Can aerosol loading explain the solar dimming over the Tibetan Plateau?

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[1] Solar radiation over the Tibetan Plateau has declined over recent three decades, whereas total cloud cover has a decreasing trend. A likely explanation to this paradox is the increase in aerosols over this clean region. However, this study shows that the radiation extinction due to aerosol loading is of one order lower in magnitude than the observed dimming, and the solar dimming is also seen in a satellite product that was produced without considering temporal variations of aerosols. Instead, the inter-annual variability and decadal change in solar radiation is contrasting to that in water vapor amount and deep cloud cover (but not total cloud cover). Therefore, we suggest that the solar dimming over the Plateau is mainly due to the increase in water vapor amount and deep cloud cover, which in turn are related to the rapid warming and the increase in convective available potential energy. **Citation:** Yang, K., B. Ding, J. Qin, W. Tang, N. Lu, and C. Lin (2012), Can aerosol loading explain the solar dimming over the Tibetan Plateau?, *Geophys. Res. Lett.*, *39*, L20710, doi:10.1029/2012GL053733.

1. Introduction

[2] Solar radiation is the dominant energy to drive the glacier melting over the Tibetan Plateau (TP). Because of low water vapor content, air mass, and aerosol concentration, the TP surface receives stronger solar radiation than its surroundings. However, the solar radiation over the TP experienced a transition from brightening to dimming around the end of the 1970s [*Tang et al.*, 2011], which is different from the widely reported transition from dimming to brightening around 1990 in China [*Che et al.*, 2005] and in the world [e.g., *Stanhill and Cohen*, 2001; *Liepert*, 2002; *Pinker et al.*, 2005]. Aerosol optical depth (AOD) change has been suggested to play a role in the radiation change over China [e.g., *Kaiser and Qian*, 2002; *Wang et al.*, 2012], India [e.g., *Ramanathan and Ramana*, 2005; *Soni et al.*, 2012], Europe [e.g., *Norris and Wild*, 2007], and other regions [e.g. *Ohmura*, 2009; *Wild*, 2012]. However, the situation over the TP is somehow unique. On one hand, this region is one of the cleanest regions in the world. A recent measured baseline AOD at 500 nm is only 0.029 at an AERONET station in central TP. Thus, *Tang et al.* [2011] speculated that the solar dimming over the TP may be caused by cloud change. On the other hand, total cloud cover (TCC) at China Meteorological Administration (CMA) stations shows an overall decreasing trend [*Xia*, 2010], whereas recent studies [*Xu et al.*, 2009; *Lu et al.*, 2012] suggested an increase in black carbon (BC) on the TP. The TOMS (Total Ozone Mapping Spectrometer) aerosol index also shows a slightly increasing trend since 1978 over the Plateau [*Yi and Zhou*, 2011]. Therefore, it is likely that the increase in aerosols may explain the paradox between the dimming and TCC decreasing. Indeed, *You et al.* [2012] suggested "transient aerosol emissions as a plausible cause" for the solar dimming. Nevertheless, a physical quantification was not given by either *Tang et al.* [2011] or *You et al.* [2012].

[3] As aerosol change over the TP and its surroundings has become a focus in terms of its hydrological effects [*Xu et al.*, 2009; *Qian et al.*, 2011], it is critical to clarify the role of aerosol loading in the dimming. In this study, we show that the solar dimming is mainly caused by the increase in water vapor amount and deep cloud cover but not aerosol loading.

2. Data

[4] The data sets of concern are the observations at 78 CMA weather stations and 10 IGRA (Integrated Global Radiosonde Archive) [*Durre et al.*, 2006] radiosonde stations on the TP (see Figure S1 in the auxiliary material for the distribution of the stations), the ERA-40 monthly-mean analysis data, and the International Satellite Cloud Climatology Project-Flux Data (ISCCP-FD).[1] The CMA data provided observed sunshine duration, air temperature, humidity, total cloud cover (TCC), low cloud cover (LCC), and visibility. The solar radiation was estimated from the sunshine data using the model developed by *Yang et al.* [2006]. The IGRA data was used to calculate convective available potential energy (CAPE) and convective inhibition energy (CIN). The ERA-40 analysis [*Uppala et al.*, 2005] provides the variation of precipitable water. The ISCCP-FD was produced from the ISCCP D1 data [*Zhang et al.*, 2004], and it provides cloud cover and surface radiation budget from satellite observations.

