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20th century changes in surface solar irradiance in simulations and observations

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[1] The amount of solar irradiance reaching the surface is a key parameter in the hydrological and energy cycles of the Earth's climate. We analyze 20th Century simulations using nine state-of-the-art climate models and show that all models estimate a global annual mean reduction in downward surface solar radiation of 1–4 W/m^2 at the same time that the globe warms by 0.4–0.7°C. In single forcing simulations using the GISS-ER model, this "global dimming" signal is shown to be predominantly related to aerosol effects. In the global mean sense the surface adjusts to changes in downward solar flux instantaneously by reducing the upward fluxes of longwave, latent and sensible heat. Adding increased greenhouse gas forcing traps outgoing longwave radiation in the atmosphere and surface which results in net heating (although reduced) that is consistent with global warming over the 20th Century. Over the 1984–2000 period, individual model simulations show widely disparate results, mostly related to cloud changes associated with tropical Pacific variations, similar to the changes inferred from the satellite data analysis. This suggests that this time period is not sufficient to determine longer term trends. **Citation:** Romanou, A., B. Liepert, G. A. Schmidt, W. B. Rossow, R. A. Ruedy, and Y. Zhang (2007), 20th century changes in surface solar irradiance in simulations and observations, *Geophys. Res. Lett.*, *34*, L05713, doi:10.1029/2006GL028356.

1. Introduction

[2] Recent reports [*Stanhill and Cohen*, 2001; *Liepert*, 2002] have suggested that anthropogenic aerosols and cloud feedbacks have induced significant reductions of the surface shortwave radiation downward (SWD) or "global dimming" (as coined by *Stanhill and Cohen* [2001]) since the beginning of the measurements in the 1950s (in this paper, we use the term global dimming to signify reductions in the global averaged SWD). Local estimates of such reductions into the 1980s range from about 2% per decade in some rural areas (such as former Soviet Union [*Abakumova et al.*, 1996]) to 10% per decade in very polluted regions (Hong Kong [*Stanhill and Kalma*, 1995]). More recent results suggest that this effect has reversed since the 1990s mostly in Europe and North America [*Wild et al.*, 2005; *Pinker et al.*, 2005] as a result of improving air quality in these regions.

[3] A negative shortwave anomaly at the ground does not automatically imply atmospheric cooling since the air layers above the ground can absorb the shortwave heating no longer reaching the surface, increasing the downward longwave radiation [*Menon et al.*, 2002; *Soden et al.*, 2002]. Such radiative flux changes complicate the interpretation of the observed response of the longwave flux incident to the surface that is expected to increase due to enhanced anthropogenic greenhouse effect [*Krishnan and Ramanathan*, 2002; *Ramanathan et al.*, 2001] and the consequent warming of the air.

[4] Here we analyze the surface solar irradiance in ensemble simulations using nine state-of-the-art coupled ocean-atmosphere-land-ice general circulation models of the 20th Century prepared for the Intergovernmental Panel of Climatic Change (IPCC) Fourth Assessment Report (AR4) (details of the models can be found at http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php. The nine models used in this study are: the NOAA Geophysical Fluid Dynamics Laboratory GFDL-CM2.0, the three NASA Goddard Institute for Space Studies (GISS) models GISS-AOM, GISS-EH, and GISS-ER, the two National Center for Atmospheric Research (NCAR) models CCSM3 and PCM, the United Kingdom Meteorological Office Hadley Center UKMO-HADCM3, the Max Planck Institute for Meteorology ECHAM5/MPI-OM model and the University of Tokyo CCSR MIROC3.2 medium resolution.

[5] We present a compilation of the geographical distribution of SWD trends over the entire 20th Century period accompanied by sensitivity experiments with a single model to help establish possible mechanisms. Over a shorter (1984–2000) period model and observational analyses from the International Satellite Cloud Climatology Project Flux Dataset (ISCCP-FD) are also compared.

