Climate Forcing by Changing Solar Radiation

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By how much does changing radiation from the Sun influence Earth's climate compared with other natural and anthropogenic processes? Answering this question is necessary for making policy regarding anthropogenic global change, which must be detected against natural climate variability. Current knowledge of the amplitudes and time scales of solar radiative output variability available from contemporary solar monitoring and historical reconstructions (Lean 1991) (Figure 1) can help specify climate forcing by changing radiation over multiple time scales.

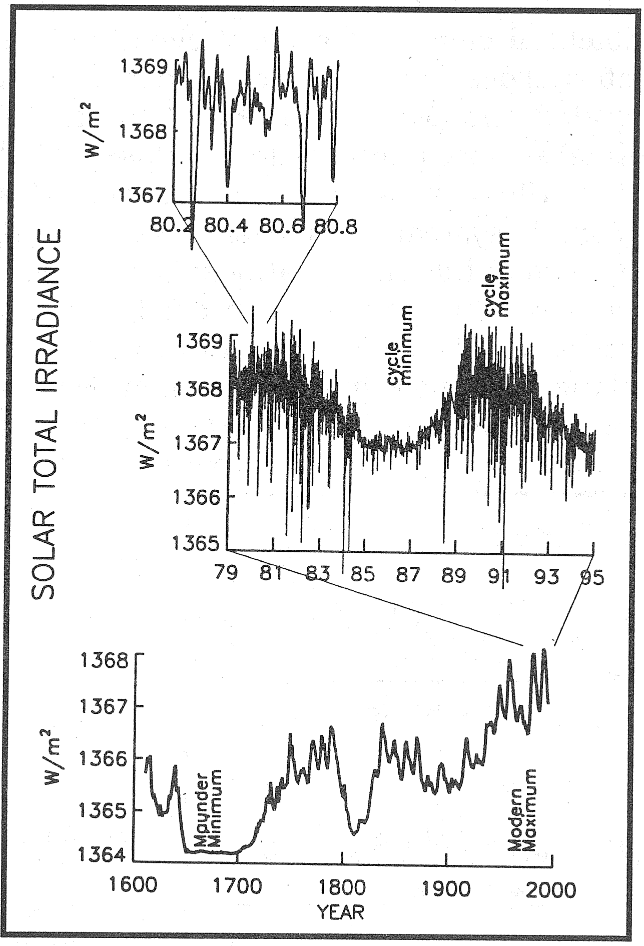

Figure 1 Time scales of observed solar total irradiance variability include the Sun's 27-day rotation (upper panel) and 11-year cycle (middle panel). The extant database is too short to verify longer term changes, such as the larger amplitude variability speculated to have occurred from the Maunder Minimum to the present (bottom panel).

Changes of a few tenths percent (2-3W/m^2) occur regularly in the Sun's total radiative output as the Sun rotates on its axis every 27 days. This rotational modulation is superimposed on an 11-year irradiance cycle with an amplitude of about 0.1%. Enhanced solar activity (such as during

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maxima of the 11-year activity cycle in 1980 and 1990) increases both the overall irradiance level and the range of the rotational modulation. Of course previous and subsequent total irradiance cycles may have quite different amplitudes, depending on the strength of solar activity and other activity-related properties. Solar total radiative output variations with larger amplitude than the 11-year cycle — 0.24% relative to the mean of present levels — are estimated to have occurred during the seventeenth century Maunder Minimum (1645-1715), based on parameterizations of the variability mechanisms identified for the 11-year cycle using proxies of solar and stellar variability (Lean *et al* 1992).

Irradiance variations associated with solar activity potentially cause natural climate fluctuations such as those evident in paleoclimate records obtained from ice-cores, tree-rings, pollen, corals, and glacial events. Other potential causes of natural climate change are volcanic eruptions and internal oscillations and couplings between the ocean and the atmosphere (Rind and Overpeck 1993; Mehta and Delworth 1995). Global mean annual surface temperature increased 0.55°C from 1860 to 1990 (Parker *et al* 1994). It is uncertain whether this warming is a response of the climate system to increasing concentrations of industrially produced CO_2 gas in the Earth's atmosphere (which increased from 280 to 353 ppmv over this period) or to combinations of the various natural influences which have also varied during this epoch (Figure 2). That the cause of the warming is indeed more complex than the influence of increasing greenhouse gases alone is suggested by statistical analyses of the climate record since 1860, which reveal significant interannual and

