Long-term Trend of Aerosol Optical Thickness over the Western Pacific Ocean

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Abstract

To support the study of surface solar radiation (SSR) decadal variations over the West Pacific Ocean (WPO) region, nearly 23-years (1981-2004) of aerosol optical thickness (AOT) data from satellite AVHRR observations over ocean have been used to study the seasonal variations of the AOT and its linear long-term trend (LLT) in the same region. Seasonal variations of AOT and its LLT have been examined for both the zonal and regional mean. The AOT trends and their seasonal variations around the major coast metropolitan cities of East Asia are also analyzed. The contribution of the AOT and its long-term trend in the WPO to its global counterpart is also evaluated.

A positive trend with distinct seasonal variations is the basic pattern of AOT long-term change in the WPO regions due to enhanced anthropogenic emissions associated with the fast economic growth in Asia during the past three decades. This study indicates the aerosol enhancement due to anthropogenic activities in East Asia is not only limited in the locations near the emission sources but can propagate to distant downwind open oceans. This may produce noticeable reduction of SSR accordingly, especially in clear-sky conditions.

Key word: Aerosol, trend

1. Introduction

Atmospheric aerosols are one of the most important modulators of the solar radiation reaching the Earth's surface (called surface solar radiation (SSR) hereafter). There is increasing evidence that SSR has undergone climatologically significant decadal variations in many regions of the world, known as solar dimming-brightening phenomenon (Ohmura, 2009; Wild, 2009). The causes of the decadal variations in SSR observed in different regions of the world have been studied in relation to the long-term changes of its primary modulators, such as aerosols (e.g., Qian et al., 2007; Riihimaki et al., 2009). To support the study of the SSR decadal variations for the Western Pacific Ocean (WPO) region, we analyze, in this paper, the long-term trend of aerosol optical thickness (AOT) over the WPO using nearly 23-years of AOT product from operational AVHRR satellite observations. Seasonal variations in both AOT and in its long-term trends will be examined.

2. Satellite AVHRR AOT data

Aerosol optical thicknesses at 0.63μm and 0.83μm channels are derived over the global ocean by using the revised independent two-channel algorithm (Zhao et al., 2004) from reprocessed AVHRR radiances that have been inter-calibrated with MODIS radiances using the simultaneous nadir overpass (SNO) approach (Heidinger et al., 2002; Cao et al., 2004). The re-calibrated reflectances are provided by the AVHRR Pathfinder Atmosphere Extended (PATMOS-x) climate data set. The derived AOT data have nearly 23-years of temporal coverage from 1981-2004. The monthly averaged AOTs on an equal angle spatial grid of 1^ox1^o for global oceans are produced and will be used in the current study. A detailed description of this new AVHRR AOT product can be found in Zhao et al. (2008).

Due to the evident water vapor contamination on the AVHRR channel 2 (0.83μm), only AOT values from the AVHRR channel 1 (0.63μm), τ_1, will be used in the current study. Monthly and seasonally averaged AOT values are used since we focus on the analysis of long-term AOT trend and seasonal variations. We will confine our analysis to the longitude zone of 110^oE-180^oE in the West Pacific Ocean from 50^oS to 50^oN since AVHRR AOT retrievals can be problematic at high solar angles (especially for the winter months). This may result in poor data sampling in the monthly AOT averages at latitudes higher than 50^oS or 50^oN. 2.5-years of data after the major volcano eruptions of El Chichón in March 1982 and Mt. Pinatubo in June 1991 are discarded to remove the abrupt AOT perturbations.

3. Zonal AOT seasonal variations

Figure 1 displays annual and seasonal latitudinal-distribution of long-term averaged zonal mean AOT for the WPO. The data are binned in 5° latitudinal interval in the zonal averaging. Distinct seasonal variations are observed. AOT reaches maximum at northern middle and high latitudes in spring due to the contribution of Asian dust and industrial pollution. AOT also peaked at southern tropical latitudes due to the emission of biomass burning from Indonesia, especially in the peak burning season of fall. AOTs in the South Pacific Ocean have the highest values in winter (austral summer) but the absolute values are much lower than their counterparts in the North Pacific Ocean year-round.

