THE SUN'S ROLE IN LONG-TERM CLIMATE CHANGE

JAMES E. HANSEN
NASA Goddard Institute for Space Studies

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Abstract. Evidence suggests that changes of solar irradiance in recent centuries have provided a significant climate forcing and that the sun has been one of the principal causes of long-term climate change. During the past two decades the solar forcing has been much smaller than the climate forcing caused by increasing greenhouse gases. But it is incorrect to assume that the sun necessarily will be an insignificant player in climate change of the 21st century. Indeed, I argue that moderate success in curtailing the growth of anthropogenic climate forcings could leave the sun playing a pivotal role in future climate change.

1. Introduction

The sun has long been suspected of being an important cause of decade-to-century climate changes. The classical paper of Eddy (1976) presented a strong case that the luminosity of the sun was lower during the Maunder minimum of solar activity in the seventeenth and early eighteenth centuries, when much of the Earth experienced notably low temperatures of the "little ice age". There are a large number of empirical relations between solar activity and climate variations that offer support for the contention that the sun has been a significant factor in climate change, even though such correlations are unsatisfactory for cause and effect analysis. The principal difficulty in quantifying the role of the sun in climate change has been the absence of precise measurements of solar irradiance that avoid the interfering effects of the Earth's atmosphere. Although rather precise data has been obtained from satellites in the past two decades (Willson and Hudson, 1991), there is disagreement as to whether these data reveal an underlying trend over the last two solar cycles (Willson, 1997; Fröhlich and Lean, 1998). For earlier times it has been necessary to estimate long-term change from assumed relationships between solar irradiance and measured solar properties, for example, the extent of convective activity visible on the Sun's surface. Hoyt and Schatten (1993) and Lean et al. (1995) have constructed such solar irradiance histories for the past two centuries using several proxy measures of solar activity. Their estimates of solar irradiance changes have significant differences, but both estimates have an increase of solar irradiance by a few tenths of a percent over the past two centuries.

An earlier, similar, version of Hoyt's solar irradiance time series was used by Hansen et al. (1981) in climate model simulations of global mean temperature for

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the period since 1880. This assumed solar variability was found to contribute to the overall global warming and to shorter period fluctuations of global temperature, but the predominant cause of long-term warming in the model was increasing atmospheric carbon dioxide. Similar conclusions have been reached in more recent studies, such as those of Rind et al. (1999) that employed the irradiance time series of Lean et al. (1995) for simulations from 1600 to the present. White et al. (1997) find evidence in global ocean temperature change of a response to changing solar irradiance.

Several studies with three-dimensional global climate models (Haigh, 1996; Balachandran et al., 1999; Shindell et al., 1999) have simulated effects of changing solar irradiance on tropospheric climate patterns that resemble observed changes. These studies present further evidence of the Sun's role in climate variability and change. But evaluation of the contribution of solar variability to past and future global temperature change can be made best on the basis of quantitative comparisons of solar and competing climate forcings. This evaluation must include both the direct and indirect climate forcings.

2. Climate Forcings, 1850–2000

Climate fluctuates even in the absence of any forcings, because of chaotic dynamical fluctuations of the atmosphere and ocean. But long-term climate changes primarily in response to climate forcings, which are imposed perturbations of the Earth's energy balance with space (Hansen et al., 1997). An example of a direct climate forcing is a change of the solar irradiance incident on the Earth. An example of an indirect climate forcing is the change of atmospheric ozone induced by solar ultraviolet changes, which thus further alters the heating of the troposphere. Other indirect solar forcings, such as cloud changes induced by solar modulation of cosmic ray fluxes, have been suggested, but in the absence of convincing observational data these remain hypotheses.

Climate forcings in the industrial era, i.e., in the past two centuries, have been estimated and discussed by IPCC (1996) and Hansen et al. (1998). The presentation here (Figure 1) is a slight modification of that of Hansen et al. (1998). Here we break down the well-mixed greenhouse gases into different categories, and order these according to their contribution to the global climate forcing. Also we associate with CH_4 its indirect effects on tropospheric ozone and stratospheric water vapor, and we associate with the chlorofluorocarbons their indirect effect on stratospheric ozone. The indirect effect of CH_4 on tropospheric ozone is assumed to be one-quarter of the total tropospheric ozone change in the industrial era, based on simulations of Lelieveld et al. (1998). The forcings due to stratospheric water vapor and stratospheric ozone changes are based on simulations with the GISS model (Hansen et al., 2000).