2. 20th Century Trends

[6] Over the 20th Century all models show global mean decreases (Figure 1a) in SWD ranging from 1 to 4 W/m^2 alongside near-surface temperature increases ranging between 0.4 and 0.7°C. We construct a multi-model mean using an equal weighting for each model's ensemble mean (Figure 1b) which shows decreases in the SWD of up to 0.07 W/m^2/yr regionally. We assessed the extent to which these trends may have been impacted by drifts in the relevant control simulations, and found that changes in sea surface temperature (SST) and the associated cloud feedbacks are of opposite sign and an order of magnitude

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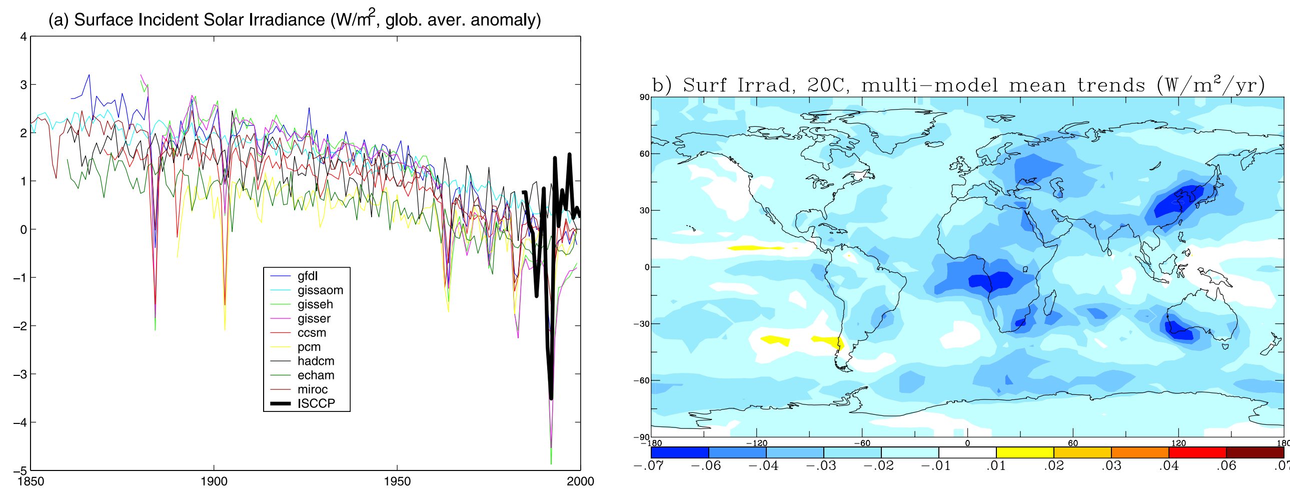

Figure 1. (a) Simulated global averages of the 20th Century SWD anomalies (W/m^2, mean 1990s seasonal cycle removed) and linear trends ($W/m^2/yr$) in the nine IPCC climate models. (b) Linear trends based on the multi-model mean monthly anomalies over the 20th century. Trends are statistically significant at the 95% confidence level everywhere except in the range [−0.01,0.02] $W/m^2/yr$.

smaller than the trends in the forced runs, where the maximums trends are within ±0.002 $W/m^2/yr$.

[7] The largest negative trends are found over land in eastern Europe, tropical Africa, east Asia and northwestern Australia. While all models exhibit negative trends in these regions, they are especially pronounced (over 0.1 $W/m^2/yr$) in the GISS-ER, GISS-EH and MIROC models which include the two aerosol indirect effects on cloud lifetime and cloud albedo. All models include anthropogenic sulfate aerosol changes while GFDL, GISS-ER, MIROC and CCSM also include carbonaceous aerosol changes based on historical industrial and biomass burning data sets. The spatial aerosol distribution and temporal trends (increased load over Europe, Northern America, east Asia, and tropical Africa) are similar across the models and that is clearly reflected in the similar SWD trends. Models without the first and second indirect aerosol effects exhibit the smallest dimming signal. Full-sky trends mirror the clear sky trends in the models but are not similar to the cloud-cover trends over the 20th century. We therefore conclude that the century-scale trends mainly relate to the aerosols.

[8] Model results generally agree with surface observations from the Global Energy Balance Archive (GEBA) which show reduction of 0.23 $W/m^2/yr$ at sites in the northern hemisphere land areas for the period from the begin of measurements in 1961 to 1990 [*Liepert*, 2002] which coincides with the period of steepest decline in SWD of about 0.05 to 0.2 $W/m^2/yr$ in all models (Figure 1a).