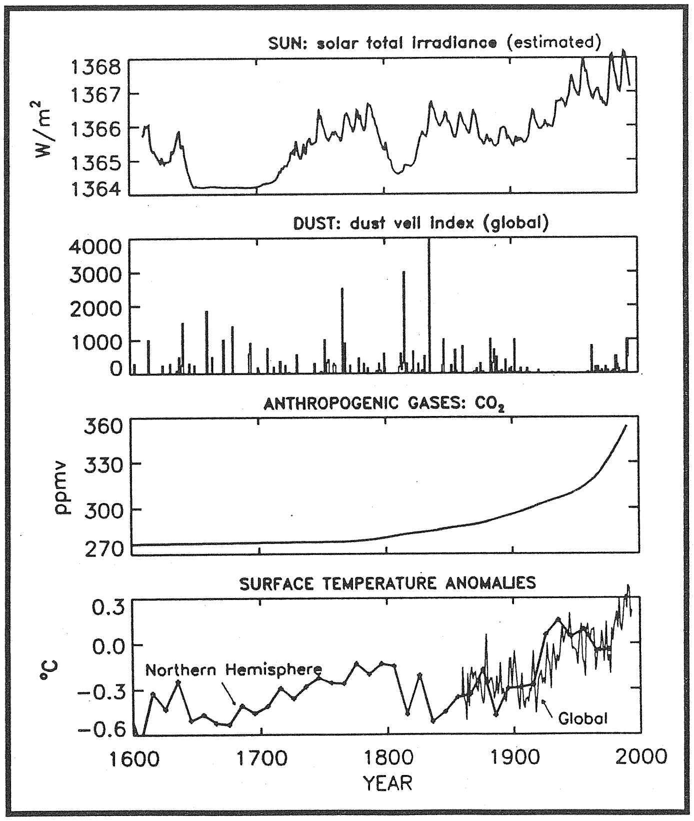

Figure 2 Compared are annual averages of: (a) estimated solar total irradiance (Lean *et al* 1995); (b) the volcanic aerosol loading according to the global dust veil index (Lamb 1977; Robuck and Free 1995); and (c) the concentration of CO_2 (Keeling and Whorf 1994). The Bradley and Jones (1993) record of decadal Northern Hemisphere surface temperature, shown in (d), suggests that the warming recorded by the IPCC (1992) data over the past 150 years is part of a longer-term trend that commenced prior to the industrial revolution.

interdecadal variability (Allen and Smith 1994; Mann and Park 1994). Furthermore, the surface temperature increase of the past 130 years appears to be part of a longer term warming that commenced in the seventeenth century (Bradley and Jones 1993), prior to the industrial epoch.

Dominant climate forcing in the past century (of the order of 2.4 W/m^2) is ascribed with some confidence to increasing concentrations of greenhouse gases (CO_2, CH_4, N_2O and halocarbons). But like greenhouse gas concentrations, the overall activity level of the Sun has risen steadily in the past few hundred years (NRC 1994) (Figure 1). Although direct solar irradiance monitoring exists only for 16 years, increasing irradiance is inferred to accompany solar activity increases over the past few centuries, based on cosmogenic isotope records of solar variability (Beer *et al* 1994; Stuiver and Braziunas 1995) and long-term monitoring of ionized Ca emission in the Sun and Sunlike stars (Baliunas and Jastrow 1990; White *et al* 1992). As well, tropospheric anthropogenic sulfate aerosol increases have accompanied the greenhouse gas increase of the industrial era (Penner *et al* 1994) while the amount of aerosols ejected into the atmosphere by volcanic eruptions decreased markedly in most of the twentieth century relative to the nineteenth century (Lamb 1977; Robuck and Free 1995). Global ozone concentrations have decreased in the stratosphere and increased in the troposphere (de Gruijl 1995). Surface albedo is changing too (Hannah *et al* 1994).

In a globally averaged sense, increasing solar radiative output and greenhouse gases both provide positive climate forcings and warmer surface temperatures because of the net increased energy input to the climate system. In contrast, increased industrial and volcanic aerosols inhibit the penetration of the Sun's radiation to the Earth's surface and lead to surface cooling. Decreasing ozone in the lower stratosphere is also thought to have a net cooling effect on surface temperature, as well as enabling increased penetration of biologically harmful solar UV radiation to the biosphere. Tropospheric ozone changes may mitigate these effects to some extent.

Amplitudes of climate forcings other than greenhouse gas concentrations, including solar radiative output variations, are thought to be smaller, but are also uncertain (Figure 3). Poorly known is the magnitude of the potentially large negative forcing (of the order of -1 W/m^2 or more) by tropospheric aerosols. Cancellation by aerosol cooling of a portion of the greenhouse gas warming increases the fraction of the net forcing potentially attributable to solar variability.

