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Uncertainty and Climate Change

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Abstract. Anthropogenic, or human-induced, climate change is a critical issue in science and in the affairs of humankind. Though the target of substantial research, the conclusions of climate change studies remain subject to numerous uncertainties. This article presents a very brief review of the basic arguments regarding anthropogenic climate change with particular emphasis on uncertainty.

Key words and phrases: Anthropogenic climate change, global warming, greenhouse effect, numerical models.

1. INTRODUCTION

Humans have been modifying the environment though processes associated with industrialization, population growth and urbanization. One of the most important results of these activities has been increased emissions of carbon dioxide (CO_2) primarily due to fossil fuel burning as well as deforestation.

Anthropogenic emissions of CO_2 and some other gases such as methane and nitrous oxide are important due to the greenhouse effect. The Earth absorbs energy from the Sun. This energy warms the surface and some is redistributed over the planet by circulations of the atmosphere and the oceans. Energy is also radiated back into space from the Earth. However, in that process some radiation is trapped by constituents of the atmosphere, chiefly water vapor, but also CO_2 and others, leading to a warming of the surface and lower atmosphere. This is the greenhouse effect. The greenhouse effect is a good thing, at least for us. Without it, the environment would be far colder. However, the extra emissions we are putting into the atmosphere create concern for an enhanced greenhouse effect, leading to unnatural global warming. Global warming can itself lead to important impacts upon climate. Global warming in combination with other anthropogenic effects may lead to very complex changes.

Investigations into the potential role of anthropogenic CO_2 in global warming have a surprisingly long history, apparently beginning with work by J. B. J. Fourier in 1827 [see Stevens (1999) for additional history]. In 1988, the World Meteorological Organization and the United Nations Environment Program organized an international panel of scientists to consider climate change. This led to the establishment of the Intergovernmental Panel on Climate Change (IPCC). This now huge (on the order of a thousand scientists participate in IPCC activities) and influential group presented its Second Assessment Report in 1995 (IPCC, 1996), claiming that:

> The balance of evidence suggests a discernible human influence on global climate.

IPCC's Third Assessment Report (TAR) claims (IPCC, 2001a):

> Most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentration. Furthermore, it is very likely that the 20th century warming has contributed significantly to the observed sea level rise.

In addition, TAR projects "further warming of 1.4–5.8°C for globally averaged surface temperature in the 21st century." (These quotes contain "likely," "very likely" and "projects," which have special meanings described below.)

In the next section, I review issues of uncertainty and its quantification in the context of climate change. In Section 3 the key elements for the claims for anthropogenic climate change are discussed. Section 4 describes how scientists seek information about future climate and potential impacts of climate change. For brevity, only a few references are given, though these serve as starting points. Additional information

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can also be obtained from (i) the IPCC at www.ipcc.ch [IPCC (2001a, b) are available at this site], (ii) the U.S. Global Change Research Program at www.usgcrp.gov and (iii) the Environmental Protection Agency at www.epa.gov. Also, see Smith (2001) for discussion and additional references of particular interest to statisticians.

2. UNCERTAINTY: ISSUES AND IMPACTS

Three critical points set the stage for discussion. First, we know climate changes without intervention from us, though quantification of natural climate variability is incomplete. Second, though often described as an "experiment" in the literature, the subjection of the Earth to anthropogenic influences is not a formal experiment. We have no collection of similar planets to which we can assign treatments, compare responses and assess causal relations, at least in a traditional statistical fashion. Third, our primary information sources regarding climate are observations and physical modeling. Both sources are voluminous, but replete with uncertainties.

2.1 Observations

Substantial observational assets are now available for monitoring the state of the climate. As reviewed in IPCC (2001b, Chapter 2), various data are collected over a network of meteorological observing stations (beyond surface temperature, upper air temperature is measured by balloons, known as radiosondes, and even rocketsondes) and via remote sensing. However, sampling issues arise: an obvious example is the relative paucity of permanent stations in the oceans. Furthermore, satellite observations are a comparatively recent advance. More generally, observational techniques evolve suggesting that measurement bias and variability change over time. An interesting example is the production of a comparatively recent (roughly 150 years) data record of land surface temperatures (e.g., Jones et al., 1999) and sea surface temperatures (e.g., Kaplan, Cane, Kushnir and Clement, 1998), along with associated assessments of uncertainty. See Santer et al. (2003) for an example of the difficulties associated with even modern observational records.

