



**Strong diurnal
aerosol changes alter
DARF regionally**

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Diurnal aerosol variations do affect daily averaged radiative forcing under heavy aerosol loading observed in Hefei, China

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Abstract

Strong diurnal variation of aerosol has been observed in many heavy polluted regions in China. This variation could alter the distribution of the direct aerosol radiative forcing (DARF) during the whole daytime that could increase the uncertainty of the normally used averaged values. To quantify the effect of using the daily averaged DARF, 196 days of high temporal resolution ground-based data collected in SKYNET Hefei site during the period from 2007 to 2013 is used to perform an assessment. We demonstrate that strong diurnal changes of heavy aerosol loading have an impact on the 24 h averaged DARF when daily averaged optical properties are used to retrieve this quantity. Though there is a high temporal sampling of aerosol properties to be used for calculation of daily averaged ones, statistical errors (up to 5.3 Wm^{-2} absolutely and 14.6% relatively) in the computed DARF still occur. These errors increase with increasing daily aerosol optical depth (AOD) is also found which indicated the high temporal resolution DARF dataset should be used in the model instead of the normal daily-averaged one, especially under heavy aerosol loading condition.

1 Introduction

The direct aerosol radiative effect (DARF) is defined as the change in radiative flux caused by the combined scattering and absorption of radiation by variety of aerosols. The DARF results from well-understood physics and is close to being an observable quantity regionally, which requires daily estimates of aerosol optical properties (AOP), such as aerosol optical depth (AOD), single-scattering albedo (SSA), and asymmetry factor (ASY). These AOP could be obtained from surface observations, such as the Aerosol Robotic Network (AERONET) (Holben et al., 1998), Sky Radiometer Network (SKYNET) (Nakajima et al., 2003), China Aerosol Remote Sensing Network (CARSNET) (Che et al., 2009) and so on. In the report of IPCC (2013), the scientific understanding of DARF has been designated as “High”. However, DARF can reach

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screening using the algorithm of Khatri et al. (2009), the spectral values of AOD (τ), SSA (ω) and ASY (g) are determined during the period from 2007 to 2013. There are 196 completely cloud free days with high temporal measurements and retrievals, which is the dataset used in this study. The derived aerosol properties (τ, ω, g) are used as key input parameters to calculate surface solar radiations based on the Santa Barbara Discrete-ordinate Atmospheric Radiative Transfer (SBDART) model (Ricchiazzi et al., 1998), which was verified with surface broadband spectrum irradiance observations (Halthore et al., 2005). The complementary parameters (columnar water vapor content, total ozone amount, and spectral surface albedo) used to run the model are retrieved from the surface microwave radiometer (Model WVR-1100, Radiometrics Corporation, USA) (Westwater et al., 1978; Ulaby et al., 1986), the Ozone Monitoring Instrument (OMI) datasets (Stajner et al., 2008), and the Moderate Resolution Imaging Spectroradiometer (MODIS) products (Schaaf et al., 2011), respectively.

To estimate the sensitivity of 24 h averaged DARF to the diurnal changes of aerosol optical properties, we use two ways to calculate it. We perform the DARF (named, F) at the surface (named, SFC) calculations with different conditions about the daily AOP (τ, ω, g) variation: (1) diurnally varying AOP according to entire time-dependent observations, AOP = actually changes of AOP, (2) no diurnally AOP variation but measurement-based, AOP = corresponding daily averaged AOP. Then we use these two sets of the AOP (the original high temporal resolution data set, which covers the complete diurnal variation, plus the additional synthetic set) and the other complementary parameters as input for the SBDART model to calculate the diurnal changes of the DARF (named, F_{org} related to instantaneous data set and F_{ave} related to synthetic data set). These DARF values at the surface are given in half an hour segments, from which we calculate the corresponding 24 h averaged DARF ($\langle F \rangle$). Thus, we obtain two sets of values of $\langle F \rangle$, which represent radiative forcings obtained from the original and daily averaged AOP. Furthermore, the absolute and relative errors of 24 h averaged DARF will be found as δF (i.e., $\langle F_{\text{ave}} \rangle - \langle F_{\text{org}} \rangle$) and $\delta F / \langle F_{\text{org}} \rangle$, respectively. These errors are

used to assess quantitatively the changes of daily averaged radiative forcing due to diurnal variation of aerosol.

