

Climate Change, Global Warming, and CO₂ - A Personal Assessment

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I. - INTRODUCTION

Underlying the ongoing debate on the need, nature, and timing of public action for dealing with the consequences of climate change and global warming are the basic technical questions of whether long-term climate change and perceived global warming are real; and if so, whether they are primarily the result of anthropogenic CO₂, or whether other mechanisms, either natural or man-made, are the primary cause. Indeed, the need at all for aggressive public policy hinges on the answer to those technical questions. If action is taken, the public must have some basis to weigh the technical and environmental risks and uncertainties versus the potential benefits of such action. We, the public, are inundated with political posturing that generally assumes as a given that anthropogenic CO₂ is the primary cause of climate change and global warming. As an extreme example, Al Gore has been quoted as saying that anyone who questions that assumption is "silly." But the question remains, and very little in the way of technical information and clarification are provided to the general public to enable concerned and informed citizens to make their own judgment.

The primary source of technical information on the subject of climate change for policy-makers internationally has been the IPCC. As per their own description of their organizational history (<http://www.ipcc.ch/organization/organization.htm>):

“The Intergovernmental Panel on Climate Change is the leading body for the assessment of climate change, established by the United Nations Environment Program (UNEP) and the World Meteorological Organization (WMO) (in 1989) to provide the world with a clear scientific view on the current state of climate change and its potential environmental and socio-economic consequences. The IPCC is a scientific body. It reviews and assesses the most recent scientific, technical and socio-economic information produced worldwide relevant to the understanding of climate change. It does not conduct any research nor does it monitor climate-related data or parameters. Thousands of scientists from all over the world contribute to the work of the IPCC on a voluntary basis. Review is an essential part of the IPCC process, to ensure an objective and complete assessment of current information. Differing viewpoints existing within the scientific community are reflected in the IPCC reports.

The IPCC is an intergovernmental body, and it is open to all member countries of the UN and WMO. Governments are involved in the IPCC work as they can participate in the review process and in the IPCC plenary sessions, where main decisions about the IPCC work program are taken and reports are accepted, adopted and approved. The IPCC Bureau and Chairperson are also elected in the plenary sessions.”

The most recent evaluation of the IPCC is the 'IPCC Fourth Assessment Report: Climate Change 2007 (AR4),' which consists of the following four volumes: 'The Physical Science Basis,' 'Impacts, Adaptation and Vulnerability,' 'Mitigation of Climate Change,' and 'The AR4 Synthesis Report.' Since the target audience of the IPCC is primarily government policy-makers, the scope of their reports goes far beyond the purely technical issues of climate, to encompass the interests and issues of the government policy-makers represented by the Working Groups that produce the reports. The public will usually hear of the work of the IPCC indirectly, through references to its published works rather than directly from its reports. When IPCC technical data and analysis are presented, it is usually in the context of advocacy of policy. So how can the general public make objective judgments? The answer is that unless they are willing and able to read and assess the thousand pages of “The Physical Science Basis” report themselves (http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html), they must depend on the judgment of others. Ideally the government, the media, and other parties acting presumably in the public interest should be providing open forums for qualified experts to air their views on the technical issues, so that a full and balanced basis for judgment emerges. The reality is that our government (currently) and the media have already decided in support of anthropogenic CO₂ as the primary cause (which agrees, in essence, with the collective findings of the IPCC). They have moved beyond to shift their focus on formulating and shaping public policy to take action, and to defend and advocate their proposed courses of action.

This paper summarizes my personal effort to assess the fundamental technical questions associated with climate change, global warming, and CO₂. With apologies to those readers with limited technical background, this paper is written in a style that assumes the reader possesses

general knowledge of the subject and is conversant in the terminology and language of technical expositions. If I were attempting to write this for general audiences, it would be necessary to define and explain every aspect of the subject from scratch, and to present it in everyday language. Recognizing that I have significantly narrowed the potential audience for this paper, I have chosen, nevertheless, the shorthand technical approach as an expedient, as a means of limiting the magnitude of this undertaking to manageable proportions.

This paper is by no means a complete review of the subject, nor does it present new factual information or data, nor is it presented as an authoritative source. Rather, it reflects a logical evaluation process from which certain personal observations and conclusions emerge, thus forming an objective basis on which I form my own impressions and conclusions. This evaluation is laced with many questions and uncertainties that I am unable to answer or resolve, primarily because of my own lack of experience and knowledge in this field, but also because of the inherent uncertainties at the cutting edge of this science. In itself this is significant; certainty of overall conclusions, whether by informed laymen or qualified experts, is just not possible. I believe this is true no matter where one resides in the spectrum of technical judgments about climate change, global warming, CO₂, and their future global significance.

The remainder of this paper presents the results of my personal assessment. Although my conclusions have been formulated at the end of a logical, objective evaluation process, I present them first in the next section (Section II), with the detailed basis for these conclusions discussed in the sections that follow (Sections III, IV). Thus, for convenience, one may choose to read no further than Section II in order to find my conclusions, or may read further to understand the basis for those conclusions.

Section III presents highlights of four technical topics that provide a broad context for global climate change. Each of these topics addresses a different aspect of global climate analysis, and provides a broad, high-level basis for detailed modeling and analysis. The four topical areas presented are: Global Energy Balance (Section III.1); Solar Energy Input (Section III.2); Global Carbon Cycle (Section III.3); and Global Climate Models (Section III.4). I have accumulated much material on these four issues over the past 5+ years, even before the publication of the most recent IPCC report. The material has provided me with valuable insight as to the nature and magnitude of the global climate and modeling of it.

In an effort to construct an objective technical basis that includes expert input from all sides of the issue, I have drawn from the writings of two recognized technical experts on climate - James Hansen and Richard Lindzen. The final section of this paper (IV) presents and comments on the technical evidence taken from the writings of each technical expert.

Note as a matter of style that in the sections that follow, I distinguish between material taken directly from referenced technical sources and my personal observations and comments. The referenced material is presented in normal font, while my personal commentary is indented and italicized.

II. - KEY OBSERVATIONS AND CONCLUSIONS

This Section summarizes key highlights that have emerged from my review and assessment of the body of technical information regarding climate change. My observations and conclusions are presented in a logical sequence that starts broadly with examination of various aspects of the nature of climate, then focuses in on specific findings and assessments based on information taken from the literature and from technical experts. The content of this Section is derived from the Sections (III, IV) that follow it, but is not necessarily presented in the same order. For completeness this Section contains certain background technical information that is not found in Sections III and IV; references are given where appropriate.

Nature of Earth's Climate

Earth is a self-contained, but not closed, system consisting of the planet itself surrounded by an atmosphere. The surface of the Earth is mostly covered with water, some of which is in the form of ice and snow. The exposed land mass of the Earth's surface is populated by vegetation and other life forms including us humans. Aside from the occasional, minor intrusion of cosmic matter or the launching of man-made spacecraft, the only flows across the Earth system's boundaries are incoming solar energy in the form of short wavelength electromagnetic radiation that is either reflected or absorbed by the Earth's atmosphere and surface, and long wavelength radiation that is emitted back into space from the Earth's surface and the atmosphere. The Earth's climate system is in dynamic energy exchange. When in equilibrium the total energy coming in equals the total energy leaving, but disturbances to the equilibrium do occur. Even in equilibrium the global energy content is transferred between, absorbed by, and distributed within, the various components that make up the Earth's climate system. This distribution results in widely varying local conditions that establish the weather and the climate. Weather is a composite description of local conditions (temperature, pressure, cloud-cover, precipitation, humidity, wind speed, etc.) over the short term, while climate is the average pattern of weather over the long term.

The oceans, which cover more than ~70% of the Earth's surface, play a fundamental and complex role in regulating climate. The oceans absorb a large fraction of the incoming solar energy; ocean currents transport this heat from the equator toward the Poles. As part of a vast planetary cycle of evaporation and rainfall, the oceans are also fundamental to the movement of water around the globe.

The atmosphere is composed of layers of air, each with its own temperature patterns. Movement of air is a key factor in establishing weather and climate patterns. Air is composed of two main components - N_2 and O_2 - but also contains large amounts of water in the form of vapor and clouds that are primary contributors to weather and climate. In addition there are gases dissolved in the atmosphere - CO_2 , CH_4 , N_2O , CFC's, and O_3 - that contribute to climate.

Life-forms also play an important role in regulating the Earth's climate. Changes in the extent and type of vegetation covering the land surface can affect key climatic processes. Respiration of animals, photosynthesis of plants, and human societal activities contribute by

addition or removal of differing amounts of gases contained in the atmosphere that affect climate.

Global climate is primarily the result of solar energy being absorbed and distributed by complex, dynamic interactions within and between the atmosphere, land, and oceans over a diverse geographic landscape. The interactions of each component with the others, and the influences of each on the others are significant and pervasive. Small perturbations to the Earth's climate system, whether internal or external, global or local, natural or man-made, are inevitable. They can trigger larger variations of conditions over time, which reflects behavior characteristic of a highly nonlinear, complex system. The response of the Earth's climate system to these perturbations and variations is what gives the climate of the Earth its characteristic nature. Thus regional changes, whether cooling or warming, intense storms or drought, feast or famine, are usually the consequence of the distribution of the climate system's heat content by its constituents, but can also be the result of the disequilibrium of the total energy content of the Earth climate system. Unless it is clearly established that the Earth global energy balance is out of equilibrium, it would be misleading to characterize climate changes as "global," when they are really a manifestation of redistribution changes that occur locally and regionally.

Global Energy Balance and the Greenhouse Effect

The global energy balance is the balance between incoming energy from the Sun and outgoing heat from the Earth. The global energy balance regulates the state of the Earth's climate. When the incoming and outgoing global energy flows are in balance, then the global climate is determined by the internal distribution mechanisms of transfer, transport, and exchange that occur between the components of the Earth's climate system - the land, oceans, atmosphere, and biosphere. When the energy flows are out of balance, conditions change naturally in order to bring it back into balance. These changes may occur over days, years, decades, or centuries, depending on the characteristic time scales associated with transfer of energy content of the various components.

The Earth's atmosphere contains a number of molecules that affect the Sun-Earth energy balance. These molecules absorb electromagnetic radiation at some wavelengths but allow radiation at other wavelengths to pass through unimpeded. The atmosphere is mostly transparent to the visible light spectrum (which is why we can see the Sun), but significantly blocks (through absorption) ultraviolet radiation due to the ozone layer, and infrared radiation due to certain other molecules. This results in the greenhouse effect, which is the net trapping of some of the incoming solar radiation by the Earth's lowest atmospheric layer (the troposphere, which is from 4 to 11 miles high depending on latitude). The Earth's greenhouse effect causes the average global temperature of the Earth's troposphere to be ~33°C higher than it would be if not for the presence of the atmosphere and its contents.

If conditions change in the oceans, in the atmosphere, or on land, such that the ability of that component to absorb, transport, or transfer energy changes, then the global energy equilibrium may be disturbed. Likewise, if the incoming solar energy is changed, either due to changes in the Sun itself, or in the Earth's orbital characteristics, or in the atmospheric and

surface conditions that reflect the incoming solar energy back to space, then the global energy balance will be disturbed. In order to bring the Earth's energy flows back into balance the temperature distribution of the atmosphere will shift to either increase or decrease the outgoing radiant energy so that it equals the incoming solar energy. This shift in global atmospheric temperature conditions is what we call global warming or cooling.

Average daily solar input at the outer boundary of the atmosphere over the entire Earth is 342 w/m^2 . Of this amount, 107 w/m^2 (31%) of the incoming short wavelength solar radiation is reflected back to space by either clouds, atmospheric molecules, or the Earth's surfaces, while the remaining 235 w/cm^2 is absorbed by either the atmosphere or the Earth's surfaces. Of the 107 w/m^2 of short wavelength radiation reflected back, most is due to clouds. Although the breakdown is not given, it is estimated that scattering by clouds is much greater than molecular scattering. Thus water in the form of clouds is responsible for most of the heating-avoidance that results from the 31% of solar energy that is reflected and therefore does not heat the Earth's atmosphere.

The 235 w/m^2 of solar energy that is not reflected back to space and is absorbed by the atmosphere and the Earth's surface is emitted back into space in the form of long wavelength infrared radiation. Infrared is absorbed by water in the form of vapor and clouds, and by the atmospheric and greenhouse gases. The absorbed energy is re-radiated in all directions throughout the troposphere. However, it is only the radiation that is emitted in the vicinity of the tropopause that escapes the atmosphere. (The tropopause is the atmospheric boundary between the troposphere and the stratosphere. Going upward from the surface, it is the point where air ceases to cool with height, and becomes almost completely dry.) Of the total infrared emissions to space, 34% comes from water in either vapor or cloud form, 17% is directly radiated from the Earth's surfaces through the 'atmospheric window,' 10% comes from CO_2 , 5% comes from the other greenhouse gases, and the rest (34%) comes from emission by normal atmospheric gases. Thus water in the form of clouds and vapor contributes ~3.5 times as much as CO_2 to the global energy balance, and that doesn't include the additional water role due to reflection of incoming solar radiation. When comparing the relative influences of water and CO_2 on global heating and cooling, it is evident that water is by far the dominant contributor.

Solar Energy Input

Our Sun as a source of energy enables climate and life as we know it to exist on Earth; it has been a relatively constant source since long before modern Man has appeared. The amount of solar energy impinging on the Earth varies due to two different types of mechanisms - changes in solar magnetic activity, and variations in Earth orbital characteristics. The latter are known collectively as Milankovitch Cycles. Variations in incoming solar radiation (insolation) are potentially significant in how they affect climate.

There seems to be a consensus agreement in the scientific community that the variation of total solar irradiance due to changes in solar magnetic activity is of a magnitude that is relatively small compared to other mechanisms that perturb global climate, both natural and man-made; this mechanism does not appear to offer explanations of recent climate variations.

However, there is serious question of the nature and magnitude of other complex and multifaceted mechanisms that alter the impact of the Sun's energy. On short time scales of decades to centuries, the indirect effect of the variation in the solar wind on the influx of cosmic rays will have an impact on the ionization in the atmosphere that affects the abundance of aerosols that serve as the nuclei of condensation for cloud formation. Cloud formation is an important greenhouse mechanism; this particular cloud effect clearly should be considered in assessing current climate variations; apparently it has not been by the IPCC.

On the time scale of millenia, the Milankovitch Cycles appear to be important mechanisms that significantly affect climate, but because of their long time scale they apparently do not offer explanations of current recent variations.

Global Measures of Climate Change

The following discussion is excerpted from the Wikipedia article, "Climate Change" http://en.wikipedia.org/wiki/Climate_change.

Climate change is a change in the statistical distribution of weather over periods of time that range from decades to millions of years. It can be a change in the average weather or a change in the distribution of weather events around an average (for example, greater or fewer extreme weather events). Climate change may be limited to a specific region, or may occur across the whole Earth.

Evidence for climate change is taken from a variety of sources that can be used to reconstruct past climates. Reasonably complete global records of surface temperature are available beginning from the mid-late 1800s. However, the instruments themselves, their number, and their locations have changed during the period since 1800. For those that have remained fixed, local land use has often changed. This means various corrections need to be made to the data. Changes in the network locations is especially important since the Earth's surface is not in equilibrium, and an average of temperatures taken at different points in a non-equilibrium system does not constitute an average temperature of the system.

For earlier periods, most of the evidence is indirect - climatic changes are inferred from changes in proxies, which are indicators that reflect climate, such as sea level change and glacial geology.

The only direct measure of global conditions on Earth that reflects on whether or not global warming is real is the temperature history of the Earth. The following summary of highlights of this history is excerpted from the Wikipedia article, "Temperature Record." http://en.wikipedia.org/wiki/Temperature_record

The figures below (Figures II-1, II-2) show the instrumental record of global average near-surface temperatures since 1850, and since 1980. Following the common practice of the IPCC, the zero on this figure is the mean temperature from 1961-1990. Of particular note is the magnitude of the average increase that has occurred since 1880, ~1°C, and since 1980 the

average has increased $\sim 0.4^{\circ}\text{C}$. It is evident that the Earth has been in a global warming trend since 1980, with consistently record-high average temperatures logged in the past decade. However, the more recent data show the increasing temperature trend in the past decade has flattened compared to the decade prior. It is noted also that the 1°C increase of the global temperature since 1880 is small ($\sim 3\%$) compared to the total greenhouse temperature effect of 33°C .

Historical temperature histories have been constructed using a variety of methods and sources of data (See Figure II-3). Proxy reconstructions extending back 2,000 years have been performed, but reconstructions for the last 1,000 years are supported by more and higher quality independent data sets. These reconstructions indicate: global mean surface temperatures over the last 25 years have been higher than any comparable period since AD 1600, and probably since AD 900; there was a Little Ice Age centered around AD 1700; there was a Medieval Warm Period centered around AD 1000, though the exact timing and magnitude are uncertain and may have shown regional variation. It is interesting to note that the average temperature of the Medieval Warm Period (not the temperature anomaly) was very close in magnitude to that which has been experienced recently.