Attempts to extend the observational data record far into the past are challenging. Since reliable observations are scarce to nonexistent, climate scientists often invoke *proxy indicators* of climate variables of interest. For example, amounts of growth estimated from tree ring data are used to infer seasonal or annual temperatures. Analyses of sea corals provide information regarding past features of oceans. Lake and ocean sediments and ice cores contain various historical or paleoclimate information. Merging all this information to produce reliable records and associated uncertainty measurements sensitive to observational errors, uncertainty induced by the use of proxies, sampling issues etc., is a formidable task (e.g., Jones, Briffa, Barnett and Tett, 1998; Mann, Bradley and Hughes, 1999) and one I believe ripe for input from statisticians. These are serious matters since the intent of climate change analysis requires some assessment of past as well as current climatic behavior.

2.2 Physical Modeling

While much of the underlying physics and chemistry of climate and weather are understood, at least at some level, implementation of that science is problematic (e.g., McGuffie and Henderson-Sellers, 1997). The climate system is large, complex and the result of complicated interactions among its subsystems (i.e., atmosphere, the oceans, ice and land processes). The operative physics are nonlinear and require numerical approximation. In attempts to numerically represent the physical, chemical and biological processes operating in the Earth system, large-scale climate models have been developed. [Various centers have developed climate models and share their output with the research community, e.g., Hadley Centre (U.K.), Canadian Climate Centre, National Center for Atmospheric Research and The Geophysical Fluid Dynamics Laboratory (U.S.A.), Max Planck Institute for Meteorology (Germany).] However, such climate models are inexact and include a variety of uncertain quantities, parameterizations [e.g., the behavior of clouds remains a critical and controversial issue, see Solow (2003)], etc. Furthermore, the models are huge, requiring substantial computational effort, and produce massive amounts of output. Also, climate models require inputs such as initializations, specifications of forcings, etc. These inputs are also unknown, so a variety of runs or ensembles are used to obtain estimates of mean responses and variability.

Not all research relies on the massive climate models. Useful information regarding forms of responses and indications of variation can be obtained from simple climate models (e.g., Wigley and Raper, 2001). Such models are less taxing to run and enable scientists to obtain comparatively large ensemble sizes, relative to the massive models. Of course, this is comforting only if the simple models capture enough of the key behaviors of the system.

3. WHAT ARE THE ARGUMENTS?

The case for anthropogenic climate change involves three fundamental arguments:

1. Climate appears to be changing.
2. Human activities have led to increases in CO_2 and other greenhouse gases, aerosols (particulate matter) and other pollutants, and have created a variety of other changes such as in land use, deforestation, etc.
3. There are scientific arguments and large-scale computer models suggesting potential for climate change due to anthropogenic inputs to the climate system.

No one of these points stands alone as a compelling argument. Therefore, scientific analyses of climate change require a quantitative integration of observations and modeling, and assessment of uncertainty. IPCC-TAR does provide a variety of such assessments. Specifically, they ascribe the following meanings to their usages of the phrases: “virtually certain” (chance of being true greater than 99%), “very likely” (90–99% chance), “likely” (66–90%), etc. Unfortunately, it is less clear to me precisely how these numbers were obtained [I am not alone; see the exchange between Reilly et al. (2001); Allen, Raper and Mitchell (2001); also see National Academy of Sciences (2001)] and how both the authors and intended readers actually interpret the word “chance” in these statements. It is clear that methods of combining expert opinions were employed (e.g., Risbey and Kandlikar, 2002). It is unclear if and how opinions were developed in light of observations. It is also unclear if and when “confidence” is intended to have a weight-of-evidence versus more traditional frequentist interpretation. Hence, final statements based on both data and opinion, as many of the critical ones must be, are a bit elusive. This general area is ripe for further research and input from statisticians.

3.1 Observations and Climate Change

According to TAR, IPCC believes that it is very likely that (i) global average surface temperature has increased 0.6 ± 0.2°C over the 20th century and (ii) the 1990s was the warmest decade and 1998 the warmest year since 1861. The oceans have also warmed by roughly 0.05°C since the 1950s. In comparisons of current behavior to the more remote past, IPCC asserted that it is likely that the 1990s was the warmest decade and 1998 the warmest year in the last 1,000 years. IPCC-TAR also reviewed recent snow cover and ice decreases. IPCC suggests that there have been no significant trends in Antarctic sea-ice, though recent discussions in *Science* (August 30, 2002) do note the loss of large sections of the ice shelves of the Antarctic Peninsula and other changes. IPCC-TAR noted that it is very likely that global average sea level rose 0.1–0.2 m over the 20th century (sea-level rise is an expected result of global warming through both thermal expansion of warmer water and through ice melting).

IPCC notes that, during the 20th century, it is very likely that “precipitation has increased by 0.5–1.0% per decade over much of the Northern Hemisphere continents at mid- and high-latitudes” and likely that “there has been a 2% increase in cloud cover over mid- and high-latitude land areas.” Regarding variability, according to IPCC, it is likely that “At mid- and high latitudes of the Northern Hemisphere, there has been a 2–4% increase in the frequency of heavy precipitation events.”