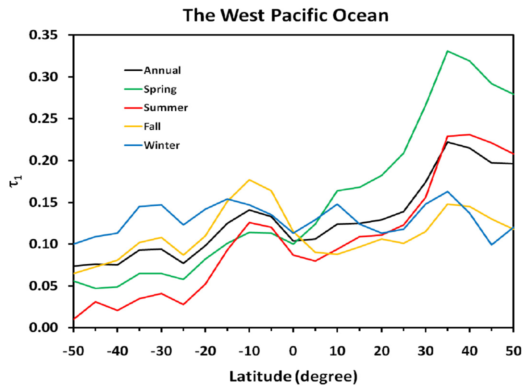

Figure 1. Annual and seasonal latitudinal-distribution for long-term averaged zonal-mean AOT.

4. Zonal AOT long-term trends

Corresponding to Figure 1, the significance of linear long-term trend (LLT) of zonal mean AOT is displayed in Figure 2. The significance of the AOT LLT is defined as LLT/σ, where σ is the standard deviation of the AOT LLT. A significance > +2 (or < -2) indicates the increasing (or decreasing) tendency is above the 5% significance level (or the 95% confidence level).

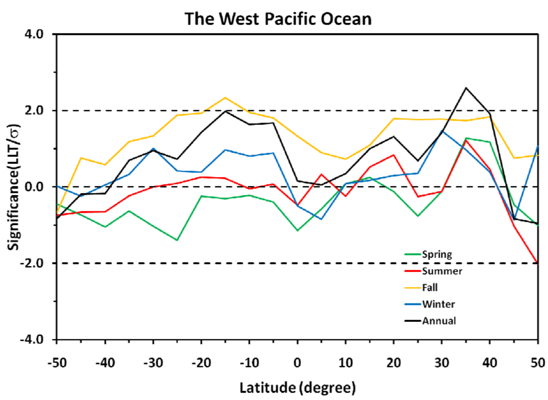

Figure 2. Annual and seasonal latitudinal-distribution for the significance (LLT/σ) of the LLT of zonal-mean AOT.

Aerosols at northern-hemisphere (NH) middle and high latitudes mainly come from the industrial pollution of China in all seasons, plus dust particles mainly in spring and summer. In the 30°N-40°N latitude belt, clear positive trends are detected in all seasons and the annual positive trend is above the 95% confidence level. In the 20°N-30°N latitude belt, a minor negative trend is detected in spring and summer. At the latitudes beyond 40°N, a more noticeable negative trend is detected in spring and summer. In the fall season, when the Asian dust storm activities reach their minimum, positive zonal trend prevails in the NH and the confidence of the trend almost reaches the 95% level at the middle latitudes. The seasonal variations of the AOT zonal trend in different NH latitude belts are probably due to the competitive contributions from the trend of the industrial pollution and the dust particles in different seasons. A monotonic positive zonal trend is detected only in the fall season when the dust contribution is absent. As a result, an annual SSR reduction is anticipated. In fact, Norris and Wild (2009) found solar dimming for both time periods from 1971-1989 and 1990-2002 in the Aug-Sep-Oct season in China from the surface SSR measurements. For the other three seasons (May-Jun-Jul, Nov-Dec-Jan, Feb-Mar-Apr), solar dimming is observed for the first period but solar brightening for the second period.

The fall season NH positive trend also extends to southern-hemisphere (SH), especially at the SH subtropical latitudes where the confidence of the trend is above the 95% level due to enhanced bio-mass burning and industrial emissions from Indonesia. Thus, SSR reduction is anticipated accordingly. In spring (or austral fall), bio-mass burning and industrial emissions reach their minimum and marine aerosols are dominant at the SH subtropical latitudes. The zonal AOT trend tends to be negative but generally below the 95% confidence level. In summer and winter, marine aerosols and aerosols originating from bio-mass burning emissions and industrial pollution are mixed together at the SH subtropical latitudes. The AOT zonal trend is variable and generally below the 95% confidence level.

5. Global contribution

To examine the contribution of AOT in the West Pacific Ocean to its global counterpart, we compare in Figure 3 the latitudinal distribution of monthly mean AOT, zonally averaged in the West Pacific Ocean (110°E-180°E) to other four longitude zones: longitudes 180°W-180°E of the global ocean, 60°W-20°E in the Atlantic Ocean, 40°E-110°E in the Indian Ocean, and 100°W-180°W in the East Pacific Ocean. These longitude zones are influenced by aerosols originating from different natural and anthropogenic sources (Kishch et al., 2009).

It is seen that the AOT zonal distributions in these four longitude zones basically determine the latitudinal features of zonal mean AOT over the global ocean. The contribution from the West Pacific Ocean is dominant in three latitude belts: 30°N-45°N, 5°S-15°S, and 25°S-45°S. The aerosols in the first latitude belt originate mainly from Asian dust and industrial pollution; aerosols in the second latitude belt mainly come from the biomass burning emission and industrial pollution from Indonesia;

aerosols in the last latitude belt are wind-driven sea-salt particles mixed with continental aerosols originating from Australia and New Zealand.