Figure II-1 - Global Surface Temperature Anomaly From 1880

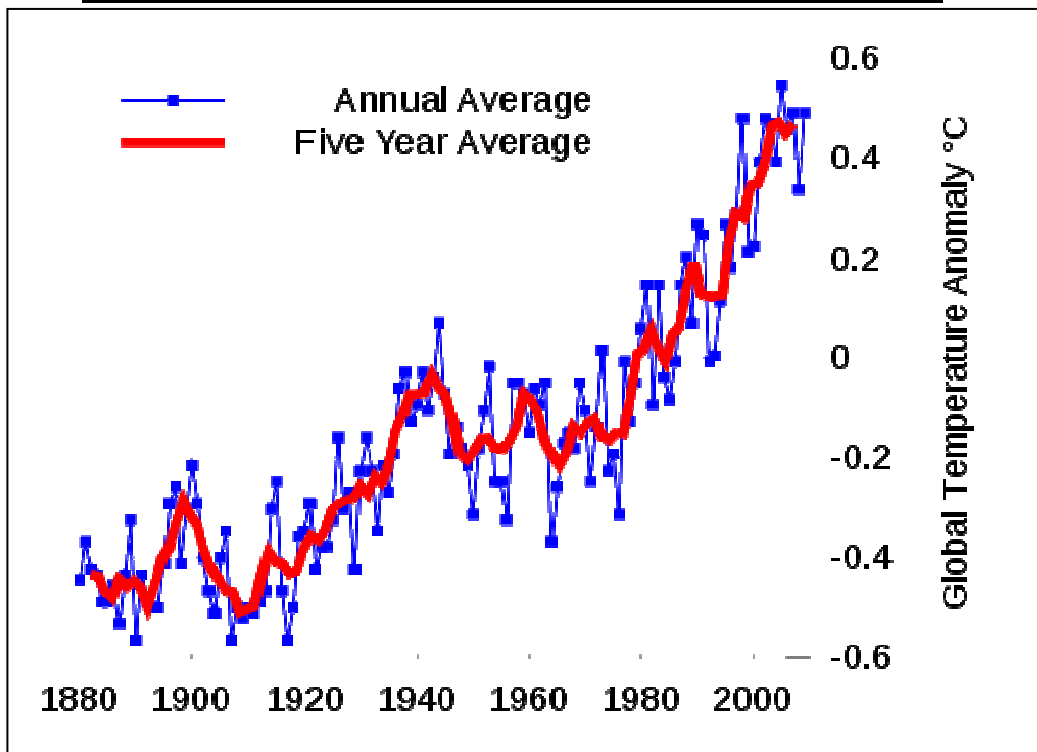


Figure II-2 - Global Surface Temperature Anomaly Since 1980

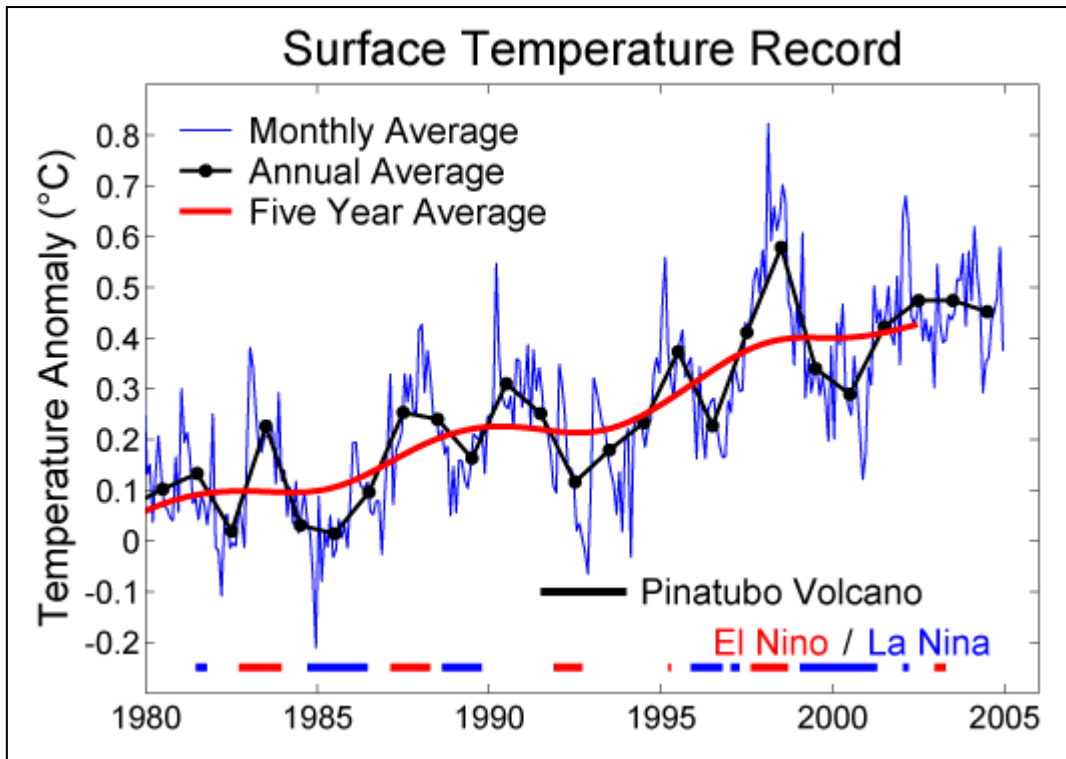
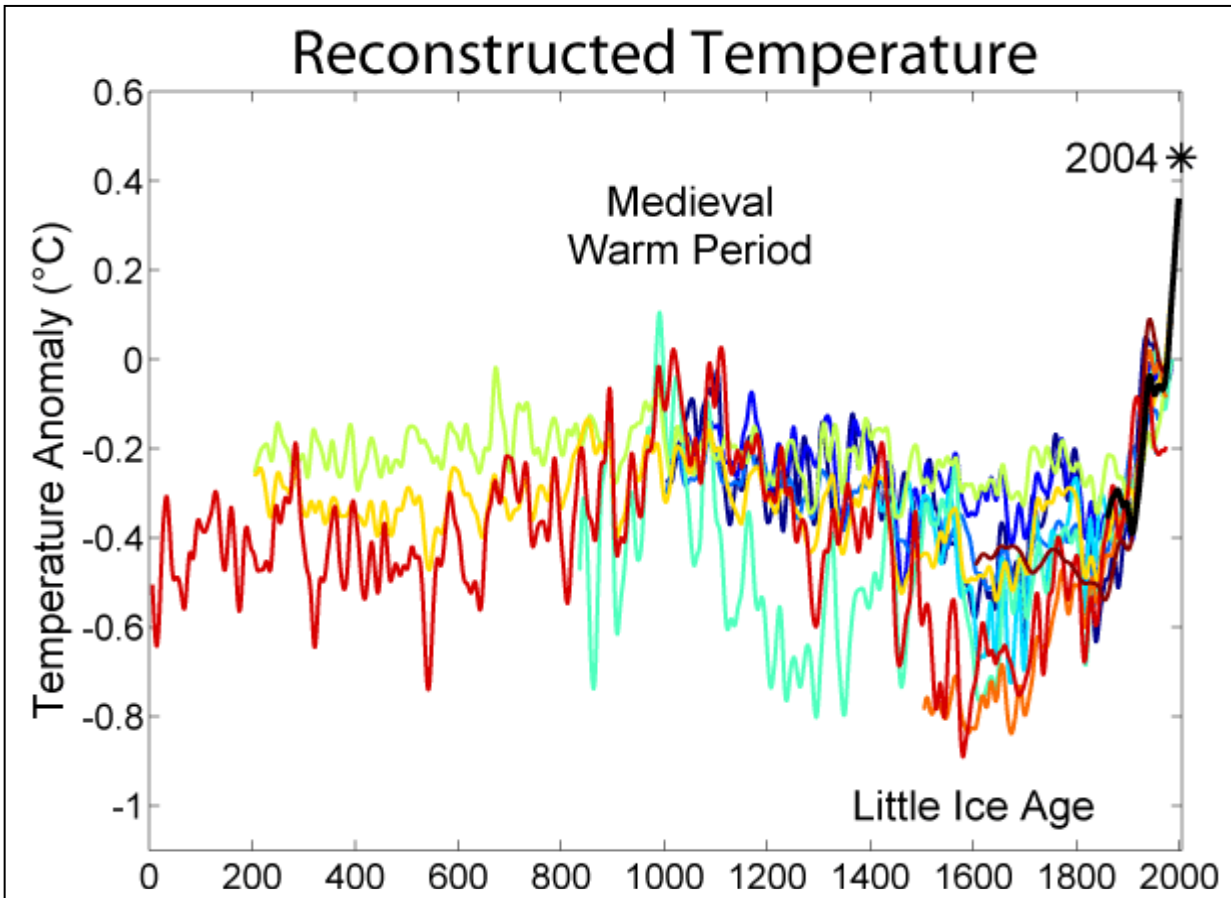


Figure II-3 is a comparison of 10 different published reconstructions of mean temperature changes during the last 2000 years. More recent reconstructions are plotted in redder colors, older reconstructions appear in bluer colors. An instrumental history of temperature is also shown in black. The medieval warm period and little ice age are labeled at roughly the times when they are historically believed to occur, though it is still disputed whether these were truly global or only regional events. The single, unsmoothed annual value for 2004 is also shown for comparison.

Figure II-3 - 2000 Year Reconstructed Temperature Anomaly



The following discussion is excerpted from the Wikipedia article, "Current Sea level Rise" http://en.wikipedia.org/wiki/Current_sea_level_rise .

Current sea level rise has occurred at a mean rate of 1.8 mm per year for the past century, and more recently, during the satellite era of sea level measurement, at rates estimated near 2.8 ± 0.4 to 3.1 ± 0.7 mm per year (1993–2003). (See Figure II-4.) Current sea level rise is due significantly to increased water temperatures and atmospheric warming. Increasing temperatures result in sea level rise by the thermal expansion of water and through the addition of water to the oceans from the melting of mountain glaciers, ice caps and ice sheets. (See Figure II-5.) At the end of the 20th century, thermal expansion and melting of land ice contributed roughly equally to sea level rise.

Figure II-4 - Sea Level Rise Since 1880

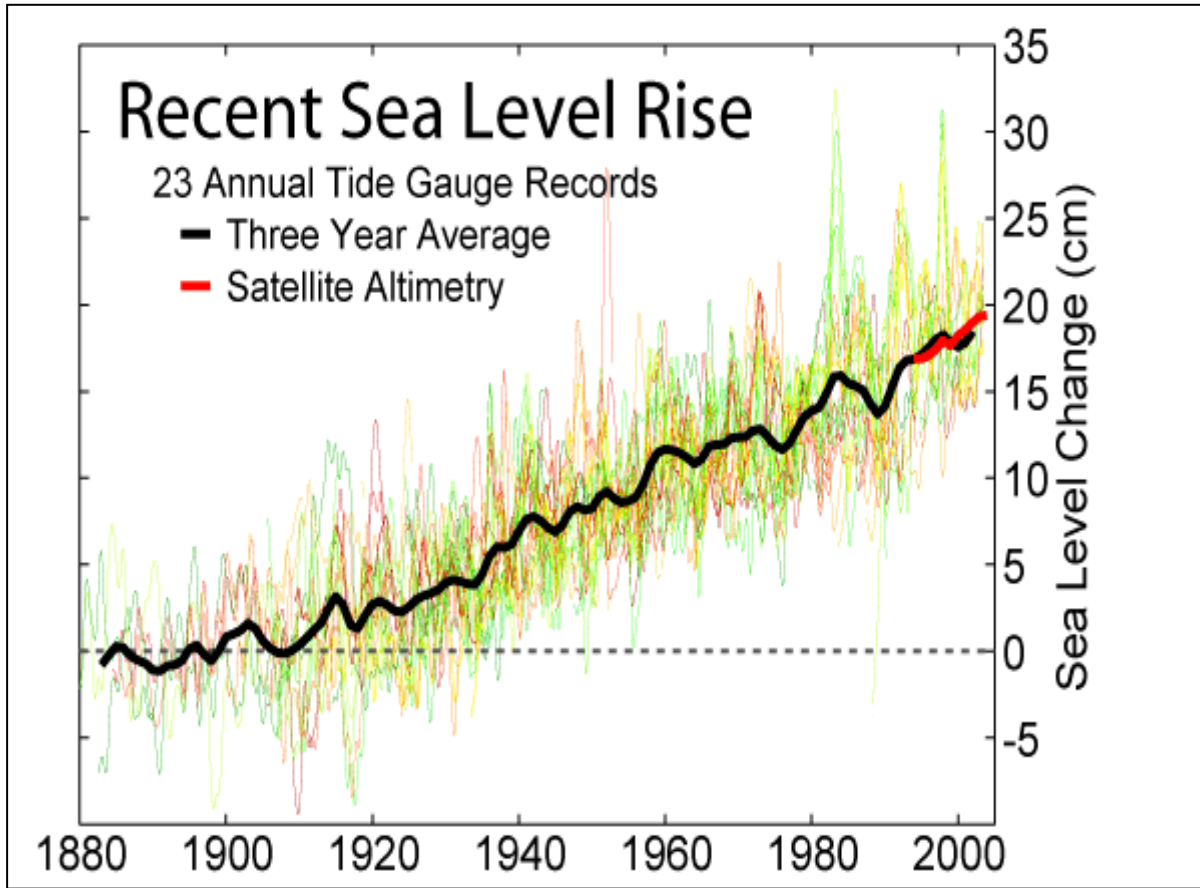
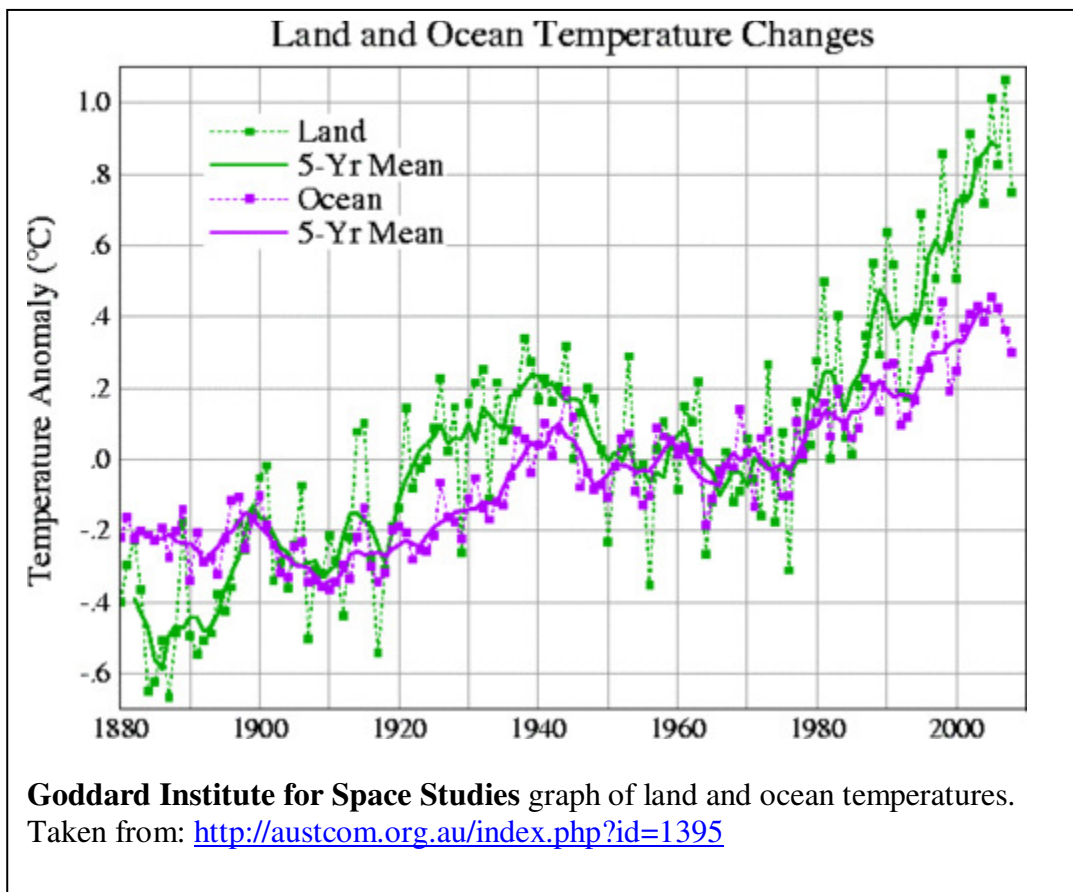


Figure II-4 shows the change in annually averaged sea level at 23 geologically stable tide gauge sites with long-term records. The thick dark line is a three-year moving average of the instrumental records. These data indicate a sea level rise of ~18.5 cm from 1900-2000. For comparison, the annually averaged satellite altimetry data are shown in red. These data indicate a somewhat higher rate of increase than tide gauge data, however the source of this discrepancy is not obvious. It may represent systematic error in the satellite record and/or incomplete geographic sampling in the tide gauge record.

Figure II-5 - Land and Ocean Temperature Anomalies Since 1880



Goddard Institute for Space Studies graph of land and ocean temperatures.
Taken from: <http://austcom.org.au/index.php?id=1395>

Each year about 8 mm (0.3 inch) of water from the entire surface of the oceans falls into the Antarctica and Greenland ice sheets as snowfall. If no ice returned to the oceans, sea level would drop 8 mm every year. To a first approximation, the same amount of water appeared to return to the ocean in icebergs and from ice melting at the edges.

Ice shelves float on the surface of the sea and, if they melt, to first order they do not change sea level. Likewise, the melting of the northern polar ice cap which is composed of floating pack ice would not significantly contribute to rising sea levels. Because they are fresh, however, their melting would cause a very small increase in sea levels, so small that it is generally neglected.

If small glaciers and polar ice caps on the margins of Greenland and the Antarctic Peninsula melt, the projected rise in sea level will be around 0.5 m. Melting of the Greenland ice sheet would produce 7.2 m of sea-level rise, and melting of the Antarctic ice sheet would produce 61.1 m of sea level rise. The collapse of the grounded interior reservoir of the West Antarctic Ice Sheet would raise sea level by 5–6 m.

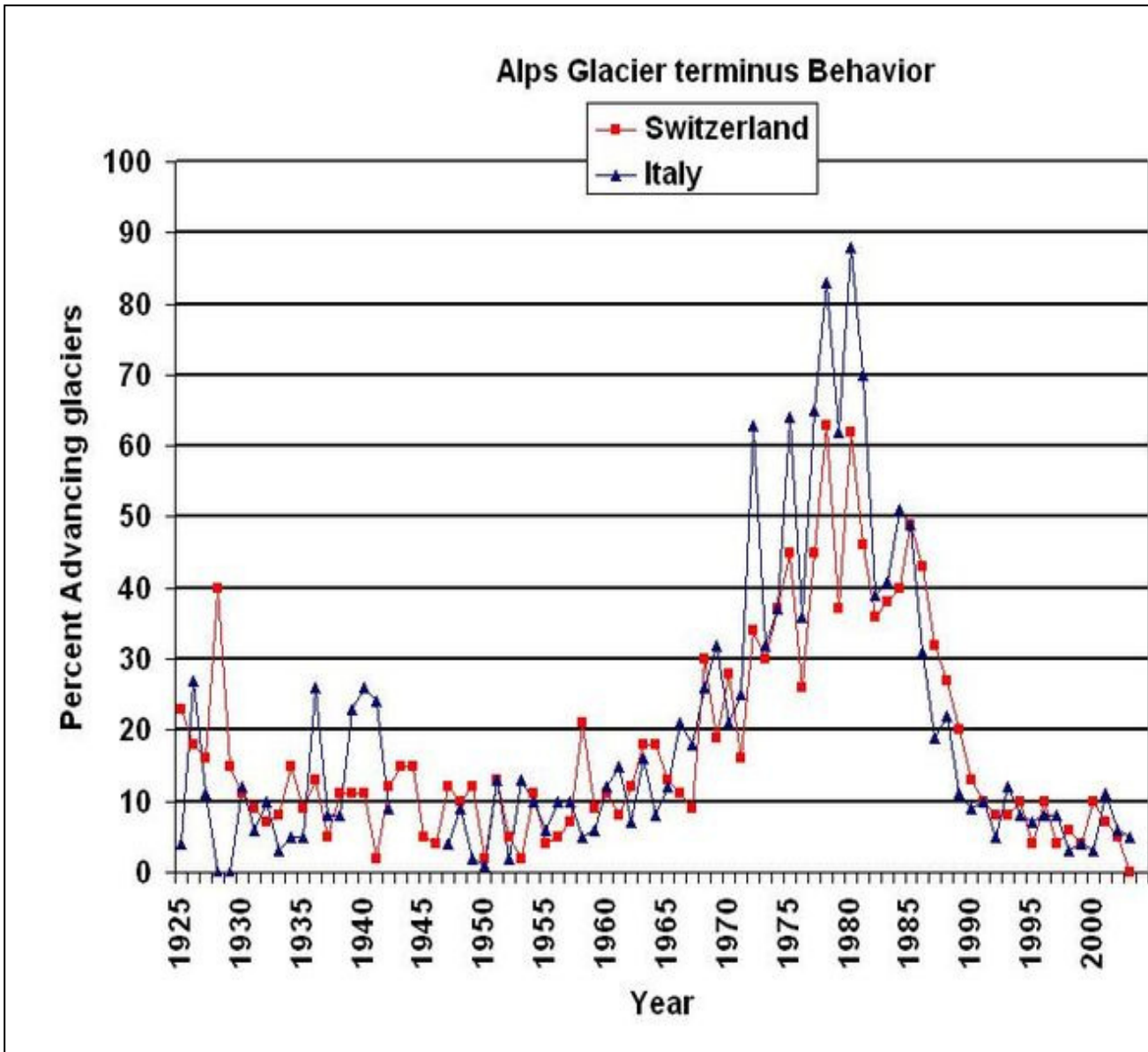
The interior of the Greenland and Antarctic ice sheets has been (as of 2009) sufficiently high (and therefore cold) enough that direct melt there cannot cause them to melt in a time-frame less than several millennia; therefore it is likely that they will not, through melting of the interior, contribute significantly to sea level rise in the coming century.

Climate changes during the 20th century are estimated from modeling studies to have led to contributions of between -0.2 and 0.0 mm/yr from Antarctica (the results of increasing precipitation) and 0.0 to +0.1 mm/yr from Greenland (from changes in both precipitation and runoff).

The following discussion of glaciers is excerpted from the Wikipedia article, "Climate Change" http://en.wikipedia.org/wiki/Climate_change.

Glaciers are considered among the most sensitive indicators of climate change, advancing when climate cools and retreating when climate warms. Glaciers grow and shrink, both contributing to natural variability and amplifying externally forced changes. A world glacier inventory has been compiled since the 1970s, initially based mainly on aerial photographs and maps but now relying more on satellites. This compilation tracks more than 100,000 glaciers covering a total area of approximately 240,000 km², and preliminary estimates indicate that the remaining ice cover is around 445,000 km². The World Glacier Monitoring Service collects data annually on glacier retreat and glacier mass balance. From these data, glaciers worldwide have been found to be shrinking significantly, with strong glacier retreats in the 1940s, stable or growing conditions during the 1920s and 1970s, and again retreating from the mid 1980s to present. (See Figure II-6). It would appear that glacial changes are not a recent phenomena, and that glacial and interglacial cycles are evidence of both short- and long-term climate history.

Figure II-6 - Glacier Growth in Alps Since 1925



Climate Modeling and Uncertainties

Global climate models are the mathematical tools with which investigators attempt to represent, analyze, and predict the climate conditions of Earth as a result of the complex, dynamical interactions of its atmosphere, oceans, and land in response to solar heating.

Climate models are systems of differential equations based on the basic laws of physics, fluid motion, and chemistry. To “run” a model, scientists divide the planet into a 3-dimensional grid, apply the basic equations, and evaluate the results. Atmospheric models calculate winds,

heat transfer, radiation, relative humidity, and surface hydrology within each grid and evaluate interactions with neighboring points.

A General Circulation Model (GCM) is a mathematical model of the general circulation of a planetary atmosphere or ocean and based on the Navier-Stokes equations on a rotating sphere with thermodynamic terms for various energy sources (radiation, latent heat). These equations are the basis for complex computer programs commonly used for simulating the atmosphere or ocean of the Earth. GCMs and global climate models are widely applied for weather forecasting, understanding the climate, and projecting climate change. These computationally intensive numerical models are based on the integration of a variety of fluid dynamical, chemical, and sometimes biological equations. An atmospheric GCM (AGCM) and an oceanic GCM (OGCM) can be coupled together to form an atmosphere-ocean coupled general circulation model (CGCM or AOGCM). With the addition of other components (such as a sea ice model or a model for evapotranspiration over land), the AOGCM becomes the basis for a full climate model. Within this structure, different variations can exist, and their varying response to climate change may be studied. AOGCMs represent the pinnacle of complexity in climate models and internalize as many processes as possible. However, they are still under development and uncertainties remain. They may be coupled to models of other processes, such as the carbon cycle, so as to better model feedback effects.

The reliability and accuracy of climate models to represent historical climate trends can be significantly sharpened by use of data-fitting, empirical correlation, and correction factors that enable the computational results to fit actual historical data. The most sophisticated and advanced climate models all use these techniques in varying ways. The fundamental and important question in assessing climate models is whether these same historical empirical corrections can be applied to predicting future climate trends correctly, completely, and accurately. In order to explore this question, it is useful to consider the uncertainties that have been identified by those in the modeling business.

The oceans constitute the largest fraction of the Earth's exposed surface, the largest heat sink for absorption of incoming solar energy, and the second-largest source and sink for the greenhouse gas CO₂. Circulation patterns and temperature distributions that exist in the oceans of Earth are complex and known to change significantly; the reasons for such changes are not fully understood, nor are they predictable except on an empirical and statistical basis. According to Hansen (Section IV.1), "Until instrumental issues are resolved and good heat storage data is obtained for the entire ocean, it is not possible to infer the net climate forcing (of the ocean) acting on Earth." Thus the global circulation models are inherently limited in how they represent the oceans.

