Past and Future Climate Forcing

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Climate change is again in the news. First the failure of the COP6[1] meeting to agree on terms for the Kyoto Protocol and now the apparent rejection of the protocol by President Bush leaves the future of climate policy uncertain. To move forward it is important understand the drivers of climate change in order to inform discussions of where mitigation efforts need to be focused. This paper will present a quantitative overview of the physical drivers of past and future climate changes. The paper will first address attribution of past climate changes, then the radiatively important substances that will drive future climate change, and, finally, the mitigation of climate change in the context of the recent Hansen *et al.* “alternative scenario”.[2]

1. Forcing and Climate Sensitivity

This discussion will be framed in terms of radiative forcing. Radiative forcing is the energy imbalance caused by a change in the climate system and is defined as the change in radiative flux at the top of the troposphere after allowing for stratospheric adjustment.[3] Since radiative forcing refers to a change, this quantity must always be given relative to some reference date or concentration level.

Radiative forcing is measured in units of Watts per square meter. A doubling of carbon dioxide concentrations, for example, will cause an imbalance of approximately 3.7 W/m^2.[4] The total forcing from all anthropogenic greenhouse gases, as compared to pre-industrial times, is presently (~ year 2000) about 2.7 W/m^2, with an offset of perhaps half this amount from aerosol cooling (see below).[5] The radiative forcing caused by carbon dioxide is known to within about 1%. Uncertainties for the other important greenhouse gases are 5-10%, with higher uncertainties for some halocarbons.[4,6]

An important property of the climate system is that the source of the radiative forcing appears to be relatively unimportant. To first order, the *global* system is thought to respond to one radiative forcing much as any other—making radiative forcing a useful tool for analysis.[7] We can, therefore, use radiative forcing to compare the relative importance of different driving forces (*e.g.,* GHG emissions, aerosols, solar luminosity variations).

What is not known with nearly as much certainty is how the climate system will respond to a given radiative forcing. The most general measure of this response is the *climate sensitivity.* The climate sensitivity is often defined as the equilibrium global-mean surface warming that would occur if carbon dioxide concentrations were doubled. The uncertainty range used by the IPCC in its 1990 through 1996 assessments is 1.5–4.5 °C per CO_2 doubling. This large range in climate sensitivity reflects uncertainty about feedbacks within the climate system.[8]

2. Attribution of Recent Changes

Our ability to explain past changes in climate is an obvious test of our understanding of the climate system. The following review of the causes of past climate change will demonstrate that there is considerable uncertainty in the causes of *past* climate change. The next section, however, will show that these uncertainties are largely irrelevant to the issue of what will drive *future* climate change.

There is broad agreement that global surface temperatures have warmed over the last century (Figure 1). The primary driving forces of these changes are thought to be variations in: greenhouse gas concentrations, aerosol particles, and solar flux. Attribution of historical changes is complicated by the intrinsic variability of the climate system apparent in Figure 1. While plausible combinations of the above components can reproduce the historical record, a deterministic reconstruction of the climate of the 20th century is not yet possible.

Some apportionment of causality could be accomplished if the radiative forcing due to each of the above components were known. While the forcing change due to greenhouse gases is quite well known, this is not the case for either solar irradiance or aerosols.

First consider solar irradiance, which is known to change slightly over a solar cycle. Changes over longer timescales, however, remain a matter of much speculation. A number of irradiance "re-constructions" have been calculated, where a solar irradiance time series is produced by using proxy variables such as sunspot number or solar cycle length.[10] The difficulty is that, even if such a correlation exists, the proportionality between such proxies and irradiance is not known for our sun over century time scales. Research to better constrain past solar irradiance changes continues.

