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Latitudinal variations of cloud and aerosol optical thickness trends based on MODIS satellite data

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Received 16 November 2006; revised 18 November 2006; accepted 19 January 2007; published 8 March 2007.

[1] Moderate Resolution Imaging Spectroradiometer (MODIS) global monthly data from the Terra satellite (MOD08_M3, Collection 4, from March 2000 to May 2006) indicated, with the exception of the tropics, declining trends in aerosol optical thickness (AOD) over much of the globe, in contrast to slightly increasing trends in cloud optical thickness (COT) at many latitudes. In the tropics, increasing AOD trends coincide with increasing COT trends. In the latitudinal distribution of COT, in the Northern Hemisphere, a transition from increasing to declining tendencies was observed between 40°N and 60°N. There is a pronounced hemispheric asymmetry in latitudinal variations of the averaged total AOD, in contrast to those of the averaged total COT. **Citation:** Kishcha, P., B. Starobinets, and P. Alpert (2007), Latitudinal variations of cloud and aerosol optical thickness trends based on MODIS satellite data, *Geophys. Res. Lett.*, *34*, L05810, doi:10.1029/2006GL028796.

1. Introduction

[2] Analyses of worldwide-distributed surface observations, as well as satellite data, revealed solar dimming from the 1960s up to 1990, followed by solar brightening from 1990 onward [*Stanhill and Cohen*, 2001; *Liepert*, 2002; *Gilgen et al.*, 1998; *Wild et al.*, 2005; *Pinker et al.*, 2005]. A change from low-latitude brightening to mid-latitude dimming, based on surface observations from 1964 to 1989, was described by *Alpert et al.* [2005]. Brightening over tropical regions was also found by *Pinker et al.* [2005] by using satellite data from 1983 to 2002. As solar radiation trends have been shown to undergo decadal variations [*Wild et al.*, 2005], the aforementioned tendencies obtained by *Alpert et al.* [2005] and by *Pinker et al.* [2005] can not directly support each other. Nevertheless, the fact that the trends in the tropics differ from those at other latitudes indicates significant latitudinal variations in trends of the main modulators of surface solar radiation, such as cloud and aerosol optical thicknesses. The current study is aimed at analyzing these variations by using the Moderate Resolution Imaging Spectroradiometer (MODIS) data from the Terra satellite launched in December 1999. Level 3 MODIS gridded global monthly products (MOD08_M3), of horizontal resolution 1° × 1°, from March 2000 to May 2006, including cloud optical thickness (COT) combined phase and aerosol optical depth (AOD) at 0.55 microns were used in this study. Unlike ground-based data, satellite data can uniformly sample nearly the entire globe; this enables the comparison of atmospheric optical thickness trends at different latitudinal zones.

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0094-8276/07/2006GL028796$05.00

2. Methodology

[3] Level 3 MODIS global monthly AOD and COT daytime data (MOD08_M3) [*Remer et al.*, 2005; *Platnick et al.*, 2003; *King et al.*, 2003; R. C. Levy et al., The second-generation operational algorithm: Retrieval of aerosol properties over land from inversion of MODIS spectral reflectance, submitted to *Journal of Geophysical Research*, 2006] were acquired using the GES-DISC Interactive Online Visualization and Analysis Infrastructure (Giovanni) as part of the NASA's Goddard Earth Sciences (GES) Data and Information Services Center (DISC) (http://g0dup05u.ecs.nasa.gov/Giovanni).

[4] Our approach to the analysis of latitudinal distributions of aerosol and cloud optical properties was based on estimating their tendencies within partly overlapped 20-degree latitudinal intervals, from 70°S to 70°N, i.e. 70°S–50°S, 65°S–45°S, 60°S–40°S,…, 45°N–65°N, 50°N–70°N. The 75-month time series of zonal-averaged AOD and COT were obtained for each latitudinal interval. Tendencies were estimated for these time series after removing annual variations by the 13-month running mean filter. The linear fit was used to determine tendencies of the data. As an example, the time series of AOD and those of COT for the latitudinal interval 20°N–40°N are shown in Figure 1. The estimates of AOD/COT trends within partly overlapped 20-degree latitudinal intervals, obtained in accordance with the aforementioned approach, were assigned to the middle of corresponding intervals.

