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Improving Predictions of Climate Change: Observational and Modeling Requirements

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Carbon dioxide (CO_2) is building up in the atmosphere, largely because of emissions from fossil fuel combustion. An increase in atmospheric CO_2 would enhance Earth's natural greenhouse effect, resulting in an increase in global mean surface temperature (GMST) and other changes in Earth's climate. The question that faces the nations of the world is the extent of climate change that will result from future increases in atmospheric CO_2. Confident knowledge of the changes in climate that might be expected for various prospective emissions profiles is essential to effective planning of the means by which the peoples of the world can meet their energy requirements over the twenty-first century and beyond. At present, however, this quantitative relation between increases in CO_2 and increases in GMST remain quite uncertain. Here and elsewhere much focus is given to increases in GMST, not because temperature is the only climate attribute that would change with increasing CO_2, or even the most important such attribute, but because other changes in climate, such as changes in precipitation, snow pack, and ice cover are expected to scale, at least approximately, with increases in GMST.

The increased concentration of CO_2 that has already occurred over the industrial period results in a calculated increase of the global average downwelling thermal infrared irradiance from the atmosphere to the surface (climate "forcing") of well less than 1%. Despite such a small change in Earth's radiation budget, there is strong theoretical reason to expect that this small change would give rise to an increase in GMST of magnitude comparable to the temperature increase observed over the past 100 years, and perhaps greater. Studies with global climate models demonstrate that the increase in temperature cannot be accounted for without including in the models the forcing due to increased concentrations of CO_2 and other greenhouse gases. However the small forcing makes it very difficult to accurately calculate the expected increase in GMST. Hence the sensitivity, the change in GMST per forcing, calculated with such models is uncertain to at least a factor of 2 (IPCC, 2007).

In addition to greenhouse gases the second key influence on Earth's radiation budget over the industrial period is that of atmospheric aerosols, suspensions of microscopic and submicroscopic particles in air. These aerosols scatter light and modify the properties of clouds, decreasing the absorption of solar radiation by Earth; the increase in atmospheric aerosols over the industrial period has led to an cooling forcing that is offsetting some of the warming forcing of increased greenhouse gases, but this aerosol forcing is highly uncertain. In turn, the total forcing of the climate system over the industrial period, which is the sum of all changes in Earth's radiation budget over this period, is highly uncertain, to an estimated factor of 4. (IPCC, 2007)

The uncertainty in total forcing over the industrial period greatly limits the confidence that can be placed in global climate model calculations which have been able to accurately reproduce the increase in GMST over the twentieth century, despite differing forcings and sensitivities. This uncertainty in forcing also precludes accurately inferring climate sensitivity empirically from knowledge of the forcing together with observed increase in GMST.

Thus at present Earth's climate sensitivity remains uncertain to at least a factor of 2 and arguably more, Figure 1. This uncertainty in climate sensitivity translates directly into a like uncertainty in the amount of fossil fuel CO_2 that can be introduced into the atmosphere consonant with a given acceptable future increase in GMST (Schwartz, 2008).

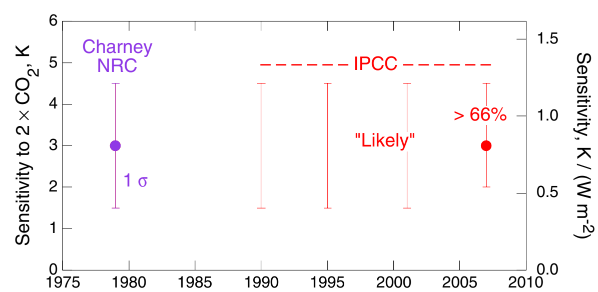

Figure 1. Estimates of Earth's climate sensitivity, expressed as the increase in global mean surface temperature GMST that would result from a doubling of the amount of CO_2 in the atmosphere $\Delta T_{2\times}$, left axis, or as the change in GMST that would result from a change in radiative flux of 1 W m^{-2}, right axis; the conversion from $\Delta T_{2\times}$ to K/(W m^{-2}) assumes a forcing of doubled CO_2 $F_{2\times}$ equal to 3.7 W m^{-2}. The notations "1 sigma", "Likely", and "> 66%" denote the likelihood that the actual climate sensitivity lies within the uncertainty range indicated. Charney: National Research Council (1979); IPCC, Intergovernmental Panel on Climate Change (2007) and earlier assessments in this series.

The importance of climate sensitivity to planning of future energy strategies suggests that it is essential and urgent that uncertainty in estimates of this sensitivity be reduced. An examination of estimates of climate sensitivity and its uncertainty over the past 30 years, Figure 1, shows little improvement over this period, despite much research. This situation calls for a much greater effort than has been applied thus far. Effort needs to be directed in two areas: reducing the uncertainty in forcing by atmospheric aerosols and improving the representation of physical processes in climate models.

Present understanding of aerosol forcing is limited both by knowledge of emissions of aerosol particles and precursor gases and by knowledge of atmospheric transformation and removal processes. Most characterization of primary emissions of aerosol particles has been focused on mass emissions, motivated mainly by considerations of air quality. However as aerosol forcing depends strongly on the size distributed composition of the particles affecting both light scattering (and its dependence on relative humidity) and the ability of aerosol particles to serve as seed particles for cloud droplet formation, there is pressing need for knowledge of the size distribution of emitted particles, including size ranges (less than 100 nm diameter) that contribute negligibly to mass emissions, and for knowledge of particle composition as a function of size. Understanding of the formation and evolution of atmospheric aerosol particles has improved markedly in recent years with new instrumentation such as aerosol mass spectrometers, which have shown the substantial contribution and often dominance of organics to total particulate matter loading. Measurements with these instruments, which have the ability to distinguish between primary and secondary organics, have shown the dominant role of secondary organic aerosols and the role of organics in new particle formation in the atmosphere. However much work remains to identify the chemical mechanisms responsible for formation of secondary organic aerosols and the precursor species and to quantify the rates of secondary organic aerosol formation and the dependence on precursor concentrations and other controlling variables. Much concerted effort is required to develop understanding of these processes in important aerosol source regions globally, requiring much international collaboration and cooperation.

At present climate models are evaluated mainly by their performance over periods of decades to centuries, a situation which results in relatively few observable quantities with which modeled quantities can be compared and only slow improvements in climate models. It is suggested that progress might be much more rapidly made by running climate models in real time and evaluating their performance with measurements that focus on the processes represented in the climate models, such as cloud formation, precipitation development, and radiation transfer, and which are highly detailed in space and time, much as is done with weather forecast models. This approach would allow model errors to be rapidly identified and corrected, resulting in much more rapid improvement in the accuracy of the models. Because of the widely differing climatic regimes that must be represented in climate models – maritime, continental, tropical, temperate, polar, etc. – such model evaluation efforts would have to be conducted in a variety of locales globally.

Each of these approaches would require efforts that are much greater than have hitherto been directed to climate change research and would require unprecedented participation and cooperation by the nations of the world. However the importance of climate change to the world's energy economy and ultimately to the peoples of the world, and the need for the information that would be developed by such a research effort would seem more than to justify such an effort.

Keywords: *Climate change, Sensitivity, Aerosol, Forcing,* CO_2*,*

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