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Recent regional surface solar radiation dimming and brightening patterns: inter-hemispherical asymmetry and a dimming in the Southern Hemisphere

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Abstract

Recent variations in surface solar radiation (SSR) at the beginning of the 21st century (2000–2007) were determined at scales ranging from local/regional to hemispherical/global, on the basis of radiative transfer computations and information from satellites, reanalyses and surface measurements. Under all-sky conditions, in the Northern Hemisphere (NH) there is no clear dimming/brightening signal after 2000, whereas in the SH there is a more clear dimming arising from both increasing clouds and aerosols. Dimming is observed over land and ocean in the Southern Hemisphere (SH), and over oceans in the NH, whereas a slight brightening occurred over NH land. However, opposite tendencies are found even within the same continent, indicating the need to assess SSR changes at regional/local scales apart from hemispherical/global ones. Copyright © 2011 Royal Meteorological Society

Keywords: solar radiation; climate; dimming; brightening; clouds; aerosols

1. Introduction

There has been observational evidence in the 20th century that surface solar radiation (SSR) has undergone climatologically significant decadal variations. Several studies based on surface measurements reported a widespread decrease in SSR from the early 1960s to the late 1980s, described as 'global dimming', and no sign of further decrease since the late 1980s, and even an increase during the 1990s at many locations, described as 'global brightening' (Wild, 2009 and references therein). The global predominance of solar dimming and brightening, which is important because of the major role that SSR plays for heat, water and carbon balances, has been questioned (Alpert *et al.*, 2005) given that they were based on local surface measurements of SSR. The extension from the local scale to regional/global scales is only possible through satellite-based studies that provide adequate spatial coverage. Such studies (Hatzianastassiou *et al.*, 2005; Pinker *et al.*, 2005; Hinkelman *et al.*, 2009) provided evidence that indeed the dimming and brightening during the 1980s and 1990s, respectively, were global rather than local in nature.

The evolution of global dimming and brightening (GDB) has been investigated only through the first years beyond 2000, as part of longer term studies, based on surface measurements, and solely over specific regions mainly in North America, Europe and Asia (Ohmura, 2009). Recently, Wild *et al.* (2009) investigated variations in SSR for selected worldwide regions based on data records from global station networks such as GEBA (Global Energy Balance Archive), WRDC (World Radiation Data Center) and BSRN (Baseline Surface Radiation Network) for the period 2000–2005. Overall, they noted a less distinct and coherent brightening after 2000 compared with the 1990s. However, such conclusions are somewhat uncertain given their incomplete spatial coverage and the existence of opposite and possibly compensating tendencies over many regions. Hinkelman *et al.* (2009) using satellite data from the NASA/Global Energy and Water Cycle Experiment (GEWEX) Surface Radiation Budget (SRB) product, version 2.8, estimated a -0.53 W m^{-2} year^{-1} global dimming over 1999–2004, with similar features in both hemispheres and significant differences between land and ocean. However, the evolution of GDB has also to be determined at the smaller regional and local scales, by performing appropriate pixel-level analyses. Moreover, given that changing points in the evolution of GDB have been identified over the last two decades of the 20th century, namely around 1990 and 2000, it is necessary to further extend the temporal coverage of GDB studies beyond 2000. In addition, some light has to be shed on identifying the causes of recent GDB tendencies.

Here, we investigate the evolution of GDB for the period 2000–2007 using a spectral radiative transfer model (RTM) with input data from global satellite databases (International Satellite Cloud Climatology Project, ISCCP; Moderate Resolution Imaging Spectroradiometer, MODIS) and Reanalysis projects (National Center for Environmental Prediction/ National Centers for Atmospheric Research, NCEP/ NCAR), with the aim to provide local, regional and hemispherical aspects of the phenomenon. The quality of model estimates of monthly SSR is ensured through comparisons against surface-station measurements from the reference GEBA and BSRN networks, and in addition by comparison with other published works that mainly relied on measurements.

In the next section, the data and applied methodology are presented. The results are discussed in Section 3 and conclusions are drawn in Section 4.