Other changes in climatic variables are outlined in TAR. A key point to note is that interactions of climate subsystems are crucial. For example, the El Niño–Southern Oscillation (ENSO) phenomenon is known to exert major controls on weather throughout much of the world. IPCC and others have suggested that warm events of ENSO have been longer, more frequent and more intense since the mid-1970s than in the previous 100 years.

3.2 Anthropogenic Forcings

The level of CO_2 in the atmosphere is believed to have hovered around 280 ppm during the last 10,000 years through about 1800. Since then, a dramatic rise has been observed, leading to current levels of about 366 ppm. Atmospheric concentrations of other greenhouse gases, particularly methane and nitrous oxide, have also seen dramatic increases in the last 150 years. There are other changes in atmospheric features [e.g., ozone, aerosols (most of which have a cooling effect)], but these are less understood. However, not all changes in forcings have been anthropogenic; natural solar radiation has apparently also increased over the last 150 years.

3.3 Linking Observations and Climate Models

Increases in global average surface temperature do not mean the planet would warm uniformly everywhere. Rather, there is a spatial pattern to the level of local warming, including the possibility that some regions actually cool. The problem is further complicated in that the patterns and levels of change ought to be time-varying. There is reasonably strong evidence that the observed changes match such patterns as estimated by climate models. Such "fingerprinting" is accomplished by statistical techniques known as detection and attribution methods (e.g., Barnett et al., 1999; IPCC, 2001b, Chapter 12). It should be noted that the results are not unequivocal. While the level of matchings for surface temperature and sea-level rise are viewed by many as compelling, results for some other variables (e.g., vertical profile of temperature in the troposphere) are not supportive. Indeed, uncertainties about internal climate variability, the effects of aerosols, etc., remain an important issue. Further, there is a need for improved methods for multiattribute methods (simultaneous treatment of fingerprinting for several physical variables); analyses targeted for various distributional changes such as variability, frequency of extremes, etc.; and combining information from different climate models (e.g., Allen et al., 2000). Finally, underlying much of these discussions are issues of dimension reduction versus loss of information.

3.4 Summary

IPCC-TAR claims that, though some uncertainties remain, the state-of-the-art in climate modeling is sufficient to provide useful information for climate change assessment and climate prediction. IPCC cites the ability of models when forced by estimates of human forcings to reproduce the observed warming trends in surface temperature during the 20th century as an indication of their value. Even beyond IPCC, there is an emerging consensus among climate scientists that our climate is changing and that anthropogenic inputs are playing a causal role in the changes. Indeed, much of the earlier research in climate change was devoted to its detection and attribution to human activities. More recently, many climate scientists appear to have accepted both detection and attribution, and are turning attention to problems of climate prediction and analyses of the impacts of climate change.

4. FUTURE CLIMATE AND IMPACTS PROJECTIONS

It is useful to consider a causal chain:

$$\text{Forcings} \rightarrow \text{Climate} \rightarrow \text{Weather} \rightarrow \text{Impacts.}$$

Forcings include anthropogenic emissions and other stresses on the climate system, as well as natural forcings such as solar radiation, volcanos, etc. Various impacts such as ecology, agriculture, etc., may be considered. Note too that climate and weather may be considered at various scales (e.g., local or regional spatial scales). It is important to note that this chain is a very simplified device for the purpose of a quick discussion. For example, it ignores potential feedbacks. Also, the chain is not deterministically usable. There are simply too many uncertainties and other random elements that contribute to the determination of impacts. Finally, though weather appears in this chain, there is no suggestion that we seek to predict weather 50 or 100 years into the future. Rather, I suggest thinking of the chain as an approximate Bayesian network. (In a formal hierarchical modeling strategy, we can consider more general formulations and model feedbacks, etc.) For example, weather is a random process whose probability distribution depends on climate. Hence, by predicting future climate, we are predicting the future probability distribution of weather, which is then usable in predicting the future probability distribution of weather-sensitive impacts.

Continuing the above stochastic model view, future climate has a probability distribution that depends upon future forcings. However, future forcings are among the most uncertain of all the aspects of the problem. IPCC has developed a collection of what are deemed plausible emissions scenarios in its Special Report on Emissions Scenarios (SRES). These scenarios vary in the level of assumed technological advances, fossil fuel burning, economic status and heterogeneity of such aspects across the nations of the world (e.g., do the major industrialized nations advance rapidly while the developing nations do not or do important developing nations "catch-up" from a technological and economic viewpoint?). Not surprisingly, there are some controversies regarding the SRES scenarios; indeed, the SRES group believes its suggestions are plausible, but refuses to assign relative likelihoods to them. Also, none of the SRES scenarios includes specific emissions reductions, such as those suggested in the Kyoto Protocol (www.unfccc.int), based on responses to the climate change problem.