3 Results and discussion

We applied our method to two typical kinds of cloud free cases observed at the SKYNET Hefei site on 14 April 2013 (CASE-I) and 12 February 2008 (CASE-II). The first case is a light polluted day, when diurnal changes of aerosol loading are moderate ranging from -12 to 19% on AOD as shown in Fig. 1. The daily averaged AOD value of CASE-I is 0.57 with a maximum 0.68 and a minimum 0.50 . On the contrary, the SSA and ASY are not changing so much with 0.90 (varying from 0.88 to 0.96) and 0.69 (varying from 0.67 to 0.71) on average, respectively. Thus, we will strongly consider AOD variability in the following discussions.

Using the original and daily averaged AOP for CASE-I as input parameter, the corresponding instantaneous DARF values are calculated with large differences as indicated in Fig. 2. For example, large overestimation (23 W m^{-2} in absolute value and 21% in relative value) at $10:00 \text{ GMT} + 8$ and large underestimation (15 W m^{-2} in absolute value and 20% in relative value) at $16:00$ of instantaneous DARF (F_{ave} vs. F_{org}) are produced by AOD variability. It is noted that this overestimation/underestimation of instantaneous DARF may be compensated partially by each other when using for estimating 24 h averaged F . The 24 h average F values are -38.1 W m^{-2} ($\langle F_{\text{ave}} \rangle$) and -42.2 W m^{-2} ($\langle F_{\text{org}} \rangle$) with the absolute (4.1 W m^{-2}) and relative (9.7%) biases are shown as well in the sub-figure of Fig. 2. As a result of CASE-I, the impact of the daily averaged aerosol properties on the 24 h average DARF may not negligible after integration of instantaneous DARF values over all daytime hours.

Note that we don't have AOP measurements to cover low solar zenith angles for calculation of F_{org} , where real measured flux (with aerosol) and calculated flux (without aerosol) are used to fill up data before the sunrise and after the sunset. Figure 3 has performed excellent shortwave radiative closure experiment using the accurate input

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parameters from SKYNET AOP measurements and high precision surface radiation fluxes by Kipp & Zonen CM21.

Another case is chosen during a high polluted day, when diurnal changes of aerosol loading are large ranging from -18 to 32% on AOD as shown in Fig. 4. And the daily averaged AOD value of CASE-II is 1.08, which is almost two times of CASE-I with a maximum 1.43 and a minimum 0.89. At the meanwhile, the SSA and ASY are 0.96 (varying from 0.94 to 0.97) and 0.69 (varying from 0.68 to 0.72) on average, respectively, with a slight changing as CASE-I. So, we will also consider AOD variability only. Figure 5 shows the corresponding instantaneous DARF values using the original and daily averaged AOP in Fig. 4, which also produces large biases. The largest overestimation part of instantaneous DARF (F_{ave} vs. F_{org}) is 24 W m^{-2} in absolute value and 17% in relative value and the largest underestimation counterpart is 16 W m^{-2} in absolute value and 15% in relative value due to AOD variability. But the 24 h average F values are -41.9 W m^{-2} ($\langle F_{ave} \rangle$) and -57.5 W m^{-2} ($\langle F_{org} \rangle$) with the absolute (15.6 W m^{-2}) and relative (27.1%) biases, which are larger than those in CASE-II.

Figure 6 shows a comparison between the SBDART simulated and the measured fluxes of downward shortwave radiations at the surface in Hefei site on 12 February 2008, which indicates a good agreement with a high correlation coefficient 99.45% . So, we can use measured data to fill up F_{org} values, which also be examined in Fig. 3.