[9] To better determine the cause of the 20th Century dimming trends, we carried out multiple sensitivity studies using an ensemble of GISS-ER model simulations [*Hansen et al.*, 2005b] with different individual forcings (Figure 2; full 20th Century forcings, well-mixed greenhouse-gases only, tropospheric aerosols direct effect only, and tropospheric aerosols including the direct and indirect effects only). We find that much of the dimming trend (Figure 2a) over the Northern Hemisphere and especially over central Africa, Europe and south and east Asia stems from the direct tropospheric aerosol effect (Figure 2c). The indirect effects of aerosols on cloud albedo and lifetime (Figure 2d) add to the dimming over these regions (by up to 60%, Figure 2e). Greenhouse-gas forced cloud and ice/snow albedo feedbacks alone result in negative trends at high latitudes (Figure 2b) whereas convective cloud and water vapor feedbacks produce positive trends in SWD over most of the mid and low latitudes. We thus conclude that SWD century long changes can be mainly attributed to aerosol direct effects and secondly to the aerosol indirect effects on clouds and not to GHG feedbacks.

[10] A more detailed look into the aforementioned sensitivity transient runs reveals that in presence of direct + indirect tropospheric aerosol effects, net radiative cooling occurs at the surface corresponding to −0.8°C which is equivalent but opposite in sign to the greenhouse only net warming corresponding to 0.8°C. The net radiative flux (tot) is a measure of the transient planetary energy imbalance [*Hansen et al.*, 2005a]. These two runs differ mainly in the latent heat flux which is twice as sensitive to temperature changes in the aerosol direct+indirect forcing experiment than in the greenhouse gas forcing run. The fact that latent heat flux is more sensitive than the net heat flux to aerosol forcing is related to the stronger regionality of the aerosol-driven solar changes and causes the very small reduction of evaporation in the full forcing experiment. These results imply that removing anthropogenic aerosols (global brightening) would warm the surface as effectively as greenhouse gases but would be twice as effective on the water cycle and hence rainfall changes. In all simulations the surface adjusts to the SWD decrease by increase in the net longwave (NLW). This is because upward longwave (LW) and downward LW are functions of surface and air temperature respectively, but the difference (NLW) is predominantly affected by atmospheric absorption which increases in both the greenhouse-gas simulations and the aerosol simulations (since aerosols and increased water vapor absorb some of the shortwave irradiance and heat the air). Sensible heat flux which is also a function of differential heating of atmosphere and surface is consequently also reduced in all

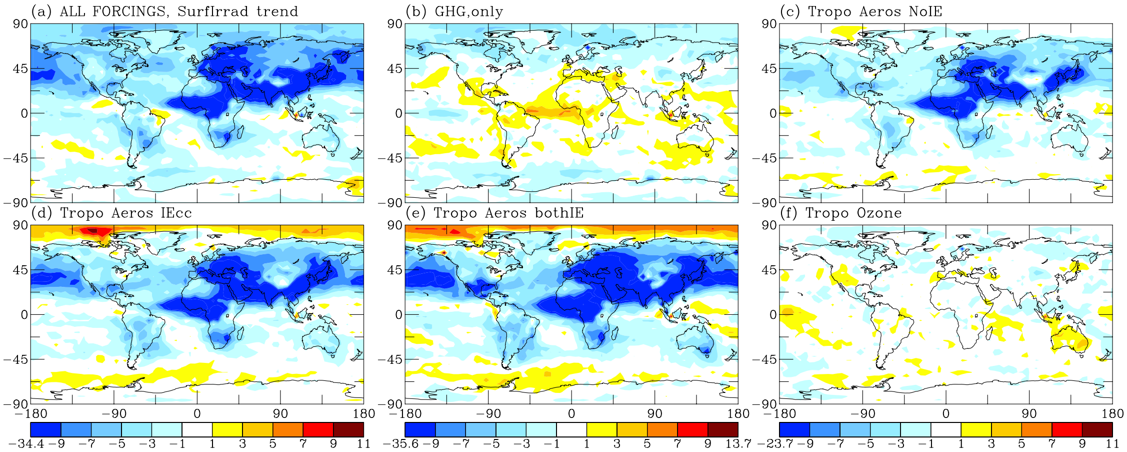

Figure 2. Sensitivity experiments of the 20th Century linear trends in SWD from the GISS-ER model (W/m^2/100 yrs). (a) All forcing agents included, (b) well-mixed greenhouse-gases only, (c) direct tropospheric aerosol effect only, (d) direct tropospheric aerosol plus aerosol-cloud lifetime indirect effect only, (e) direct tropospheric aerosol plus cloud lifetime and cloud albedo indirect effects, and (f) tropospheric ozone effect only. Trends related to other forcings (such as volcanoes, solar forcing, stratospheric ozone, soot effects on snow albedo, and land use) are found to be relatively unimportant in this diagnostic.

simulations. In the full-forcing run the 20th Century global dimming (of 3 W/m2) co-exists with global warming (of 0.4°C) although the surface energy imbalance is half of the greenhouse gas forcing experiment.

