Effects of Aerosols on the Surface Solar Radiation at the CWB Tainan Station

Ming–Dah Chou, Po–Hsiung Lin, Po–Lun Ma
Department of Atmospheric Sciences,
National Taiwan University

Ho–Jiunn Lin
Research Center for Environmental Changes
Academia Sinica

Abstract

Surface radiation measurements at an urban site in southern Taiwan during the dry winter season, December 2003-March 2004, are used to investigate the aerosol properties and the effects of aerosols on the surface solar radiation in clear skies. The AERONET–retrieved monthly mean aerosol optical thickness at 0.5 m ranges from 0.52 to 1.18 with a mean of 0.73 for the four winter months. The single–scattering albedo and asymmetry factor remain nearly constant with a mean of ~0.95 for the former and ~0.70 for the latter. Thus, the air of Tainan during the winter is highly polluted, and the aerosols are moderately absorbing. A new approach is developed to estimate the effect of aerosols on the surface radiation from surface observations. The relationship between the surface radiation and the aerosol optical thickness is established for narrow intervals of the solar zenith angle by regression of the atmospheric path transmission against the aerosol optical path. Based on the relationship, the effect of aerosols on the surface radiation and the sensitivity of surface radiation to the aerosol optical thickness are computed. For the four–month average, the effect of aerosols is to reduce the incident surface solar radiation by ~39 Wm^{-2}, and the sensitivity of the surface radiation to aerosols is a reduction of ~53 Wm^{-2} per unit increase of the aerosol optical thickness. These results are in good agreement with radiative transfer model calculations.

Key word: Aerosol, surface observation, surface radiative forcing, surface radiative sensitivity.

1. Introduction

Aerosol optical properties and their impact on the solar heating can be derived from radiation measurements at the surface. The multi–channel and multi–angle radiance measurements from the surface, such as the measurements using Cimel sunphotometers of the AERONET project [*Holben et al.*, 1998], can provide information on the absorption and scattering of solar radiation by aerosols. To reliably estimate the impact of aerosols on surface radiation, it requires co–located broadband solar radiation measurements with aerosol measurements. There are not many sites around the world with co–located aerosol and broadband solar radiation measurements, and there are only a few studies in recent years addressing the aerosol radiative effect at the surface using both sets of surface measurements. *Jayaraman et al.* [1998] derived the sensitivity of surface solar radiation to the aerosol optical thickness using simultaneous measurements of aerosol optical thickness, size distribution, and incoming solar radiation. The measurements were conducted in January–February 1996 during a cruise over the Arabian Sea and the Indian Ocean. *Podgorny et al.* [2000] validated the model–calculated surface radiation with that observed on the island of Kaashidhoo (4.97N, 73.47E). Aerosol chemical, microphysical, and optical properties, as well as radiative fluxes were measured during February and March of 1998 as part of the first phase of the INDOEX [*Ramanathan et al.*, 1996] field experiment. They found that aerosols over tropical Indian Ocean have a large impact on the clear–sky radiation budget of the atmosphere and the surface.

In this study, we investigate the impact of aerosols on the surface radiation using simultaneous measurements of aerosol optical properties and surface radiation in the city of Tainan on the southwest coast of Taiwan. We also examine in detail the sensitivity of the surface radiation to the aerosol optical thickness as a function of the solar zenith angle. The monthly mean sensitivity of the surface flux to the aerosol optical thickness and the impact of aerosols on the surface radiation are then calculated. Finally, the results derived from measurements are compared with calculations using a radiative transfer model. Details of our study are published in Chou et al. (2006).

2. Surface Observations

To investigate processes of the production and transport of ozone and aerosols in Taiwan, the Research Center for Environmental Changes (RCEC), Academia Sinica, has conducted a set of radiation measurements at the regional weather station of the Taiwanese Central Weather Bureau in Tainan. The measurements include the total solar flux (0.296 μm-3.0 μm) using Eppley Precision Spectral Pyranometers (PSP) and the radiances in seven spectral channels ranging from 0.34 μm to 1.02 μm using Cimel sunphotometers. The Cimel measures the direct solar radiation at a 15-min resolution and the sky radiation at a 1–hr resolution. As part of the AERONET project, data measured by the Cimel are sent to US NASA/Goddard Space Flight Center for the retrievals of aerosol optical thickness, single–scattering albedo, and asymmetry factor [*Dubovik et al.*, 2000]. When the sky is clear (cloud–free), the aerosol optical thickness is retrieved at a resolution of 15 min, and the single–scattering albedo and asymmetry factor are retrieved at a resolution of 1 hr. The data used in this study cover four months from December 2003 to March 2004.