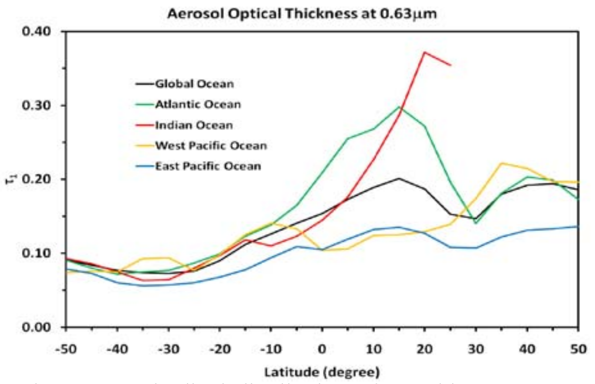

Figure 3. Latitudinal distribution of monthly mean AOT, zonally averaged over longitudes 180°W-180°E of the global ocean, 60°W-20°E in the Atlantic Ocean, 40°E-110°E in the Indian Ocean, 110°E-180°E in the West Pacific Ocean, and 100°W-180°W in the East Pacific Ocean.

6. AOT Trends in Coast Areas

The annual and seasonal AOT LLT for the East Coast of China and South China Sea are examined in Figure 4. Seasonal variation in the AOT LLT is evident in these two coastal regions and a positive trend is a general tendency for the coast AOT in the past three decades due to the off-shore transport of enhanced industrial emissions due to economic growth in China. The trend is most evident in fall season (the relatively clean season) and can be easily above the 95% confidence level (LLT/$\sigma > 2$).

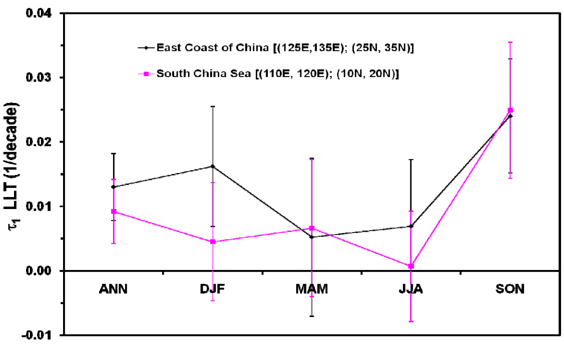

Figure 4. Annual and seasonal AOT LLT for two selected coastal regions. Vertical bars are $\pm 1\sigma$ error.

Annual and seasonal AOT LLT for the surrounding water areas of 5 metropolitan cities (Tianjin, Qingdao, Shanghai, Hong Kong, and Taipei) with populations of more than 6 million are plotted in Figure 5. The values are for the box area of ±5° latitude and longitude around the cities. Positive trends are detected for almost all seasons in these cities except in spring for Taipei when a minor negative trend is observed but with confidence below the 95% level (LLT/$\sigma \sim -0.15$). For the two northern cities (Tianjin and Qingdao), the maximum positive trend occurs in summer and the minimum positive trend occurs in winter. For the left three southern cities, the maximum trend occurs in fall and the minimum trend occurs in spring. This different seasonal pattern between the northern and southern cities is probably due to the different contribution of dust particles (relative to pollution aerosols) in the northern and southern parts of China.

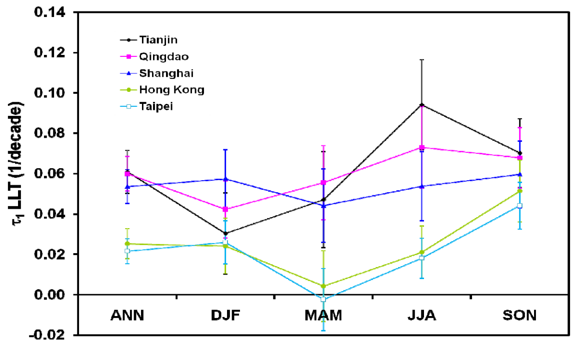

Figure 5. Annual and seasonal AOT LLT for the box area of ±5° latitude and longitude around the five metropolitan cities over the coast of East Asia. Vertical bars are $\pm 1\sigma$ error.