[11] Surface latent heat flux decreases in the aerosol simulations (due to the reduction in SW heating) but increases in the greenhouse-gas simulations (due to LW warming). In the full-forcing case the effects almost balance to produce a very small reduction of evaporation. The net heating, which is a measure of the transient planetary energy imbalance [*Hansen et al.*, 2005a], is positive in the full and greenhouse-gas simulations, and negative in the aerosol-only cases. The fact that latent heat flux is more sensitive than the net heat flux to aerosol forcing is related to the stronger regionality of the aerosol-driven latent heat flux changes and demonstrates that the sensitivity of the hydrologic cycle (also discussed by *Liepert et al.* [2004]) is more complicated than simply whether the globe is warming or cooling.

3. 1984–2000 Trends

[12] For the shorter modern period we compare the model simulations to SWD anomalies from ISCCP-FD [*Zhang et*

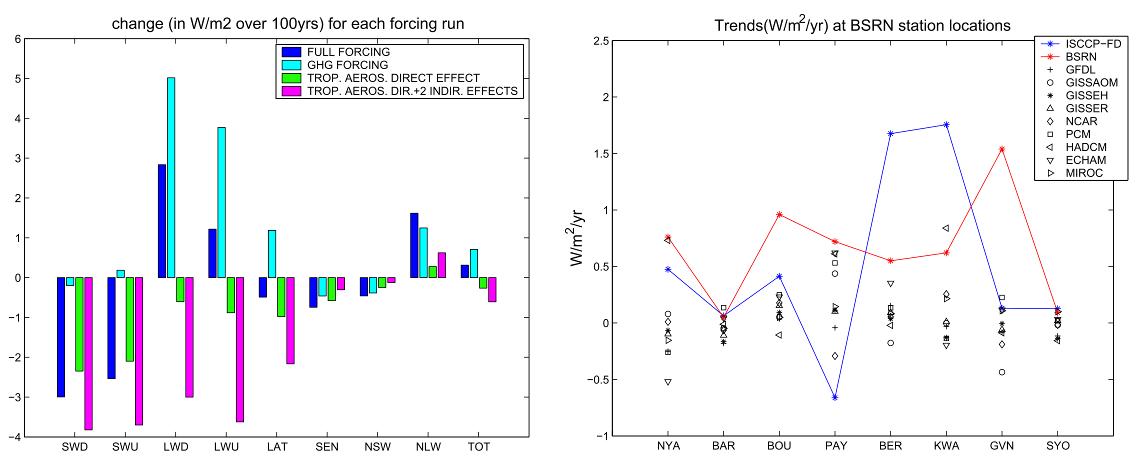

Figure 3. (left) Linear trends (W/m^2/100 years) from four different sensitivity experiments with the GISS-ER model: (1) full-forcings, (2) well-mixed greenhouse-gases only, (3) direct effect only and (4) direct and two indirect effects only. All surface energy budget components are shown: SWD -downward shortwave radiation (positive down), SWU -upward shortwave (positive up), LWD -downward longwave (positive down), LWU -upward longwave (positive up), LAT -latent heat flux (positive up), SEN -sensible heat flux (positive up), NSW -net shortwave (positive down), NLW -net longwave (positive down) and TOT -total energy balance (positive down). (right) Linear trends of SWD monthly anomalies (W/m^2/yr) from BSRN and the nine IPCC models for the period 1984–2000 at 8 BSRN sites discussed by *Wild et al.* [2005]. NYA- Arctic Ocean, BAR- Barrow Alaska, BOU- Boulder, PAY- Central Europe, BER- Bermuda, KWA- Kwajalein, GVN and SYO- Antarctica.