Measured changes in total solar irradiance are small when compared to historical greenhouse gas forcing changes. Consider a 0.2% change in solar irradiance, which is about twice the variation seen over one solar cycle and only slightly less than some estimates of the solar irradiance change since the Maunder minimum. This change translates into a 0.5 W/m^2 change in radiative forcing. This is several times smaller than the historical increase in greenhouse gas forcing over the last century (§ 1). It is possible that the effect of these irradiance changes are magnified in some way, such as through chemical changes in the atmosphere due to the much larger change seen in solar UV emissions.[11]

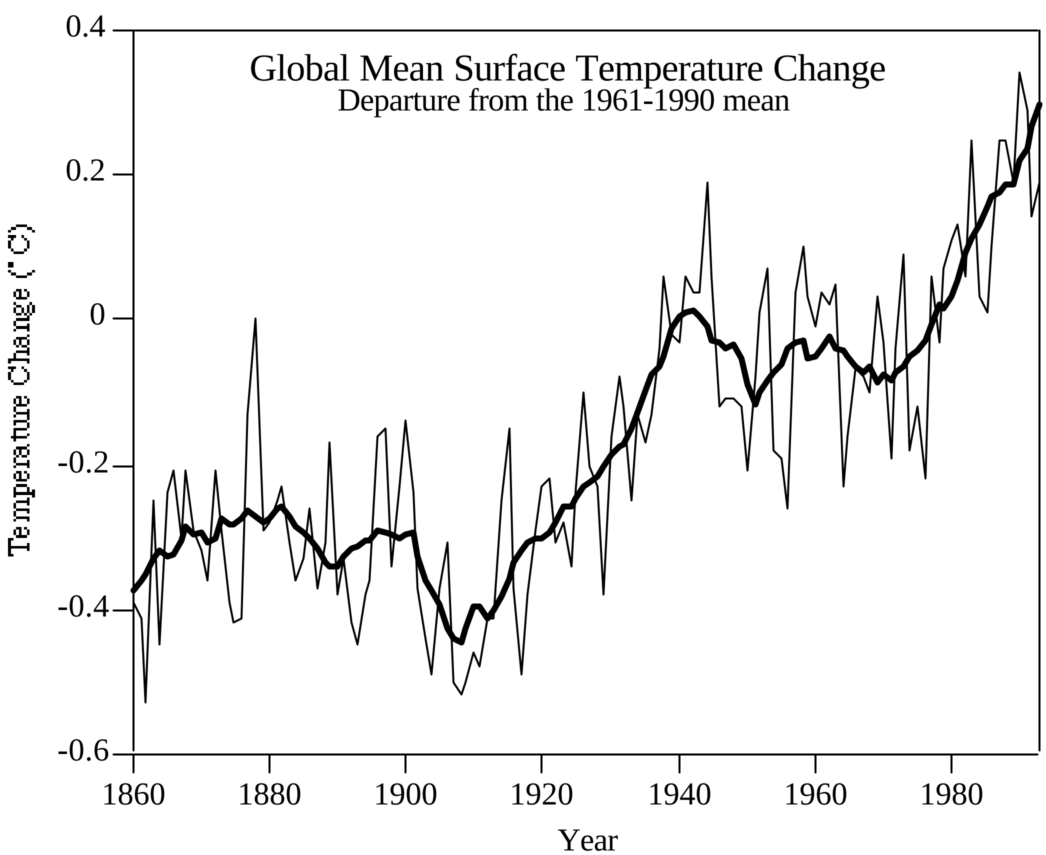

Figure 1 — Global average surface temperature (Thin line: monthly values, thick line: 11-year running average).[9]

Aerosol particles, which derive both from direct particle emissions and from chemical reactions in the atmosphere, have a number of climate effects. Light-colored particles, such as sulfate aerosols, reflect sunlight and cause a cooling. Black carbon particles (*i.e.,* soot) absorb sunlight and cause a warming. Aerosol particles can also act as cloud condensation nuclei, thus changing the number density and lifetimes of clouds. Other effects are also possible.[2] Injection of aerosol particles into the stratosphere by volcanic activity can also cause a transient cooling, an effect seen after the Mount Pinatubo eruption in 1991.[12]

From a climate perspective the dominant aerosol precursor compound at present is thought to be sulfur dioxide. Also the primary cause of acid rain, sulfur dioxide is emitted when coal and oil products are burned and subsequently forms sulfate aerosols in the atmosphere. The net result is thought to be a cooling effect on the climate of perhaps -1.4 W/m^2, although the uncertainty range on this figure is very large.[3,13] The radiative forcing associated with black carbon aerosols, which are emitted due to incomplete combustion of fossil fuels, is even more uncertain. An additional source of both types of aerosol is biomass burning.