The atmosphere is the primary locus of interactions that determine the characteristics of weather and climate. The most significant uncertainties and shortcomings in modeling of the atmosphere are the way in which atmospheric temperatures gradients are related to surface temperatures, the modeling of cloud formation, and the way in which aerosols are modeled.

Atmospheric temperature distribution is mostly due to the structure of the mean circulation in the troposphere. The primary circulation pattern (Hadley cell) dominates the tropical atmosphere, with rising motion near the equator, poleward flow 10-15 kilometers above the surface, descending motion in the subtropics, and equatorward flow near the surface. The vertical temperature profile of the troposphere is strongly affected by the greenhouse effect. According to Lindzen (Section IV.2), a fundamental shortcoming of the modelers' approach to representing the global greenhouse effect in the General Circulation Models (GCM) used by the IPCC is the oversimplified and inappropriate way in which global surface temperatures are related to atmospheric temperature gradients in altitude and latitude.

Both Hansen and Lindzen acknowledge that climate models do not adequately represent the formation of clouds in the atmosphere and their role in reflecting incoming solar energy and emitting outgoing energy. According to Lindzen, "As all assessments of the IPCC have stated, the models simply fail to get the clouds right. . . The treatment of clouds (in IPCC models) involves errors an order of magnitude greater than the forcing from a doubling of CO₂."

Aerosols in the atmosphere play a significant role as one of the climate forcings that determine the greenhouse effect. Hansen's table of climate forcing mechanisms (Section IV.1) lists two different aerosol effects (reflection of incoming solar, and affecting cloud formation) as larger in magnitude than CO₂ but opposite in sign, with an uncertainty that is larger than any of the other listed forcing mechanisms. In reference to the way in which climate models are interpreted, Lindzen points out that, "The claim that models cannot account for recent warming without external forcing is held to imply the role of human forcing. To be sure, current models can simulate the recent trend in surface temperature, but only by invoking largely unknown properties of aerosols and ocean delay in order to cancel most of the (calculated) greenhouse warming." And according to Hutton (Section III.2), climate models only include the direct effects of variations in the direct solar radiation without the feedback effects of cosmic rays on clouds.

The approximations, limitations, and uncertainties evident in global climate models do not negate their value and utility for certain types of analysis. Apparently they are very useful for analyzing climate past history, and they should be useful for doing short-term (i.e. weather) predictions. However, climate, by definition, is long-term. It would appear inappropriate to use such models for predicting the consequences of small perturbations to climate (i.e. forcings) that have large uncertainties associated with them when the models are limited in their ability to represent these perturbing mechanisms.

Another uncertainty that could affect the use of global climate models to predict long-term climate change is the inherent mathematical nature of the models. Modern global climate models are highly non-linear; strong feedback mechanisms are pervasive. Such systems possess an inherent character in which small perturbations can cause large and even chaotic response. Unless the modelers can identify and avoid regimes of such behavior, it is extremely difficult to believe that their predictions can be trusted to predict the climate of the future, particularly over a years-to-decades time frame. And it would seem equally unlikely that averaging the predictions

of a multiplicity of different models used by different investigators, such as the IPCC has done, can eliminate or even mitigate this inherent uncertainty.

The Carbon Cycle

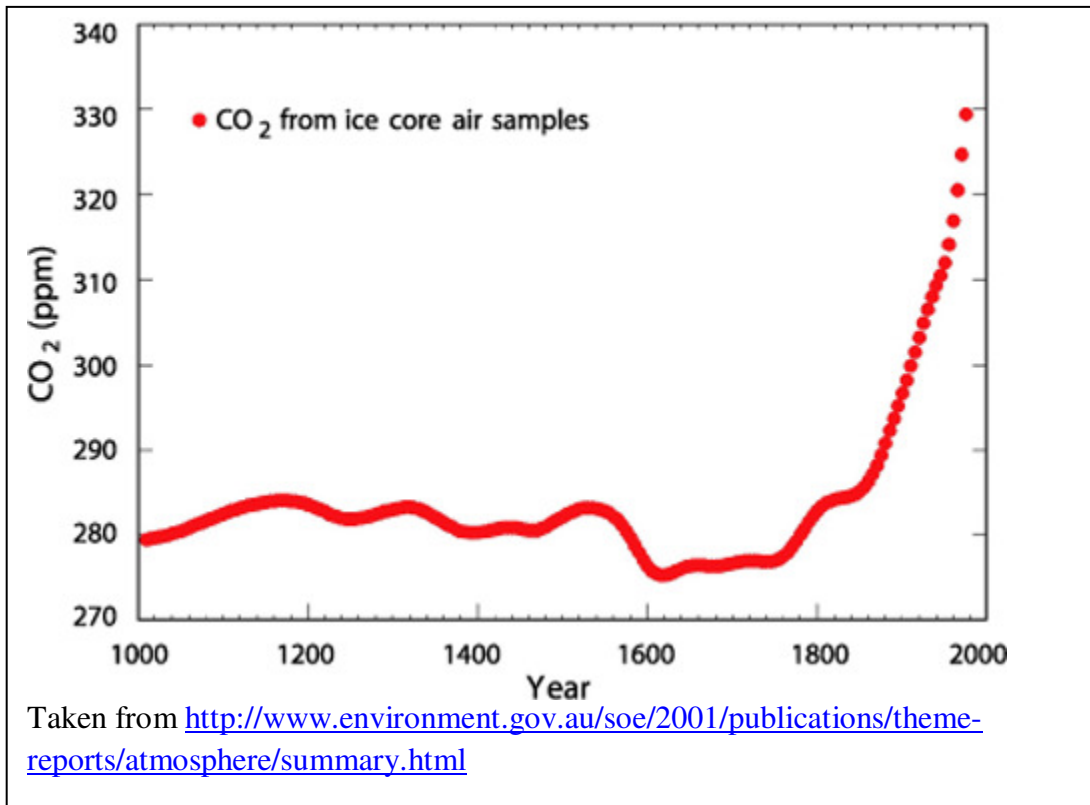
Carbon dioxide (CO₂) plays a role in the context of global climate as one of several gases in the atmosphere that contribute to the greenhouse effect. But more broadly it is a key component in one of the most important cycles of the Earth because of its role in sustaining life. The carbon cycle allows for carbon to be recycled and reused throughout the biosphere and all of its organisms. One small contributor to the global carbon cycle is the burning of fossil fuels. It is generally believed that this anthropogenic process is responsible for the buildup of CO₂ in the atmosphere over the past century. Since the concentration of CO₂ in the atmosphere is the net result of multiple dynamical processes of exchange, it is useful to examine the magnitude of all the exchange mechanisms to determine how likely it is that anthropogenic CO₂ production is the cause of CO₂ buildup.

The global carbon cycle is usually thought of as five major reservoirs of carbon interconnected by pathways of exchange. These reservoirs are: the atmosphere (which contains CO₂); the terrestrial biosphere (which is usually defined to include fresh water systems and non-living organic material such as soil carbon); the oceans (including dissolved inorganic carbon and living and non-living marine biota); the sediments (including fossil fuels); and the Earth's interior (carbon from the Earth's mantle and crust is released to the atmosphere and hydrosphere by volcanoes and geothermal systems).

The Earth's carbon cycle is in a constant state of motion. Through processes that take place over seconds, days, years and millennia, carbon is constantly being transferred between all the various reservoirs. But what does this mean for the size of any given reservoir? In particular, consider the atmosphere. The fact that carbon moves into and out of the Earth's atmosphere doesn't, on its own, mean that the carbon content of the atmosphere must change. In fact, if the amount of carbon moving into the atmosphere is matched by an equal amount of carbon moving out, the carbon content remains constant. But the CO₂ content of the atmosphere clearly has increased (See Figure II-7). In 1850, atmospheric CO₂ concentration was about 280 ppm, and today it is about 385 ppm. There appears to be an imbalance in the carbon cycle that is resulting in an increased content of the atmosphere.

As part of the carbon cycle, ~90 Billion tons of C (GtC) in the form of CO₂ are released annually from the oceans into the atmosphere, primarily as a result of evaporation and dissolution in warmer climes. It is estimated that ~92 GtC is taken up by the oceans, primarily by solution in the colder climes. According to these estimates, there is an imbalance in the oceans' intake and release of CO₂. What is the cause of this imbalance, and how sensitive is it to ocean currents and temperature conditions? Apparently available data and models cannot answer that question accurately.

Figure II-7 - 1000 Year Atmospheric CO₂ Concentration History



An additional 120 GtC are released annually to the atmosphere as a result of plant, animal, and soil respiration. An equal amount is estimated to be taken up by photosynthesis in the vegetation that populates the land and the oceans. The 6 GtC of CO₂ produced annually by human activities is very small compared to the inputs from land and ocean. Anthropogenic production amounts to less than 3% of the total carbon emitted into the atmosphere.

Houghton's assessment of the major contributors to the carbon budget for the atmosphere (See Section III.3) shows that an unaccounted-for carbon sink of magnitude 2.9 GtC/year is needed to explain the measured annual rate at which CO₂ is building up in the atmosphere. Unidentified mechanisms and uncertainties in CO₂ release and absorption in the major pathways of the carbon cycle could easily be of the same magnitude as the annual anthropogenic CO₂ production rate, and could account for the buildup of CO₂.

A popular theory presented by CO₂ advocates is that the measured decline of the ratio of C¹⁴/C¹² in the atmosphere over the past 45 years proves that the burning of fossil fuels is the primary cause of the increase in CO₂ concentration in the atmosphere. The theory is based on the following logic: Before the industrial revolution, the C¹⁴/C¹² ratio was approximately at steady state. With the onset of industrialization and changing land use, the natural carbon cycle was perturbed. The burning of fossil fuels released carbon in the form of CO₂ that is devoid of C¹⁴, so-called dead carbon, therefore the atmospheric ¹⁴CO₂ was being diluted and the ratio C¹⁴/C¹²

decreased (termed the Suess effect). Since actual measurements of C^{14}/C^{12} over the past 45 years reveal the trend expected with the Suess effect, the theory appears to be confirmed. However, nuclear bomb testing in the 50's and 60's increased the C^{14} level by 70-fold, peaking in 1965. With the cessation of atmospheric testing the ratio has been decreasing exponentially ever since. Investigators point out that "The large bomb spike has masked the effects of fossil fuel burning and changing land use on the $^{14}CO_2$ distribution, making it difficult to directly assess their impact." Thus the current trend in decreasing C^{14}/C^{12} ratio cannot be taken directly as evidence that fossil fuel burning is the main cause of atmospheric CO_2 increase.

The IPCC Position

The following history of the contributions of The Intergovernmental Panel on Climate Change (IPCC) is taken from http://www.ipcc.ch/organization/organization_history.htm

"The IPCC is 21 years old, and experienced very important outcomes. Its latest major report, 'Climate Change 2007', clearly brought to the attention of the world the scientific understanding of the present changes in our climate and led the organization to be honored with the Nobel Peace Prize at the end of that same year.

It is in fact because of the need of broad and balanced information about climate change that the organization was created back in 1989. It was set up by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) as an effort by the United Nations to provide the governments of the world with a clear scientific view of what is happening to the world's climate. The initial task for the IPCC as outlined in the UN General Assembly Resolution 43/53 of 6 December 1988 was to prepare a comprehensive review and recommendations with respect to the state of knowledge of the science of climate change; social and economic impact of climate change; and possible response strategies and elements for inclusion in a possible future international convention on climate.

The scientific evidence brought up by the first IPCC Assessment Report of 1990 unveiled the importance of climate change as a topic deserving a political platform among countries to tackle its consequences. It therefore played a decisive role in leading to the creation of the United Nations Framework Convention on Climate Change (UNFCCC), the key international treaty to reduce global warming and cope with the consequences of climate change.

Since then the IPCC has delivered on a regular basis the most comprehensive scientific reports about climate change produced worldwide, the Assessment Reports. It also continued to respond to the need of the UNFCCC for information on scientific technical matters.

The IPCC Second Assessment Report of 1995 provided key input in the way to the adoption of the Kyoto Protocol in 1997. The Third Assessment Report came out in 2001, and the Fourth in the course of 2007."

A substantial fraction of "The Physical Science Basis," the first volume of the IPCC Fourth Assessment Report, is devoted to reporting and assessing changes in human and natural

drivers of climate, observations of changes in climate, and understanding and attributing climate change. In highlighting the most robust of their findings and key uncertainties (http://www.ipcc.ch/publications_and_data/ar4/wg1/en/tssts-6.html), the following are directly excerpted as most relevant to this paper:

Changes in Human and Natural Drivers of Climate

- Current atmospheric concentrations of CO₂ and CH₄, and their associated radiative forcing, far exceed those determined from ice core measurements spanning the last 650,000 years.
- Fossil fuel use, agriculture and land use have been the dominant cause of increases in greenhouse gases over the last 250 years.
- It is virtually certain that anthropogenic aerosols produce a net negative radiative forcing (cooling Influence) with a greater magnitude in the Northern Hemisphere than in the Southern Hemisphere.
- From new estimates of the combined anthropogenic forcing due to greenhouse gases, aerosols and land surface changes, it is extremely likely that human activities have exerted a substantial net warming influence on climate since 1750.
- Solar irradiance contributions to global average radiative forcing are considerably smaller than the contribution of increases in greenhouse gases over the industrial period.
- The full range of processes leading to modification of cloud properties by aerosols is not well understood and the magnitudes of associated indirect radiative effects are poorly determined.
- The causes of, and radiative forcing due to stratospheric water vapor changes are not well quantified.
- The geographical distribution and time evolution of the radiative forcing due to changes in aerosols during the 20th century are not well characterized.
- Land surface properties and land-atmosphere interactions that lead to radiative forcing are not well quantified.

Observation of Changes in Climate

- Global mean surface temperatures continue to rise. Eleven of the last 12 years rank among the 12 warmest years on record since 1850.
- Increases have occurred in the number of heavy precipitation events.
- Droughts have become more common, especially in the tropics and subtropics, since the 1970s.
- While changes in large-scale atmospheric circulation are apparent, the quality of analyses is best only after 1979, making analysis of, and discrimination between, change and variability difficult.
- Multi-decadal changes in diurnal temperature range (DTR) are not well understood, in part because of limited observations of changes in cloudiness and aerosols.
- The amount of ice on the Earth is decreasing. There has been widespread retreat of mountain glaciers since the end of the 19th century. The rate of mass loss from glaciers and the Greenland Ice Sheet is increasing.

- Ice thinning occurred in the Antarctic Peninsula and Amundsen shelf ice during the 1990s. Tributary glaciers have accelerated and complete breakup of the Larsen B Ice Shelf occurred in 2002.
- There are insufficient data to draw any conclusions about trends in the thickness of Antarctic sea ice.
- Limited knowledge of basal processes and of ice shelf dynamics leads to large uncertainties in the understanding of ice flow processes and ice sheet stability.
- The global temperature (or heat content) of the oceans has increased since 1955.
- Global average sea level rose during the 20th century. There is high confidence that the rate of sea level rise increased between the mid-19th and mid-20th centuries. During 1993 to 2003, sea level rose more rapidly than during 1961 to 2003.
- Thermal expansion of the ocean and loss of mass from glaciers and ice caps made substantial contributions to the observed sea level rise.
- The observed rate of sea level rise from 1993 to 2003 is consistent with the sum of observed contributions from thermal expansion and loss of land ice.
- The rate of sea level change over recent decades has not been geographically uniform.
- Limitations in ocean sampling imply that decadal variability in global heat content, salinity and sea level changes can only be evaluated with moderate confidence.
- Global average sea level rise from 1961 to 2003 appears to be larger than can be explained by thermal expansion and land ice melting.

Understanding and Attributing Climate Change

- Greenhouse gas forcing has very likely caused most of the observed global warming over the last 50 years. Greenhouse gas forcing alone during the past half century would likely have resulted in greater than the observed warming if there had not been an offsetting cooling effect from aerosol and other forcings.
- It is extremely unlikely (<5%) that the global pattern of warming during the past half century can be explained without external forcing, and very unlikely that it is due to known natural external causes alone. The warming occurred in both the ocean and the atmosphere and took place at a time when natural external forcing factors would likely have produced cooling.
- It is likely that anthropogenic forcing has contributed to the general warming observed in the upper several hundred meters of the ocean during the latter half of the 20th century. Anthropogenic forcing, resulting in thermal expansion from ocean warming and glacier mass loss, has very likely contributed to sea level rise during the latter half of the 20th century.
- A substantial fraction of the reconstructed Northern Hemisphere inter-decadal temperature variability of the past seven centuries is very likely attributable to natural external forcing (volcanic eruptions and solar variability).
- Confidence in attributing some climate change phenomena to anthropogenic influences is currently limited by uncertainties in radiative forcing, as well as uncertainties in feedbacks and in observations.
- Attribution at scales smaller than continental and over time scales of less than 50 years is limited by larger climate variability on smaller scales, by uncertainties in the small-scale details of external forcing and the response simulated by models, as well as uncertainties

in simulation of internal variability on small scales, including in relation to modes of variability.

- Despite improved understanding, uncertainties in model-simulated internal climate variability limit some aspects of attribution studies. For example, there are apparent discrepancies between estimates of ocean heat content variability from models and observations.
- Lack of studies quantifying the contributions of anthropogenic forcing to ocean heat content increase or glacier melting together with the open part of the sea level budget for 1961 to 2003 are among the uncertainties in quantifying the anthropogenic contribution to sea level rise.

The "Robust Findings and Key Uncertainties" section of the IPCC first volume, "The Physical Science Basis" also includes findings and uncertainties of their projections of future changes in climate. However, because their projections are based on global climate models, only those findings and uncertainties associated with model evaluation are included in this excerpted summary, not the projections themselves.

Model Evaluation

- Climate models are based on well-established physical principles and have been demonstrated to reproduce observed features of recent climate and past climate changes. There is considerable confidence that AOGCMs provide credible quantitative estimates of future climate change, particularly at continental scales and above. Confidence in these estimates is higher for some climate variables (e.g., temperature) than for others (e.g., precipitation).
- Confidence in models has increased due to:
 - improvements in the simulation of many aspects of present climate, including important modes of climate variability and extreme hot and cold spells;
 - improved model resolution, computational methods and parameterizations and inclusion of additional processes;
 - more comprehensive diagnostic tests, including tests of model ability to forecast on time scales from days to a year when initialized with observed conditions; and
 - enhanced scrutiny of models and expanded diagnostic analysis of model behavior facilitated by internationally coordinated efforts to collect and disseminate output from model experiments performed under common conditions.
- A proven set of model metrics comparing simulations with observations, that might be used to narrow the range of plausible climate projections, has yet to be developed.
- Most models continue to have difficulty controlling climate drift, particularly in the deep ocean. This drift must be accounted for when assessing change in many oceanic variables.
- Models differ considerably in their estimates of the strength of different feedbacks in the climate system.
- Problems remain in the simulation of some modes of variability, notably the Madden-Julian Oscillation, recurrent atmospheric blocking and extreme precipitation.
- Systematic biases have been found in most models' simulations of the Southern Ocean that are linked to uncertainty in transient climate response.

- Climate models remain limited by the spatial resolution that can be achieved with present computer resources, by the need for more extensive ensemble runs and by the need to include some additional processes.

In essence, the consensus technical view of the IPCC Fourth Assessment Report boils down to this:

1. The global mean surface temperature is always changing. Over the past 60 years, it has both increased and decreased. Over the past 30 years it has probably increased by about $0.6^\circ \pm 0.15^\circ\text{C}$. In other words, there has been some global mean warming.
2. CO₂ is a greenhouse gas, and its increase contributes to warming. It is, in fact, increasing, and a doubling would increase the greenhouse effect by about 2%.
3. There is good evidence that man is responsible for the recent increase in CO₂, although climate itself, as well as other natural phenomena, can also cause changes in CO₂.
4. Greenhouse gas forcing has very likely caused most of the observed global warming over the last 50 years.
5. It is extremely unlikely (<5%) that the global pattern of warming during the past half century can be explained without external forcing, and very unlikely that it is due to known natural external causes alone.
6. Global projections of future changes in climate based on global climate models predict equilibrium climate sensitivity is likely to be in the range 2°C to 4.5°C with a most likely value of about 3°C; it is very unlikely to be less than 1.5°C. (Climate sensitivity is a metric used to characterize the response of the global climate system to a given forcing. It is broadly defined as the equilibrium global mean surface temperature change following a doubling of atmospheric CO₂ concentration.)
7. There is considerable confidence that global climate models provide credible quantitative estimates of future climate change, notwithstanding their many simplifications, uncertainties and shortcomings.

There is no question that the IPCC has performed an important service in assembling data on global climate and convening international forums for reviewing and assessing those data. By its own admission, the IPCC scope goes beyond the purely technical, to address social and economic impact of climate and possible response strategies. However, in keeping with the scope of this paper, this section is limited only to present the technical approach and key technical findings of the latest IPCC assessment report. Though the social, economic, and political aspects have not been addressed in this paper, it is apparent that the technical conclusions reached by the IPCC Technical Working Group form the basis for a strong consensus position that advocates international political action. Given: the individual national self-interests of the nations represented in the IPCC; the role of participating governments in approving the IPCC findings and recommendations; and the historical social, economic, and political differences that distinguish the industrialized nations from the developing nations and the third world; one can only speculate on whether the technical judgments and conclusions of the IPCC have been influenced by foregone national agendas, and whether the IPCC documentation of these conclusions has been written to reflect those influences.