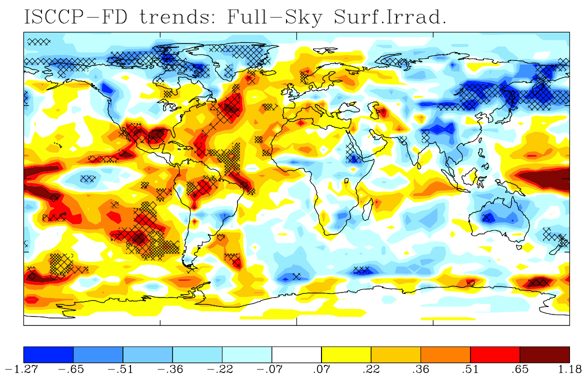

Figure 4. ISCCP-FD linear trends (1984–2000) in the monthly anomaly time series of full-sky SWD (W/m^2/yr). Hatched regions denote statistically significant trends at the 95% confidence level.

al., 2004]. For the entire globe, the intraseasonal and the interannual variability of the satellite product agrees very well with the Baseline Surface Radiation Network (BSRN [*Ohmura et al.*, 1998]) ground measurements (the correlation coefficients of the collocated SWD anomaly time series is well above 0.65 (statistically significant to the 95% confidence level) for most BSRN station locations and there are no systematic differences between ISCCP-FD and BSRN trends over co-located grid boxes, although individual discrepancies arise due to area averaging and the fact that ISCCP-FD does not account for all biomass burning events). In fact ISCCP-FD is not using the 1990's reversal in aerosol emissions (neither does the GISSER model). This fact degrades the agreement with BSRN which is however already high and this shows that mostly cloud effects rather than aerosols are associated with short-term changes in SWD.

[13] The 1984–2000 period includes the period of recently reported 'brightening' trends over some sites [*Wild et al.*, 2005; *Pinker et al.*, 2005]. ISCCP-FD shows similar average brightening trends (0.5 W/m^2/yr) over 8 BSRN locations [*Wild et al.*, 2005] and over the same period. However, model trends at the same sites usually differ from either observation by as much as the observations differ from each other (Figure 3, right).

[14] Globally averaged trends (Figure 4 from ISCCP-FD show only slight brightening by 0.04 W/m^2/yr for the period 1984–2000, mostly over oceans (0.1 W/m^2/yr). Averaged over land they show dimming by 0.1 W/m^2/yr. ISCCP-FD global mean trends also show only a quarter of the brightening tendency previously described from other satellite products [*Pinker et al.*, 2005] (this analysis includes a significantly smaller dimming effect ($\sim$4 W/m^2) in the years following the Pinatubo eruption in 1991 [see *Pinker et al.*, 2005, Figure 1]. We conclude that the 8-station brightening trend is thus not representative of either the land averages or of the global averages.

[15] Trends in the ISCCP-FD full and clear sky SWD flux and ISCCP cloud cover, show that the brightening over the Atlantic and Pacific is due to reductions in the cloud cover and not clear-sky flux transparency. Observed cloud-cover changes in the tropics are associated with the anomalously large number of El-Niño events during the 1990s compared to the 1980s, during which the warming of the eastern equatorial Pacific significantly increases cloud coverage and reduces SWD. At the same time, the warm pool and subtropical cloud amount decreases resulting in the observed "horseshoe" pattern (Figure 4). These changes are consistent with the observed intensification of the Hadley and Walker cells over the tropical Pacific in the 1990s [*Chen et al.*, 2002; *Wielicki et al.*, 2002].

[16] Tropical "horseshoe" patterns similar to that observed are found in a select few of the climate models over 1984–2000 (GFDL, HADCM and ECHAM), consistent with similar trends in real world ENSO behavior over this short period. However, these trends are over too short a time period to be statistically significant, and thus given the dominance of the intrinsic interannual/interdecadal variations of both clouds and SWD, we cannot discern an aerosol-related change in SWD over this short period on a global scale.

4. Conclusions

[17] To summarize we show that there is a robust "global dimming" signal (by which we mean reduced globally averaged SWD) in climate models over the 20th Century. Overall, global mean model and satellite observational trends are smaller than previously reported for single sites or partial-global averages. This signal is attributable to the increased anthropogenic aerosol load rather than cloud feedbacks. However, over shorter decadal timescales, climate and SWD variability is dominated by cloud cover changes mainly associated with ENSO-related variability. Hence we conclude that recently reported evidence for "brightening" does not necessarily signify a general reversal of the 20th Century dimming trend due to reduced air pollution since the attribution of these changes in the presence of significant intrinsic variability is extremely difficult.

[18] The long-term dimming coincides with increases in surface air temperature in the models due to the dominant role of longwave forcing related to anthropogenic greenhouse-gases. In all cases including greenhouse gas forcing, the positive transient planetary energy imbalance clearly demonstrates that global warming and global dimming can coexist. Global dimming is seen to play an important role in the latent heat trends whereas global warming dominates the surface energy budget trends.

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