The analysis strategy is to use each scenario as input to climate models, thereby producing "climate projections." The word projection is used to differentiate the process from prediction. That is, IPCC produces a collection of plausible future climates, but does not combine them to form a prediction. Such a prediction would require assignments of probabilities to the SRES scenarios. Note too that there is some variability across climate models for given emissions scenarios and that a particular scenario for future economic and technological development would not exactly specify future emissions.

Nevertheless, IPCC notes a few features common to most of the climate projections. First, anthropogenic greenhouse gas emissions are expected to increase and be a dominant controller of climate in the 21st century. Virtually all scenarios and climate models indicate further global warming, with globally averaged surface temperature increasing by 1.4–5.8°C. IPCC also suggests that over the next 50 years it is likely that nearly all land areas will warm more rapidly than the global average. This is indicated particularly at northern latitudes in the cold season: "Most notable ... is the warming in the northern regions of North America, and northern and central Asia, which exceeds global mean warming in each model by more than 40%." Regarding precipitation, both global average water vapor and precipitation are expected to increase during the 21st century. Larger annual variations in precipitation are anticipated in those regions where increased precipitation is expected (e.g., northern mid- to high latitudes). At low latitudes the projections are highly variable regionally, with some locales displaying increases while others are expected to have decreases in precipitation. IPCC also projects some changes in extremes, such as higher maximum temperatures and more hot days and fewer cold days over land; increase in heat index over most land areas; and more intense precipitation events. Given increased temperatures, global mean sea level is projected to rise by 0.09–0.88 m by the end of the 21st century by all scenarios. IPCC notes potential changes in ENSO and other important climate features. Interesting speculations also indicate the possibility of rapid climate changes.

IPCC and other groups (e.g., the U.S. Global Change Research Program) have accepted the challenge of making regional projections. Regional climate information is developed by using combinations of high and variable resolution atmospheric models, regional climate models and statistical–dynamical models, all driven by output from global models (e.g., McGuffie and Henderson-Sellers, 1997).

Projections for the next century indicate an increase in U.S. average temperature of 3–6°C (note that this is higher than the projected global increase). While many U.S. regional projections are consistent with a warmer and wetter climate system, there are important variations spatially and seasonally as well as among models. Increases in precipitation are projected to be greatest in the Southwest (including southern California). Most models project increases in precipitation for north-central states, but the projections (some increases, other decreases) for other regions are highly variable.

Various other climate and impacts projections are being considered. For example, impacts ranging from increased erosion due to higher storm surges for U.S. coastal systems are anticipated due to sea level rise. Impacts on U.S. agriculture have been investigated (Reilly, 2002). For an interesting case study on potential impacts on an urban region, see Rosenzweig and Solecki (2001).

5. DISCUSSION

IPCC (2001a) lists a variety of uncertainty issues which require further attention. Some of these involve specific research on modeling and climate model development to reduce uncertainties (critical topics include better understanding of natural variability, regional and local climate behaviors and climate system feedbacks). Others relate to better statistical analyses of data (e.g., improved assessments of historical climate information) and methods for uncertainty management and uncertainty propagation. One such suggestion involves the need for production of larger ensembles from climate and impacts models. Of course, increased ensemble sizes provide more information about climate model responses, but not necessarily more information about the behavior of the actual planet.

Climate change analyses offer challenges in the formulation and interpretation of probability when used to quantify uncertainty. Classical or frequentist analyses and probability statements based on statistical analyses of observations have been used to deal with questions about the state of the climate and whether or not the climate has changed and by how much. Relying on climate model output to develop models for potential trends due to anthropogenic forcing, traditional statistical methods have been applied in attribution studies (Barnett et al., 1999). In view of the need for combining complex, diverse and uncertain information sources and difficulties in demonstrating the causal nature of anthropogenic effects by traditional statistical arguments, there is strong interest in Bayesian approaches to climate change analysis. The Bayesian approach is also natural for future climate and impacts studies since there are (i) uncertainties in future emissions and (ii) uncertainties in the specific controls future climate may impose on future weather, regional and local climate patterns, and weather-sensitive human activities such as agriculture, power production and consumption, etc. It is arguable that uncertainty in many climate change problems can only be quantified from a Bayesian viewpoint (see Berliner, Levine and Shea, 2000; Moss and Schneider, 2000; Reilly et al., 2001; and references therein).

I have described various uncertainties related to climate change, and thereby listed numerous challenges to the statistics community. To these, we can add the problems of policymaking and decision theory in the face of climate change (e.g., Claussen, Cochran and Davis, 2001). I suggest that, despite the importance of the problems and the richness of the challenges, the statistics community has not participated in the area sufficiently. Hopefully, that will change.

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