Table 1 shows the mean aerosol optical thickness, τ, single-scattering albedo, ω_o, and asymmetry factor, g, as well as the range of these parameters within the individual months of December 2003-March 2004. The air of Tainan in the winter is highly polluted. The monthly mean aerosol optical thickness at 0.5 μm increases from 0.52 in December 2003 to 1.18 in March 2004 with a mean of 0.73 for the four winter months. The monthly mean single–scattering albedo and asymmetry factor remain nearly constant at ~0.95 and ~0.70, respectively. Thus, the aerosols are moderately absorbing.

Table 1. Aerosol optical thickness, τ, single–scattering albedo ω_o, asymmetry factor, g, retrieved from Cimel radiance measurements.

Month	Days[a]	τ	$\Delta\tau$[b]	ω_o	$\Delta\omega_o$[b]	g	Δg[b]
Dec. 2003	9	0.52	0.38–0.93	0.963	0.94–0.98	0.685	0.68–0.73
Jan. 2004	14	0.51	0.32–0.81	0.958	0.94–0.98	0.700	0.69–0.72
Feb. 2004	9	0.72	0.30–0.78	0.946	0.92–0.97	0.696	0.65–0.73
March 2004	19	1.18	0.31–2.01	0.941	0.92–0.96	0.695	0.68–0.72
Mean		0.73		0.952		0.694	

[a] Number of days when all the three aerosol parameters are retrieved at least twice a day.

[b] Delta denotes the range of the aerosol optical properties within a month.

The surface radiation measured by the PSP, F_{obs}^{total}, during the four months is shown in Table 2. The incoming solar radiation at the top of the atmosphere and the atmospheric transmission function are also shown in the table. For the four months, the solar radiation incident at the surface is half of the insolation at the top of the atmosphere, and the mean atmospheric transmission is 0.5. The 50% extinction of the solar radiation is due to the absorption and scattering by aerosols, clouds, and atmospheric gases, such as water vapor and ozone. If we assume the surface albedo is 0.2, then the surface absorbs about 40% of the incoming solar radiation at the top of the atmosphere.

Table 2. Mean incoming solar radiation at the top of the atmosphere, $\overline{\mu_o S_o}$, the downward surface solar radiation measured by PSP, F_{obs}^{total}, and the atmospheric transmission, T_{atm}.

Month	$\overline{\mu_o S_o}$	F_{obs}^{total}	T_{atm}
Dec. 2003	273.7	150.2	0.549
Jan. 2004	287.5	146.1	0.508
Feb. 2004	336.6	163.3	0.485
March 2004	390.2	184.6	0.473
Mean	322.0	161.0	0.500

[a] Here, μ_o is the cosine of the solar zenith angle and S_o is the extraterrestrial solar radiation. Units of fluxes are W m^{-2}.

3. Radiative Transfer Model Calculations

The aerosol radiative effect is also investigated with calculations using the radiative transfer model of *Chou and Lee* [1996] and *Chou and Suarez* [1999]. The model includes the absorption by ozone, water vapor, oxygen and CO_2, as well as the absorption and scattering by clouds, aerosols, and molecules (Rayleigh scattering).

There are no atmospheric soundings at the Tainan site, but at the Central Weather Bureau's Ping–Dong station 60 km south of Tainan there are radiosondings twice a day at 6:00 am and 6:00 pm LT. We use monthly mean temperature and humidity profiles measured at Ping–Dong as input data to the radiative transfer model for computing the daily mean solar radiation in Tainan. The surface solar radiation is insensitive to the column ozone amount. Therefore, we use a single value of 0.3 (cm–atm)$_{stp}$ for the column ozone amount in the computation of solar radiation.

Observations of aerosol diurnal variation is not possible due to the presence of clouds. Therefore, we use daily mean aerosol optical properties in the model calculations of solar radiation. The solar radiation is calculated only for those days when there are Cimel–retrieved daily mean aerosol properties. The first two columns of Table 3 shows the model–calculated downward solar radiation at the surface without aerosols (F_{mod}^{NA}) and with aerosols (F_{mod}^{WA}), which are ~ 76% and 64% of the incoming solar radiation at the top of the atmosphere, $\overline{\mu_o S_o}$, as shown in Table 2.

Table 3. Mean surface radiation of cloud-free skies calculated from a radiation model and estimated from surface observations for skies without aerosols and with aerosols.

Month	F^{NA}_{mod}	F^{WA}_{mod}	F^{NA}_{obs}	F^{WA}_{obs}
Dec. 2003	203.3	176.2	186.2	162.7
Jan. 2004	217.3	190.8	194.0	170.2
Feb. 2004	255.8	223.1	236.3	198.4
March 2004	295.8	234.4	280.0	209.5
Mean	243.7	206.5	224.9	185.6

[a]Units are W m^{-2}. Here, *mod*, calculated from a radiation model; *obs*, estimated from surface observations; *NA*, for skies without aerosols; *WA*, for skies with aerosols.