The overall forcing picture for past climate change is that greenhouse gases and anthropogenic aerosols are likely to be have been the dominant forcing agents over the last few decades. Solar variability and other forcings (such as changes in average volcanic activity) may have played more important roles earlier in the 20th century. The largest uncertainty is in the forcing effect of aerosols. The combination of uncertainty in aerosol forcing, uncertainty in climate sensitivity, and the presence of unforced climate variability means that the anthropogenic contribution to past climate change cannot be determined with great accuracy.

This also means that historical data cannot be used to determine the climate sensitivity unless these uncertainties are substantially reduced. Since definitive attribution of past climate is not likely to be achieved for some time, policies will need to be based on a wide range of data and theoretical knowledge that can be used to project possible future changes.

3. The Drivers of Future Climate Change

Future anthropogenic forcing will depend on emissions of greenhouse gases and the precursor compounds of aerosols and tropospheric ozone. Future emissions of greenhouse gases can never be predicted in a deterministic sense because emissions of these substances depend on future socio-economic developments. Instead of a deterministic prediction, scenario analysis offers a method of establishing reasonable bounds on the magnitude of future emissions.

The most recent international effort along these lines is the IPCC Special Report on Emission Scenarios (SRES), which presents 40 scenarios of future emissions of greenhouse gases in the absence of additional climate policies.[14] These scenarios represent a wide range of possible economic, social, technological, and demographic developments. In some scenarios greenhouse gas forcing increases throughout this century while in others greenhouse gas forcing stabilizes by the end of the century — although it remains to be determined if those stabilization levels would be sufficient to avoid "dangerous anthropogenic interference with the climate system", the goal of the FCCC.

Using these emission scenarios, a conservative estimate of the range of additional radiative forcing over the next 100 years is 2.3 to 6.8 W/m^2.[15] This is in addition to the 2.7 W/m^2 of current greenhouse forcing minus any current aerosol cooling offset. These figures are illustrative and different model parameters (*e.g.,* carbon cycle parameters, sulfate aerosol forcing strength, inclusion of tropospheric ozone chemistry, etc.) would lead to somewhat different values.

Even given these uncertainties, we can predict with a high degree of confidence that neither solar nor volcanic influences are likely to exceed the magnitude of the forcing changes expected from anthropogenically-driven increases in greenhouse gas concentrations.

Now consider the future role of aerosol particles. Emissions of soot particles and sulfur dioxide have decreased substantially in Japan, Western Europe, and the United States. These decreases are due to concerns over acid rain, human health effects, and visibility issues. In the long term, global emissions of both of these compounds are expected to decrease further as increasing affluence drives ever more concern with "quality of life" issues. Eventual reductions in sulfur dioxide emissions are a key finding of the SRES.

These considerations indicate that the future will be simpler than the past, at least with respect to radiative forcing. Instead of a multiplicity of possible anthropogenic and natural forcing agents, greenhouse gases and aerosols will likely be the dominant climate forcing agents over the next several decades. By the end of the century, increases in greenhouse gas concentrations and probable decreases in aerosol emissions will leave greenhouse gases as the dominant radiative forcing agents. Note that, while the cause of future climate changes will be more certain, the amount of climate change remains uncertain due to the unknown climate sensitivity and the wide range of possible future emissions.

