A multi-data comparison of shortwave climate forcing changes

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Received 17 June 2005; revised 17 August 2005; accepted 2 September 2005; published 2 November 2005.

[1] Traditionally the Earth's reflectance has been assumed to be roughly constant, but large decadal variability, not reproduced by current climate models, has been reported lately from a variety of sources. We compare here the available data sets related to Earth's reflectance, in order to assess the observational constraints on the models. We find a consistent picture among all data sets of an albedo decreased during 1985–2000 between 2–3 and 6–7 W/m^2, which is highly climatically significant. The largest discrepancy among the data sets occurs during 2000–2004, when some present an increasing reflectance trend, while CERES observations show a steady decrease of about 2 W/m^2. **Citation:** Pallé, E., P. Montañés-Rodriguez, P. R. Goode, S. E. Koonin, M. Wild, and S. Casadio (2005), A multi-data comparison of shortwave climate forcing changes, *Geophys. Res. Lett.*, *32*, L21702, doi:10.1029/2005GL023847.

1. Introduction

[2] The net shortwave forcing of the Earth's climate is determined by the solar output and the Earth's albedo or reflectance. Traditionally the Earth's albedo has been assumed to be roughly constant (about 30%), but large decadal variability, that is not reproduced by current global circulation climate models (GCMs), has been reported lately from a variety of sources [*Liepert*, 2002; *Wielicki et al.*, 2005; *Wild et al.*, 2005; E. Pallé et al., Seasonal and interannual trends in Earth's reflectance 1999–2004, submitted to *Journal of Geophysical Research*, 2005, hereinafter referred to as Pallé et al., submitted manuscript, 2005]. Further, there are discrepancies of up to 7% among the mean albedo estimates of different GCMs [*Charlson et al.*, 2005]. Clearly the present knowledge of the shortwave branch of the Earth's radiation budget is not as advanced as the thermal infrared branch is.

[3] The Earth's reflectance is tightly related to cloud amount and properties, and there are clear indications that these have changed over longer than decadal scales [*Pallé and Butler*, 2002], leading one to suspect long-term changes in the Earth's reflectance, as well. In fact, global compilations from ground-based radiometer data from the Global Energy Balance Archive (GEBA) suggest that there has been a decrease in solar irradiance reaching the ground (i.e., an increase in the top of the atmosphere albedo) during the 1960–1990 period [*Gilgen et al.*, 1998; *Liepert*, 2002]. From analysis of sunshine records, this 'global dimming' can be extended back in time to the beginning of the 20th century [*Stanhill and Cohen*, 2001; *Pallé and Butler*, 2001], but it is difficult to quantify on a global scale due to the local nature of the few available data sets in the first half of the 20th century. Thus, in this paper, we have concentrated on the more modern period starting in 1983, when the first satellite observations became available, to the present.

[4] Despite individual uncertainties and the wide magnitude range of the albedo change estimates given in the literature, the authors argue that the observational discrepancies are not as large as it has previously been suggested [*Charlson et al.*, 2005], and that a coherent picture is emerging from all data sets. We compare here all the available data sets related to the Earth's albedo, i.e., the Earth's shortwave reflectance, in order to assess the observational constraints on the models. We concentrate in the observational records rather than discussing climate simulations.

2. Shortwave Forcing Data Sets

[5] There are five major ways to measure or derive estimates of the Earth's shortwave reflectance.

[6] • From space platforms, the Earth Radiation Budget Experiment (ERBE) and the Clouds and the Earth's Radiant Energy System (CERES) missions, both measure reflected shortwave (and infrared) radiances to derive estimates of the Earth's broadband albedo. *Wielicki et al.* [2002, 2005] calculated the long-term anomalies of the tropical (ERBE) and global (CERES) reflected shortwave flux.

[7] • Ground based astronomical observations of the bright and dark side (earthshine) of the Moon also allow large-scale instantaneous measurements the Earth's effective albedo (ES) [*Pallé et al.*, 2003], typically over a third of the Earth's surface at a given time. *Pallé et al.* [2004] derived the long-term anomalies in the earthshine effective albedo since ES measurements began in 1998.