A Personal Perspective

My perspective on the question of global warming starts with my acceptance as a given of the observations and measurements of changes in climate, and changes in human and natural drivers of climate, as reported by the IPCC. These records indicate a small increase in global temperature and a relatively large increase in CO₂ content of the atmosphere. Like Richard Lindzen (Section IV.2), along with others who may question the interpretation of these facts, I would concur that "If you increase the concentration of greenhouse gases in the atmosphere, you will also increase the Earth's average temperature. It is indisputable that we have increased greenhouse gas concentrations in the air as a result of human activity, and it's also indisputable that over the last few decades average global temperatures have gone up." However, it is generally recognized that "There are many sources of climate change, and that profound climate change has occurred many times both before and after man appeared on the Earth; given the ubiquity of climate change, it is implausible that all change is for the worse. Moreover, the coincidence of increasing CO₂ and the small warming over the past century hardly establishes causality."

A glaring reality that challenges the IPCC perspective is that the average global surface temperature of the Earth has increased only 0.8°C since 1880, and about 0.4°C in the past 30 years. Those are very small changes compared to the overall greenhouse effect, which causes a 33°C increase in global atmospheric temperature. Thus we are faced with the challenges of explaining the response of the Earth's climate system to small variations, local and global, natural and man-made, in order to understand whether the observed large variations in local and regional weather and climate conditions are a "normal" manifestation of the internal dynamics of the Earth climate system, or whether they are attributable to this small global warming.

To interpret the nature of observed variations in the Earth climate system, the IPCC has depended on global climate models for their insight. To address the question of whether observed variations and trends can be attributed to anthropogenic sources of greenhouse gases or to other causes, again the IPCC depends on the models to seek answers. My perspective on the answers to these questions is primarily based on whether or not I am convinced that the models used by the IPCC are complete and accurate, and whether or not they can predict future climate changes with a high degree of confidence.

Global climate models are highly complex and detailed mathematical representations of the physical, chemical, and biological processes that go on in the Earth climate system. Every conceivable process is represented, to the best of the modelers' knowledge and abilities. Current and past observations and measurements are used to fit the models, and to test the models' accuracy and completeness. I believe the climate modeling effort has made great progress, and has provided great insight as to the nature of global climate. However, I do not believe that the models are sufficiently complete and accurate to be used to forecast long-term climate changes, and to accurately predict the sensitivity of the climate to small perturbations. My reasons are as follows:

- The Earth climate system is characterized by pervasive interactions between its components, resulting in strong feedback influences that can amplify greatly the

consequences of small perturbations, and can lead to tipping points that create chaotic conditions. We accept as natural the large geographic and temporal differences in weather and climate conditions due to the diurnal cycle, the seasons, the effects of latitude on solar incoming radiant energy, differences in geography, and hemispheric differences. Thus the intrinsic characteristic of variations in the Earth climate system is that of complex non-linear systems - small differences and perturbations may be amplified to produce large changes in local and regional conditions. It is the inherent nature of the Earth climate system that it may amplify and magnify the consequences of small perturbations, and it will self-adjust to keep the global energy flows in balance. It is the amplifying feedback mechanisms that drive the entire system, both in response to perturbations and as the normal dynamic internal to the Earth climate system. Nevertheless, the approach of climate change investigators is to identify the forcings, or small perturbations to the system, and to compute the sensitivity of the Earth climate system in response, thus separating the forcings from the natural variations that are always occurring within the system. Generally speaking, you can't do that in a nonlinear system because the perturbations and the natural variations are not additive. It is necessary to analyze the dynamics of the entire Earth climate system in order to understand the characteristics of climate change in response to each individual perturbation. That is why the IPCC uses global climate models to do sensitivity analyses of forcings. Global climate sensitivity analyses using global climate models would have a reasonable degree of certainty if it is certain that all feedback mechanisms are accurately and completely represented, and all physical processes are included and are shown to be represented accurately. However, such is not the case; the IPCC, as well as other investigators, have pointed out many such shortcomings of the IPCC models. To wit:

- Water vapor and clouds are the largest and most important feedback mechanisms. By all admissions, the IPCC models fail to get them right. The treatment of clouds involves errors an order of magnitude greater than the forcing from a doubling of CO₂.
- Aerosols are included in models as a forcing mechanism that is of the same magnitude as CO₂, however with an effect opposite to that of CO₂. IPCC models have used an empirical procedure to adjust for the difference between model calculations of conditions of the past 30 years and actual observations; they attribute the difference to aerosols, and empirically adjust aerosol properties to fit the difference. Thus the aerosol modeling does not represent known science, but rather has been used as a fudge factor to enable fitting past history; that is no basis for predicting future climate change.
- The oceans are the largest heat sink and second-largest source of CO₂ emitted to the atmosphere. According to Hansen (Section IV.1), "Until instrumental issues are resolved and good heat storage data is obtained for the entire ocean, it is not possible to infer the net climate forcing (of the ocean) acting on Earth." Thus the global circulation models are inherently limited in how they represent the oceans.
- Atmospheric temperature distribution from the Earth's surface to the stratosphere is dictated by the greenhouse effect. According to Lindzen (Section IV.2), a fundamental shortcoming in representing the global greenhouse effect in the General Circulation Models (GCM) used by the IPCC is the oversimplified and inappropriate way in which global surface temperatures are related to atmospheric temperature gradients in altitude and latitude.

- On the issue of whether there are phenomena at work that current models do not take into account, or fail to replicate at anywhere near the magnitudes observed, Lindzen enumerates and describes a number of examples (Section IV.2), which include the Intraseasonal Oscillations of the tropics, El Nino, El Nina; the Quasi-biennial Oscillation of the tropical stratosphere; the Little Ice Age; or the Medieval Warm Period. "The examples merely show that current models fail to describe many known climate changes, and that, therefore, the models' failure to account for the recent warming (largely confined to the period 1976 - 1995) hardly requires the invocation of anthropogenic forcing. It is nonetheless commonly argued by modelers that coupled models do adequately portray natural unforced variability despite acknowledging the cited shortcomings. . . Thus, the claim that models cannot account for recent warming without external forcing is held to imply the role of human forcing. To be sure, current models can simulate the recent trend in surface temperature, but only by invoking largely unknown properties of aerosols and ocean delay in order to cancel most of the greenhouse warming."

On the question of whether observed climate variations should be attributed to anthropogenic sources of greenhouse gases or to other causes, the IPCC depends on the models to seek answers. According to Lindzen (Section IV.2), IPCC modelers conclude that it must be due to CO₂, since they claim to include all known forcings in their models, and only CO₂ could account for the recent warming. Considering the incompleteness and uncertainties enumerated previously, the IPCC modelers' conclusions are not convincing.

A different aspect of the anthropogenic attribution question is revealed in an assessment of the magnitude of sensitivities of different climate forcing mechanisms predicted by the IPCC models. According to Hansen (Section IV.1), the combined anthropogenic radiative forcings add up to ~3 w/m², which, according to Lindzen (Section IV.2) is about 86% of the radiative forcing associated with the IPCC benchmark of doubled CO₂. "That is to say, we are almost at the radiative forcing associated with the benchmark of doubled CO₂. (From the IPCC models), we see that a doubling of CO₂ leads to surface warming of from 1.5° to 3.5°C. By contrast, the observed warming over the past century amount to only about 0.6° - 0.8°C, not all of which need be due to increased greenhouse gases. On the face of it, this would seem to confirm that models are much too sensitive to anthropogenic greenhouse forcing, assuming that all the observed warming was due to increasing greenhouse gases." Thus, "The defense of the attribution of recent warming to man involves an observed warming that is smaller than expected, and where the attribution, itself, depends on relatively subjective claims concerning the ability of current models to accurately portray natural unforced climate variability."

In the previous subsection I summarize the essence of the consensus technical view of the IPCC Fourth Assessment Report. In concluding this assessment, I present the essence of my own perspective on climate, global warming, and CO₂, in the form of my response to a series of fundamental questions that frame the issue:

Is long-term global climate change real?

In the past several decades changes in climate indicators such as increased warming periods, rising sea level, glacier melting, and increased storm intensity and frequency have been observed. In my view this climate variability is real, but is local and regional in nature, is well within the range of natural variability that is characteristic of the Earth climate system, and has occurred previously as part of the Earth's climate history. By its definition, climate change is measured over the long-term - decades, centuries, and longer. It is far too premature to conclude that this variability is global in nature and indicative of real long-term change.

Is global warming real?

The measured increase in the global average surface temperature of the Earth over the past century has been about 0.8°C, and over the past 30 years about 0.4°C. The 0.8°C increase is very small (<3%) compared to the total greenhouse temperature increase of 33°C. In my view, therefore, a small amount of global warming has occurred in the past century and is real. However, representation of local and regional temperature trends as "global warming" is misleading since very little warming on average over the Earth has actually occurred; to be more accurate and complete, localized thermal variability should be referred to as "regional warming and cooling."

Is global climate change the result of global warming?

Given the small amount of global warming that has actually occurred, it is very unlikely that it is the direct cause of whatever regional and local climate changes might have occurred. Rather, what we observe and interpret as manifestations of climate change are primarily the result of feedback amplification that occurs during the normal distribution and exchange of energy within the Earth climate system.

Is global warming primarily the result of CO₂ in the atmosphere?

CO₂ in the atmosphere is a greenhouse gas, and its increase contributes to warming. However, CO₂ is one of several greenhouse gases, and is, at best, only a minor contributor to the greenhouse effect. Water vapor and clouds are the most dominant contributors to the greenhouse effect, and the most dominant atmospheric feedback mechanism. The effects of water vapor and clouds on the Earth's energy balance are at least 3.5 times larger than that of CO₂.

Climatologists have not been able to reliably analyze and predict the warming consequences of a CO₂ increase separately from other forcing mechanisms that are equal or larger in magnitude. In my view it is not possible to say with any degree of confidence that what little global warming has occurred is the result of CO₂.

Is anthropogenic production of CO₂ the reason that atmospheric content of CO₂ is rising?

Measurement of CO₂ content in the atmosphere indicates a steady rise of 37% since 1850. CO₂ is produced globally by anthropogenic means at the rate of 6 billion tonnes of carbon per year, compared to release from the oceans of 90 billion tonnes C/year and release by plant, animal, and soil respiration of 120 billion tonnes C/year. Carbon in the atmosphere appears to be far from being in a state of balance; climatologists have hypothesized the reasons and mechanisms for the net increase, but have failed to confirm an explanation. Uncertainty in their predictions is of the same magnitude as the annual increase in atmospheric CO₂ itself. In my view, it is far from clear whether the CO₂ content of the atmosphere is increasing due to natural or anthropogenic means.

Are global climate change and global warming a direct consequence of anthropogenic CO₂?

My approach to answering the question has been to examine the technical basis for characterizing each step in the logical connection between climate change and CO₂, as outlined by the series of questions above. Following that approach, my answer to this question is "Highly unlikely" for all of the reasons given previously. The observed increase in atmospheric CO₂ that has occurred concurrently with a small increase in global temperature indicates some correlation but does not appear to be causation.

An alternate approach to answering the question has been taken by climatologists and the IPCC by using highly complex and sophisticated mathematical global climate models to analyze and predict the relationships between climate change, warming, CO₂, and all the other physical mechanisms they could think of, both natural and man-made, that could contribute to climate change. A careful review of their approach reveals those models to be empirical, incomplete, uncertain, and with limited long-term predictive capabilities with regard to analyzing the consequences of small forcings, thus warranting a low level of confidence. Until such time that global climate models can improve such predictive capabilities, conclusions and judgments by the IPCC on the question of CO₂ causality should be viewed as speculative and tentative.

III. - BACKGROUND ASPECTS OF GLOBAL CLIMATE AND MODELING

Any consideration of Earth's climate must be understood in its broad astronomical context. The Earth is just one of eight (or nine?) planets orbiting the star we call the Sun. Our Sun is the sole source of energy that sustains Earth's global environment and drives the climate. The Earth and its atmosphere constitute a system. Only a specific amount of radiant energy comes in to the Earth/atmosphere system from the Sun and that same amount of energy (in energy equilibrium) radiates out from the Earth's atmosphere to outer space. Primarily because of water in the form of vapor and clouds, this dynamic energy exchange results in what we call the greenhouse effect. Understanding the global energy dynamics of planet Earth is fundamental to an understanding of climate dynamics. Thus the first part of this section (III.1) is devoted to establishing the broad energy context in which we consider all aspects of climate change, and to highlighting certain aspects that are important to this assessment.

One particular aspect of the global energy balance is the amount of energy emitted by the Sun that actually reaches Earth. It is the sole input to Earth's global energy balance; without solar energy input, life on Earth would not exist as we know it. It is important to understand that the Sun itself experiences dynamical changes that result in variations in emitted energy, which then translate into variations in global energy that can have significant and direct effects on climate. Thus the next part of this section (III.2) is devoted to revealing the nature of solar energy variations as the most important natural source for the global energy context.

In the current debate on climate change, many have accepted the hypothesis as a given that man-made greenhouse gases, primarily CO₂, are the primary cause of increased global surface temperature and climate change. To examine this hypothesis in depth, we need to understand the various ways in which CO₂ enter and leave the Earth's atmosphere in terms of the carbon cycle, as the broader context for evaluating the impact of man-made CO₂. Thus the next part (III.3) is devoted to explaining the nature of, and contributors to, the Earth's global carbon balance.

The main method by which scientific investigators analyze global climate, evaluate the impact of perturbations, both natural and man-made, and forecast the consequences resulting from these perturbations, is through mathematical models. There is a general impression that these models are an accurate and complete representation of the complexities of climate dynamics, and that model computations are an accurate source of information that will provide a reliable basis for forecasting and decision-making. The last part of this section (III.4) explores the nature and limitations of mathematical climate modeling to provide a basis for judging the extent to which we can depend on their results.

As a matter of style, note that in each of the four parts that follow, the information taken directly from the referenced technical sources is presented in normal font, while my personal observations and comments are indented and italicized.

III.1 - Global Energy Balance

A qualitative description of the Earth's energy system and the greenhouse effect can be found in any basic text on earth science or climatology. The following is excerpted from "The Encyclopedia of the Atmospheric Environment" (<http://www.ace.mmu.ac.uk/eae/index.html>)

" The global energy balance is the balance between incoming energy from the Sun and outgoing heat from the Earth. The global energy balance regulates the state of the Earth's climate, and modifications to it as a result of natural and man-made climate forcing, cause the global climate to change.

Energy released from the Sun as electromagnetic radiation has a temperature of approximately 6000°C. At this temperature, electromagnetic radiation is emitted as short wavelength visible and ultraviolet light energy. Electromagnetic radiation travels across space at the speed of light. When it reaches the Earth's, some is reflected back to space by clouds, some is absorbed by the atmosphere, and some is absorbed at the Earth's surface.

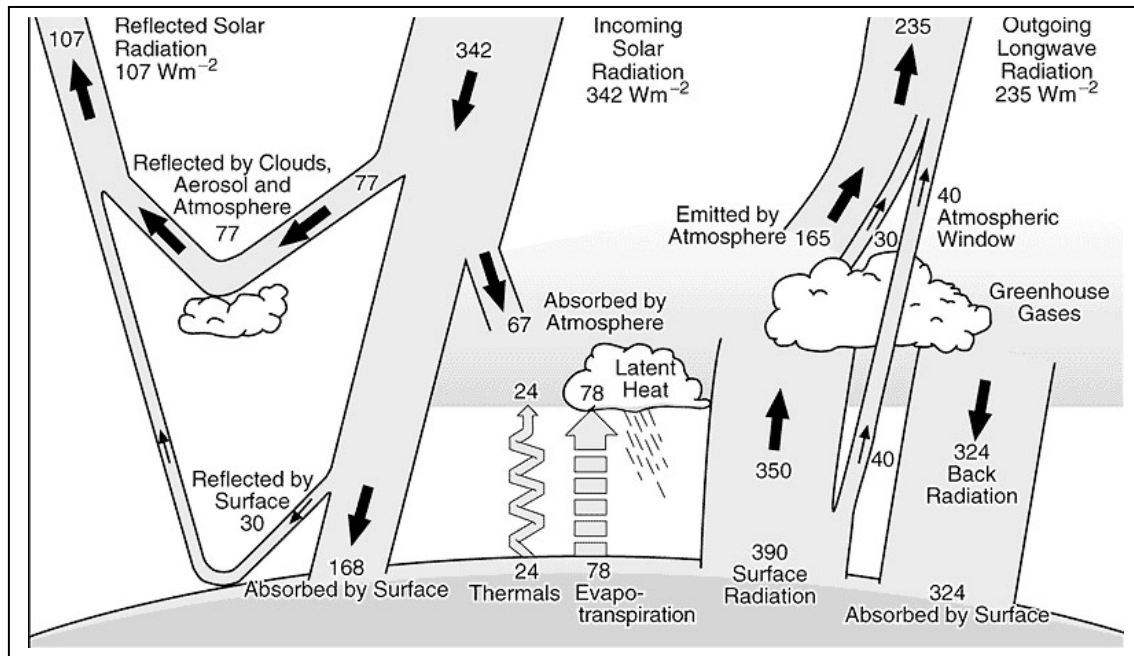
The Earth releases a lot of energy it has received from the Sun back to space. However, since the Earth is much cooler than the Sun, its radiating energy is longer wavelength infrared energy, or heat. Sometimes, we can indirectly see heat radiation, for example as heat shimmers rising from a tarmac road on a hot sunny day. The energy received by the Earth from the Sun balances the energy lost by the Earth back into space. In this way, the Earth maintains a stable average temperature and therefore a stable climate (although of course differences in climate exist at different locations around the world).

The Earth's atmosphere contains a number of molecules that affect the Sun-Earth energy balance. These molecules absorb electromagnetic radiation at some wavelengths but allow radiation at other wavelengths to pass through unimpeded. The atmosphere is mostly transparent to the visible light spectrum (which is why we can see the Sun), but significantly blocks (through absorption) ultraviolet radiation due to the ozone layer, and infrared radiation due to certain other molecules. This results in the greenhouse effect, which is the net trapping of some of the incoming solar radiation by the Earth's lowest atmospheric layer (the troposphere, which is from 4 to 11 miles high depending on latitude). The Earth's greenhouse effect causes the average global temperature of the Earth's troposphere to be ~33°C higher than it would be if not for the presence of the atmosphere and its contents.

The absorption of infrared radiation trying to escape from the Earth back to space is particularly important to the global energy balance. Such energy absorption by the greenhouse gases heats the lower atmosphere (troposphere), and so the Earth stores more energy near its surface than it would if there was no atmosphere. The average surface temperature of the moon, about the same distance as the Earth from the Sun, is -18°C. The moon, of course, has no atmosphere. By contrast, the average surface temperature of the Earth is 15°C. This heating effect is the result of the natural greenhouse effect."

The following discussion of the Earth's annual global mean energy budget and Figure III-1 are taken from a paper on that subject by Kiehl and Trenberth (<http://www.geo.utexas.edu/courses/387h/PAPERS/kiehl.pdf>). Other graphic summaries are available online that depict quantitatively the global energy balance, with differences in values noted.

Figure III-1 - Global Energy Balance



Solar radiation flux at the top of the atmosphere averages 342 w/m^2 over the entire globe. Part of the total incoming solar energy is reflected back into space, part is absorbed by clouds and atmospheric gases and the rest is absorbed by the Earth's surfaces. The 49% that is absorbed by the surface is returned to the atmosphere as 'sensible' and 'latent' heat by turbulence and convection and the rest as infrared radiation. The atmosphere radiates infrared radiation in all directions. When balance is achieved in the atmosphere, the total upward radiation from the top of the atmosphere equals the incoming radiation received from the sun.

Although one may find in the literature a range of values associated with the various energy transport mechanisms, certain key observations are still valid. The following points are noted, based on the values shown in Figure III-1:

- At Earth's average distance from the Sun (about 150 million kilometers), the average intensity of solar energy reaching the top of the atmosphere directly facing the Sun is about 1360 watts/m^2 , according to measurements made by the most recent NASA satellite missions. This is known as the total solar irradiance. Because only half the Earth is ever lit by the Sun at one time, and because the curvature of the Earth's spherical surface causes a progressive decrease in the angle of solar illumination with increasing latitude, the average solar input over the entire planet is only one-fourth of the total solar

irradiance, or 340 w/m^2 . For consistency in comparing values taken from Figure III-1, an average energy flux of 342 w/m^2 will be used.

- Average daily solar input at the outer boundary of the atmosphere over the entire Earth is 342 w/m^2 . Of this amount, 107 w/m^2 (31%) of the incoming short wavelength solar radiation is reflected back to space by either clouds, atmospheric molecules, or the Earth's surfaces, while the remaining 235 w/cm^2 is absorbed by either the atmosphere or the Earth's surfaces. Of the 107 w/m^2 of short wavelength radiation reflected back, most is due to clouds. Although the breakdown associated with each atmospheric gas is not given, Kiehl and Trenberth say that "Scattering by clouds is much greater than molecular scattering." Thus water in the form of clouds is responsible for most of the heating-avoidance that results from the 31% of solar energy that is reflected and therefore does not heat the Earth's atmosphere.

Of particular note is that Hansen (Section IV.1) uses the surface absorption of 240 w/m^2 as the basis for comparing the magnitude of forcings, rather than the average solar input of 340 w/m^2 . Thus he ignores the effect of clouds on reflection as a major mechanism, and thereby tends to magnify the relative importance of the greenhouse gases.