4. Climate Mitigation and the "Hansen, *et al.*" paper

The previous discussion leads to the conclusion that limiting the amount of future climate change (mitigation) in the long term will require limiting concentrations of greenhouse gases. Over shorter time horizons the situation is less clear. The recent paper by Hansen *et al.*[2] created some controversy over which substances were the appropriate targets for mitigation action. Hansen *et al.* sketch an "alternative scenario" under which the additional radiative forcing from carbon dioxide over the period 2000-2050 is kept to 1 W/m^2 (the period beyond 2050 is not addressed). Their mitigation scheme then calls for no net increase in forcing from the combination of non-CO_2 greenhouse gases and aerosols. Limiting forcing change to only 1 W/m^2 over the next 50 years is quite ambitious. This would represent limiting additional climate forcing over this time to considerably less than in any of the "no climate policy" SRES scenarios.[16]

The controversy engendered by the Hansen et al. paper was largely due to the perception that they had argued that little needed to be done to reduce carbon dioxide emissions and that, instead, efforts should focus on non-CO_2 forcing agents. The lead author of the paper, however, in an open letter to the community has stated that "we expect that equal emphasis is needed on non-CO_2 and CO_2 forcings to keep the net forcing [increase] at 1 Watt" over the next 50 years.

As has been noted elsewhere, the Hansen et al. CO_2 forcing target would likely require quite a strong climate policy.[16] In the set of SRES scenarios, for example, the increase in carbon dioxide forcing over this period ranges from 1.1–2.7 W/m^2. Under the most optimistic set of assumptions the 1 W/m^2 CO_2 target could be met with minimal action. Under most of the SRES scenarios, however, achieving this target would require significant action.

While action to limit carbon dioxide emissions is a part of most mitigation scenarios, an integral part of the Hansen *et al.* mitigation scheme is to reduce emissions of black carbon (soot) particles, which is a new suggestion for climate mitigation. Such a reduction would, indeed, tend to reduce climate forcing. But the net change in aerosol effect depends on emissions of other precursor compounds, particularly sulfur dioxide. The synergistic effects of further pollution controls and a stringent carbon dioxide constraint are most likely, however, to result in a net forcing increase due to a decrease in total aerosol cooling.[16] Producing a net increase in aerosol cooling, or probably even a constant level of aerosol cooling, is inconsistent with a strong carbon dioxide emissions constraint.

Hansen *et al.* also propose to achieve a net decrease by 2050 of 0.1 W/m^2 in tropospheric ozone forcing. Control of tropospheric ozone levels in urban areas in developed regions has proved to be a difficult task. These efforts are, however, underway and a global decrease of tropospheric ozone due to such efforts by 2050 cannot be ruled out.

They also propose a 0.2 W/m^2 decrease in methane forcing over this period. The proposed decrease in methane forcing compares to an estimated increase of 0.1-0.4 W/m^2 in methane forcing with no climate policy, although projections of methane concentrations are particularly uncertain. The potential for methane emissions reductions (i.e., mitigation) is area of active research.[17] Methane emissions grow from 2000 to 2050 in all of the SRES scenarios. This growth is driven, in large part, by emissions from increased agricultural production (particularly ruminant animals and rice) driven, in turn, by both increasing population[18] and increasing incomes. A net reduction in emissions seems possible, although implementing the necessary changes in developing countries poses a challenge (as is also the case for reductions in carbon dioxide emissions).

Our examination of this "alternative scenario" indicates that the likely gains from decreasing the levels of conventional pollutants such as soot and ozone are not sufficient to remove the main focus of any climate policy from carbon dioxide and the other greenhouse gases.[16]

5. Conclusion

As the century progresses, the effect of greenhouse gases as a climate forcing agent will increasingly dominate other possible forcings. While the radiative effects of greenhouse gases at present are likely to be partially offset due to aerosols, the likely continuation of reductions in "conventional" pollutant emissions in the future will "unmask" the full effect of increasing greenhouse gas concentrations. Among the greenhouse gases, carbon dioxide is still the "800 pound gorilla" of climate change.[16] This is, in large part, because carbon dioxide is unique among greenhouse gases in that it is not destroyed in the atmosphere. Some portion, therefore, of any fossil-fuel emission will make an essentially permanent contribution to atmospheric concentrations.[19]

As a final note, addressing future climate change will likely require a combination of emission reductions (*i.e.*, mitigation) and adaptation to climate changes that are not or cannot be mitigated. How this should be done, how much, and by what time, are difficult questions. In part their answers are not determined by science, but on values. The value placed on natural systems, for example, and the acceptable level of risk tolerance play important roles in determining the answers to these questions.[20]

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1 Sixth meeting of the Conference of the Parties (COP) to the Framework Convention on Climate Change (FCCC)

2 Hansen *et al*. "Global warming in the twenty-first century: An alternative scenario" *PNAS* **97(18)** 9875–9880 (2000).