[8] • Also ground-based are the observations of the solar radiation incident on the Earth's surface, S, from the Baseline Surface Radiation Network (S_{BSRN}) measured by means of radiometers [*Ohmura et al.*, 1998]. Here we use the average of the time series anomalies in S_{BSRN} recorded at each station of this network [*Wild et al.*, 2005].

[9] • The International Satellite Cloud Climatology Project (ISCCP) data set provides globally averaged satellite observations of cloud amount and properties at 280x280 km grid cell resolution every 3 hours [*Rossow et al.*, 1996]. Based on these data, globally averaged estimates of the solar radiation incident to the Earth's surface (S_{mod}) were

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0094-8276/05/2005GL023847$05.00

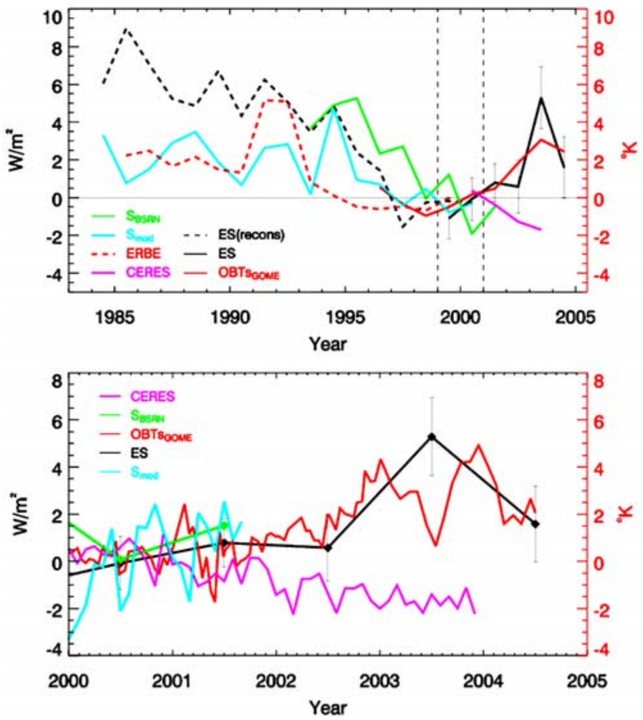

Figure 1. (top) Annual mean anomalies of: 1984–2000 ES albedo reconstruction [*Pallé et al.*, 2004] (broken, black) and 1999–2004 measured ES albedo anomalies (solid, black); S_{BSRN} (green); OBT_{GOME} (red); CERES (magenta) and ERBE (broken, red) shortwave flux anomalies; and S_{mod} (blue). All anomalies are relative to the 1999–2001 period indicated by the two broken bars. (bottom) A blowup of Figure 1 (top) over the 2000–2005 period. Some of the Figure 1 (top) data sets are plotted here as monthly means when available. Anomalies are normalized to the year 2000 value. In both panels: S_{BSRN} and S_{mod} data have been inverted, because of their inverse relationship with albedo, but the data were not re-scaled. For the ES observations, ±1 σ error bars are also plotted.

derived by *Pinker et al.* [2005] and are also discussed in this work. *Pallé et al.* [2004] used ISCCP data, together with ES measurements, to empirically estimate changes in the Earth's reflectance since 1983. *Zhang et al.* [2004] also used the ISCCP cloud data set to derive model estimates of the top-of-the-atmosphere shortwave fluxes and albedo. The results of the *Zhang et al.* [2004] simulations are consistent with ERBE and S_{BSRN} measurements at the top of the atmosphere and the Earth's surface, respectively.

[10] • Changes in Earth's outgoing radiance affect the thermal equilibrium of spaceborne instruments, and produce detectable variations in satellite on-board temperatures. Although longwave radiances may have a small contribution, the shortwave radiance reaching the Global Ozone Monitoring Experiment (GOME) is believed to be the essential driver of the thermal changes in the instrument [*Casadio et al.*, 2005]. Here we also make use of the GOME on-board instrumental temperature records (OBT_{GOME}) derived by *Casadio et al.* [2005].