3. Results and Discussion

3.1. The Paradox Between Solar Dimming and Cloud Cover Change

[5] Figure 1 shows the temporal variations of annual mean sunshine duration, solar radiation, and TCC during

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL053733.

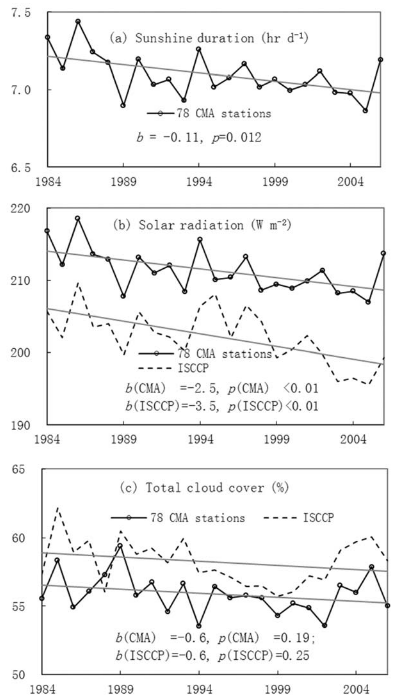

Figure 1. Temporal variation of station-averaged annual mean (a) sunshine duration, (b) solar radiation, and (c) TCC over the TP for the period of 1984–2006. *b* is the slope (given by unit per decade) of the line trend of each time series and *p* is the significance level.

1984–2006 when the solar dimming occurred over the TP. ISCCP-FD radiation and cloud are plotted to compare with the CMA data. The trend slopes shown in Figures 1a and 1b indicate that the CMA-observed sunshine duration and solar radiation have a decreasing trend over this period. ISCCP solar radiation values differ from the CMA observation by several W m^{-2}, but it shows a decreasing trend similar to the observed one. In both data sets, the magnitude of the solar dimming over the summer is larger by a factor of 2∼3 times than the one over the other seasons (not shown). By contrast, both datasets give a negative trend in TCC, although not very significant. Therefore, there is a paradox between the observed solar dimming and the TCC decreasing.

3.2. The Effect of Aerosol Loading

[6] In light of the paradox between the solar dimming and the TCC decreasing, the increase in aerosol loading is suggested to be a cause for the solar dimming over China [*Kaiser and Qian*, 2002]. *You et al.* [2012] drew a similar conclusion for the TP case. The following gives a quantitative analysis to show how much this effect could be.

[7] The aerosol measurements are very sparse for the TP regions. *Xia et al.* [2011] show that the AOD at a Tibet site (Nam Co, 30.773°N, 90.962°E, 4730 m ASL) had an evident seasonal change, higher in spring (0.07) and lower in other seasons (0.025–0.05), with annual mean value of 0.046. The decadal change in AOD over the TP is much less than over other regions of China during last 30 years [*Guo et al.*, 2011], and it is not expected that the annual mean AOD over the TP would have changed by more than 10% or 0.005. This small change may be further supported by the visibility observations at the CMA stations, which shows an upward trend over the Tibet, in contrast to a downward trend over South China (Figure 2a). As visibility is negatively correlated with tropospheric AOD [*Kaiser and Qian*, 2002; *Wang et al.*, 2009], the visibility trend does not support a significant increase in AOD over the TP.

[8] To quantify the aerosol effect on the solar dimming, we used an approximate relation between AOD and its extinction on solar radiation, after *Yang et al.* [2006]:

$$E_a \approx \gamma(1 - \tau_a), \tag{1}$$

$$\tau_a = \exp\left\{-m\,\beta\left[0.6777 + 0.1464\,(m\,\beta) - 0.00626\,(m\,\beta)^2\right]^{-\alpha}\right\}, \tag{2}$$

$$\beta = \delta(\lambda)\lambda^{\alpha}, \tag{3}$$

where E_a is the radiation extinction rate, τ_a the transmittance due to aerosol scattering, γ the ratio of aerosol backscattering to total scattering, m the air mass, β the Ångström turbidity coefficient, α the Ångström exponent, and $\delta(\lambda)$ the AOD at wavelength $\lambda(\mu\text{m})$.