4. Atmospheric Path Transmission and Aerosol Optical Path

To estimate the aerosol radiative effect from surface observations, we need to know the relationship between the surface radiation and the aerosol optical depth. This relationship is a function of the extraterrestrial solar radiation, S_o, and the solar zenith angle, θ_o. When the surface radiation is normalized by the incoming solar radiation at the top of the atmosphere, data from different months can be put together for deriving the relationship between the surface radiation and the aerosol optical thickness. In essence, the normalized surface radiation is the atmospheric path transmission given by

$$T = F_{obs} / (\mu_o S_o) \tag{1}$$

where F_{obs} is the observed surface radiation, and μ_o is the cosine of the solar zenith angle.

The AERONET retrieval algorithm identifies skies which are free of clouds and retrieves the aerosol optical thickness, τ, single-scattering albedo, ω_o, and asymmetry factor, g, using the Cimel radiation measurements. We group surface radiation and the aerosol optical thickness into θ_o-bins with an interval of 10°, and the atmospheric path transmission, T, is plotted against the aerosol optical path (τ/μ_o). The upper panel of Figure 1 shows only the scatterplot of the 40-50° θ_o-bin. Results of the other θ_o-bins are not shown. Each point in the plot represents 1-min mean PSP-measured atmospheric path transmission and the instantaneous AERONET-retrieved aerosol optical path during the 4-month period from December 2003 to March 2004. For comparisons, the atmospheric path transmission is computed as a function of the optical properties using the solar radiation model. The results are shown in the lower panel of Figure 1. The atmospheric path transmission derived from surface radiation measurements agree well with that computed from radiation model calculations. The straight lines given by the following equation are the least-square-error fit to the data,

$$T = \alpha + \gamma\tau / \mu_o \tag{2}$$

where α and γ are the regression coefficients.

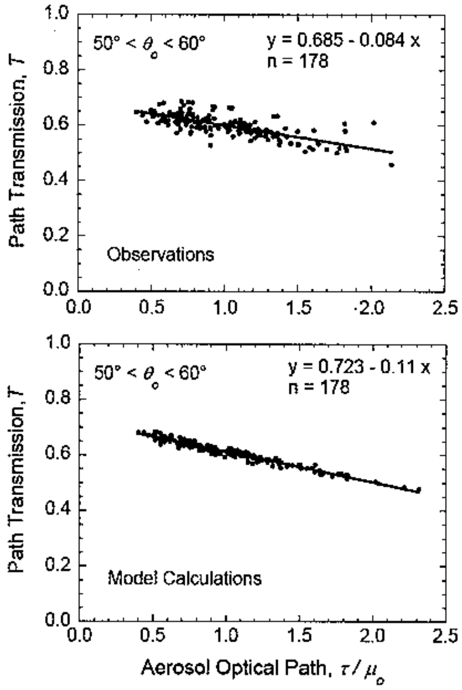

Figure 1. Relation between the atmospheric path transmission and the aerosol optical path. The line is the linear regression, and *n* is the number of data point. Data are taken from surface observations (upper panel) and radiation model calculations (lower panel).

5. Aerosol Radiative Effect (ARE) and Sensitivity (ARS)

The situation that there are no clouds in a day is very rare in Tainan. It is nearly impossible to estimate the effect of aerosols on the clear-sky surface radiation for individual days, and composite of clear-sky surface radiation measurements at various θ_o is necessary for the estimation of the mean ARE over an extended period of time, such as a month or a season.

The clear-sky surface radiation at local time t can be estimated from Equations (1) and (2),

$$F(t) = S_o\mu_o(t)[\alpha(\mu_o) + \gamma(\mu_o)\tau(t) / \mu_o(t)] \tag{3}$$

and the daily mean clear-sky surface radiation with aerosols (WA) and without aerosols (NA) can be computed from

$$F^{WA}{}_i = S_{o,i} \int \mu_o(t)\left[\alpha(\mu_o) + \gamma(\mu_o)\overline{\tau_i} / \mu_o(t)\right]dt \tag{4}$$

$$F^{NA}{}_i = S_{o,i} \int \mu_o(t)\alpha(\mu_o)dt \tag{5}$$

where $\overline{\tau_i}$ is the mean aerosol optical thickness at 0.5 μm of the day *i*, and the integration is over a day. It is noticed that the function $\mu_o(t)$ changes from day to day, whereas $\alpha(\mu_o)$ and $\gamma(\mu_o)$ are not a function of *i*. There is only one set of $\alpha(\mu_o)$ and $\gamma(\mu_o)$, given in Table 4, for the entire 4–month period from December 2003 to March 2004.

Table 4. Intercept and slope of the linear regression for $10^\circ\ \theta_o$–bins.