[5] Note that AOD is derived from 500 m pixels and COT from 1 km pixels. In a 1-degree box, MODIS has the opportunity to view aerosols even if there are plenty of clouds there. Therefore, aerosols can not be masked by clouds (L. Remer, personal communication, 2006).

[6] In addition to those tendencies, which we call absolute trends, the relative tendencies of AOD (COT) were obtained as well. The relative AOD (COT) trends are equal to the AOD (COT) absolute trends normalized on the averaged total AOD (COT). The 75-month time series of zonal-averaged AOD (COT) for each latitudinal interval were used in order to estimate the averaged total AOD (COT). The variations of those absolute and relative trends as a function of latitude provide a way of analyzing latitudinal variations of the tendencies in two main modulators of surface solar radiation.

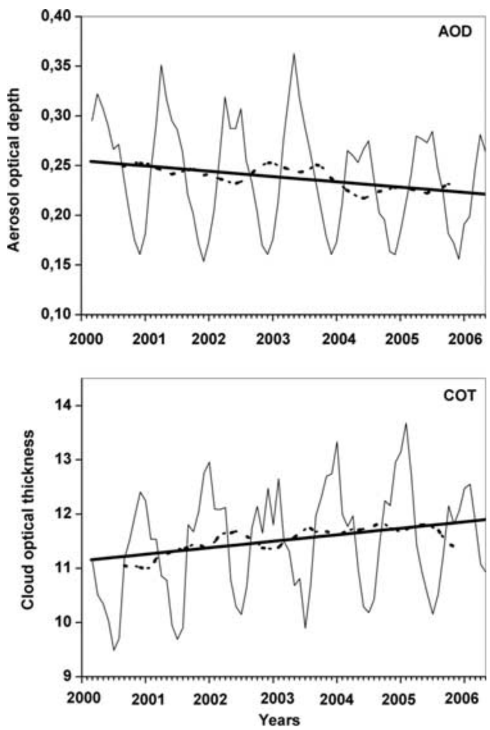

Figure 1. The time series of (top) aerosol optical depth and (bottom) cloud optical thickness combined phase, zonal averaged within the latitudinal interval from 20°N to 40°N. Each plot presents the original time series with annual variations (solid lines) and those after the removal of annual variations (dotted lines) together with their linear fit (straight lines).

[7] In this study, we place the emphasis on the differences in tendencies in aerosol-cloud optical thickness between various latitudinal zones, rather than on absolute values of trends, taking into account a relatively short period of available MODIS observations from March 2000 to May 2006.

3. Results

[8] In this section, an overview of latitudinal variations of the absolute trends is given first, followed by that of the averaged total AOD/COT and of the relative trends.

3.1. Absolute Trends

[9] Our findings highlight the fact that there is a pronounced asymmetry in COT and AOD absolute trends between the Northern and Southern Hemispheres (Figure 2): in particular, the asymmetry is an essential feature in COT latitudinal distributions, having transition from increasing to declining tendencies between 40°N to 60°N. As far as AOD is concerned, its decline in the Northern Hemisphere is almost twice as pronounced as that in the Southern Hemisphere, at corresponding latitudes.

[10] It is noteworthy that the decline in aerosol optical depth prevails in its latitudinal distribution (Figure 2, top plot). As for cloud optical thickness, however, the opposing (increasing) tendencies predominate in its latitudinal distribution (Figure 2, bottom plot). Moreover, there are two latitudinal zones where AOD tendencies coincide with the ones for COT. In particular, at latitudes between 50°N and 70°N, a decline is observed in AOD as well as in COT. In contrast, in the equatorial zone from 20°S to 10°N, increasing tendencies in both aerosol and cloud optical thicknesses are seen. Note that the AOD decline in mid-latitudes is much stronger than the increase in the equatorial zone.