[9] The observed α is 0.62 at Nam Co site [*Xia et al.*, 2011]. Generally, γ is less than 0.5, because the aerosol backscattering is less than the forward scattering. Given $\alpha = 0.62$, $\gamma = 0.5$, $\lambda = 0.5$ μm and $m = 1$, equations (1)–(3) yield the radiation extinction due to AOD scattering (Figure 2b). If AOD over the TP changes by 10% (according to the preceding evidence), the radiation extinction changes by 1 W m^{-2}. This is equivalent to a radiation extinction of 0.38 W m^{-2} $decade^{-1}$. Therefore, the dimming due to the direct effect of aerosol loading is not comparable to the observed one (2.5 W m^{-2} $decade^{-1}$). The indirect effect of aerosol loading is neither significant, as suggested by the small difference (0.13 W m^{-2} $decade^{-1}$ over 1960–2005) between clear-sky radiation trend and all-sky radiation trend in ECAHM-HAM simulations [see *You et al.*, 2012, Table 4].

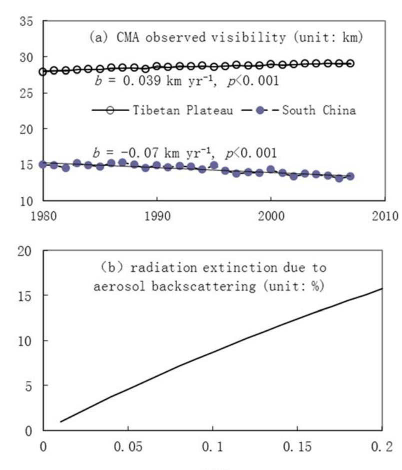

Figure 2. (a) Temporal variation of station-averaged annual mean visibility over the TP. The case for South China is plotted as a reference (*b* is the slope of the line trend of each time series and *p* is the significance level). (b) Change of solar radiation extinction with respect to AOD values.

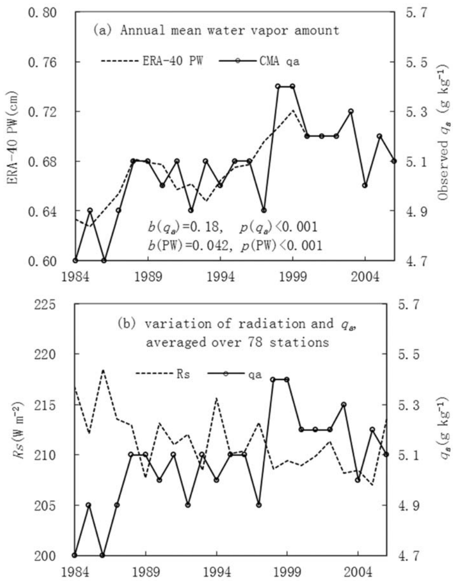

Figure 3. (a) Temporal variation of annual mean station-observed specific humidity (q_a) and ERA-40 precipitable water (PW) over the TP (b is the line trend slope given by unit per decade and p is the significance level). (b) Contrast variations of observed solar radiation (Rs) and specific humidity (q_a) over the TP.

[10] This minor effect of aerosols may be further confirmed by ISCCP-FD. The latter approximately reproduced the observed dimming over this period (Figure 1b), but it did not consider decadal change of aerosols for its radiation calculation. This further suggests that the AOD change did not play a major role in the solar dimming over the TP and that *You et al.* [2012] may have over-emphasized the effect of aerosol loading. Their major evidence is the significant decrease in the clear-sky solar radiation derived from the CMA coarse-resolution (6-hr) data. However, this derivation can be risky, as the Plateau is often covered by rapidly changing clouds. Another evidence to support their conclusion is that the ECHAM5-HAM simulation with increasing AOD reproduced the solar dimming. We noted that the annual mean AOD in the simulation increases by 0.07 over 1960–2005 [*You et al.*, 2012, Figure 7], which even exceeds current AOD level (0.046) observed at the Tibet site (Nam Co), so the model may have overestimated the aerosol effect on solar radiation.