- The 235 w/m^2 of solar energy that is not reflected back to space and is absorbed by the atmosphere and the Earth's surface is emitted back into space in the form of long wavelength radiation (infrared). Infrared is absorbed by water in the form of vapor and clouds, and by the atmospheric and greenhouse gases. The absorbed energy is re-radiated in all directions throughout the troposphere. However, it is only the radiation that is emitted in the vicinity of the tropopause that escapes the atmosphere. (The tropopause is the atmospheric boundary between the troposphere and the stratosphere. Going upward from the surface, it is the point where air ceases to cool with height, and becomes almost completely dry.) Of the total infrared emissions to space, Kiehl and Trenberth calculate that 34% comes from water in either vapor or cloud form, 17% is directly radiated from the Earth's surfaces through the 'atmospheric window,' 10% comes from CO_2 , 5% comes from the other greenhouse gases, and the rest (34%) comes from emission by the normal atmospheric gases. Thus water in the form of clouds and vapor contributes ~3.5 times as much as CO_2 to the global energy balance, and that doesn't include the additional role that water plays in reflecting incoming solar radiation.

When comparing the relative influences of water and CO_2 on global heating and cooling, it is evident that water is by far the dominant contributor.

III.2 - Solar Energy Input

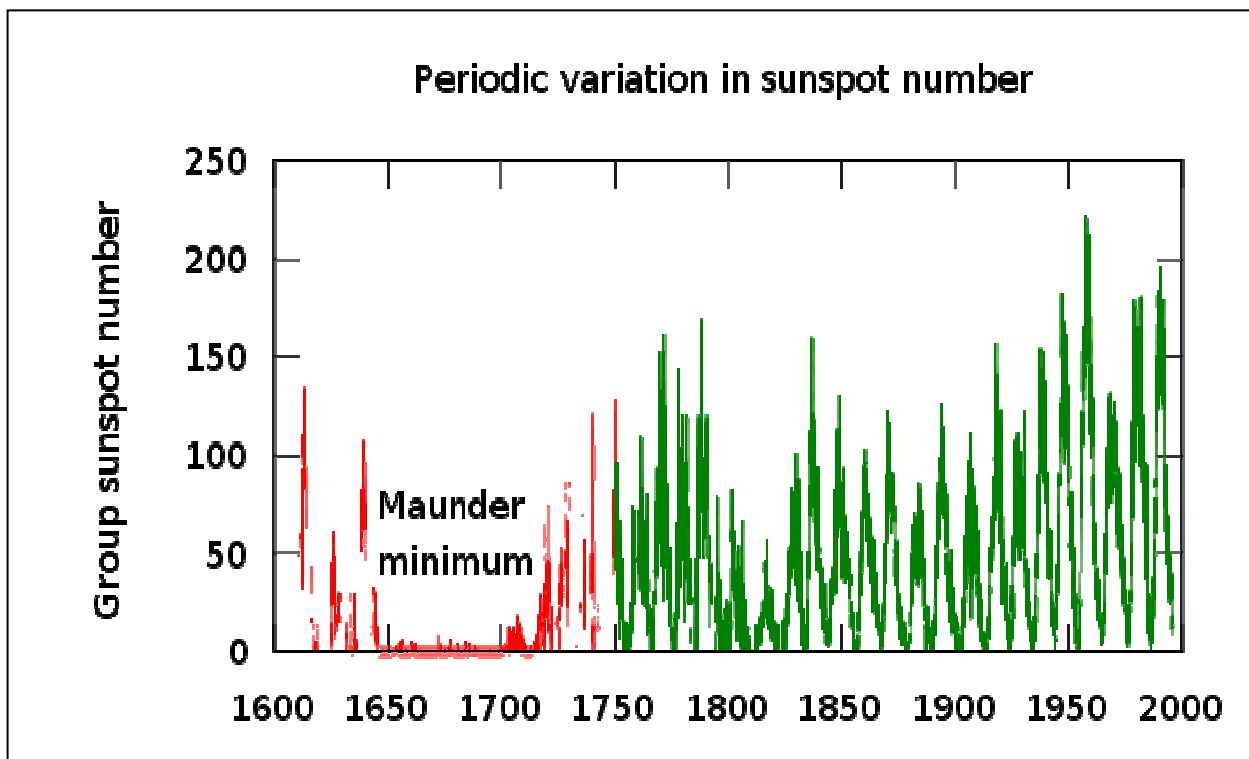
The following background information includes excerpts from the following Wikipedia web sites:

1. "Solar Cycle": http://en.wikipedia.org/wiki/Solar_cycle
2. "Solar Variation": http://en.wikipedia.org/wiki/Solar_variation
3. "Milankovitch Cycles": http://en.wikipedia.org/wiki/Milankovitch_cycles

Our Sun as a source of energy enables climate and life as we know it to exist on Earth; it has been a relatively constant source since long before modern Man has appeared. And Earth, in its 24 hour rotation about its axis and its 365 day revolution around the Sun, has been relatively constant in these motions. Thus we take diurnal changes (day and night) and changing seasons for granted. But these mechanisms of nature are not absolutely constant. We need to understand their variations and impact in order to take them into account as natural forcings that affect climate.

Consider first the Sun itself, specifically the solar magnetic activity cycle, which is the main source of periodic solar variation. The solar cycle, which is powered by a hydromagnetic dynamo process driven by the inductive action of internal solar flows, structures the Sun's atmosphere, corona and wind; modulates the solar irradiance; modulates the flux of short-wavelength solar radiation, from ultraviolet to X-ray; modulates the occurrence frequency of flares, coronal mass ejections, and other geoeffective solar eruptive phenomena; and indirectly modulates the flux of high-energy galactic cosmic rays entering the solar system. The solar cycle is observed by counting the frequency and placement of sunspots visible on the sun (See Figure III-2). There are periodic components to these variations over multi-annual to multi-millennial time scales, the principal one being the 11-year solar cycle.

Figure III-2 - Variation in Sunspot Number Since 1600



http://en.wikipedia.org/wiki/File:Sunspot_Numbers.svg

The total solar irradiance (TSI) is the amount of solar radiative energy incident on the Earth's upper atmosphere. TSI variations were undetectable until satellite observations began in

late 1978. The major finding of satellite observations is that TSI varies in phase with the solar magnetic activity cycle, with an amplitude of about 0.1% (1.3 watts/m²). Variations about the average up to -0.3% on a 10 day timescale (-4.1 watts/m²) are caused by large sunspot groups (relatively dark areas) and of +0.05% for up to 6 months (+0.7 watts/m²) by large faculae (brighter areas that form around sunspot groups) and bright network on a week to 10 day timescale. The sunspot cycle variation of 0.1% has small but detectable effects on the Earth's climate. TSI variations over the several decades of continuous satellite observation show small but detectable trends.

TSI is higher at solar maximum, even though sunspots are darker (cooler) than the average photosphere. This is caused by magnetized structures other than sunspots during solar maxima, such as faculae and active elements of the 'bright' network, that are brighter (hotter) than the average photosphere. They collectively overcompensate for the irradiance deficit associated with the cooler but less numerous sunspots. The primary driver of TSI changes on solar rotational and sunspot cycle timescales is the varying photospheric coverage of these radiatively active solar magnetic structures.

There seems to be a consensus agreement that the variation of total solar irradiance due to variations in solar magnetic activity is of a magnitude that is relatively small compared to other forcings, both natural and man-made. However, there is serious question of the nature and magnitude of other complex and multifaceted mechanisms that alter the impact of the Sun's energy. Specifically, it is recognized that the indirect effect of the variation in the solar wind on the influx of cosmic rays will have an impact on the ionization in the atmosphere that affect the abundance of aerosols that serve as the nuclei of condensation for cloud formation.

According to Reference 2 in this Section, ". . . Ionization levels potentially affect levels of condensation, low clouds, relative humidity, and albedo due to clouds. Clouds formed from greater amounts of condensation nuclei are brighter, longer lived, and likely to produce less precipitation. Changes of 3-4% in cloudiness and concurrent changes in cloud top temperatures have been correlated to the 11 and 22 year solar sunspot cycles. . . Global average cloud cover change has been found to be 1.5-2%. . . However, not all scientists accept this correlation as statistically significant, and some that do attribute it to other solar variability (e.g. UV or total irradiance variations) rather than directly to galactic cosmic ray changes. Difficulties in interpreting such correlations include the fact that many aspects of solar variability change at similar times, and some climate systems have delayed responses."

According to Carslaw et al, the correlation between cosmic ray modulation and clouds is clear, it is the exact mechanism for forming cloud nuclei that is controversial. (See K.S. Carslaw, R.G.Harrison, and J. Kirkby, "Cosmic Rays, Clouds, and Climate", Science 298, 1732 (2002).)

As discussed elsewhere in this paper, cloud formation is a large and important feedback mechanism that affects the Earth's energy balance. Climate models only include the

direct effects of variations in the direct solar radiation without the feedback effects of cosmic rays on clouds. Further discussion of this mechanism is found in:

4. *"Here Comes the Sun" by Dr. A. Neil Hutton, Reservoir, Issue 5, Pp. 31-39(May 2009).*

There are variations in total solar irradiance that are not due to solar changes but rather due to the Earth moving closer to or further from the Sun, or changes in the orientation of the Earth's axis of rotation. These have caused variations of as much as 25% (locally; global average changes are much smaller) in TSI over long periods. Collectively these effects are known as Milankovitch Cycles. The following description of the various mechanisms that comprise the Milankovitch Cycles is excerpted directly from Reference 3 of this Section.

The Earth's axis completes one full cycle of precession approximately every 26,000 years. At the same time, the elliptical orbit rotates, more slowly, leading to a 21,000 year cycle between the seasons and the orbit. In addition, the angle between Earth's rotational axis and the normal to the plane of its orbit moves from 22.1 degrees to 24.5 degrees and back again on a 41,000 year cycle; currently the angle is 23.44 degrees and is decreasing.

The Earth's orbit is an ellipse. The eccentricity is a measure of the departure of this ellipse from circularity. The shape of the Earth's orbit varies in time between being nearly circular (low eccentricity of 0.005) and being mildly elliptical (high eccentricity of 0.058) and has a mean eccentricity of 0.028. Orbital shape varies on a 100,000-year cycle (variation of -0.03 to $+0.02$). The present eccentricity is 0.017. The relative increase in solar irradiation at closest approach to the Sun (perihelion) compared to the irradiation at the furthest distance (aphelion) is slightly larger than 4 times the eccentricity. For the current orbital eccentricity this amounts to a variation in incoming solar radiation of about 6.8%, while the current difference between perihelion and aphelion is only 3.4% (5.1 million km). Perihelion presently occurs around January 3, while aphelion is around July 4. When the orbit is at its most elliptical, the amount of solar radiation at perihelion will be about 23% greater than at aphelion.

The angle of the Earth's axial tilt (obliquity) varies with respect to the plane of the Earth's orbit. These slow 2.4° obliquity variations are roughly periodic, taking approximately 41,000 years to shift between a tilt of 22.1° and 24.5° and back again. When the obliquity increases, the amplitude of the seasonal cycle in insolation (INcoming SOLar radiATION) increases, with summers in both hemispheres receiving more radiative flux from the Sun, and the winters less radiative flux. But these changes of opposite sign in the summer and winter are not of the same magnitude. The annual mean insolation increases in high latitudes with increasing obliquity, while lower latitudes experience a reduction in insolation. Cooler summers are suspected of encouraging the start of an ice age by melting less of the previous winter's ice and snow. So it can be argued that lower obliquity favors ice ages both because of the mean insolation reduction in high latitudes as well as the additional reduction in summer insolation. However no significant climate changes are associated with extreme axial tilts. Currently the Earth is tilted at 23.44 degrees from its orbital plane, roughly half way between its extreme values. The tilt is in the decreasing phase of its cycle, and will reach its minimum value around the year 10,000 C.E.. This trend, by itself, would tend to make winters warmer and summers colder.

Axial precession is the change in the direction of the Earth's axis of rotation relative to the fixed stars, with a period of roughly 26,000 years. This gyroscopic motion is due to the tidal forces exerted by the sun and the moon on the solid Earth, associated with the fact that the Earth is an oblate spheroid shape and not a perfect sphere. The sun and moon contribute roughly equally to this effect. When the axis is aligned so it points toward the Sun during perihelion, one polar hemisphere will have a greater difference between the seasons while the other hemisphere will have milder seasons. The hemisphere which is in summer at perihelion will receive much of the corresponding increase in solar radiation, but that same hemisphere will be in winter at aphelion and have a colder winter. The other hemisphere will have a relatively warmer winter and cooler summer. When the Earth's axis is aligned such that aphelion and perihelion occur near the equinoxes, the Northern and Southern Hemispheres will have similar contrasts in the seasons. At present, perihelion occurs during the Southern Hemisphere's summer, and aphelion is reached during the southern winter. Thus the Southern Hemisphere seasons are somewhat more extreme than the Northern Hemisphere seasons, when other factors are equal.

Apsidal precession is when the orbital ellipse itself precesses in space, primarily as a result of interactions with Jupiter and Saturn. This orbital precession is in the same sense to the gyroscopic motion of the axis of rotation, shortening the period of the precession of the equinoxes with respect to the perihelion from 25,771.5 to ~21,636 years.

The inclination of Earth's orbit drifts up and down relative to its present orbit with a cycle having a period of about 70,000 years. Milankovitch did not study this three-dimensional movement. This movement is known as "precession of the ecliptic" or "planetary precession". More recent researchers noted this drift and that the orbit also moves relative to the orbits of the other planets. The invariable plane, the plane that represents the angular momentum of the solar system, is approximately the orbital plane of Jupiter. The inclination of the Earth's orbit has a 100,000 year cycle relative to the invariable plane; by chance, this is very similar to the 100,000 year eccentricity period. This 100,000-year cycle closely matches the 100,000-year pattern of ice ages.

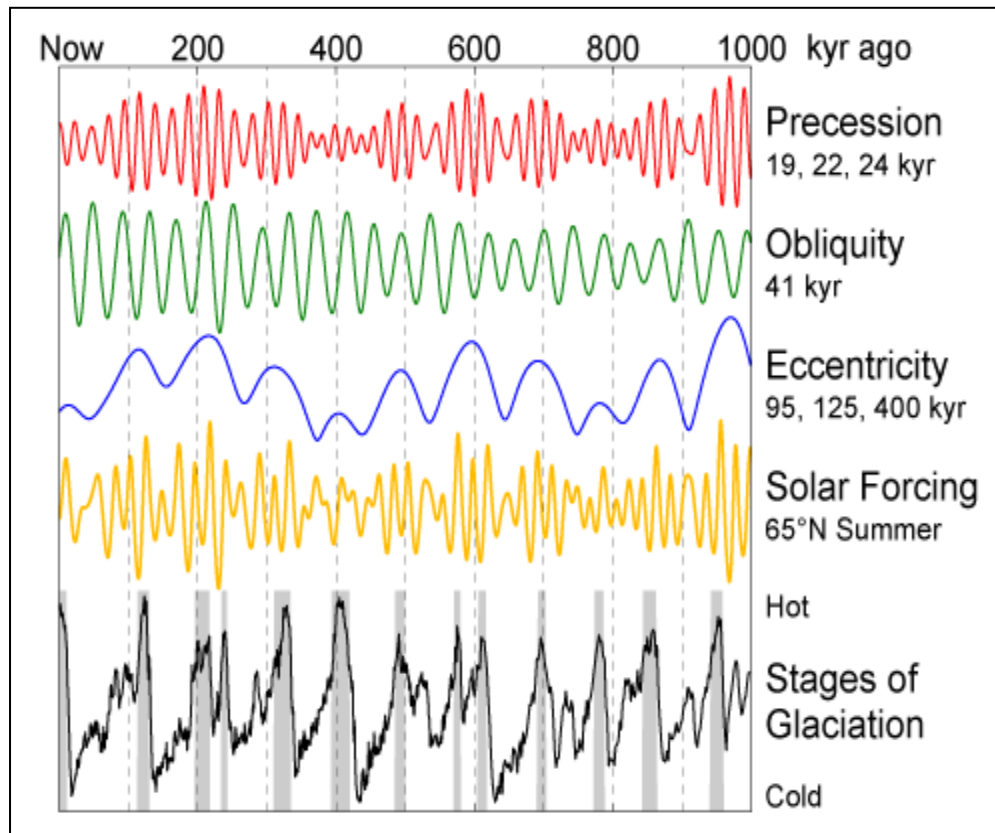
Figure III-3, taken from Reference 2 in this Section, shows the major Milankovitch Cycle contributors and how they correlate with stages of glaciation over the past million years.

From this graphic it appears that on a scale of millenia, the Milankovitch Theory of climate change seems well-correlated with historic climate. According to Reference 3 in this Section, "The . . . theory is not perfectly worked out; in particular, the largest response is at the 100,000 year timescale, but the forcing is apparently small at this scale, in regard to the ice ages. Various explanations for this discrepancy have been proposed, including frequency modulation or various feedbacks (from CO₂, cosmic rays, or from ice sheet dynamics)." There are also problems in explaining the shift from a 41,000 yr ice age cycle to a 100,000 yr cycle that occurred some half a million years ago.

What emerges for me from this review corresponds in most respects to the conclusions of Hutton in Reference 4 in this Section: "On short time scales of decades and centuries, solar variations that affect cosmic ray flux in the atmosphere have the potential to be a

principal forcing of climate through their influence on cloud formation. The cloud effect clearly should be considered in assessing current climate variations; apparently it has not by the IPCC. On the scale of millenia, the Milankovitch Cycles appear to be important mechanisms that significantly affect climate, but because of their long time scale, they apparently do not offer explanations of current climate variations."

Fig. III-3 Milankovitch Cycle Contributors



http://en.wikipedia.org/wiki/File:Milankovitch_Variations.png

III.3 - Global Carbon Cycle

The carbon cycle is the biogeochemical cycle by which carbon is exchanged among the components that comprise the Earth climate system. It is one of the most important cycles of the Earth and allows for carbon to be recycled and reused throughout the biosphere and all of its organisms. It is important in the context of climate change because of the presence of CO₂ in the atmosphere, and its contribution to climate as one of the greenhouse gases. Since the concentration of CO₂ in the atmosphere is the net result of a dynamical process of exchange, it is useful as a contextual basis to examine the magnitude of all the exchange mechanisms, and how anthropogenic CO₂ production compares with those other mechanisms.

The following summary and overview is excerpted from the following two sources:

1. "Carbon Cycle," http://en.wikipedia.org/wiki/Carbon_cycle
2. "An Introduction to the Global Carbon Cycle," U. of New Hampshire <http://globecarboncycle.unh.edu/CarbonCycleBackground.pdf>

The global carbon cycle is usually thought of as five major reservoirs of carbon interconnected by pathways of exchange. These reservoirs are:

- The atmosphere
- The terrestrial biosphere, which is usually defined to include fresh water systems and non-living organic material, such as soil carbon.
- The oceans, including dissolved inorganic carbon and living and non-living marine biota,
- The sediments including fossil fuels.
- The Earth's interior; carbon from the Earth's mantle and crust is released to the atmosphere and hydrosphere by volcanoes and geothermal systems.

The annual movements of carbon, the carbon exchanges between reservoirs, occur because of various chemical, physical, geological, and biological processes. The ocean contains the largest active pool of carbon near the surface of the Earth, but the deep ocean part of this pool does not rapidly exchange with the atmosphere in the absence of an external influence, such as a black smoker or an uncontrolled deep-water oil well leak.

Figure III-4, taken from Reference 2 of this section, shows a simplified summary of the reservoirs that serve as sources and sinks for the global dynamic exchange of carbon.

The mechanisms of carbon intake and release that are at work in each of the major global reservoirs are as follows:

In the atmosphere, carbon exists primarily as CO₂, plus smaller amounts contained in methane and chlorofluorocarbons. Atmospheric total content of carbon is 750 GtC; the global average carbon concentration is 385 parts per million.

Carbon is released into the atmosphere in several ways:

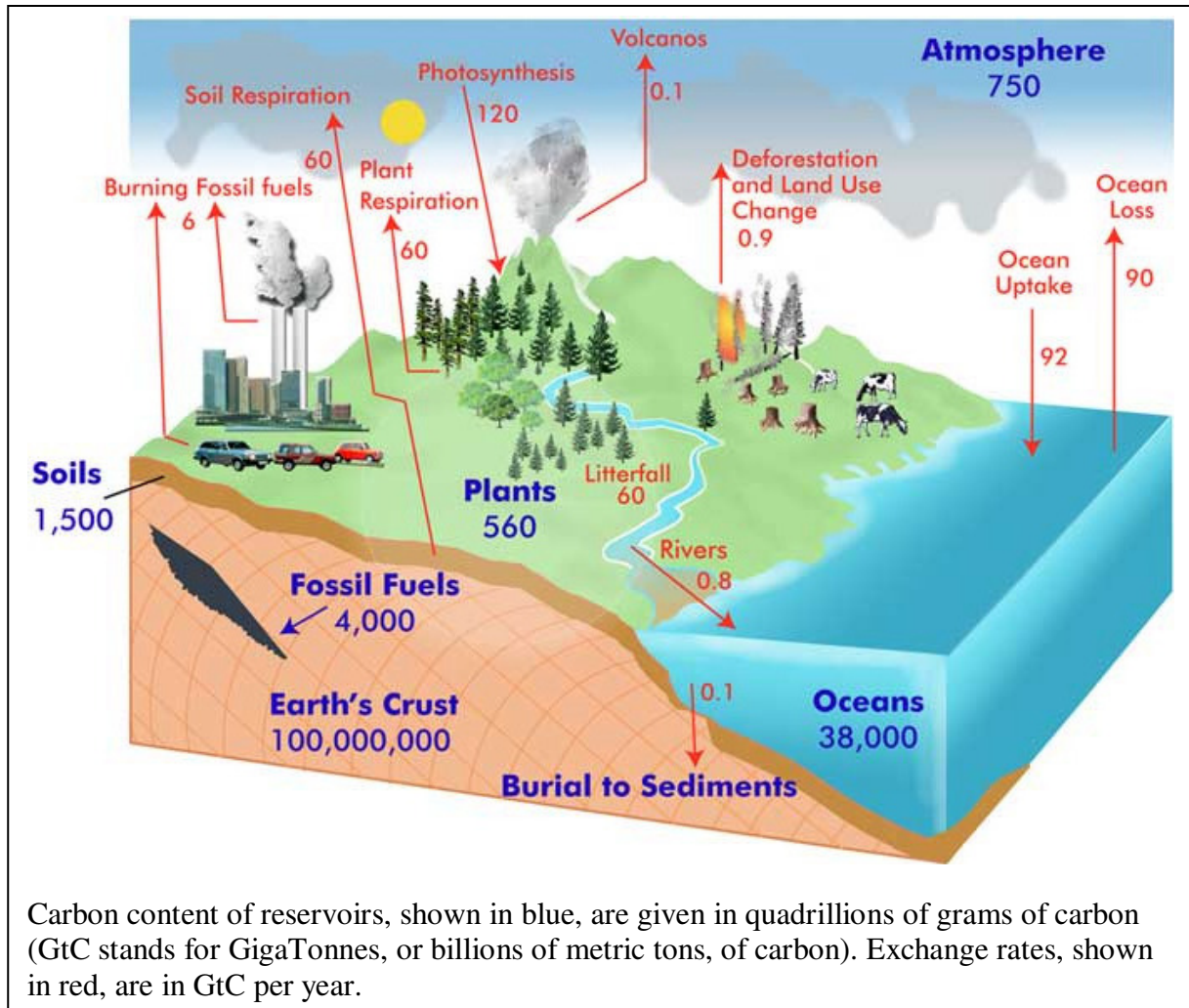
- Through the respiration performed by plants and animals
- Through the decay of animal and plant matter
- Through combustion of organic material
- Through production of cement; CO₂ is released when limestone (CaCO₃) is heated to produce lime (CaO), a component of cement.
- At the surface of the oceans where the water becomes warmer or evaporates, dissolved CO₂ is released back into the atmosphere.
- Volcanic eruptions and metamorphism release gases into the atmosphere. Volcanic gases are primarily water vapor, carbon dioxide and sulfur dioxide.