Thus, an important result related to aerosol loading issue can be drawn from the two cases. The strong diurnal changes of heavy aerosol loading in SKYNET Hefei site have a considerable impact on the 24 h averaged F value when daily averaged AOP is used to retrieve this quantity.

Let us consider the impact of daily averaged AOD on F value for all selected 196 days, where high temporal resolution AOD is obtained throughout the day. Figure 7 shows the frequency distributions of daily mean AOD at 500 nm, the corresponding absolute and relative biases for 24 h average F calculation in SKYNET Hefei site from 2007 to 2013. From these 196 cloud free days, the aerosol loading covers clean clear day and heavy polluted day with daily averaged AOD ranging from 0.14 to 1.88.

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Large day-to-day variability of AOD is also found from Fig. 7a with an averaged AOD 0.63 ± 0.29 except for the large diurnal difference discussed before. As a sequence, the absolute and relative biases for 24 h average F calculation are $5.3 \pm 4.4 \text{ W m}^{-2}$ (varying from -0.7 to 23.4 W m^{-2}) and $14.6 \pm 9.7 \%$ (varying from 0.5 to 34.6%), respectively.

That means the overall impact is significant and cannot be neglected for all days considered here, instead of opposite findings for regions, where the observed conditions (AOD less than 0.4) are prevalent from other study (Kassianov et al., 2013).

The relationship between DARF at SFC and AOD is examined and high correlation (0.82 and 0.79) has been found between AOD and 24 h average F_{ave} and F_{org} , respectively. At the same time, there is an increase trend of absolute biases (δF) for 24 h average F calculation with increasing daily mean AOD (τ) at 500 nm, and a large scattering in data points is responded to high AOD as well (Fig. 8). The phenomena in Fig. 6 indicate as follows: (1) the AOD with strong diurnal variation is more contributed to the corresponding 24 h averaged F than SSA and ASY with weak temporal changes, (2) the well-established fact that the instantaneous DARF at SFC is linearly proportional to AOD (McComiskey et al., 2008) is partly related to the high polluted area (Li et al., 2010), (3) the extremely high biases for 24 h averaged F are produced by strong diurnal variation of AOD and/or high aerosol loading. Because the observed conditions mentioned in this study are prevalent in many climatologically important regions with heavy aerosol loadings frequently, such as Xianghe (Li et al., 2007), Taihu (Xia et al., 2007), and Beijing (Che et al., 2014), the daily average radiative forcing calculation requires not only daily averaged optical properties, but also diurnal changes of them. Thus, observation-based long-term high temporal aerosol data must be considered over aiming to accurate radiative transfer calculations in high pollution region.

4 Summary

We assess the impact of the strong diurnal changes of aerosol on the 24 h average DARF at the surface using ground-based sky-radiometer data collected with high tem-

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poral resolution in SKYNET Hefei site, China, during 196 cloud free days from 2007 to 2013. The assessment evaluates the temporal variability of AOP, such as AOD, SSA, and ASY, and estimates the importance of this variability in determining DARF averaged over 24 h. To perform such assessment, we retrieve observed high temporal resolution optical properties and their daily averaged ones as input for the SBDART model, and we then compare the 24 h average DARF calculated for these inputs.

The impact of the daily averaged aerosol properties on the 24 h average DARF can up 15.6 W m^{-2} absolutely and 27.1 % relatively for cases, which may not negligible. The strong diurnal changes of heavy aerosol loading in SKYNET Hefei site appear frequently, we require paying a considerable attention to the impact on the 24 h averaged F value calculation when using daily averaged AOP.

Using all selected 196 days' dataset, there is an increase trend of absolute biases for 24 h average F calculation with increasing daily mean AOD at 500 nm. The statistical absolute and relative biases for 24 h average F calculation are $5.3 \pm 4.4 \text{ W m}^{-2}$ and $14.6 \pm 9.7 \%$, respectively. Thus, care must be given when aiming to accurate radiative transfer calculations in high pollution region based on measured-retrieved long-term high temporal aerosol data.