2. Data and methodology

SSR fluxes were computed with a deterministic spectral RTM that was developed from a radiative-convective model (Vardavas and Taylor, 2007). In brief, the sky is divided into clear and cloudy (for low-, mid- and high-level clouds) fractions. The model input data include cloud amounts, cloud scattering/absorption optical depth, cloud-top pressure and temperature, cloud geometrical thickness (cloud data from ISCCP-D2, Rossow and Schiffer, 1999), aerosol optical properties (from MODIS-Terra C005 and the Global Aerosol Data Set) and vertical temperature and specific humidity profiles (from NCEP/NCAR global reanalysis project, Kistler *et al*., 2001). The model takes into account Rayleigh scattering due to atmospheric gas molecules, as well as absorption by O_3, CO_2, H_2O and CH_4. Total O_3 column abundance (in Dobson units), is taken from Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) archived in the ISCCP-D2 dataset. For CO_2 a fixed total atmospheric amount is taken, equal to 0.54 g cm^{-2}, corresponding to 345 parts per million by volume (ppmv). The water vapour data used are taken from the NCEP/NCAR Global Reanalysis Project. The mixing ratio of CH_4 is set equal to 1.774 ppmv, corresponding to 10^{-3} g cm^{-2}. The radiative transfer equations are solved for 118 separate wavelengths for the ultraviolet–visible part of the spectrum, and for ten bands for the near-infrared part, using the modified Delta-Eddington method of Joseph *et al*. (1976). The accuracy of the model 2.5° monthly SSR fluxes has been tested (Hatzianastassiou *et al*., 2005) against measurements from GEBA and BSRN, addressing issues of temporal and spatial resolutions and non-linearities. For a detailed model and data description the reader is referred to Hatzianastassiou *et al*. (2005, 2007) and Vardavas and Taylor (2007).

Although the temporal coverage of the study is for 7 years, from March 2000 to June 2007, specific emphasis was given to SSR changes (ΔSSR) for the period from January 2001 to December 2006, in order to ensure a complete annual coverage. Given the relatively short study period, involving possible influences from its initial or last few years, the robustness of the computed tendencies over 2001–2006 were evaluated by comparing them with ΔSSR either for the complete 7-year period or for other sub-periods, namely 2001–2005 and 2002–2006.

The RTM SSR fluxes were validated through comparisons against two major reference sources: the GEBA at ETH Zurich (Ohmura *et al*., 1989) and the BSRN (Ohmura *et al*., 1998) of the World Climate Research Programme (WCRP) Global Climate Observing System (GCOS). From the total number of GEBA and BSRN stations, in this study, we included only 91 GEBA and 14 BSRN stations, which have complete records from January 2001 to December 2006.

3. Results

Globally distributed changes or 'tendencies' of model SSR, based on linear regression fits applied to the time series of deseasonalized monthly SSR anomalies of each grid box, are presented in Figure 1. To date, this is the first time that SSR tendencies beyond 2000 are examined at the local (pixel-level) scale all over the globe. White-shaded areas correspond to cases for which model computations were not possible because of the lack of ISCCP or MODIS-Terra model input cloud and aerosol data. Aerosol data over bright surfaces like the Sahara desert are available from other databases, such as MODIS Deep Blue, but were not used here because they are not yet adequately validated. At first glance there is no uniform GDB pattern, but a rather mixed picture appears, with opposite SSR tendencies (solar brightening and dimming) in contiguous world regions, within the USA, Europe,

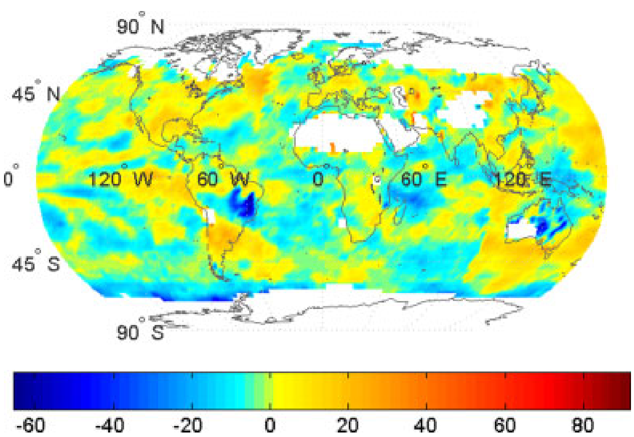

Figure 1. Tendencies of deseasonalized anomalies of model-computed monthly downward surface solar radiation (in W m^{-2}) over the period 2001–2006.

Africa, Asia, South America or the Atlantic and Pacific Oceans.