[11] In the transition areas, where the AOD and COT trends change from negative to positive values or vise versa, as shown in Figure 2, a linear fit is not suitable for determining tendencies of the data. To be specific, in those areas we estimate and plot the resulting slopes, even though these slopes are not significant; i.e. their significance levels are too high.

3.2. Averaged Total AOD/COT

[12] There is a pronounced asymmetry in latitudinal variations of the averaged total AOD between the Northern and Southern Hemispheres, in contrast to those of the averaged COT (Figure 3). Specifically, the averaged AOD between 20°N–40°N is twice as much as that between 20°S–40°S. In the tropics, the averaged total AOD significantly increases northward, in contrast to the averaged total COT, which is quite symmetrical in both hemispheres and varies only slightly. The minimum of the averaged total AOD is located at 30°S and the maximum is located at 40°N. In the Northern Hemisphere, northward from 40°N, a negative correlation is observed between the averaged total cloud and aerosol optical thickness (Figure 3): the averaged total AOD decreases, while the averaged total COT

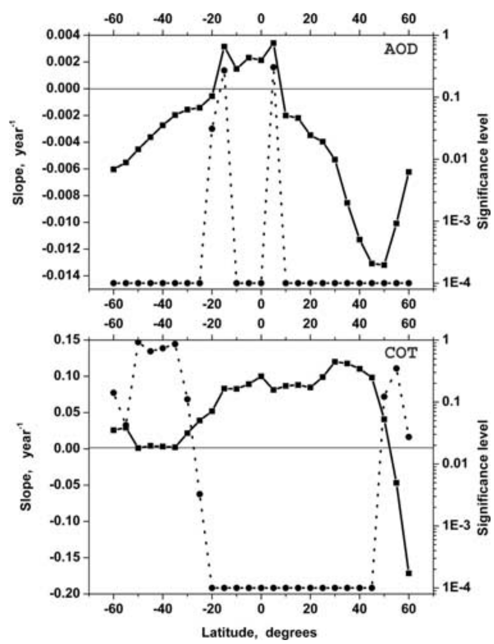

Figure 2. Latitudinal distributions of the absolute tendencies in (top) aerosol optical depth and (bottom) cloud optical thickness. Solid lines designate the tendencies, determined by the slope of linear fit. The significance levels of the derived tendencies are designated by dots. The horizontal lines correspond to a zero slope. The MODIS data (2000–2006) were used.

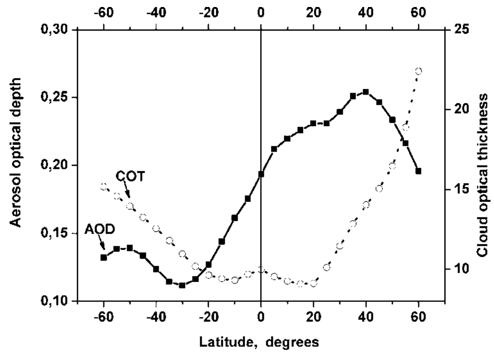

Figure 3. Latitudinal distributions of the averaged total AOD and COT. The lines with squares correspond to AOD, while the lines with open circles correspond to COT. The vertical line corresponds to the equator. The MODIS data (2000–2006) were used.

increases. However, in the Southern Hemisphere, southward from 40°S, one can see a positive correlation between the averaged total AOD and COT.

3.3. Relative Trends

[13] The relative trends provide us with an opportunity of quantitative comparisons between AOD and COT tendencies at different latitudes. In percentage terms, the COT relative trends vary only slightly (around 1% per year) between 20°S to 40°N (Figure 4). Note, however, that the aforementioned transition from increasing to declining tendencies, between 40°N and 60°N in the COT absolute trends, remains as the essential feature of the COT relative tendencies. The AOD relative trends vary more significantly with latitude (from −5.7% to 2.0% per year), compared to the COT relative trends. The decline in AOD relative trends also prevails in their latitudinal variations, as it does in the AOD absolute trends. However, the latitudinal variations of AOD relative trends are much more symmetrical than those of AOD absolute trends. The AOD relative trends highlight a pronounced difference between the tropics and the extra-tropics: AOD trends increase in the tropics in line with those in COT.