3.3. The Effect of Water Vapor

[11] Figure 3a shows both the station data and ERA-40 give a significant moistening process ($p < 0.001$) over the TP since the 1980s. The increase of specific humidity (q_a) averaged over the CMA stations increased by 0.18 g kg^{-1} or 3.5% decade^{-1}. This increase is related to the Plateau surface warming (0.48°Cdecade^{-1} during the study period) by a ratio of 7.3%/°C, which is consistent with the Clausius-Clapeyron relation. The correlation coefficient between the q_a and the ERA-40 precipitable water (PW) is as high as 0.95, and therefore, ERA-40 PW is used to quantify the water vapor effect on solar radiation.

[12] Figure 3b shows that the radiation is highly and negatively correlated with water vapor observed at the stations, indicating that water vapor is a substantial controlling factor to the solar radiation variability. This control lies in a direct effect and an indirect effect. The direct effect is its absorption to solar radiation. In ERA-40, PW increased by about 0.1 cm or less over the dimming period; in response, solar dimming due to its absorption is about 1 Wm^{-2} or less, which is much lower than the observed one ($\sim$6 Wm^{-2}). The indirect effect is water vapor-cloud interaction, i.e., more water vapor is favorable to generating more or stronger clouds and thus less radiation. This is associated with the discussion below.

3.4. Increase in Deep Cloud Cover and Its Cause

[13] As the aerosol extinction and the vapor absorption are not sufficient to explain the observed dimming, we investigated the role of cloud change in the solar dimming. At CMA stations, both TCC and LCC were observed, and LCC was determined according to cloud base. Many low clouds over the TP may develop into deep clouds, due to low air density and strong surface heating. To some degree, deep cloud cover (DCC) change may be indicated by LCC change in CMA data.

[14] In ISCCP, the daytime cloud types are classified according to cloud top pressure: LCC is for below 680 hPa, MCC (middle cloud cover) is for 440–680 hPa, and HCC (high cloud cover) is for above 440 hPa surface [see *Rossow and Schiffer*, 1999, Figure 2]. Because the TP region is so high that low clouds (Types 1–6) are seldom seen in the ISCCP and middle clouds (Types 7–12) represent shallow clouds. Cloud Types 13–15 are cirrus, cirrostratus and deep convection, respectively. The DCC in this data is equal to the cloud cover of Type 15.

[15] Both the CMA and ISCCP cloud data contain uncertainties, because multi-layer clouds develop well over the TP for its strong thermal forcing. A ground observer has difficulty to see some cirrus clouds. Satellites may have difficulty in detecting both high clouds (i.e., cirrus, for its limitation of measurement channels) and low clouds (for viewing angle) in this low latitude region. Other issues (insufficient contrast between small-scale cumulus and surface radiance, overlap of clouds and snow/ice etc.) also add uncertainties in satellite observations [*Ackerman et al.*, 1998]. In order to reduce uncertainties in the cloud analysis, we used both surface and satellite observations.

[16] Figure 4 shows the temporal variations of the radiation and DCC in CMA and ISCCP. The radiation and DCC have contrasted inter-annual variability. Actually, the radiation is more correlated with DCC than with TCC in both CMA and ISCCP data (Table 1), indicating that the importance of cloud type in determining solar radiation and its trend, as also suggested by *Padma Kumari and Goswami* [2010]. The DCC exhibits an upward trend while the solar radiation exhibits a negative trend. This clearly indicates that the DCC decadal change is a critical factor to control the solar dimming over the TP.

[17] Besides, we found that the inter-annual variability of cirrostratus cover (ISCCP type 14) is significantly correlated with the ISCCP radiation ($p < 0.05$), but their decadal changes are different: the cirrostratus cover has no trend during the summer (JJA) while the solar dimming is most prominent in this season. Other cloud covers do not show significant correlations with solar radiation at either seasonal or annual scales over the Plateau.

