuss model validation, but uses a less demanding term: evaluation. Validation requires that a model be tested against an independent set of data. Evaluation involves discussing whatever information the model builders choose to use in support of their model. Even using the lower standard of evaluation, WG I finds that major problems exist in the design of climate models.
- Most impact models are empirical models based on an analysis of historical data. Empirical models are excellent tools, but their accuracy is limited to the range of conditions in the data used in their development. Their accuracy for conditions significantly outside that range is unknown. The temperature and rainfall conditions projected by climate models for the late 21st century are often well outside the range of conditions covered by impact models.
- The comparison of projected conditions to current conditions assumes that current conditions are well known and that they represent what future conditions would be without climate change. Both assumptions are questionable. In some cases, e.g., agricultural productivity in developed countries, the assumption that present conditions are known is valid. In other cases, e.g., species extinction rate, the assumption is not valid, because the data on current conditions is either nonexistent or suspect.

The assumption that without climate change future conditions will be the same as current conditions is incorrect in many cases. All projections of future climate are based on the assumption that the world, particularly the developing world, will use large amounts of fossil fuels and significantly raise atmospheric concentrations of CO_2. If this occurs, it will result in significant economic development in what today are under-developed countries, and those countries being far better equipped to address climate change impacts than they are today. It will also mean that they will be able to adopt lower carbon technologies, continuing the decarbonization trend that has been in progress since 1850.

The projection of future conditions also does not address the benefits of technology or take into account likely adaptations. Many projections are based on the so-called "dumb farmer" assumption, that farmers (and society in general) will continue following the same practices even if climate changes. WG II acknowledges that a wide array of technology and adaptation options is available, but emphasizes only the barriers to their use. This is an overly negative assessment. Society has a long history of adapting to changing climate, and there is no reason to believe that it will not continue to develop and apply the necessary technology to adapt to future changes in climate.

To summarize, WG II's projections of future impacts of climate change are based on the use of the SRES scenarios, which do not take actions to control greenhouse gas emissions into account, in unvalidated climate models, to predict future climate. This projection of future climate is then used in empirical impact models, whose accuracy for extreme conditions is unknown. Impacts are assessed without taking into account that global capacity to respond to climate change will grow over the next century as a result of economic growth, adaptation and improved technology.

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