7. Summary and conclusions

Nearly 23-years of aerosol optical thickness data from AVHRR satellite observations over the ocean have been used to study the seasonal variations of the AOT and its linear long-term trend over the West Pacific Ocean in order to support the study of the SSR decadal variations in the same region. The positive LLT of zonal mean AOT with a confidence of about 95% is detected in the latitude belt and season without influence by the Asian dust but influenced by industrial pollution from China or by the bio-mass burning and industrial pollution from Indonesia. For the latitude belt and seasons under the influence of both Asian dust and industrial pollution, the trend is variable but can be significant sometimes.

Our analyses indicate that the WPC AOT contribution to its global counterpart is mainly in three latitude belts. One is at northern middle-latitudes where Asian dust and industrial pollution are dominant. Second is at southern tropical latitudes where aerosols mainly come from the biomass burning emissions and industrial pollution from the Indonesian islands. The last is at southern middle-latitudes where aerosols are composed of wind-driven sea-salt and continental aerosols originating from Australia and New Zealand.

AOT LLT analyses for the coastal regions and the surrounding areas of major coast metropolitan cities reveal a general positive trend with distinct seasonal variations. The positive trend is most evident in the fall season and can easily reach 95% confidence level for broad coastal regions. For the oceans surrounding the major coast metropolitan cities, the seasonal pattern is influenced by the different contribution of dust particles (relative to pollution aerosols) in the northern and southern parts of China. For the northern cities heavily influenced by the Asian dust, the maximum positive trend occurs in summer and the minimum positive trend occurs in winter. For the southern cities with minor influence of dust particles, the maximum trend occurs in fall and the minimum trend occurs in spring.

Our study indicates the aerosol enhancement due to anthropogenic activities in the East Asia are not only limited in the locations near the emission sources but can propagate to the distant downwind WPO. This may produce a noticeable reduction of SSR accordingly, especially in clear-sky conditions. On the other hand, more rigid emission regulations will reduce the anthropogenic aerosol loading not just near the emission areas, but also in the downwind open oceanic regions.

Acknowledgement

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References

Cao, C., M. Weinreb, and H. Xu, 2004: Predicting Simultaneous Nadir Overpasses among polar-orbiting meteorological satellites for the intersatellite calibration of radiometers, *J. Atmos. Oceanic Tech.,* 21, 537-542.

Kishcha, P., B. Starobinets, O. Kalashnikova, C. N. Long, and P. Alpert, 2009: Variations of meridional aerosol distribution and solar dimming, *J. Geophys. Res.*, 114, D00D14, doi:10.1029/2008JD010975.

Heidinger, A. K., C. Cao, and J. Sullivan, 2002: Using Moderate Resolution Imaging Spectrometer (MODIS) to calibrate Advanced Very High Resolution Radiometer (AVHRR) reflectance channels, *J. Geophys. Res.*, 107 (D23), 4702, doi: 10.1029/2001JD002035.

Norris, J. R., and M. Wild, 2009: Trend in aerosol radiative effects over China and Japan inferred from observed cloud cover, solar “dimming” and solar “brightening”, *J. Geophys. Res.*, 114, D00D15, doi:10.1029/2008JD011378.

Ohmura, A., 2009: Observed decadal variations in surface solar radiation and their causes, *J. Geophys. Res.*, 114, D00D05, doi:10.1029/2008JD011290.

Qian, Y., W. Wang, L. R. Leung, and D. P. Kaiser, 2007: Variability of solar radiation under cloud-free skies in China: The role of aerosols, *Geophys. Res. Lett.*, 34, L12804, doi:10.1029/2006GL028800.

Riihimaki, L. D., F. E. Vignola, and C. N. Long, 2009: Analyzing the contribution of aerosols to an observed increase in direct normal irradiance in Oregon, *J. Geophys. Res.*, 114, D00D02, doi:10.1029/2008JD010970.

Wild, M., 2009: Global dimming and brightening: A review, *J. Geophys. Res.*, 114, D00D16, doi:10.1029/2008JD011470.

Zhao, X., O. Dubovik, A. Smirnov, B. N. Holben, J. Sapper, C. Pietras, K. J. Voss, and R. Frouin, 2004: Regional evaluation of an advanced very high resolution radiometer (AVHRR) two-channel aerosol retrieval algorithm, *J. Geophys. Res.*, 109, D02204, doi:10.1029/2003JD003817.

Zhao, T. X.-P., I. Laszlo, W. Guo, A. Heidinger, C. Cao, A. Jelenak, D. Tarpley, and J. Sullivan, 2008: Study of long-term trend in aerosol optical thickness observed from operational AVHRR satellite instrument, *J. Geophys. Res.*, 113, D07201, doi:10.1029/2007JD009061.