Carbon is taken from the atmosphere in several ways:

- Plants convert carbon dioxide into carbohydrates during photosynthesis, releasing oxygen in the process. This process is most prolific in relatively new forests where tree growth is still rapid. The effect is strongest in deciduous forests during spring leafing out. This is

visible as seasonal fluctuations in the hemispheres. Northern hemisphere spring predominates, as there is far more land in temperate latitudes in that hemisphere than in the southern. Forests store 86% of the planet's above-ground carbon and 73% of the planet's soil carbon.

Figure III-4 Global Carbon Cycle



- At the surface of the oceans towards the poles, seawater becomes cooler and more carbonic acid is formed as CO₂ becomes more soluble. This is coupled to the ocean's thermohaline circulation which transports dense surface water into the ocean's interior.
- In upper ocean areas of high biological productivity, organisms convert reduced carbon to tissues, or carbonates to hard body parts such as shells and tests. These are, respectively, oxidized and redissolved at lower average levels of the ocean than those at which they formed, resulting in a downward flow of carbon.
- In the weathering of silicate rock, carbonic acid reacts with weathered rock to produce bicarbonate ions. The bicarbonate ions produced are carried to the ocean, where they are

used to make marine carbonates. Unlike dissolved CO₂ in equilibrium or tissues which decay, weathering does not move the carbon into a reservoir from which it can readily return to the atmosphere.

In the biosphere, ~ 42,000 GtC are present. Carbon is an essential part of life on Earth. It plays an important role in the structure, biochemistry, and nutrition of all living cells. Biosphere carbon is divided into three carbon pools: living biomass, dead biomass and soil. Carbon storage in the biosphere is influenced by a number of processes on different time-scales: while net primary productivity follows a diurnal and seasonal cycle, carbon can be stored up to several hundreds of years in trees and up to thousands of years in soils. Carbon is exchanged in the biosphere in several ways:

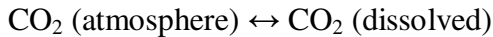
- Autotrophs are organisms that produce their own organic compounds using CO₂ from the air or water in which they live. To do this they require an external source of energy. Almost all autotrophs use solar radiation to provide this, and their production process is called photosynthesis. A small number of autotrophs exploit chemical energy sources in a process called chemosynthesis. The most important autotrophs for the carbon cycle are trees in forests on land and phytoplankton in the Earth's oceans.
- Carbon is transferred within the biosphere as heterotrophs feed on other organisms or their parts (e.g., fruits). This includes the uptake of dead organic material (detritus) by fungi and bacteria for fermentation or decay.
- Most carbon leaves the biosphere through respiration. When oxygen is present, aerobic respiration occurs, which releases CO₂ into the surrounding air or water. Otherwise, anaerobic respiration occurs and releases methane into the surrounding environment, which eventually makes its way into the atmosphere or hydrosphere (e.g., as marsh gas or flatulence).
- Burning of biomass (e.g. forest fires, wood used for heating, anything else organic) can also transfer substantial amounts of carbon to the atmosphere
- Carbon may also be circulated within the biosphere when dead organic matter (such as peat) becomes incorporated in the geosphere. Animal shells of calcium carbonate, in particular, may eventually become limestone through the process of sedimentation.

In the ocean, there are ~ 38,000 GtC, most of which is in the form of dissolved inorganic carbon stored at great depths where it resides for long periods of time. A much smaller amount of carbon, approximately 1,000 GtC, is located near the ocean surface. This carbon is exchanged rapidly with the atmosphere through both physical processes, such as CO₂ gas dissolving into the water, and biological processes, such as the growth, death and decay of plankton. Although most of this surface carbon cycles rapidly, some of it can also be transferred by sinking to the deep ocean pool where it can be stored for a much longer time. Extreme storms such as hurricanes and typhoons bury a lot of carbon, because they wash away so much sediment. Inorganic carbon, that is carbon compounds with no carbon-carbon or carbon-hydrogen bonds, is important in its reactions within water. This carbon exchange becomes important in controlling pH in the ocean and can also vary as a source or sink for carbon.

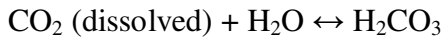
Carbon is readily exchanged between the atmosphere and ocean. In regions of oceanic upwelling, carbon is released to the atmosphere. Conversely, regions of downwelling transfer

carbon (CO₂) from the atmosphere to the ocean. When CO₂ enters the ocean, it participates in a series of reactions which are locally in equilibrium:

Solution:



Conversion to carbonic acid:



First ionization:



Second ionization:



This set of reactions, each of which has its own equilibrium coefficient, determines the form that inorganic carbon takes in the oceans. The coefficients, which have been determined empirically for ocean water, are themselves functions of temperature, pressure, and the presence of other ions (especially borate). In the ocean the equilibria strongly favor bicarbonate. Since this ion is three steps removed from atmospheric CO₂, the level of inorganic carbon storage in the ocean does not have a proportion of unity to the atmospheric partial pressure of CO₂. The factor for the ocean is about ten: that is, for a 10% increase in atmospheric CO₂, oceanic storage (in equilibrium) increases by about 1%, with the exact factor dependent on local conditions.

In the oceans, dissolved carbonate can combine with dissolved calcium to precipitate solid calcium carbonate, CaCO₃, mostly as the shells of microscopic organisms. When these organisms die, their shells sink and accumulate on the ocean floor. Over time these carbonate sediments form limestone which is the largest reservoir of carbon in the carbon cycle. The dissolved calcium in the oceans comes from the chemical weathering of calcium-silicate rocks, during which carbonic and other acids in groundwater react with calcium-bearing minerals liberating calcium ions to solution and leaving behind a residue of newly formed aluminum-rich clay minerals and insoluble minerals such as quartz.

The Earth's carbon cycle is in a constant state of motion. Through processes that take place over seconds, days, years and millennia, carbon is constantly being transferred between all the various reservoirs discussed previously. But what does this mean for the size of any given reservoir? In particular, consider the atmosphere. The fact that carbon moves into and out of the Earth's atmosphere doesn't, on its own, mean that the carbon content must change. In fact, if the amount of carbon moving into the atmosphere is matched by an equal amount of carbon moving out, the carbon content remains constant. But the CO₂ content of the atmosphere clearly has increased. In 1850, atmospheric CO₂ concentration was about 280 ppm, and today it is about 385 ppm. It is assumed that this increase is due to burning of fossil fuels. In order to examine this assumption, it is useful to construct a carbon budget for the atmosphere (Table III-1), accounting for all the carbon inputs and outputs. The flows are taken from Figure III-4.

Table III-1 - Carbon Budget for Atmosphere

Carbon Inputs		Carbon Removals	
Ocean losses (Evaporation, dissolution) =	90 GtC	Ocean uptake (solution) =	92 GtC
Plant, animal respiration =	60 GtC	Photosynthesis =	120 GtC
Soil respiration =	60 GtC		
Deforestation & land use change =	0.9 GtC		
Burning fossil fuels =	6 GtC		
Totals	216.9 GtC		212 GtC

Carbon in the atmosphere appears to be far from being in a state of balance. While random variation in natural processes such as climate and forest fires often results in some degree of imbalance on an annual basis, the large imbalance in today's carbon cycle is usually attributed to the processes of fossil fuel combustion and land cover change, as discussed earlier. Although CO₂ is indeed building up in the atmosphere, the rate at which it is accumulating is less than the rate at which it is being emitted by fossil fuel burning, and the difference is difficult to account for through present estimates of uptake by the land and oceans. The primary hypothesis scientists are exploring is that carbon uptake by forests and other ecosystems is larger than has been estimated and that carbon accumulation in plants and soils has kept the atmosphere from increasing at an even greater pace. But if this is correct, why are present estimates too low and where in the world's ecosystems is the missing carbon going?

A recent article, "Balancing the Global Carbon Budget," by Richard Houghton on the Woods Hole Research Center website (<http://www.whrc.org/carbon/index.htm>) summarizes the major contributors to the overall global carbon balance, to show that a carbon sink of magnitude 2.9 GtC/year is needed to account for the measured annual atmospheric increase in carbon. His equation is summarized in Figure III-5:

Figure III-5 - Global Carbon Balance								
3.2 (±0.2)	=	6.3 (±0.4)	+	2.2 (±0.8)	-	2.4 (±0.7)	-	2.9 (±1.1)
Atmospheric Increase		Emission from fossil fuels		Net emissions from changes in land use		Oceanic uptake		Missing C sink

The nature and magnitude of the mechanisms that comprise the global carbon cycle reveal significant discrepancies and uncertainties in accounting for the rise in carbon content in the atmosphere, which is commonly attributed to fossil fuel burning. Change in land usage, carbon uptake by forests, and carbon accumulation in plants and soils, are identified as mechanisms that inadequately account for the disposition of carbon.

Another mechanism of significant magnitude that has been identified as a source of uncertainty is ocean uptake. Given the following factors:

- *the magnitude of carbon exchange between the ocean and the atmosphere is a factor of 15 larger than that associated with fossil fuel burning;*
- *the size and geographic diversity of the Earth's bodies of water;*
- *the complexity and variability of ocean circulation patterns;*

- *the large variations of temperature; latitudinal and in depth, of the global bodies of water;*

there is a significant uncertainty as to whether the increasing carbon content of the atmosphere is, primarily the result of fossil fuel burning, or whether other mechanisms due to natural ocean-related phenomena are responsible.

A popular theory presented by CO₂ advocates is that the measured decline of the ratio of C¹⁴/C¹² in the atmosphere over the past 40 years proves that the burning of fossil fuels is the primary cause of the increase in CO₂ concentration in the atmosphere. The theory is based on the following logic, as described by Currie et al (K. Currie et al, "¹⁴CO₂ in the Southern Hemisphere Atmosphere - the Rise and the Fall," Chemistry in New Zealand (April 2006)):

- Before the industrial revolution in the mid-18th century the upper atmosphere production of C¹⁴ balanced the radioactive decay over the long term and the system was in an approximately steady state situation.
- With the onset of industrialization and changing land use in the mid-18th century, the natural carbon cycle was perturbed. The burning of fossil fuels released carbon in the form of CO₂ that is devoid of C¹⁴, so-called dead carbon, therefore the atmospheric ¹⁴CO₂ was being diluted and the ratio C¹⁴/C¹² decreased (termed the Suess effect).
- Since actual measurements of C¹⁴/C¹² over the past 45 years reveal the trend expected with the Suess effect, the theory is supported.

However, Currie et al report measurements that show that nuclear bomb testing in the 50's and 60's increased the C¹⁴ level by 70-fold, peaking in 1965, and with the cessation of atmospheric testing the ratio has been decreasing exponentially ever since. They point out that "The large bomb spike has masked the effects of fossil fuel burning and changing land use on the ¹⁴CO₂ distribution making it difficult to directly assess their impact."

Thus the current trend in decreasing C¹⁴/C¹² ratio cannot be taken directly as evidence that fossil fuel burning is the main cause of atmospheric CO₂ increase.

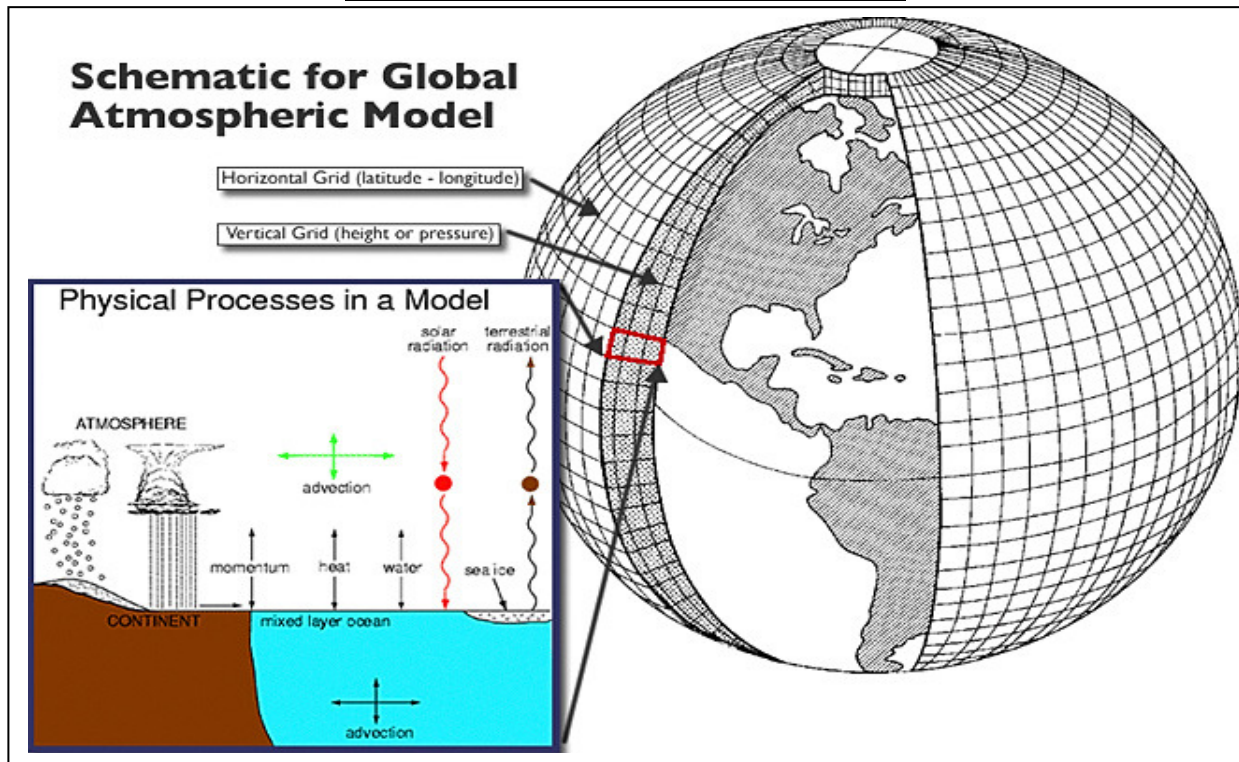
III.4 - Global Climate Models

Global climate models are the mathematical tools with which investigators attempt to represent, analyze, and predict the climate conditions of Earth as a result of the complex, dynamical interactions of its atmosphere, oceans, and land in response to solar heating. The following general description and Figure III-6 are excerpted from the Wikipedia article, "Global Climate Model" (http://en.wikipedia.org/wiki/Global_climate_model).

A General Circulation Model (GCM) is a mathematical model of the general circulation of a planetary atmosphere or ocean and based on the Navier-Stokes equations on a rotating sphere with thermodynamic terms for various energy sources (radiation, latent heat). These equations are the basis for complex computer programs commonly used for simulating the atmosphere or ocean of the Earth. GCMs and global climate models are widely applied for weather forecasting, understanding the climate, and projecting climate change. These computationally intensive numerical models are based on the integration of a variety of fluid

dynamical, chemical, and sometimes biological equations. An AGCM and an OGCM can be coupled together to form an atmosphere-ocean coupled general circulation model (CGCM or AOGCM). With the addition of other components (such as a sea ice model or a model for evapotranspiration over land), the AOGCM becomes the basis for a full climate model. Within this structure, different variations can exist, and their varying response to climate change may be studied.

Figure III-6 - Global Atmospheric Model



Climate models are systems of differential equations based on the basic laws of physics, fluid motion, and chemistry. To “run” a model, scientists divide the planet into a 3-dimensional grid, apply the basic equations, and evaluate the results. Atmospheric models calculate winds, heat transfer, radiation, relative humidity, and surface hydrology within each grid and evaluate interactions with neighboring points.

The fluid equations for AGCMs are discretized using either the finite difference method or the spectral method. For finite differences, a regular grid (i.e. with constant grid spacing) in latitude and longitude is most common. However, variable resolution grids can be used. The "LMDz" model can be arranged to give high resolution over any given section of the planet. HadGEM1 (and other ocean models) use an ocean grid with higher resolution in the tropics to help resolve processes believed to be important for ENSO. Spectral models generally use a gaussian grid, because of the mathematics of transformation between spectral and grid-point space. Typical AGCM resolutions are between 1 and 5 degrees in latitude or longitude: the Hadley Centre model HadAM3, for example, uses 2.5 degrees in latitude and 3.75 in longitude,

giving a grid of 73 by 96 points; and has 19 levels in the vertical. This results in approximately 500,000 "basic" variables, since each grid point has four variables [u,v (wind speed), T (temperature), Q (humidity)], though a full count would give more (clouds; soil levels). HadGEM1 uses a grid of 1.25 degrees in latitude and 1.875 degrees in longitude.

For a standard finite difference model, the gridlines converge towards the poles. This would lead to computational instabilities [In mathematics, the Courant–Friedrichs–Lewy condition (CFL condition) is a necessary condition for convergence while solving certain partial differential equations (usually hyperbolic PDEs) numerically. It is not in general a sufficient condition.] and so the model variables must be filtered along lines of latitude close to the poles. Ocean models suffer from this problem too, unless a rotated grid is used in which the North Pole is shifted onto a nearby landmass. Spectral models do not suffer from this problem.

Early generations of AOGCMs required a somewhat *ad hoc* process of "flux correction" to achieve a stable climate. The danger, however, is that a model may need flux corrections because of unrealistically strong feedback processes that result in a transition to a different climate state. As a result, there has been strong movement away from the use of flux corrections, and the vast majority of models used in the current round of IPCC do not use them. The model improvements that now make flux corrections unnecessary are various, but include improved ocean physics, improved resolution in both atmosphere and ocean, and more physically consistent coupling between atmosphere and ocean models.

Moist convection causes the release of latent heat and is important to the Earth's energy budget. Convection occurs on too small a scale to be resolved by climate models, and hence must be parameterized. This has been done since the earliest days of climate modeling, in the 1950s. The behavior of clouds is still poorly understood and is parameterized.

Most models include software to diagnose a wide range of variables for comparison with observations or study of atmospheric processes. An example is the 1.5 meter temperature, which is the standard height for near-surface observations of air temperature. This temperature is not directly predicted from the model but is deduced from the surface and lowest-model-layer temperatures. Other software is used for creating plots and animations.

No model – whether a wind tunnel model for designing aircraft, or a climate model for projecting global warming – perfectly reproduces the system being modeled. Such inherently imperfect models may nevertheless produce useful results.

The effects of clouds are a significant area of uncertainty in climate models. Clouds have *competing* effects on the climate. One of the roles that clouds play in climate is in cooling the surface by reflecting sunlight back into space; another is warming by increasing the amount of infrared radiation emitted from the atmosphere to the surface. In the 2001 IPCC report on climate change, the possible changes in cloud cover were highlighted as one of the dominant uncertainties in predicting future climate change.

Thousands of climate researchers around the world use climate models to understand the climate system. There are thousands of papers published about model-based studies in peer-reviewed journals - and a part of this research is work improving the models. Improvement has been difficult but steady (most obviously, state of the art AOGCMs no longer require flux correction), and progress has sometimes led to discovering new uncertainties.

One might infer from the above discussion that as general circulation and climate models are refined, and as bigger and more powerful computers become available, the prediction of future climate trends using these models will become more reliable. More powerful computers simply allow a finer grid—forecasts do not necessarily get better on a finer grid. Additionally, the inherent mathematical nature of these models imposes uncertainties and limitations that will limit their utility in that regard. This fact is rarely pointed out when model results are used to forecast long-term climate trends. The following discussion elaborates on this point.