4. Conclusions

[14] Very little is known about the spatial and temporal patterns of COT and AOD. MODIS data (2000–2006) used in the current study provide us with some important results, which could be of interest in future studies.

[15] A general decrease in the AOD trends over much of the globe, with the exception of the tropics, was observed in contrast to slightly increasing COT trends (Figure 4). In the latitudinal distribution of COT, in the Northern Hemisphere, a transition from increasing to declining tendencies was observed between 40°N and 60°N. This transition is in line with the aforementioned mid-latitude brightening [*Wild et al.*, 2005; *Pinker et al.*, 2005]. Moreover, J. R. Norris and M. Wild (Trends in aerosol radiative effects over Europe inferred from observed cloud cover, solar "dimming" and solar "brightening," submitted to *Journal of Geophysical Research*, 2006) pointed to the declining tendencies in AOD over Europe and slightly increasing tendencies in cloud cover during the period 1987–2002, which only slightly overlaps with the MODIS data periods in consideration. However, *Weller and Gericke* [2005] detected some decrease in AOD from 1994 up to 2005, at monitoring stations across Germany from the Baltic Sea to the Alps, which corroborates declining AOD trends obtained in the current study. Furthermore, *Mishchenko et al.* [2007] also obtained statistically significant decrease in AOD between 1991 and 2005, by using global satellite data over the ocean.

[16] Our analysis highlights the fact that AOD and COT tendencies coincide only at two latitudinal zones: in the tropics and at mid-latitudes to the North from 50°N (Figure 4). A pronounced difference in AOD trends between the tropics and the extra-tropics is of importance, taking into account the fact that other studies [*Alpert et al.*, 2005; *Pinker et al.*, 2005] also obtained similar differences between the tropics and the extra-tropics (in surface solar radiation trends) during different periods. Moreover, the latest aerosol-climate model simulations of the surface solar radiation show increasing radiation trends over the extra-tropics and decreasing radiation trends over the tropics from 1990 to 2002 (M. Wild, personal communication, 2006); though the period only slightly coincides with the MODIS data periods in consideration. The ECHAM5-HAM model [*Stier et al.*, 2005], with all major aerosol components included, was used.

[17] The fact that both negative and positive correlations between AOD and COT trends were observed at different latitudes is noteworthy. It seems that not only aerosols but also some other meteorological factors could drive the clouds, such as sea surface temperatures, global warming of the atmosphere and climate responses, or pure natural variability. To define the role of each separate factor, further research is needed.

[18] As for the asymmetry in the averaged total AOD between the Northern and Southern Hemispheres (Figure 3), it seems reasonable to suggest the effect of several factors including anthropogenic effects, the water-to-land ratio and desert locations, as it is well known that their distributions are completely different in the two hemispheres.

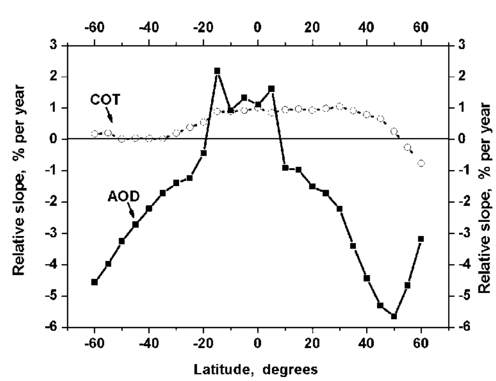

Figure 4. Latitudinal distributions of the relative AOD and COT tendencies. The lines with squares correspond to AOD, while the lines with open circles correspond to COT. The horizontal line corresponds to a zero slope. The MODIS data (2000–2006) were used.

[19] **Acknowledgments.** This study is dedicated to the memory of our colleague Yoram J. Kaufman. We gratefully acknowledge L. Remer, M. Wild, G. Feingold, M. King for helpful discussion and anonymous reviewers, whose helpful comments resulted in a much more complete final paper. We also acknowledge the GES-DISC Interactive Online Visualization and Analysis Infrastructure (Giovanni) as part of the NASA's Goddard Earth Sciences (GES) Data and Information Services Center (DISC) for providing MODIS data.

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