The regional patterns of SSR changes in Figure 1 are found to be in good agreement with similar trends indicated by surface measurements, reported by other recent works. For example, the solar brightening in Europe is in agreement with surface measurements (Ohmura, 2009; Wild *et al*., 2009) that indicate brightening in various European regions, including the Iberian (Sanchez-Lorenzo *et al*., 2009) and Greek (Zerefos *et al*., 2009) peninsulas. Therefore, there appears a post-2000 solar brightening in Europe that has succeeded a similar brightening during the 1990s (Wild *et al*., 2009), which is however opposite to the reported 1999–2004 dimming over Europe by Hinkelman *et al*. (2009). Nevertheless, note that some regions that are not covered by stations, but are included in this work, namely the southern Italian peninsula, the Mediterranean and Black Seas, exhibit a decreasing tendency in SSR. In North America, there is a clear brightening pattern, which is especially strong in the Great Plains, whereas solar dimming is limited to the western part (Sierra Nevada and Rocky Mountains), in agreement with station measurements from the Atmospheric Radiation Measurements (ARM), Surface Radiation (SURFRAD) and BSRN networks (Long *et al*., 2009; Wild *et al*., 2009). A clear solar dimming is found in central America, which is in agreement with the few stations measurements (e.g. Guadeloupe, Martinique, Trinidad and Tobago) given by Wild *et al*. (2009). There is also a strong SSR dimming over the large Lake Eyre Basin in Central Australia, in line with the increased cloud cover and flooding rains over the study period, in this usually desiccated region. In Asia, there are opposite SSR tendencies, with a uniform decrease over India except for the Gujara State in north-western India where there is an increase in SSR, as also suggested by surface measurements (Ohmura, 2009; Wild *et al*., 2009; Kumari and Goswami, 2010), and an increase over the largest part of China, North Korea, Vietnam, Laos, Thailand, Cambodia and the biggest part of Japan. However, SSR has decreased in north-east China and adjacent sea areas (Bohai, Yellow and Japan Seas) and also over Mongolia, in agreement with the findings of Wild *et al*. (2009) based on station measurements. Although recent tendencies in SSR for Africa are not reported in the literature, because of the lack of systematic radiation measurements, there is some brightening based on two station measurements in Zimbabwe (Ohmura, 2009) which is in line with Figure 1. Good agreement is also found between our model-based SSR tendencies and surface data for other regions, such as the brightening over New Zealand and Israel (Liley, 2009; Stanhill and Cohen, 2009).

The model's ability to reproduce the ground-based tendencies in SSR was assessed through comparisons of the model-computed SSR tendencies over 2001–2006 against the corresponding computed tendencies for selected GEBA and BSRN stations, distributed over all continents. The model and station SSR changes (Figure 2(a) and (b)) are in good agreement. Specifically, in 54 out of 91 GEBA stations, i.e. in 60%, the model reproduces the same tendencies of SSR with GEBA, which is quite satisfactory considering that the average over a cell of about 280×280 km^2 is compared to a site measurement and that SSR tendencies and not absolute amounts are compared. The model's good performance is also demonstrated by the computed correlation coefficients r (R^2) between model and GEBA time series of deseasonalized SSR anomalies, with 63 and 57 stations having r values larger than 0.6 and 0.65, respectively. Using higher quality data from 14 BSRN stations, the comparison is further improved since in only 1 (in Indonesia) out of the 14 stations there is a different SSR tendency, whereas in the rest there is agreement. In addition, the correlation coefficients between the model and BSRN station SSR time series exceed 0.94 for 10 out of 14 stations.

Tendencies of SSR beyond 2000 were examined also on the hemispheric scale, as well as over land and