[18] We further investigated the cause of the DCC changes by means of CAPE and CIN, following previous studies

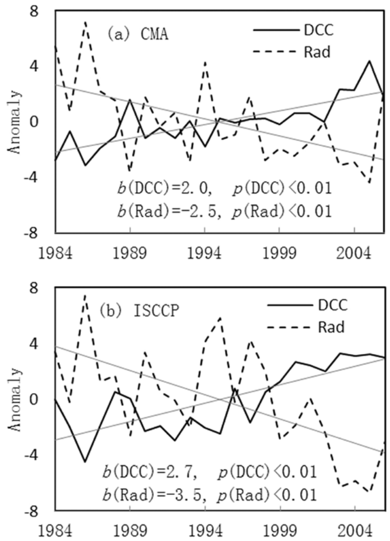

Figure 4. Contrast variations of anomalies of annual mean radiation (W m^{-2}) and DCC index (%) in (a) CMA and (b) ISCCP, after averaged over 78 TP stations. *b* is the slope (given by unit per decade) of the line trend and *p* is the significance level.

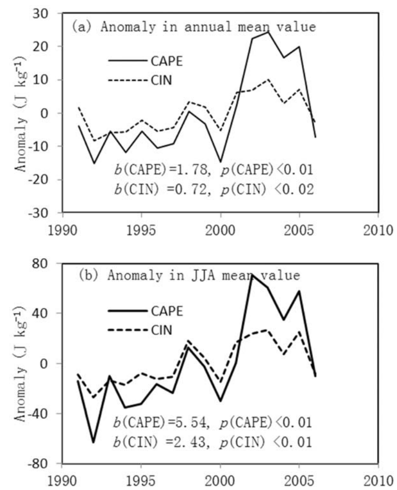

Figure 5. Anomaly in CAPE and CIN calculated from 00UTC and 12UTC radiosonde data and then averaged over the 10 IGRA stations on the TP (a) for annual mean and (b) for JJA mean; *b* is the slope (given J kg^{-1} yr^{-1}) of the line trend and *p* is the significance level. IGRA data on the TP are missing between 1984∼1991 and thus not shown. Note CIN values are negative and thus the positive trend in CIN indicates the convective inhibition becomes weakening.

[*Mani et al.*, 2009; *Goswami et al.*, 2010]. CAPE is an indicator of atmospheric instability, and CIN is an opposite indicator. CAPE takes positive values and CIN takes negative values. As shown in Figure 5a, both annual mean CAPE and CIN calculated from radiosonde data show positive trends over the Plateau, indicating that CAPE became stronger and CIN became weaker during the study period. This condition is favorable to triggering more deep convection over the Plateau. The positive trends are more prominent in the summer, corresponding to a rapid increase in summertime DCC (not shown). We noted a high correlation (R = 0.78) between specific humidity and DCC in the summer (not shown), suggesting that the increase in CAPE and CIN may be related to the warming and moistening.

4. Concluding Remarks

[19] The TP has experienced solar dimming for the past three decades, and the dimming is particular outstanding in summer. In this study, we found that TCC has decreased and is not able to explain the solar dimming. The aerosol loading over the TP is neither substantial in terms of its effect on solar dimming, although considerable increases in black carbon have been found in previous studies. Instead, we showed that the solar dimming over the TP is mainly due to the increase in water vapor amount and DCC, which may be further attributed to the surface warming and the increase in CAPE. As deep convection over the TP can effectively transport water vapor from the troposphere into the stratosphere [*Fu et al.*, 2006], it would be interesting to investigate how the increases in deep convection and water vapor over the TP may influence the troposphere-stratosphere exchange.

Table 1. Correlation Coefficient Between Annual Mean Solar Radiation (Rad) and Cloud Cover (TCC, DCC) in CMA and ISCCP Data Sets for the Period of 1984–2006

	CMA	ISCCP
R(Rad,TCC)	−0.47	−0.27
R(Rad,DCC)	−0.77	−0.79

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