General circulation and climate models mathematically are of the nature of nonlinear dynamic systems that are highly complex. The history of what has been discovered about the nature of such systems is revealing and relevant to characterizing the limitations of the predictions obtained from climate models. The following discussion of the nature and history of such systems of equations is excerpted from these books:

1. "Sync" by Steven Strogatz, Hyperion (2003)
2. "Nonlinear Dynamics and Chaos" by Steven Strogatz, Perseus Books (1994)
3. "Deep Simplicity" by John Gribbin, Random House (2004)

In nature, most physical processes are nonlinear, meaning that there are interactions between the constituents that make up the physical system, and those interactions cause feedback that influences the behavior of each constituent. In modern science and engineering, it is often acceptable to simplify the representation of such systems by linearizing them, meaning that the feedback effects are assumed small and ignored. Linear equations are tractable because they are modular. Each part of the system can be analyzed separately and solved, and finally all the separate answers can be recombined to give the results for the entire system. But when a system cannot be linearized - because it is far from equilibrium, or it is synergistic and highly interactive, or it experiences a high degree of feedback - it becomes very difficult to analyze mathematically. (Reference 1, this section, Pp. 179-182).

Modern climate models had their modest beginnings in 1959 when Edward Lorenz, a mathematical meteorologist working at MIT, developed a simplified model of convection rolls (Horizontal convective rolls are counter-rotating vortex rolls that are nearly aligned with the mean wind of the convective boundary layer) in the atmosphere to gain insight to the notorious unpredictability of the weather. He used the modest computers available at the time to run simulations of convection patterns for various conditions. Lorenz found that natural processes would drive the model atmosphere into one of a relatively small number of stable states (that now are called attractors), but that more generally the solutions to his equations never settled down to equilibrium or to a periodic state - instead they continued to oscillate in an irregular,

aperiodic state. Moreover, if he started his simulations from two slightly different initial conditions, the resulting behaviors would soon become totally different. The implication was that the system was inherently unpredictable - tiny errors in measuring the current state of the atmosphere would be amplified rapidly, eventually leading to embarrassing forecasts. But Lorenz also showed that there was structure in the chaos - when plotted in three dimensions, the solutions to his equations fell onto a butterfly-shaped set of points. He argued that this set had to be an infinite complex of surfaces - today we would regard it as an example of a fractal (Reference 2, this section, P. 3).

Lorenz's work had little impact until the 1970's, the boom year for chaos. A most surprising discovery by Feigenbaum revealed that there are certain universal laws governing the transition from regular to chaotic behavior; roughly speaking, completely different systems can go chaotic in the same way. His work established a link between chaos and phase transitions, popularly known as tipping points (Reference 2, this section, P. 3).

Strogatz (Reference 1, this section, Pp. 260-268, 322) describes the phenomenon of tipping point in his examples of human network interactions from which unanticipated forms of collective behavior can emerge that are not obvious from the properties of the individuals themselves. Although the use of the phrase was first introduced in 1957, it became popular due to Gladwell's 2000 best-seller, "The Tipping Point: How Little Things Can Make a Big Difference." The term has been used in the context of climate change to refer to a set of climate conditions in which small perturbations could lead to disproportionately large, adverse consequences. It should be generally noted that a fundamental difference that distinguishes linear from non-linear systems is that small perturbations to dynamic linear systems lead to small proportionate responses, while for dynamic nonlinear systems small perturbations can lead to disproportionately large responses.

The weather, it turns out, is highly nonlinear, and sometimes it can be more chaotic than at other times. When meteorologists run the numerical simulations these days, they don't just take the exact data from their grid points of observations as the raw material for a single forecast. Instead, to find out if the errors and uncertainties inherent in the observations matter significantly, they usually run each forecast several times with slight variations in the starting conditions. If all the forecasts come out more or less the same, they know the overall pattern of the forecasts can be trusted. But sometimes when they run the same forecast with slightly different starting conditions, they get widely different predictions for the weather a few days ahead. This tells them that the weather is in a chaotic state, and none of the forecasts can be trusted (Reference 3, this section, Pp. 60-61).

Modern global climate models have grown tremendously in both size and complexity since the early days of the Lorenz model, but have retained the same inherent character. Climate of the Earth is a dynamic, non-equilibrium system of transfer of heat, mass, and momentum between atmosphere, oceans, and land, spread over diverse geography. It is characterized by a complexity of interactions between the constituents; strong feedback mechanisms are pervasive. There are obviously many localized "attractor" conditions that have been experienced on Earth over time, as evidenced by the history of climate,

but there also have been many tipping points and conditions of incipient chaos, again evidenced by past climate history. Given the inherently uncertain and potentially chaotic nature of the mathematical models used to represent Earth's climate, it is extremely difficult to believe that their predictions can reliably predict the climate of the future, particularly over a years-to-decades time frame. And it would seem equally unlikely that averaging the predictions of the multiplicity of different models used by different investigators can eliminate or even mitigate this inherent uncertainty.

IV. - INPUT FROM TECHNICAL EXPERTS

As a citizen with substantial technical training and experience, I have been frustrated by the absence of a flow of complete and objective technical information from credible and reliable sources. Although I do not have direct experience in the field of meteorology, climatology, and earth science, I do have substantial experience in heat, mass, and momentum transfer. My background enables me to analyze and evaluate the science and the evidence on technical matters, without depending on others to tell me the conclusion. In fact, this paper is the culmination of 5+ years of reading and evaluating technical information that could be gleaned in bits and pieces from the literature and the media. But that is insufficient for this purpose. In an effort to construct an objective technical basis that includes expert input from all sides of the issue, I have drawn from the writings of two recognized technical experts on climate - James Hansen and Richard Lindzen.

What finally prompted me to attempt to systematically assess the technical issues associated with global climate change in the form of this paper was my reading of the following book:

1. "Storms of my Grandchildren" by James Hansen, published in 2009 by Bloomsbury USA.

In discussions with a colleague, Hansen's book was cited as giving a "simpler" technical basis for concluding that anthropogenic CO₂ is the major cause of current climate change. Dr. Hansen heads the NASA Goddard Institute for Space Studies in New York City, a part of the Goddard Space Flight Center in Greenbelt, Maryland, Earth Sciences Division. He has held this position since 1981. He is also an adjunct professor in the Department of Earth and Environmental Sciences at Columbia University. He is a credible source of technical information on this general question.

In addition I have elected to use the writings of Richard S. Lindzen of MIT as the other primary expert technical source that represents an opposing point of view on the question of causality of climate change. Professor Lindzen is an atmospheric physicist and Alfred P. Sloan Professor of Meteorology at the Massachusetts Institute of Technology, and is known for his work in the dynamics of the middle atmosphere, atmospheric tides and ozone photochemistry. He has published more than 200 scientific papers and books, and was a lead author of Chapter 7, 'Physical Climate Processes and Feedbacks,' of the IPCC Third Assessment Report on climate change. Professor Lindzen is recognized as a leading expert in meteorology and climatology, and is widely quoted as a critic of some global warming theories and what he states are political pressures on climate scientists. I have used his following published writings as the second primary source of expert technical input to this assessment:

2. - "An Exchange on Climate Science and Alarm" taken from Chapters 2 & 3 of the book "Global Warming: Looking Beyond Kyoto" edited by Ernesto Zedillo and published by

the Brookings Institution Press and the Center for the Study of Globalization at Yale.
<http://www.junkscience.com/mar08/Lindzen-Rahmstorf-Exchange.pdf>

3. - "Taking Greenhouse Warming Seriously" by Richard S. Lindzen. Reprinted from Energy & Environment, Volume 18, No. 7-8, December 2007, Pp 937-950 (14)
<http://www.cfa.harvard.edu/~wsoon/ArmstrongGreenSoon08-Anatomy-d/Lindzen07-EnE-warm-lindz07.pdf>

Sections IV.1 and IV.2 that follow present Hansen's and Lindzen's technical input, accompanied by my commentary. As a matter of style, note that in each of the two sections the information given directly by Hansen and Lindzen is presented in normal font, while my personal observations and comments are indented and italicized.

IV.1 - Hansen's Perspective

Hansen is considered to be one of the leading technical experts on climate issues. But more than that, he has become a strong activist in promoting his conclusion that CO₂ is the primary cause of climate change, and has become a strong advocate for public policy and action that follow from that conclusion. His book, written for the general public and for policy-makers, does contain sufficient technical information to understand the basis for his judgment. But the great majority of the book is about his experiences in trying to influence the prevailing view and his urgent manifesto for future policies and action. For my purposes I have found it necessary to separate his technical analysis and rationale from his sociopolitical activism, so that I may incorporate the technical basis of a credible spokesperson representing his particular perspective as part of my assessment.

Climate forcing is defined as an imposed perturbation of the Earth's energy balance by a specific mechanism, measured in watts/meter² (w/m²). In defining forcings (Reference 1, this section, P. 5), Hansen uses as the Earth's total energy input 240 w/m², which is the amount of short wavelength solar radiation absorbed by the Earth's surface.

This is technically correct, but misleading. As pointed out in Section III.1 of this paper, the total amount of solar short wavelength radiation impinging on the outer boundary of the Earth's atmosphere is actually 340 w/m². Of that amount, 31% is reflected back to outer space, primarily by clouds and atmospheric molecules. The remainder, 235 w/m², is absorbed by the Earth and its atmosphere. Thus, to be more complete in identifying potential perturbation mechanisms that affect the Earth's energy balance, those mechanisms that affect the reflection of solar input should be included when identifying forcings.

Hansen identifies the following mechanisms responsible for climate forcings in the calendar period between 1750 and 2000 (ibid, Figure 1, P. 5):

Table IV-1 - Climate Forcings

<u>Mechanism</u>	<u>Forcing, Watts/m²</u>
Gases:	
1. CO ₂	+1.5±.15
2. N ₂ O, CFC's, CH ₄	+1.2
3. O ₃	+0.4±.15
Aerosol Effects:	
4. Black Carbon Aerosols	+0.6±.3
5. Reflective Aerosols	-1.0±.5
6. Aerosol Cloud Changes	-1.0±.6
7. Land Cover Change	-0.1±.2
8. Sun	+0.3±.2
9. Volcanoes	+0.15±.1

The first seven mechanisms listed are anthropogenic, the last two are natural. The magnitude of uncertainties is noteworthy, particularly for the negative feedback mechanisms of aerosols, and how they would affect any conclusions regarding overall anthropogenic effects in relation to measured global temperature changes. Also noteworthy is the absence of references to the influences of water in all its forms (vapor, clouds, ocean, ice), which actually dominate the global climate dynamic. These are separately classified by Hansen as feedback, not forcing, mechanisms, and, as such, are not considered in this same context. This is, of course, based on the global climate models that do the same thing: clouds, oceans, vapor, and ice are included in the model and greenhouse gases are isolated to be independently varied. But this perspective creates a misleading view of the overall global climate dynamic. Global climate is primarily the result of solar energy impinging on a complex, dynamic interaction of atmosphere, land, and ocean. It is subject to large local, natural variations over time that are the consequence of perturbations to the system, whether global or local, natural or man-made. Such is the nature of the global climate system, which is a classic example of nonlinear, chaotic, complex systems. For such systems it is not the small perturbing influences that determine the fundamental nature of the system, but the large, localized responses to these perturbations and the conditions at which these occur. It is necessary to consider all components of the global energy balance to put forcings into a more realistic and complete context. See Section III.1 for a discussion of global energy balance.

Climate sensitivity is defined as the magnitude of change in global atmospheric average temperature as a result of a specific forcing. Hansen presents the case that "Paleoclimate information provides precise knowledge of how sensitive climate is to changes of climate forcings (ibid, P. 34)." This is his logic:

- Actual data from various sources are available that show the history of temperature, CO₂, and sea level for the past 425,000 years (ibid, Figure 3, P., 37). The Figure shows that variations in temperature, sea level, and CO₂ concentration appear to be correlated in time. The temperature history shown comes from ice cores taken from the Antarctic ice sheet, but temperature histories from many places around the world are obtained in analogous ways. The CO₂ concentration data come from the same ice core sources. Sea level changes are the result of melting or formation of land-based ice sheets. Sea level changes are large during this period, changing by over 100 meters, and can be correlated with global ice ages and warming periods. Hansen notes that temperature changes precede the CO₂ changes by several hundred years (ibid, P. 38). He points out this is the norm for natural climate changes. The length of the delay of the CO₂ response to temperature change is due to the ocean turnover time, which is several centuries.

All of these observed factors suggest that natural mechanisms associated with the ocean as a dynamic heat and CO₂ sink and source would likely be important for establishing the temporal history of trends in global climate change over the past 100 years.

Sea level change is driven by the thermal expansion/contraction of sea water in response to warming/cooling of the ocean; additional runoff to the oceans from the melting of land-based ice sheets and glaciers; and changes in anthropogenic use and storage of water. Although not explicitly stated by Hansen, it is noted by Barry (http://www.arctic.noaa.gov/essay_barry.html) that the Antarctic and Greenland ice sheets hold the majority of the earth's ice, an amount equal to 70 m of sea level. Antarctica alone holds 90% of the world's ice. The mass balance of the Antarctic ice sheet currently is in approximate equilibrium and may represent only about 10 percent of the current contribution to sea level rise coming from glaciers. The Greenland Ice Sheet, however, may be contributing about 30 percent of all glacier melt to rising sea level. Mid-latitude glaciers and ice caps, although making up only about 4% of the total land ice area, may have provided as much as 60 percent of the total glacier contribution to sea level change since the 1990s.

- Referring to the paleoclimate data in Figure 3, Hansen points out that starting about 150,000 years ago the Earth entered the Eemian period during which temperatures declined and at which time the Earth descended into full ice age conditions. This ice age persisted until about 20,000 years ago, by which time sea level had dropped by 110 meters and global temperatures had dropped by ~10° C. The last ice age ended about 20,000 years ago; temperature and sea level began to increase as the earth entered the Holocene period, the interglacial period in which we now live. About 7,000 years ago the warming trend seemed to reverse, and sea level rise slowed markedly.
- Hansen compares the conditions he assumes existed 20,000 years ago to the conditions of the late Holocene, the recent interglacial period which started 7,000 ago, to derive the magnitude of climate sensitivity for CO₂. He assumes that Earth was in energy balance during both periods, which he says is inferred by the observation that if it weren't in

energy balance then either ice would have melted and the sea level risen, which it didn't, or the ocean would have warmed, which it didn't.

- Hansen observes that global average temperature was $5 \pm 1^\circ \text{C}$ warmer in the Holocene than in the last ice age. He then considers the possible mechanisms at work that could have caused the warming. He dismisses change in the sun's luminosity. He observes that there were increases in the concentration of all the long-lived greenhouse gases (CO_2 , CH_4 , N_2O) from the ice age to the late Holocene, which resulted in net forcings of $3 \pm 1 \text{ watts/m}^2$. Finally he points out the largest changes in the Earth's surface were the reduction of the ice sheets covering Canada, parts of the US, and smaller areas in Eurasia, resulting in an increase in the absorption of sunlight and a forcing of $\sim 3.5 \text{ watts/m}^2$.
- Hansen concludes that a total forcing of about 6.5 watts/m^2 maintained an equilibrium temperature change of 5°C , implying a climate sensitivity of about 0.75°C for each w/m^2 of forcing.
- Hansen then applies his empirically derived sensitivity value to the forcings derived from the atmospheric composition and sea level history data in his Figure 3, assuming sea level records imply the changing size of continental ice sheets, and calculates a temperature history to compare to the Antarctic temperature divided by 2. The comparison is shown in Figure 4 (ibid, P. 47). He claims that by deriving the climate sensitivity in this manner, "All physical mechanisms that exist in the real world are included - and furthermore they are included correctly; the physics is exact."

The significance of this result is that it gives Hansen a sensitivity value with which he may estimate changes in global temperature due to various forcing mechanisms. There are many assumptions built into this analysis that raise questions of applicability and completeness of the sensitivity when applied to conditions that exist in the current Earth climate system. But more importantly, at issue is Hansen's evaluation of the forcings, the feedbacks, and the climate mechanisms at work now, and whether Hansen has adequately and completely taken them all into account, both in magnitude and timing. My impression is that Hansen's focus on the forcings tends to direct attention away from the large and significant effects of the feedback mechanisms, which are the more important determinants of global temperature, and the dynamics of our complex global climate system in a time frame that is not typified by the time frame of his paleoclimate data. What follows are excerpts from Hansen's discussions, along with my reaction, that contribute to this impression.

"Climate, the average weather over a finite interval, fluctuates without any forcing, because the atmosphere and ocean are chaotic fluids that are always sloshing about. There is no way to predict far ahead of time where and how big any particular slosh will be.... Yet despite this unpredictable sloshing, if weather is averaged over a long enough time, the system is deterministic..... Not every year though, because chaos and sloshings also occur on greater time and space scales than local day-to-day weather. (ibid, P. 4)."

This is consistent with my understanding of the inherent potentially chaotic nature of the Earth's climate system. But it also raises the question of whether the averaging of behavior of a potentially chaotic system can be deterministic. I believe not (See Section III.4).

Hansen discusses the magnitude of changes in the sun's irradiance (i.e. brightness) as a forcing mechanism (ibid, Pp. 6-7), and concludes that it is much smaller than CO₂ and that it could not account for the magnitude of temperature changes in the past 250 years.

As discussed earlier, Hansen states in reference to Figure 3 (ibid, P. 37), which plots Antarctic temperature, CO₂ concentration, and sea level for the past 425,000 years, "...Temperature changes precede the carbon dioxide changes by several hundred years. Carbon dioxide change in response to climate change is an important feedback process that affects climate sensitivity....But the sequence (CO₂ change following temperature change) and the delay (several hundred years) are as expected for these natural climate changes. The length of the delay of the CO₂ response to temperature change is due to the ocean turnover time, which is several centuries (ibid, P. 38)".

The primary significance of this excerpt is in the importance of CO₂ as a natural feedback mechanism that lags temperature change due to ocean turnover time. What is cause and what is effect? How is that reflected in the current trends in CO₂? It is noted that recent work tracing the distribution of tritium from nuclear testing shows that substantial mixing of the ocean can take place on shorter time scales (See G. Marsh, "Seawater pH and Anthropogenic Carbon Dioxide," <http://www.gemarsh.com/wp-content/uploads/SEAWATER%20pH%20&%20ANTHRO%20CO2%20V2.pdf>)

Hansen computes the no-feedback climate sensitivity of "instantly" doubling CO₂ without changing anything else on Earth as 0.3° C per w/m² of climate forcing. The simple calculation is based on applying the Stefan–Boltzmann law (the total energy radiated by a black body is proportional to the fourth power of the black body's absolute temperature) to compute that the Earth's atmosphere must heat up by 1.2° C in order to emit the additional 4 w/m² absorbed by the atmosphere due to CO₂.

This is a revealing figure, but overly simplified, in my estimation. It does not reflect the long lag time associated with turnover of the ocean. Additionally, the actual radiant energy transfer from the surface of the Earth to space is far more complex than that represented by the simple model. It seems to me that one must examine greater detail of the radiant energy transfer in order to arrive at this estimate. This question is addressed further under "Lindzen's Perspective" (Section IV.2).

" The most important climate feedbacks all involve water, in either its solid, liquid, or gas form (ibid, P. 42)." Hansen briefly mentions why water vapor provides feedback that could be positive or negative. He goes on to describe feedback caused by clouds, but admits that climatologists are not able to adequately model clouds or determine whether cloud feedback is

positive or negative (ibid, P. 43). He also mentions aerosols, but acknowledges the difficulty in modeling aerosols and determining the nature of their feedback (ibid, P. 43).

The sum total of this discussion is to emphasize the uncertainty associated with important forcings and feedbacks, and the inability of modelers to get it right. "Climate sensitivity will never be defined accurately by models (ibid, P. 44)."

Hansen does acknowledge the various insolation (i.e. incident solar radiation) and Earth orbital variability cycles in conjunction with his evaluation of causes for the cyclical changes in temperature over the past 425,000 years (ibid, P. 47). In addition to the 11 year solar cycle, he describes a 20,000 year cycle, a 41,000 year cycle, and a 100,000 year cycle, each due to different orbital mechanisms and each with a different forcing. He concludes that the natural forcing due to insolation variations is a small fraction of 1 w/m^2 , and is effective only over long periods by bringing into play powerful, slow feedbacks.

See Section III.2 of this paper for more discussion of solar heating.

Hansen believes that "We really do have a planet in peril" because of the danger of pushing the climate system to a point such that future disasters might occur out of our control (ibid, P. 71).

In my view that is really the nature of the problem - small forcings, by whatever mechanisms, can cause large variations due to feedback that could exceed a tipping point (See Section III.4). It is the feedbacks, not the forcings, that represent the largest and most important mechanisms in terms of influencing climate change. The paleoclimate data may show the eventual, very-long-term consequences of the changes due to long-term forcings, but those data provide no insight to the response on shorter time scales, the order of centuries. Nor do they explain whether different mechanisms become important in different time frames. Hansen discusses inertia and feedback as they influence climate dynamics. He points out that amplifying feedbacks are dominant on time scales from decades to hundreds of thousands of years (ibid, P. 75). Water in all its forms plays a big role. But Hansen does not mention in this context the negative feedback due to water-based clouds.

Hansen's approach to assessing trends in climate emphasizes the nature and magnitude of forcing mechanisms, both natural and man-made. But uncertainties in predicting these mechanisms loom large. He characterizes the aerosol cooling effect as a Faustian climate bargain that humanity inadvertently entered through the use of fossil fuels (ibid, Pp. 98-100). This refers to the fact that aerosol production creates a negative forcing that is believed to counter, to a large extent, man-made greenhouse gas production.