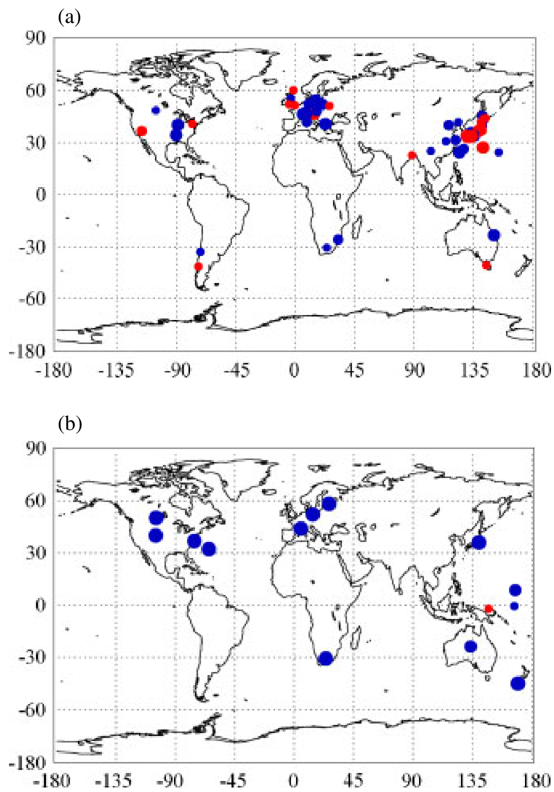

Figure 2. Comparison of model-computed tendencies of SSR against GEBA (a) and BSRN (b) station measurements. The global maps show the locations for which model computations and GEBA (a) and BSRN (b) station measurements indicate same (in blue colour) and opposite (in red colour) trends in surface solar radiation over the period 2001–2006. The size of the circles corresponds to cases for which correlation coefficients r between model-computed and ground-measured surface solar radiation fluxes are >0.9 (biggest circles), $0.9 > r > 0.8$, $0.8 > r > 0.7$ and $r < 0.7$ (smallest circles).

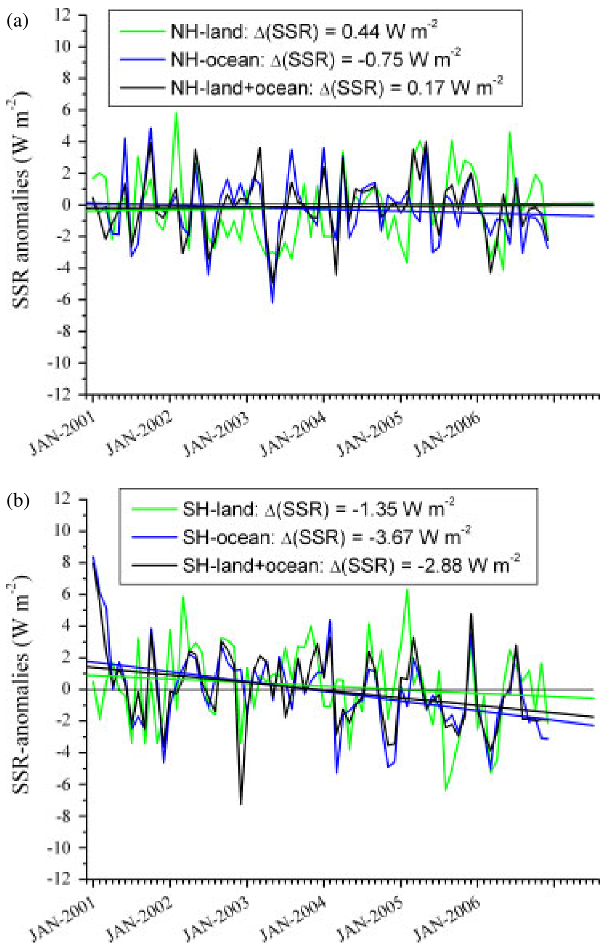

Figure 3. Time series of deseasonalized anomalies of monthly downward surface solar radiation (SSR) averaged over land (green lines), ocean (blue lines) and land + ocean (black lines) regions (also including coastal areas) of the Northern Hemisphere (a) and Southern Hemisphere (b), over the period 2001–2006. GDB magnitudes [Δ(SSR)] over the period 2001–2006 are also given.