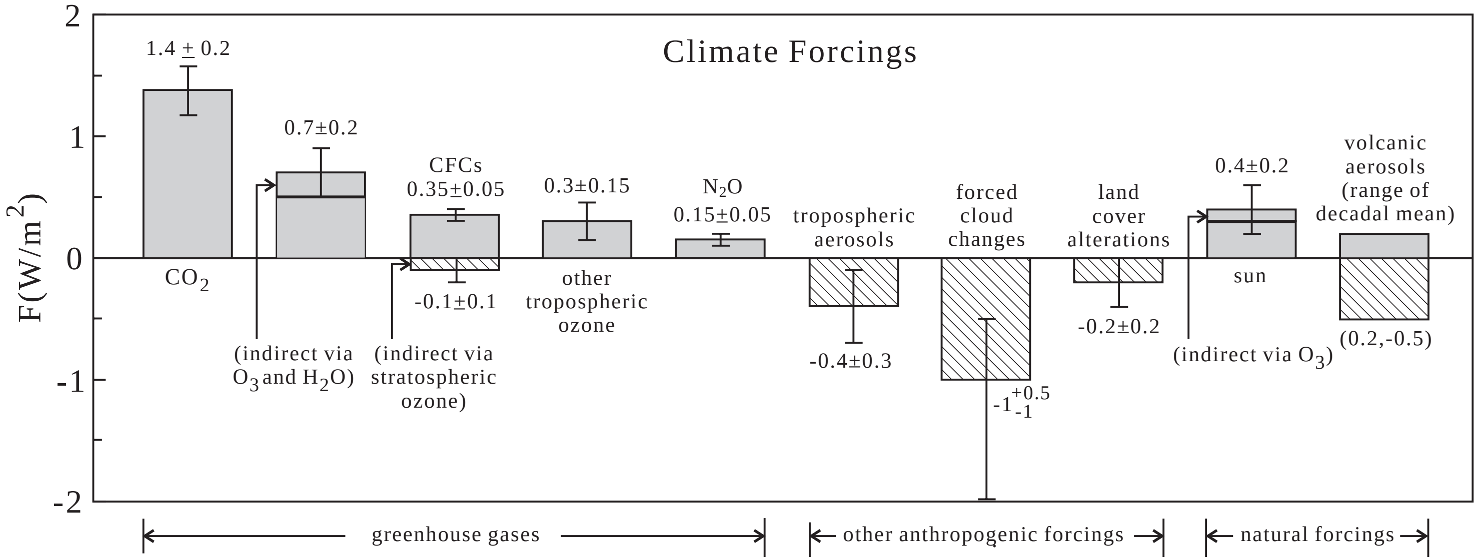

Figure 1. Estimated global climate forcings between 1850 and 2000.

A common misconception that is perhaps promoted by comparisons such as in Figure 1, especially when the greenhouse gas forcings are stacked one on top of another, is that the solar forcing is negligible. But a more relevant comparison of the solar forcing is with the net forcing by all mechanisms. Current estimates of the net forcing for the past century are only of the order of 1 to 1.5 W/m^2. In that event a contribution of 0.4 W/m^2 from the sun is far from negligible. Indeed, if the solar forcing had instead been –0.4 W/m^2, the global temperature change in the past century might have been so small as to be insignificant. A similarly pivotal role for the sun is possible next century, depending upon the balance among the competing forcings.

Note that assessment of the net forcing, in the past and future, depends critically on better understanding of the contribution of aerosols, including their indirect effect on clouds. Considerable attention has been paid to sulfate aerosols, especially subsequent to the paper of Charlson et al. (1992). The direct effect of absorbing aerosols, primarily black carbon, has also been addressed (Haywood and Shine, 1995, 1997; Penner et al., 1998). Less attention has been paid to the semi-direct effect of aerosol absorption on cloud cover (Hansen et al., 1997) and the indirect effects of absorbing inclusions within cloud particles (Chylek et al., 1995; Heintzenberg and Wendisch, 1996). Anthropogenic carbonaceous aerosols, including black carbon and weakly absorbing organic aerosols, are produced mainly by the burning of fossil fuels and biomass.

One reason to break down the climate forcings as in Figure 1 is that the growth rates of the different greenhouse gases vary, as illustrated in Figure 5 of Hansen et al. (1998). Between 1960 and 1990 the growth rate of climate forcing by CO_2 increased from about 0.1 W/m^2 per decade to just over 0.2 W/m^2 per decade. But the additional forcing by trace gases, mainly CFCs and CH_4, increased even more rapidly, to almost 0.2 W/m^2, before declining in the 1990s.

The distinction between CO_2 and the trace gases is important, because the same activities that produce most of the CO_2, burning of fossil fuels and land conversion, also produce aerosols. The net climate forcing by aerosols, direct plus indirect, is almost certainly one of cooling, which would tend to at least partially obscure globally warming due to increasing CO_2. Thus I suggest that the sharp global warming trend that began in the 1960s was primarily a consequence of the activities producing the trace gases, mainly CFCs and CH_4 , as these gases produce only warming. Prior to the 1960s the warming and cooling forcings were closer to being in balance than they have been since the 1960s, and thus the net forcing prior to 1960 was more dependent on the contribution of the sun. We must consider whether such a closer balance (of anthropogenic positive and negative forcings) is also possible in the future.