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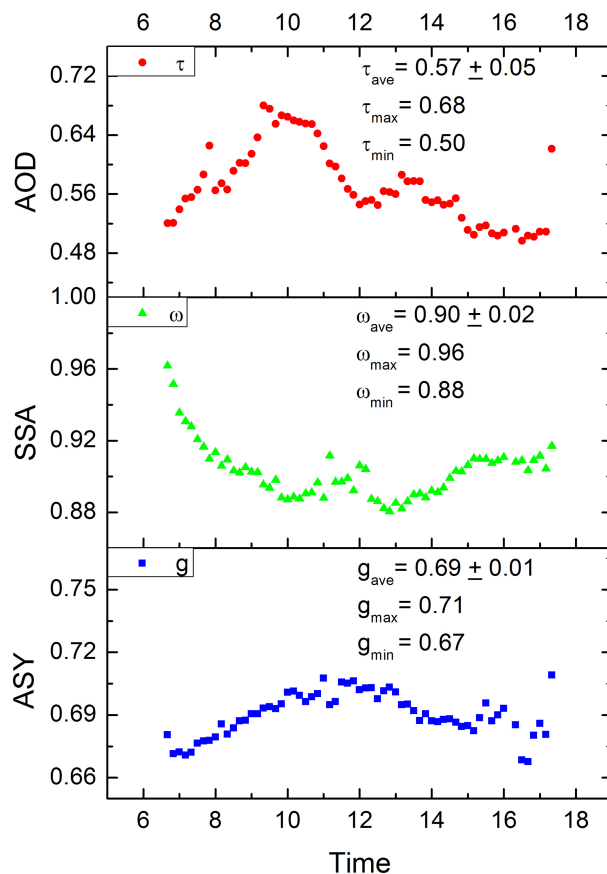


Figure 1. Daily variations of retrieved 500 nm AOD (red), SSA (green) and ASY (blue) on 14 April 2013. This represents a typical light polluted case (mean AOD of 0.57) with moderate diurnal changes of AOP.

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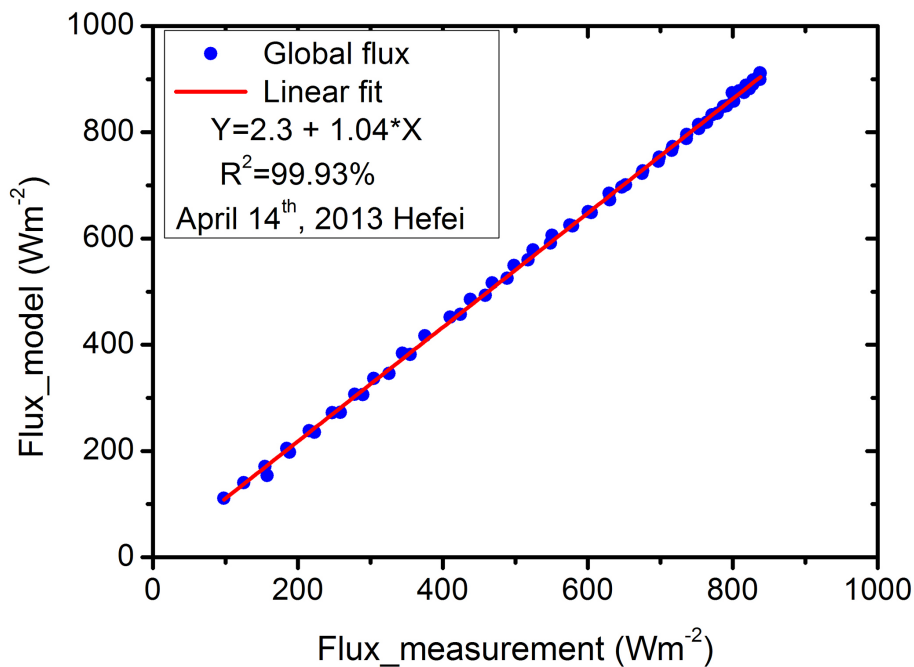


Figure 3. Comparisons between the SBDART simulated and the measured fluxes of downward shortwave radiations at the surface in Hefei site on 14 April 2013.