ocean areas separately (Figure 3). The computations for the period 2001–2006, also compared for the sub-periods 2001–2005 and 2002–2006, are summarized in Table 1. The selection of these different time periods for the computation and comparison of SSR tendencies was made to ensure the robustness of the computed tendencies, given the relatively short time period covered. The tendencies agree in terms of their sign, but also of inter-hemispherical and land–ocean GDB differences, which strengthens the robustness of the conclusions on GDB. Therefore, the discussion is henceforth focused on the results for the period 2001–2006. In the Northern Hemisphere (NH) (including land, ocean and coastal areas), SSR has just slightly increased, by 0.17 W m^{-2} (or 0.028 W m^{-2} year^{-1}), while it has significantly decreased by 2.88 W m^{-2} (or 0.48 W m^{-2} year^{-1}) in the Southern Hemisphere (SH). Thus, it appears that there is an inter-hemispherical difference in GDB, consisting of a slight brightening in the NH against a stronger dimming in the SH. If averaged globally, they yield an overall dimming equivalent to −1.53 W m^{-2} (or −0.26 W m^{-2} year^{-1}). Hinkelman *et al.* (2009) reported a dimming in both hemispheres, of about −0.51 W m^{-2} year^{-1}. The differences with our results, especially in NH, may be attributed to their shorter time period (1999–2004), which starts and ends earlier than ours thus not including mostly positive SSR anomalies in the NH after 2004 (Figure 3(a)). In addition, the year 2000 is largely characterized by positive SSR anomalies which, if taken into account, result in a dimming of −0.39 W m^{-2} year^{-1} in NH over the period 2000–2007. The overall all-sky dimming beyond 2000 seems to mark a change in the GDB pattern at the dawn of the 21st century, since an overall brightening of 0.15–0.24 W m^{-2} year^{-1} occurred from the early 1980s to 2000 (Hatzianastassiou *et al.*, 2005; Pinker *et al.*, 2005; Wild *et al.*, 2005). Our separate analysis over land and oceans indicates the existence of opposite tendencies in SSR. Thus, SSR exhibits an increase (brightening) of 0.44 W m^{-2} (0.07 W m^{-2} year^{-1}) over NH-land, while over oceans it has decreased by 0.75 W m^{-2} (−0.125 W m^{-2} year^{-1}). The situation is different in the SH, where SSR has decreased over both land and oceans, but more over oceans (−3.67 W m^{-2} or −0.61 W m^{-2} year^{-1}) than land (−1.35 W m^{-2} or −0.225 W m^{-2} year^{-1}). Globally, SSR has decreased over land by 0.455 W m^{-2} (or −0.076 W m^{-2} year^{-1}), while over oceans it has decreased by 2.21 W m^{-2} (or −0.37 W m^{-2} year^{-1}). Note that from the above tendencies, only those for SH oceans and SH land plus oceans are statistically significant at the 95% confidence level.

Table 1. Tendencies of surface solar radiation (W m^{-2}) computed over the periods 2001–2006 (reference), 2001–2005, 2002–2006, and March 2000–February 2007.

	2001–2006	2002–2006	2001–2005	2000–2007
NH land	0.44	1.38	0.78	− 0.44
NH ocean	− 0.75	− 0.76	0.31	− 2.94
NH	0.17	0.05	1.42	− 2.73
SH land	− 1.35	**− 3.09**	− 0.71	**− 0.57**
SH ocean	**− 3.67**	**− 3.01**	**− 3.11**	**− 5.62**
SH	**− 2.88**	**− 2.29**	**− 2.09**	**− 3.38**

Results are given separately over land, ocean and land + ocean (including coastal areas, i.e. ISSCP pixels with both land and ocean). Bold numbers indicate statistically significant trends at the 95% confidence level. Yellow- and blue-coloured cells indicate same and opposite tendencies compared to the reference period (2001–2006).

The performed analysis (based on radiative transfer model computations) attributing the overall SSR changes to the various model input parameters which are relevant to solar radiation, revealed that primarily clouds, and secondarily aerosols, are responsible for the computed SSR tendencies. They clearly dominate the contributions of the rest of parameters, e.g. O_3 and H_2O, and thus only these two are discussed here. The model computations using Collection 005 MODIS-Terra data show that decreasing/increasing aerosol optical depth (AOD) values in the NH/SH by 0.0076 (−3.93%) and 0.0025 (2.02%), respectively, resulted in a brightening/dimming of 0.61 and −0.36 W m^{-2}, respectively, from 2001 to 2006. Changes in the other aerosol optical properties, namely single scattering albedo and asymmetry parameter, were too small (order of 0.1%), thus not affecting essentially the changes in SSR over 2001–2006. At the same time, the ISCCP data indicate an increase in cloud cover by 0.89 and 1.29% (absolute terms) in the NH and SH, resulting in a dimming of 1.22 and 2.98 W m^{-2}, respectively. Given that differences have been found between ISCCP cloud trends and others, such as advanced very high resolution radiometer, AVHRR-based pathfinder atmosphere, PATMOS-x (Cermak *et al.*, 2010), changes in cloudiness were also examined using data from the MODIS dataset. A similarity was found between cloud cover changes on the basis of ISCCP and MODIS data, in terms of regional patterns over the world. The worldwide changes of cloud cover from the two databases were found to be significantly correlated (*r* value of 0.65). Increasing cloud cover is also seen in MODIS data, albeit a bit of lower magnitude, especially in the SH. Given that changes in extraterrestrial solar radiation over 2001–2006 did not exceed 0.04 W m^{-2} on a hemispherical basis, clouds are thus found to be the primary contributor for the post-2000 SSR changes. Although clouds are known to be the greatest regulators of the earth's radiation budget, it is the first time that their primary role in modulating SSR in the 21st century is documented here, while it has certainly to be further investigated and continuously monitored. Nevertheless, the predominance of clouds is valid only on a global/hemispherical basis, but not always at the regional/local scale. Thus, aerosols can also be the main contributor to post-2000 GDB over specific world areas, such as the Amazonian basin, where increasing AOD up to 2006 (e.g. Koren *et al.*, 2007) produced a solar dimming (Figure 1). Aerosol changes can be also responsible for modifications of SSR over urban areas (e.g. Alpert *et al.*, 2005). The solar dimming in the Amazonian basin has occurred despite the decrease in total cloud cover (not shown here) as derived from ISCCP-D2 and MODIS data. Nevertheless, in most of the world regions the tendencies of cloud cover and SSR are in line, from a physical point of view, i.e. increasing/decreasing cloud cover has produced a solar dimming/brightening over the globe. This is in line with detailed sensitivity studies (e.g. Hatzianastassiou *et al.*, 2005) that have documented the strong dependence of SSR on cloud cover. In this study, the general solar brightening observed over Europe (Figure 1) is accompanied by a decrease in cloud cover there, by up to 5–10% in absolute terms. This is also the case in other world regions; for example, the dimming observed over India and northern Indian Ocean in Figure 1 is in line with an increase of cloud cover there. The computed correlation coefficient between the globally distributed changes of total cloud cover and SSR over the study period is equal to −0.45, indicating an anti-correlation between the two parameters.