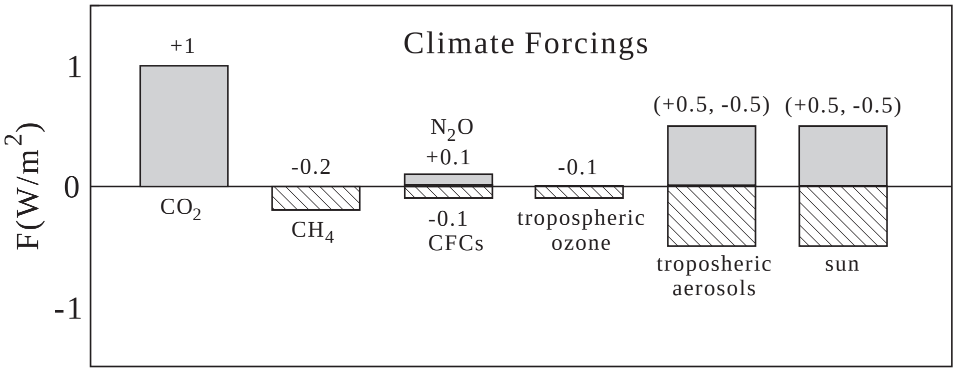

Figure 2. A scenario for additional climate forcings between 2000 and 2050. The sense and magnitudes of the uncertain aerosol and solar forcings strongly influence the net forcing.

3. Future Climate Forcings

Climate change scenarios for the future commonly have rapidly increasing greenhouse gases. The IPCC (1996) scenario that is used most frequently in climate simulations, IS92a, is sometimes called "business-as-usual" and has a rapid growth of greenhouse gases equivalent to almost 1% CO_2 increase per year or about 0.5 W/m^2 per decade. In that case most other climate forcings, including plausible variations of solar irradiance, are unimportant.

But such a trend is only one possible scenario, and it is not necessarily representative of actual trends. Indeed, as shown in Figure 5 of Hansen et al. (1998), the growth rate of the greenhouse gas climate forcing has declined by about 30% since the late 1970s and now falls below the lowest IS92 scenario. Future growth rates will depend not only on CO_2, but also on the continuing changes of CFCs and CH_4.

Let us assume, for example, that attempts to constrain CO_2 growth rates are partially successful, such that increased emissions in some countries are approximately balanced by decreases in other countries. In that case the CO_2 climate forcing increase is about 0.2 W/m^2 per decade or 1 W/m^2 in 50 years (Figure 2). CFC-11 and CFC-12, because of regulations already enacted, are expected to decline in abundance over the next 50 years. However, other CFCs are expected to increase over that period. Thus the net climate forcing by halocarbons over the next 50 years is likely to be near zero, but it could be slightly negative if regulations were extended to include additional gases, such as HFC-134a, and destruction of the accessible bank of CFC-12.

CH_4 has the potential to either increase or decrease. Its growth rate has declined by more than half in the past decade (Dlugokencky et al., 1998; Etheridge et al., 1998). A fraction of the decrease in its growth rate may be associated with stratospheric ozone depletion (Lelieveld et al., 1998), in which case there may be a CH_4 increase associated with future stratospheric ozone recovery. However, the principal reason for the slowdown is probably a reduced growth rate of CH_4 sources (Etheridge et al., 1998). Because the lifetime of CH_4 is short, about 8–10 years, the CH_4 abundance rapidly reflects changes in sources and sinks.

There are many opportunities to reduce the sources of atmospheric CH_4 (Hogan et al., 1991), including the tapping of landfills for CH_4 fuel, capture of CH_4 in mining operations, reducing pipeline losses, and more efficient agricultural practices. The indirect effects of CH_4 change will have the same sign as the direct effect. Thus a 30% decrease in the methane source would cause a negative forcing of about –0.2 W/m^2. Reduction of CH_4 would have the added benefit of increasing atmospheric OH and reducing tropospheric O_3, a pollutant that is harmful to human health and agriculture (McKee, 1994).

A global strategy that links the air pollution and global warming issues should be attractive to both the developed and developing worlds. Technology for reducing air pollution, including black carbon, already exists. We suggest that a climate forcing scenario at least as likely as "business as usual" is one with concerted introduction of modern efficient energy systems and with special attention paid to reducing trace gas amounts and black carbon emissions. In this scenario the net change of anthropogenic climate forcing over the next 50 years could plausibly be less than 1 W/m^2.

Assuming that anthropogenic climate forcings follow a path similar to this alternative scenario, then the contributions of competing climate forcings, particularly solar irradiance, become important. If the change of solar forcing in the next 50 years, direct and indirect, is say –0.5 W/m^2, as opposed to say +0.5 W/m^2, that would have a large effect on the net climate forcing. The Maunder Minimum of solar activity has been estimated to represent a reduction of solar radiation of at least 0.2%, equivalent to a direct solar forcing of about –0.5 W/m^2. Given our present understanding of the sun, we can not rule out a solar climate forcing of either +0.5 W/m^2 or –0.5 W/m^2 in the next 50 years. This suggests the need for research to understand the nature of solar variability and perhaps develop predictive capabilities for future solar change. Finally, I note that I am not disputing the merits of "business as usual" scenarios. It is appropriate to use these as a warning of potential climate effects should worst case practices be followed. At the same time, for the sake of comparison, we should consider less extreme alternative scenarios that may be achievable. Better understanding of all climate forcings is needed for reliable prediction of where climate is headed and for determination of the most effective ways to influence the direction of future climate change.

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Address for Offprints: James Hansen, NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025; jhansen@giss.nasa.gov