In fact, aerosols are now being used by the IPCC to explain why global temperatures have not continued to rise in the past decade. However, there is a large uncertainty in measuring and modeling the aerosol effect. Aerosols do not necessarily counter greenhouse gas production. For example, Shindell and Faluvegi (D. Shindell and G.

Faluvegi, "Climate response to regional radiative forcing during the twentieth century", Nature Geoscience 2, 294 (2009)) estimate that ~45% of the arctic warming since 1970 is due to decreasing concentrations of sulphate aerosols and increasing concentrations of black carbon.

It would be logical to assume that if two counteracting mechanisms of the same magnitude are responsible for a certain result, and one of the mechanisms is very uncertain, any conclusions thus derived are only as good as the most uncertain. This is not the sense one would get from following Hansen's approach.

He also discusses the ocean as a heat sink, where the excess of heat in the Earth's presumed energy imbalance is being absorbed. Two previous studies of global ocean temperatures by Levitus and Willis (ibid, Pp. 101-102), have attempted to find evidence supporting the contention that the Earth's energy is out of balance, but both studies have been found lacking. Hansen concludes that "Until instrumental issues are resolved and good heat storage data is obtained for the entire ocean, it is not possible to infer the net climate forcing acting on Earth."

Yet it is this global energy imbalance that forms the basis for his own conclusions.

Hansen does address the contention that the sun is the dominant climate forcing and the most important factor in climate change. Figure 11 (ibid, P. 103) shows the total solar irradiance from 1978 to the present. It shows a period of about 11 years and a solar forcing of 0.2 w/m^2 , which is about a 0.1% variation averaged over the cycle. He points out that there are mechanisms by which the sun's effect may be magnified or diminished, and concludes that there may be an amplifying efficacy of 100-200% (ibid, P. 107). He goes on to compare the relative magnitudes of CO₂ forcing to solar forcing and concludes that "Human-made forcing now overwhelms the natural climate forcing (P. 107)."

See Section III.2 of this paper for further discussion of solar variations.

2008 was a cool year, the coolest since 2000. Hansen explains this (ibid, P. 108) by a strong La Nina, which is the cooling phase of equatorial Pacific Ocean temperature variation and another mechanism that is natural, cyclical, and contributes to the climate dynamic. It is highly questionable to depend on a perturbation analysis approach to determining the impact of individual mechanisms when the entire global climate system is so interconnected, interactive, complex, and potentially chaotic.

Because of his focus on CO₂ as the primary cause of global warming, Hansen devotes some detail to an understanding of the carbon cycle, which accounts for the movement of carbon between the atmosphere, biosphere, soil, and ocean reservoirs (ibid, Pp 117-124). Much is revealed in this analysis. Table IV-2 is a tabulation of the sources, sinks, and rates of exchange of carbon for each as shown in Figure 15 (ibid, P. 118). Note that the unit of measure for carbon (as contained in CO₂) is billions of metric tons (Gigatons, GtC). Note also that 1 ppm of CO₂ in the global atmosphere is equivalent to ~ 2.12 GtC.

Table IV-2 - Global Carbon Cycle

<u>Sources & Sinks</u>	<u>Content, GtC</u>	<u>Rate of Exchange, GtC/yr</u>
Earth's Crust	100,000,000	--
Soil (not shown)	1,500	?
Ocean	40,000	+3
Ocean Sediment	?	-.1
Volcanoes	--	+1
Fossil Fuels	5,000	+8.5
Forests	600	+1
Atmosphere	800	+4.5

"Large, natural back-and-forth fluxes of carbon pass among these reservoirs. Plants take up CO₂ in photosynthesis, but plants and soils rapidly respire a similar amount of CO₂ back to the atmosphere. CO₂ dissolves into cold ocean regions, but a similar amount is released to the atmosphere at other places. These uptakes and losses nearly balance over the year, but small imbalances occur and provide important climate feedbacks. For example, in interglacial-to-glacial climate change, as the ocean becomes colder, it dissolves more CO₂, causing the atmosphere and plants to contain less CO₂, which then drives further cooling. Conversely, when Earth's orbit or the tilt of the spin axis cause melting of snow and ice, this increases absorption of sunlight, and the warming ocean and soil release CO₂ and CH₄. This greenhouse gas amplifying feedback....accounts for nearly half the glacial-interglacial global temperature change (ibid, Pp. 118)."

A significant issue is what the dynamics of exchange are with the ocean. Hansen's table would lead one to believe that the rate of exchange of CO₂ among the sources and sinks are of similar magnitude, with fossil fuel burning being the largest and most significant. But in the case of the ocean that is not true. Other information sources indicate that the rate of release of CO₂ from the ocean surface is ~90 GtC/yr, due to release of CO₂ from evaporation and dissolution of surface water, which happens more in the tropical regions, while absorption of CO₂ from the atmosphere is the result of cooler water surfaces having a greater solution potential. Thus different regions of the Earth will contribute in differing amounts to each mechanism resulting in a net that could be zero, negative, or positive. To make an accurate assessment of the net carbon exchange with the atmosphere, and to assess whether it is the burning of fossil fuels or the ocean that dominates the atmospheric carbon content requires a much more detailed analysis of the ocean dynamic. See Section III.3 for further discussion of the carbon cycle.

In his Chapter 8 Hansen analyzes the long-term temperature changes that occurred on Earth over the past 65 million years. Figure 18 (ibid, P. 153) shows the deep ocean temperature during the Cenozoic era (the past 65 million years, from the time the dinosaurs went extinct until today). About 50 million years ago the Paleocene-Eocene thermal maximum (PETM) occurred, which was a minor extinction event - almost half the deep ocean foraminifera (microscopic shelled animals) disappeared - but little of the land plants and animals were affected. The average global temperature at that time was ~ 13 °C and has been cooling ever since,

experiencing a drop of ~14 °C. Hansen considers three possible causes of this long cooling trend. He concludes that change in solar brightness could not have been the cause and changes in the continental configuration were too small to have been the cause, so that changes in the atmosphere must have been the cause. "The amount of atmospheric CO₂ during the Cenozoic varied from as little as 170 ppm in recent ice ages to 1000-2000 ppm in the early Cenozoic (ibid, P. 156)." From this he concludes that "CO₂ changes in the Cenozoic caused a forcing of ~12 w/m² - at least 10 times greater than the climate forcing due to either the sun or Earth's surface. It follows that changing CO₂ is the immediate cause of the large climate swings over the last 65 million years (ibid, P. 157)."

This conclusion is at odds with his earlier explanation (ibid, P. 38) that "Temperature changes precede the CO₂ changes by several hundred years....The sequence (CO₂ change following temperature change) and the delay (several hundred years) are as expected for these natural climate changes. The length of the delay of the CO₂ response to temperature change is due to the ocean turnover time, which is several centuries."

From Cenozoic data, the CO₂ concentration 34 million years ago - when Antarctica became cold enough to harbor a large ice sheet - was found to be 450 ppm with an uncertainty of 100 ppm (ibid, P. 160). From this Hansen draws a "...Clear, strong implication for what constitutes a dangerous level of atmospheric CO₂." He goes on to build a case that a target limit to CO₂ should be set no higher than 350 ppm (ibid, Pp. 164-166).

Returning to the cause of the PETM warming, Hansen concludes that it was due to a huge injection of light carbon into the atmosphere - ~3000 Gt - injected in two bursts, each about 1000 years in duration. He concludes these were due to methane hydrate release, opening the question of whether it was an exogenous trigger or climate feedback (ibid, P. 161). If it were exogenous (e.g. asteroid strike, or intrusion of hot magma from below), then humans have no control over future such events; however the probability of such a future event in the next 100 years is too low to care about. If melting of the methane hydrate is the result of a warming climate, then "...It is a whole different ball game (ibid, P. 162)." From paleoclimate data Hansen observes that methane releases occurred at times of natural warming events. Thus his concern that the current burning of fossil fuels will continue warming trends that will be amplified in the high latitudes and that will trigger the large positive climate feedback caused by melting methane hydrate.

I find the chain of Hansen's logic difficult to challenge, for lack of detailed knowledge or for insufficient grasp of the mechanisms at work. I respect Hansen's efforts to simplify the big picture, focus on select data, and extract meaningful results, but I respect even more the wisdom attributed to Einstein, "Everything should be made as simple as possible, but not simpler." I find Hansen's interpretation of paleoclimate data requires a simplification of the complexity of the climate system to such a degree that it exceeds credibility, especially when considering the limitations encountered when trying to model and project current climate data in a 100-200 year time frame that is much shorter than the scale associated with paleoclimate effects. Also, in line with my observations earlier in this Section, this analysis tends to reinforce my concern that Hansen's entire focus is misleading - it is not the small perturbing influences that determine the fundamental

nature of the climate system, but the large, localized responses to these perturbations and the conditions at which these occur that determine the nature of global climate. The integral character of the system must be analyzed as a whole; a linearized approach to separately analyzing individual forcing mechanisms cannot be depended upon. Yet global climate modeling, which is the current standard being used by the climatology community, is inherently limited by its mathematical nature, and, by Hansen's own admission, by the inability of modelers to accurately represent the most important forcing and feedback mechanisms.

IV.2 - Lindzen's Perspective

Two articles by Lindzen (References 2 & 3, this Section) provide his technical input for my assessment. In each of these articles he addresses two related issues. First is his critique - in technical terms - of the IPCC technical basis for its assessment of the causality of global warming. Second is his critique - in more subjective terms - of the manner in which defenders of CO₂ as the main cause of global warming are creating an atmosphere of alarmism by interpreting selective aspects of the IPCC approach to forecast alarming consequences. I have selected only the technical aspects of his papers to use as technical input, and have left his subjective assessment to a different forum for assessing politics and policy-making.

To set the stage for his technical assessment, Lindzen introduces his approach with the following commentary (ibid Ref. 2, Pp. 21-22):

"Elizabeth Kolbert in the New Yorker says, 'All that the theory of global warming says is that if you increase the concentration of greenhouse gases in the atmosphere you will also increase the Earth's average temperature. It is indisputable that we have increased greenhouse gas concentrations in the air as a result of human activity, and it's also indisputable that over the last few decades average temperature has gone up.'

"Given the alarm surrounding the issue, such statements seem peculiarly inconclusive and irrelevant to the catastrophes cited. To be sure these references are one-sided. They fail to note that there are many sources of climate change and that profound climate change has occurred many times both before and after man appeared on the Earth; given the ubiquity of climate change it is implausible that all change is for the worse. Moreover, the coincidence of increasing CO₂ and the small warming over the past century hardly establishes causality. For the most part, I do not disagree with the consensus, but I am disturbed by the absence of quantitative considerations. Indeed, I know of no serious split and suspect that the claim that there is opposition to this consensus amounts to no more than setting up a straw man to scoff at. However, I believe that people are being led astray by the suggestion that this agreement constitutes support for alarm. . . . The components that constitute this consensus (are):

1. The global mean surface temperature is always changing. Over the past 60 years, it has both increased and decreased. For the past century, it has probably increased by about $0.6^{\circ} \pm 0.15^{\circ}\text{C}$. That is to say, we have had some global mean warming.

2. CO₂ is a greenhouse gas, and its increase contributes to warming. It is, in fact, increasing, and a doubling would increase the greenhouse effect (mainly due to water vapor and clouds) by about 2%.
3. There is good evidence that man is responsible for the recent increase in CO₂, although climate itself (as well as other natural phenomena) can also cause changes in CO₂.

In some respects these three pillars of consensus are relatively trivial. Remaining completely open is the question whether there is any reason to consider these facts as particularly alarming."

Entirely independent of Lindzen's papers, I had reached the same conclusions myself and thus would agree with his articulated consensus position as the starting point for exploring the technical issues that follow. Following are the specific technical assessments he makes in addressing the nature and magnitude of global warming and climate change, the mechanisms that have produced the actual results observed for those phenomena, and the tools and methods used by the IPCC to reach their technical conclusions.

According to Lindzen, a fundamental shortcoming of the modelers' approach to representing the global greenhouse effect in the General Circulation Models (GCM) used by the IPCC is the oversimplified and inappropriate way in which global surface temperatures are related to atmospheric temperature gradients in altitude and latitude. Lindzen points out (ibid Ref. 3, Pp. 938-944) that, "The main greenhouse gas, water vapor, generally maximizes at the surface in the tropics and sharply decreases with both altitude and latitude. There is so much greenhouse opacity immediately above the ground that the surface cannot effectively cool by the emission of thermal radiation. Instead, heat is carried away from the surface by fluid motions. . . . These motions carry the heat upward and poleward to levels where it is possible for thermal radiation emitted from these levels to escape to space. . . . This level (which varies with the amount of water vapor at any given location) is referred to as the characteristic emission level.

Crudely speaking, "When the Earth is in radiative balance with space, the net incoming solar radiation is balanced by the outgoing longwave radiation (OLR) . . . (effectively at) the characteristic emission level. When greenhouse gases are added to the atmosphere, the characteristic emission level is elevated in altitude, and because the temperature of the atmosphere decreases with altitude, the new characteristic emission level is colder than the previous level. As a result, the OLR no longer balances the net incoming solar radiation and the Earth is no longer in thermal balance with space. In order to reestablish balance, the temperature at the new characteristic emission level must increase. It is the warming at the characteristic emission level that is the fundamental warming associated with the climate greenhouse effect."

General Circulation Models prove helpful to understand how warming at the characteristic emission level relates to warming at the surface. Lindzen referred to studies using four different models that show that the warming at the characteristic emission level in the tropics is from more than twice to three times larger than near the surface regardless of the sensitivity of the particular model. "Stated somewhat differently, if we observe warming in the

tropical upper troposphere, then the greenhouse contribution to warming at the surface should be between less than half and one third the warming seen in the upper troposphere."

Since the 1960's atmospheric temperature gradients have been measured with balloons and satellites. Recent results have concluded that there is indeed warming in the atmosphere. Based on data taken at the UK's Hadley Center, a warming trend in the troposphere of about 0.1°C per decade is noted. Based on measured atmospheric temperature gradients from surface to troposphere, this should be associated with a surface trend of between 0.033 and somewhat less than 0.05° C per decade. "Contrary to the iconic statement of the latest IPCC Summary for Policymakers, this is only on the order of a third of the observed trend at the surface, and suggests a warming of about 0.4° C per century. It should be added that this is a bound more than an estimate. . . . Had we used globally averaged temperatures, it would have been almost impossible to correctly relate the underlying physics to the observations. It must also be recognized that a one-dimensional picture of the greenhouse effect is not equivalent to a global average."

"The above is a bound on climate sensitivity based on basic theory, observations and modeling studies. The modeling studies establish that the ratio of upper tropospheric tropical warming to surface warming is approximately 2.5:1 regardless of the model sensitivity. The bound does not depend on any specific feedback mechanism, but it does imply that strong positive feedbacks in current models (due to water vapor) are either wrong or more than balanced by negative feedbacks missing from these models."

I find Lindzen's case rather compelling. It does not negate the general conclusion that there is warming at the surface as well as the troposphere, but it does highlight the questionable credibility of the arguments that are based on the alleged relationships between greenhouse gas forcings, global surface temperature, and global mean temperature. It is not clear whether more data from different locations would yield a different conclusion.

Lindzen's last conclusion, stated above, raises the question of how did the IPCC reach its conclusion that most of the surface warming over the past 30 years is due to anthropogenic forcing.

Lindzen claims that the modelers for the IPCC concluded that most of surface warming over the past 30 years is due to anthropogenic forcing because they could not find anything else that could account for it. He refers to the same table of individual forcings that have been reported by the IPCC and were used by Hansen to analyze the climate sensitivity (See Section IV.1). For reference purposes, Lindzen uses the same radiative forcing associated with a doubling of CO₂ of ~3.5 w/m² as the IPCC. He points out that the major anthropogenic greenhouse gas forcings add up to ~3 w/m², which is about 86% of the radiative forcing associated with a doubling of CO₂. He points out that now we are almost at the radiative forcing associated with the benchmark of doubled CO₂. The IPCC models predict that a doubling of CO₂ leads to a surface warming of from 1.5-3.5° C, yet by contrast the observed warming amounts to only about 0.6° C, not all of which need be due to increased greenhouse gases. Lindzen

concludes that on the face of it this would seem to confirm that current models are much too sensitive to anthropogenic greenhouse forcing, assuming that all the observed warming was due to increasing greenhouse gases.

Lindzen (ibid Ref. 2, P. 22) elaborates further on the above question. He points out that "The impact of CO₂ is nonlinear in the sense that each added unit contributes less than its predecessor. For example, if doubling CO₂ from its value in the late nineteenth century - from about 290 ppm to 580 ppm - causes a 2% increase in radiative forcing, then to obtain another 2% increase in radiative forcing we must increase CO₂ by an additional 580 ppm rather than by another 290 ppm. At present the concentration of CO₂ is about 380 ppm. . . It should be stressed that we are interested in climate forcing and not simply levels of CO₂; the two are most certainly not linearly proportional."

Although this point does not bear directly on modeling, it is important in assessing the impact of increasing CO₂ on climate sensitivity.

Lindzen points out that the upper end of the IPCC model forecasts of temperature due to doubling CO₂ is about 3.5° C, which is much larger than the 1° C sensitivity from simply doubling CO₂. This is due to the amplifying positive feedback of the most important greenhouse substances - water vapor and clouds. "However, as all assessments of the IPCC have stated, the models simply fail to get clouds right. . . The treatment of clouds (in IPCC models) involves errors an order of magnitude greater than the forcing from a doubling of CO₂ (ibid Ref. 2, Fig. 2-1)."

This point seems to reflect a consensus view by those in the climate business.

Lindzen gives an extended explanation (ibid Ref. 2, Pp. 24-26) of the circular procedure the IPCC used to justify the correctness and applicability of their model predictions. "They assume their model is correct. Then differences between the model behavior in the absence of external forcing and observed changes in global mean temperature are attributed to external forcing. Next natural forcing is introduced, and a best fit to the observations is obtained. If, finally, it is possible to remove any remaining discrepancies by introducing anthropogenic forcing, part of the observed change must be attributable to the greenhouse component of anthropogenic forcing. Of course the internal variability of the model is not correct, and anthropogenic forcing includes not only CO₂ but also aerosols, which are unknown by a factor of ten to twenty (and perhaps even the sign is unknown). Finally, there is little quantitative knowledge of natural forcing, so this too is adjustable. . . . The argument just presented is the basis for all popular and scientific claims that man is responsible for much of the observed warming. . . In point of fact, the impact of man remains indiscernible simply because the signal is too small compared to the natural one."

Description of their analytical process by the IPCC corresponds to Lindzen's description. I find it troubling that modelers can be so confident in the applicability of their models when it is obvious that they require much empiricism and curve fitting to fit each step in the analytical process. And the fact that there are many different modelers and models

does not add to the confidence level that they all must be right if they can reach the same conclusions.

On the question of whether there are phenomena at work that current models do not take into account, or fail to replicate at anywhere near the magnitudes observed, Lindzen enumerates and describes a number of examples (Ref. 2, P. 947-948), which include the Intraseasonal Oscillations of the tropics, El Nino, El Nina, the Quasi-biennial Oscillation of the tropical stratosphere, the Little Ice Age, or the Medieval Warm Period. "The examples merely show that current models fail to describe many known climate changes, and that, therefore, the models' failure to account for the recent warming (largely confined to the period 1976 - 1995) hardly requires the invocation of anthropogenic forcing. It is nonetheless commonly argued by modelers that coupled models do adequately portray natural unforced variability despite acknowledging the cited shortcomings. . . Thus, the claim that models cannot account for recent warming without external forcing is held to imply the role of human forcing. To be sure, current models can simulate the recent trend in surface temperature, but only by invoking largely unknown properties of aerosols and ocean delay in order to cancel most of the greenhouse warming."

Although I do not have any feeling for the magnitude or significance of this aspect of modeling as it affects the results derived from the models, it adds to the lack of confidence that I have in climate modeling in general.

Lindzen points out a related technical issue that originates not from the technical community but from policy advocates and the media (ibid Ref. 2, P. 27). "According to any textbook on dynamic meteorology, one may reasonably conclude that in a warmer world, extratropical storminess and weather variability will decrease. . . Judging by historical climate change, changes are greater in high latitudes than in the tropics. Thus in a warmer world, we would expect the temperature difference between high and low latitudes to diminish. However, it is precisely this difference that gives rise to extratropical large-scale weather disturbances. . . . Given that we expect high latitudes to warm much more than low latitudes in a warmer climate, the difference is expected to diminish, leading to less variance. Nevertheless, advocates and the media tell us that exactly the opposite is the case - that the models predict this (which, to their credit, they do not). . . Clearly more storms and greater extremes are regarded as more alarming than not. Thus the opposite of our current understanding is invoked in order to promote public concern. The crucial point here is that once the principle of consensus is accepted, agreement on anything is taken to infer agreement on everything."

It is difficult for me to take exception or challenge the technical logic and individual arguments offered by Lindzen. It does seem, however, that much of his position depends on actual measurements, data, and uncertainties associated with them. For example, he places strong dependence on the atmospheric temperature gradient data accumulated at one place, the Hadley Center, to challenge the way in which surface temperatures are used to interpret climate sensitivity.. It would certainly add to the credibility of his case to be able to incorporate many other data sources that confirm the essential nature of surface to atmospheric temperature gradients through the troposphere.

The completeness and accuracy of models is another weakness that Lindzen highlights. It is not clear whether it will ever be possible to refine the models to the extent that they can reliably take into account all the natural as well as the anthropogenic mechanisms that affect climate. Although the consensus is that global warming is a real phenomenon, I find Lindzen's arguments compelling that both the models and the way they are used cannot be depended on to analyze the details of global warming, particularly with respect to what is the contribution of anthropogenic mechanisms.

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