In fact, surface temperatures correlate well with solar activity over the past 140 years (Reid 1991; Friis-Christensen and Lassen 1991), with correlation coefficients as high (0.7) as the correlation between surface

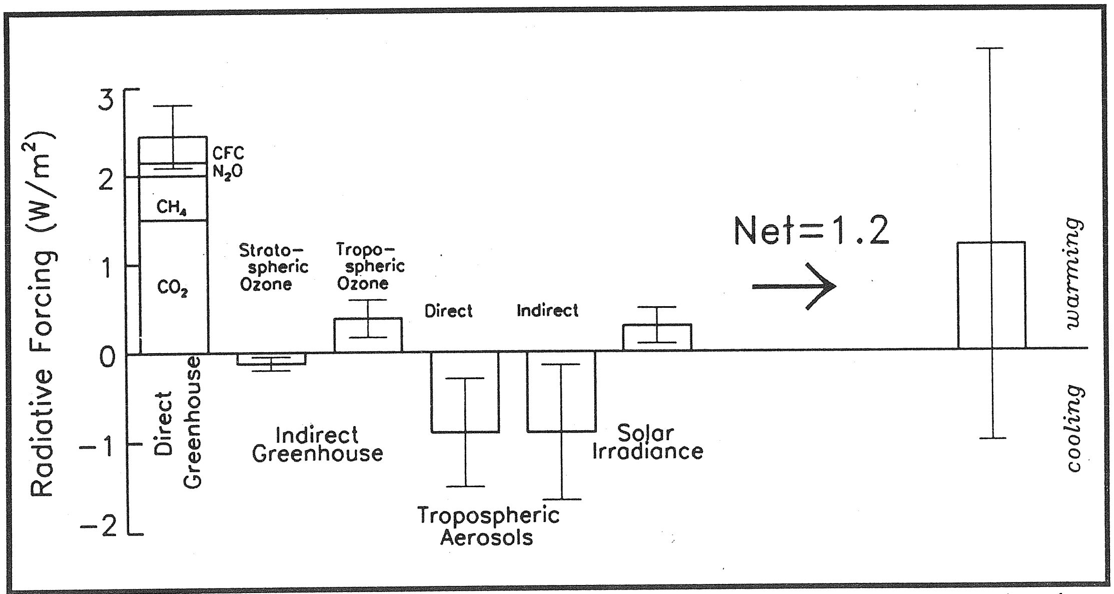

Figure 3 Amplitudes of the natural and anthropogenic climate forcings in the past 140 years, from 1850 to 1990 are shown from IPCC (1995). Each individual forcing is expected to impact the climate system in different ways depending on its latitude, altitude and history. However, climate change assessments lack the complexity to account for the myriad pathways of the climate system response, and global scale studies often assume a common climate sensitivity to the different forcings (see also, Hansen *et al* 1993).

temperatures and greenhouse gas concentrations. Eleven and 22-year periods evident in solar activity proxies also appear in many climate and paleoclimate records (Mitchell *et al* 1979; Newell *et al* 1989; Dunbar *et al* 1994), and some solar and climate time series correlate strongly over multi-decadal and centennial time scales (Wigley and Kelly 1990; Burroughs 1992). These statistical relationships suggest a response of the climate system to the changing Sun.

Examination of the pre-industrial period from 1610 to 1800 can provide insight to climate forcing by changing solar radiation in an epoch prior to the influence of anthropogenic greenhouse gases. The correlation of decadal means of reconstructed solar irradiance S and Northern Hemisphere surface temperature anomalies ΔT from 1610 to 1800 (using data such as those shown in Figure 2) is 0.86, implying a predominant solar influence on climate during this period and allowing an empirical quantification of the effect ($\Delta T = -200.44 + 0.1466 \times S$). Extending the pre-industrial correlation to the present suggests that solar forcing may have contributed about half of the observed 0.55°C surface warming since 1860 but only one-third of the warming since 1970 (Figure 4) (Lean *et al* 1995). An equilibrium simulation by the GISS GCM predicts a Northern Hemisphere surface temperature change of 0.51°C for a 0.25% solar irradiance reduction (Rind and Overpeck 1993), in general agreement with the estimate from the pre-industrial parameterization of the warming from the Maunder Minimum to the present.