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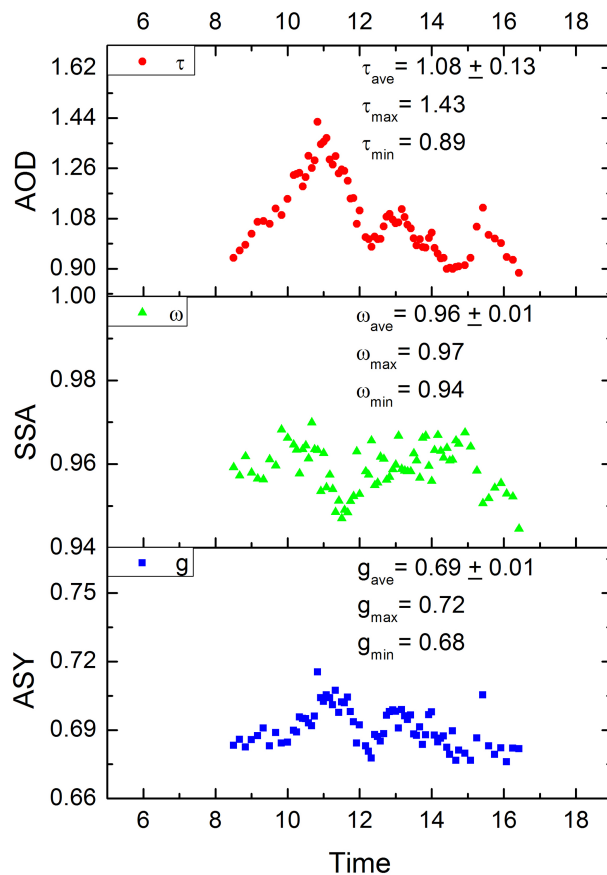


Figure 4. The same as Fig. 1 but for a day with large diurnal changes of aerosol loading under high polluted (AOD equals to 1.08 in average) weather condition on 12 February 2008.

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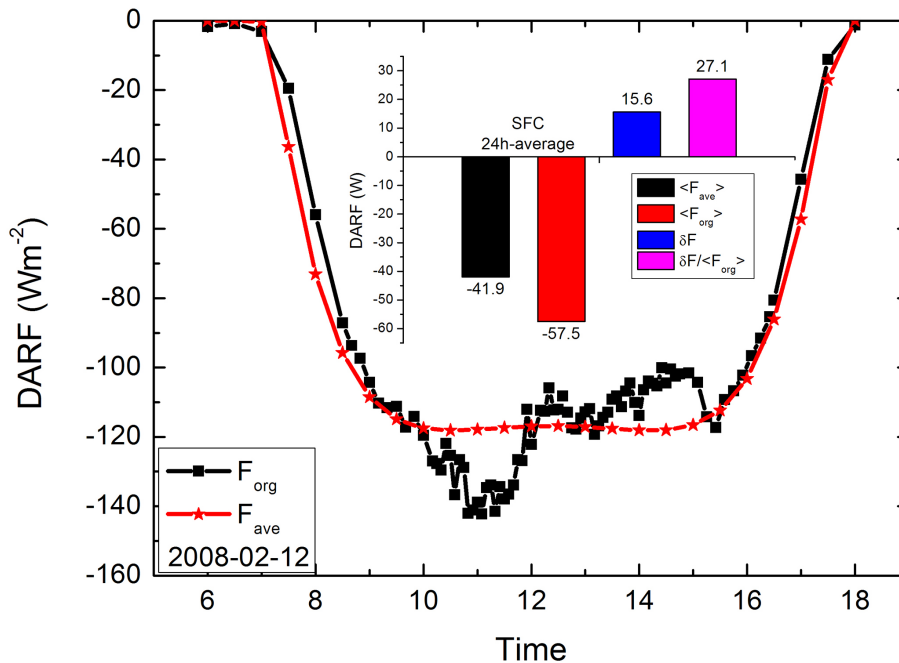


Figure 5. The same as Fig. 2 but using the AOP in Fig. 4.