4. Conclusions

Previous studies identified changing points in the evolution of GDB over the last two decades of 20th century, namely around 1990 and 2000. In this study, we updated GDB beyond 2000 by extending the time period into this century and obtained the analyses of SSR variations over various world regions, as well as at global/hemispherical/continental scales or station sites, also providing some insight into their possible causes. The SSR variations were obtained here all over the globe, for the first time at the local (pixel-level) scale, based on 2.5° × 2.5° analysis.

An overall global dimming (based on coastal, land and ocean pixels) is found to have taken place on the earth for all-sky conditions, from 2001 to 2006, arising from a stronger solar dimming in the SH (ΔSSR = −2.88 W m^{-2} or −0.48 W m^{-2} year^{-1}) and a slight brightening in NH (ΔSSR = 0.17 W m^{-2} or 0.028 W m^{-2} year^{-1}), thus exhibiting an inter-hemispherical difference. This inter-hemispherical difference in post-2000 GDB, which has not been reported in previous studies, translates to a substantial difference in the magnitude of the decreasing SSR tendencies over oceans, and even to a different sign of tendencies over land, with Δ(SSR) = −0.225 W m^{-2} year^{-1} (dimming) in the SH and Δ(SSR) = 0.07 W m^{-2} year^{-1} (brightening) in the NH. Moreover, the regional patterns have a remarkably patchy spatial structure, with opposite SSR tendencies in neighbouring areas, even within the same continents, as for example in Europe, USA, South America, Africa and Asia. The model-computed tendencies of SSR are supported to a large degree by surface-station measurements taken from the GEBA and BSRN networks, which strengthens the validity of the post-2000 GDB findings of this study.

Clouds appear to have been primarily responsible for GDB beyond 2000, with aerosols playing a secondary role on a hemispherical/global basis. Possible doubts on these findings related to possible inherent problems with the ISCCP cloud data are resolved by the similarity between the results obtained using ISCCP and MODIS cloud data (correlation coefficient equal to 0.85). Although there is some uncertainty of MODIS-Terra AOD trends over dark land surfaces, and MODIS radiometric shift issues around 2006 (Zhang and Reid, 2010), the use of MODIS-Aqua data and computed tendencies for 2001–2005 show that the main findings of this study, with respect to inter-hemispherical GDB patterns, remain unchanged.

Our findings on post-2000 GDB can have implications for evaporation and the hydrological cycle (e.g. Lau *et al.*, 2006; Wild *et al.*, 2008; Teuling *et al.*, 2009; Matsoukas *et al.*, 2011) as well as for global warming since it has been shown (Wild *et al.*, 2007) that solar dimming masked greenhouse warming up to the 1980s, while the subsequent brightening in the 1990s led to accelerated global warming. Therefore, the post-2000 dimming and associated inter-hemispherical differences, documented in this study, are expected to have similar effects that need to be systematically monitored and further investigated in the future.

Acknowledgements

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