3 Shine, K.P., Forster, P.M. de F. "The effect of human activity on radiative forcing of climate change: a review of recent developments" *Global and Planetary Change* **20**, 205–225 (1999).

4 Myhre, G., Highwood, E.J., Shine, K. P., Stordal, F. "New estimates of radiative forcing due to well mixed greenhouse gases" *GRL* **25**, 2715-2718 (1998).

5 This forcing figure includes carbon dioxide, methane, nitrous oxide, halocarbon, tropospheric ozone. An offsetting negative forcing due to stratospheric ozone depletion by CFC's has been applied.

6 Jain, A. K., B. P. Briegleb, K. Minschwaner, D. J. Wuebbles. Radiative forcings and global warming potentials of thirty-nine greenhouse gases, J. Geophys. Res. **105**, 20,773-20,790 (2000).

7 The response difference is likely to be largest for substances with non-uniform spatial distributions. Even here, any difference seems to be within about 20% (L.D.D. Harvey *Global Warming: The Hard Science*, Prentice Hall, NY, 2000, pp. 48–51), which is an order of magnitude smaller than the currently accepted uncertainty range for the climate sensitivity.

8 The current consensus is that, overall, climate feedbacks are positive. Therefore, the effect of any given forcing is amplified. For example, a warmer troposphere will tend to hold more water vapor, which is itself a greenhouse gas, thus causing more warming. Warmer temperatures will also tend to melt snow and ice, reducing surface reflectivity. The largest uncertainty concerns clouds, which can act to both cool and warm the surface.

9 P.D. Jones, D.E. Parker, T.J. Osborn, and K.R. Briffa. “Global and hemispheric temperature anomalies--land and marine instrumental records” In *Trends: A Compendium of Data on Global Change*. (Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A., 2000). http://cdiac.esd.ornl.gov/

10 J. Lean, J. Beer, and R. Bradley “Reconstruction of solar irradiance since 1610: Implications for climate change” *GRL* **22**, 3195–3198 (1995). D.V. Hoyt , K.H. Schatten “A Discussion Of Plausible Solar Irradiance Variations” 1700-1992 *JGR* **98** 18895-18906 (1993).

11 J. Lean, O.R. White, and A. Skumanich “On The Solar Ultraviolet Spectral Irradiance During The Maunder Minimum” *Global Biogeochem Cy* **9: (2)** 171-182 (1995)

12 L. Bengtsson, E. Roeckner, M. Stendel “Why is the global warming proceeding much slower than expected?” *J. Geophys. Res.* **104**, 3865 (1999).

13 IPCC Working Group I Summary for Policymakers, Third Assessment Report (2001). http://www.ipcc.ch/

14 Nakicenovic, N. et al. *Special Report on Emissions Scenarios* (Cambridge, U.K., Cambridge University Press, 2000).

15 S. J. Smith, N. Nakicenovic and T.M.L. Wigley “Radiative Forcing in the IPCC SRES scenarios” (unpublished). The reason this estimate is conservative is that possible changes in atmospheric chemistry, particularly increases in tropospheric ozone, were not considered. Consideration of these compounds increases the overall range, although there are reasons to believe that these increases may not be realistic (Smith *et al. in preparation*).

16 Steven J. Smith, Tom M.L. Wigley, and Jae Edmonds “A new route toward limiting climate change?” (perspective) *Science* **290** 1109 (2000).

17 U.S. EPA *U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions* (Washington, DC, 1999).

18 Note that the SRES scenarios assume that increasing income levels lead, overall, to decreasing fertility levels. World population in 2050 in two of the four SRES scenario families peaks at slightly under 9 billion near 2050 and declines thereafter, which is lower than many past projections.

19 “Permanent” on time scales of at least several thousand years.

20 The author would like to thank Hugh Pitcher for helpful comments on the manuscript.