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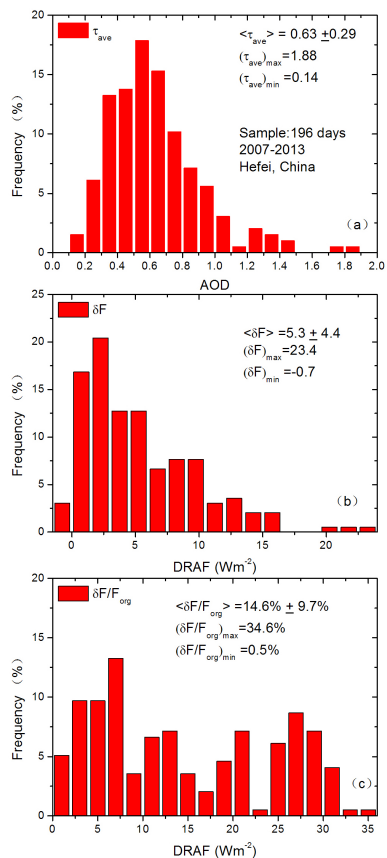


Figure 7. The frequency distributions of τ_{ave} , δF , and $\delta F / F_{\text{org}}$ selected in SKYNET Hefei site from 2007 to 2013.

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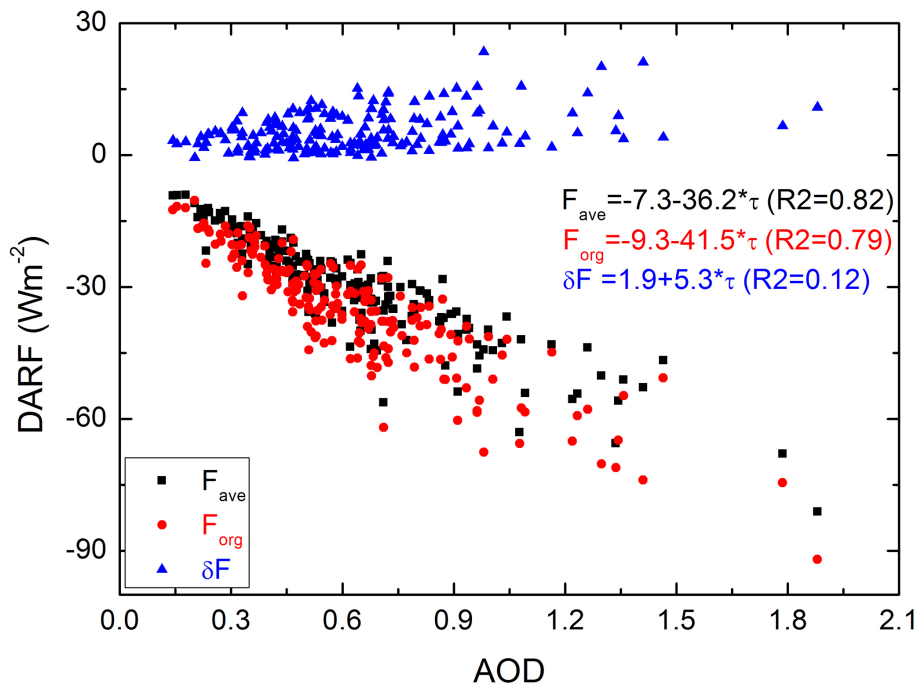


Figure 8. Correlations between aerosol forcing at the surface and AOD (F_{ave} : black; F_{org} : red; δF : blue) with linear fitting equations.

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