[11] The geographical and temporal sampling differences between these data sets are large and each has its intrinsic limitations ranging from poor time/space coverage, especially for ground-based observations, to long-term calibration issues, especially for satellite observations. For example, while earthshine data samples instantaneously about a third of the Earth during a few hours of observations for about half the days each month, the OBT_{GOME} data covers the whole Earth surface in about 35 days, S_{BSRN} detectors measure instantaneously during all daylight hours but at a fixed location, and the CERES satellite samples each point of the Earth twice a day always at local noon and midnight. In this sense, the availability of several independent data sets is an advantage that should be exploited in order to understand the physical drivers of albedo changes, and overcome the limitations of each separate data set.

3. Discussion

[12] In Figure 1, the time series anomalies for all albedo related data sets, in W/m^2, are shown. There is a consistent picture among all data sets by which the Earth's albedo has decreased over the 1985–2000 interval. The amplitude of this decrease ranges from 2–3 W/m^2 [*Wielicki et al.*, 2005; *Pinker et al.*, 2005] to 6–7 W/m^2 [*Pallé et al.*, 2004; *Wild et al.*, 2005], but any value inside these ranges is highly climatologically significant and implies major changes in the Earth's radiation budget (see Table 1).

[13] S_{BSRN} data are local in nature, but its advantage resides in instrumental precision and temporal resolution. The overall decreasing trend in S_{BSRN} observed at 8 individual sites over the 1993–2001 period, amounts to 6.6 W/m^2 [*Wild et al.*, 2005] and is quantitatively in line with the change in the net solar fluxes at the top of the atmosphere estimated by the earthshine method during the same period (6 W/m^2). Although a simple average from only 8 stations is a crude approximation, it is the best available representation of a global observed mean surface solar radiation, at least over land areas. The decrease in reflected shortwave flux from ERBE data is only about half, however, we speculate that the discrepancies might be reconcilable if the different wavelength (ES: 0.4–0.7 μm; S_{BSRN} 0.3–2.8 μm; ERBE 0.3–4 μm) and spatial (ERBE covers tropical regions only) coverage of the three data sets are taken into account.

Table 1. Globally Averaged Estimates of the Shortwave Forcing Changes Estimated by Different Data Sets Over Several Periods of Time[a]

Measurement Technique	1750-Present	1985–2000	2000–2004
Low-orbit satellites	–	+2.0	+2.0 (+0.5)
Modeled Irradiance at Earth's surface	–	+3.0	n.y.a.
Measured Irradiance at Earth's surface	negative	+6.0	n.y.a.
Earthshine method	–	+6.0	−2.0
Satellite on-board temperature method	–	positive	negative
GHG	+2.5	+0.8	∼+0.1
Aerosols	−0.5	−0.2	∼−0.05

[a]Also given are the best estimates of the forcing change introduced by the amount of GHG and atmospheric aerosols over the same periods [*Intergovernmental Panel on Climate Change*, 2001]. All forcing changes are given in W/m^2. 'n.y.a.': data not yet available; '–': data do not exist. The exact forcing size is not always know for some of the data sets; in these cases we indicate whether the data presents a positive or negative shortwave forcing.

[14] The earthshine albedo changes are mostly attributed to clouds [*Pallé et al.*, 2004]. However, similar S_{BSRN} long-term trends are found under both all sky and clear sky conditions, indicating that, apart from clouds, changes in the optical properties of the cloud-free atmosphere are also present [*Wild et al.*, 2005]. Anthropogenic aerosols affect the Earth's radiation budget both directly, by absorbing and reflecting solar radiation, and indirectly, by altering cloud micro-physics and albedo. While all data sets in Figure 1 will be affected by both cloud and aerosol changes (the ES reconstruction will detect only the indirect aerosol effect through changes in cloud optical thickness), the S_{mod} simulations are mainly based on cloud amount, which might explain their low amplitude trend. A probe of the importance of atmospheric (in this case stratospheric) aerosols, is the large albedo anomaly produced by the Pinatubo eruption in 1991, detected in Figure 1 only by the ERBE data. The other two data sets that cover these years, the ES reconstruction and the S_{mod}, do not contain information on stratospheric aerosol loading. Distinguishing between the effects of clouds and/or aerosols in the albedo, is a current challenge for modern climate observing and modeling efforts, as it affects our understanding and ability to predict climate change.