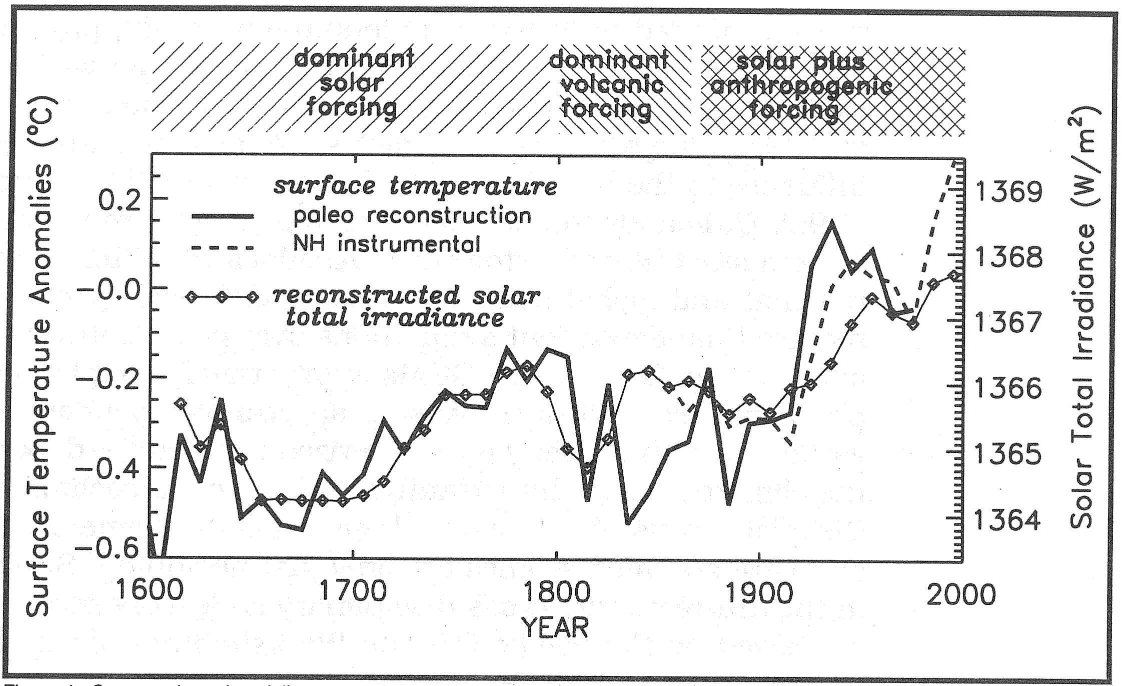

Figure 4 Compared are decadally average values of the Lean *et al* (1995) reconstructed solar total irradiance (diamonds) and Northern Hemisphere summer temperature anomalies from 1610 to the present (similar annually averaged data are shown in Figures 1 and 2). The solid line is the Bradley and Jones (1993) Northern Hemisphere summer surface temperature reconstruction from paleoclimate data (primarily tree rings), scaled to match the Northern Hemisphere instrumental data (IPCC 1992) (dashed line) during the overlap period.

However, attributing a significant fraction of recent climate warming to solar forcing presents serious ambiguities about the impact of increasing greenhouse gas concentrations whose radiative forcing has been significantly larger than solar forcing over this period. Attempts to attribute the entire surface warming of the industrial epoch by solar radiative forcing alone have been refuted, because simulations of this scenario with simple climate-ocean energy balance models require climate sensitivities beyond the expected conservative range of 0.3 to 1.0°C/Wm^{-2}, or solar irradiance variability larger than the 0.1% change observed over a recent Schwabe (11-year) cycle (Schlesinger and Ramankutty 1992; Kelly and Wigley 1992). More generally, however, presently specified climate sensitivity overpredicts the magnitude — and cannot replicate the shape — of the observed surface warming expected from radiative forcing by greenhouse gases alone, of amplitude shown in Figure 3. This underscores the need to better quantify all other natural and anthropogenic influences, including those of lesser magnitude than greenhouse gases, since the assumption of similar climate response to forcings of similar magnitude may not be valid.

Given the apparent climate system response to solar irradiance variability implied by a variety of Sun/climate statistical relationships over the past few centuries, continued space-based solar irradiance monitoring is important to quantify natural solar forcing of future climate. Additional work is needed to improve understanding of the physical pathways by which the climate system responds to direct as well as indirect solar radiative forcing, such as potentially associated with UV irradiance variability impacts on the Earth's atmosphere, and coupling of this influence to the biosphere and climate system (Rind and Balachandran 1995). Ultimately, the impact of changing solar radiation on the climate system must be understood over decadal and centennial time scales, and regional and global spatial scales, in different epochs. This will likely require time-dependent simulations over past centuries, in the present, and into the future, with GCMs appropriately coupled to middle atmosphere models, utilizing realistic, spectrally-dependent solar irradiance variations with properly parameterized wavelength-dependent impact on the climate system. Importantly, analysis of paleoclimate data from over the globe must be integrated into the assessment of results of the simulations. Such studies are only just beginning. Sun/climate studies in the future require cross-disciplinary endeavors such as promoted and conceived by the Pacific Climate Workshop and Analysis of Rapid and Recent Climatic Change.

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