[15] Over the more recent period 2000–2004, also studied by *Wielicki et al.* [2005], the ES data show an increase of about 2 W/m^2 in planetary albedo, while OBT_{GOME} data present a small variability during 1998–2000, and a progressive increase afterwards [*Casadio et al.*, 2005]. Note that OBT_{GOME} anomalies are in $^{\circ}K$ (in the satellite on-board temperatures) and they may or may not correspond to the same forcing amplitude in W/m^2, but this evolution is highly consistent with ES observations (Figure 1 (bottom)). This reinforces the conclusion that the high albedo in 2003 is real, although might be overestimated in the ES data due to low data intake during that year (Pallé et al., submitted manuscript, 2005). S_{mod} and S_{BSRN} data also present an increasing trend over this period, but they are only updated to 2001, a period too short to derive any strong conclusions. On the other hand, CERES data show a steady decrease of about 2 W/m^2 [*Wielicki et al.*, 2005] which is the major discrepancy in Figure 1 (bottom), although the size of the decrease may be overestimated by a factor 4 due to the hemispheric scan mode used by CERES during the first two years on orbit [*Wielicki et al.*, 2005]. A detailed inter-comparison study of all data sets is needed in order to resolve this crucial issue, particularly interesting will be the ISCCP, S_{mod} and S_{BSRN} data update to 2004.

[16] At the moment of writing this manuscript, although the data are still not publicly available, the ISCCP data have been updated to 2004 (isccp.giss.nasa.gov). The updated data show an continuous increase in global cloud amount of about 2–3% from 2000 to the end of 2004, consistent with the ES and OBT_{GOME} larger albedo values over that period, and an overall albedo increase in 2000–2004.

[17] One of the theoretical arguments used by *Wielicki et al.* [2005] against the large albedo increase in 2003 was the lack of response (cooling) in global temperatures and/or ocean heat content. This can be solved by the new ISCCP data, where the cloud increase 2000–2004 is mainly due to increasing mid and high clouds. These high altitude clouds will increase the Earth's reflectance, especially if the increase occurs over the relatively dark oceanic areas, but the net forcing of these high cloud changes is probably near zero or even positive, due to their strong infrared absorption.

[18] We also note that the largest inter-annual and long-term consistency for all series is found between ES, OBT_{GOME}, and S_{BSRN} data. These are all direct and independent measurements of the relevant physical quantities: albedo, temperature and solar flux respectively. On the other hand the CERES and ERBE radiance measurements, and in particular S_{mod} estimates, rely heavily on modeling.

[19] Ground-based observations of albedo and surface radiation cannot provide simultaneously the large spacial/temporal resolution accomplished from satellite platforms, which is crucial for the improvement of GCMs and our understanding of climate change, but they provide a very necessary complement to the complex satellite data sets, especially for validation and long-term calibration.

4. Conclusions

[20] Summarizing, over the roughly defined periods: i) 1960–1985: The Earth's albedo may have increased by as much as 7 W/m^2 [*Gilgen et al.*, 1998; *Stanhill and Cohen*, 2001; *Liepert*, 2002]; ii) 1985–2000: the Earth's albedo has decreased by a quantity from 2–3 W/m^2 [*Wielicki et al.*, 2002; *Pinker et al.*, 2005] to 6–7 W/m^2 [*Pallé et al.*, 2004; *Wild et al.*, 2005]; iii) 2000–2004: the trends for two of the data sets in Figure 1, are toward an albedo increase of about 2 W/m^2 [*Pallé et al.*, 2004] and 2^oK [*Casadio et al.*, 2005] and a large peak in 2003 with a drop in 2004, while CERES data shows a decrease of about 2 W/m^2 [*Wielicki et al.*, 2005]. Newly updated ISCCP data seems to support the increasing trend shown by the ES and OBT_{GOME}. Updated time series of the remaining data sets are needed to solve this discrepancy.

[21] In any case, regardless of discrepancies over the very recent years, all the observational estimates of the Earth reflectance presented in this paper are broadly consistent and suggest changes in the Earth's shortwave forcing, both at the surface and at the top of the atmosphere, that will have a large impact on the planet's radiation budget. Clearly a more in-depth inter-comparison and integration of the several data sets presented here is needed, together with an improved model representation of the changes in the shortwave branch of the Earth's radiation budget.

[22] **Acknowledgment.** This research was supported in part by a grant from NASA (NASA-NNG04GN09G).

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