θ_o Bin	Intercept α	Slope γ
$20° < \theta_o < 30°$	0.750[b]	−0.127[b]
$30° < \theta_o < 40°$	0.740	−0.115
$40° < \theta_o < 50°$	0.724	−0.102
$50° < \theta_o < 60°$	0.685	−0.084
$60° < \theta_o < 70°$	0.633	−0.075
$70° < \theta_o < 80°$	0.554	−0.051
$80° < \theta_o < 90°$	0.430[b]	−0.015[b]

[a] The solar zenith angle θ_o in Tainan during the winter months December–March is always >23°.

[b] Approximation from extrapolation.

Finally, the aerosol radiative effect, is computed from

$$ARF_i = F^{WA}{}_i - F^{NA}{}_i \tag{6}$$

and the sensitivity of surface radiation to aerosol optical thickness, or aerosol radiative sensitivity (ARS), is given by

$$\frac{dF^{WA}{}_i}{d\bar{\tau}} = S_{o,i} \int \gamma(\mu_o)dt \tag{7}$$

The monthly and seasonal mean clear–sky surface radiation with aerosols, $F_{obs}{}^{WA}$, and without aerosols, $F_{obs}{}^{NA}$, estimated from observations using Equations (4) and (5) are shown in Table 3. It can be seen in the table that both $F_{obs}{}^{NA} < F_{mod}{}^{NA}$ and $F_{obs}{}^{WA} < F_{mod}{}^{WA}$ by ~ 20 Wm^{-2}. It is likely we have underestimated $F_{obs}{}^{NA}$ and $F_{obs}{}^{WA}$ and overestimated $F_{mod}{}^{NA}$ and $F_{mod}{}^{WA}$.

The ARE estimated from surface observations and computed from model calculations are shown in Table 5. It is computed from Equation (6) with F^{NA} and F^{WA} taken from Table 3. The agreement between the two different assessments of ARE is very good. The potential problem of the radiation model concerning the absorption of solar radiation by water vapor, as mentioned above, does not seem to have any significant impact on the calculation of ARE because both $F_{mod}{}^{WA}$ and $F_{mod}{}^{NA}$ are calculated using the same parameterization for water vapor absorption.

Table 5 also shows the ARS estimated from surface observations and computed using a radiation model. The former is computed using Equation (7) whereas the latter is computed as the ratio of the ARE to the aerosol optical thickness τ given in Table 2. It can be seen that the two estimates of ARS are in good agreement. For the four–month mean, the ARS is practically identical between surface observations and model calculations. For individual months, the difference is ≤ 10%.

Table 5. Aerosol radiative effect (ARE) and aerosol radiative sensitivity (ARS) derived from surface radiation observations and from radiation model calculations.

Month	ARE (Observed)	ARE (Model)	ARS (Observed)	ARS (Model)
Dec. 2003	−23.5	−27.1	−45.2	−52.1
Jan. 2004	−23.8	−26.5	−46.7	−52.0
Feb. 2004	−37.9	−32.7	−52.6	−45.4
March 2004	−70.6	−61.4	−59.8	−52.0
Mean	−39.0	−37.0	−51.0	−50.5

[a] Units are W m^{-2}. ARE, aerosol radiative effect; ARS, aerosol radiative sensitivity.

6. Conclusions

A new approach is developed to estimate the effect of aerosols on the surface radiation from surface observations. The relationship between the atmospheric path transmission and the aerosol optical path is derived by normalizing the incident surface radiation by the incoming solar radiation at the top of the atmosphere, $\mu_o S_o$, and aerosol optical thickness by the cosine of the solar zenith angle, μ_o. It is found that the relationship between the atmospheric path transmission and the aerosol optical path is surprisingly linear. The intercept and the slope of the regression lines represent, respectively, the atmospheric transmission free of aerosols and the sensitivity of surface radiation to aerosols. Because the atmospheric water vapor path and the aerosol optical path increase with increasing solar zenith angle, θ_o, both the coefficients of the regression decrease with increasing θ_o. Therefore, the regression is applied to narrow θ_o–intervals.

Applying the daily mean optical thickness retrieved from the Cimel radiance measurements to the relationship between the atmospheric path transmission and the aerosol optical path, the effect of aerosols on the surface radiation and the sensitivity of surface radiation to the variation of aerosol optical thickness are computed. It is found that the effect of aerosols is to reduce the incident surface solar radiation by ~39 Wm^{-2}, and the sensitivity of the surface radiation to aerosols is a reduction of ~51 Wm^{-2} per unit increase of aerosol optical thickness at 0.5 μm. These results are in good agreement with radiative transfer model calculations using the surface–based observations of temperature, humidity, and aerosol optical properties.

The AERONET–retrieved monthly mean aerosol optical thickness at 0.5 μm measured in Tainan ranges from 0.52 to 1.18 with a mean of 0.73 for the four months December 2003-march 2004. The single–scattering albedo and asymmetry factor remain nearly constant for the four months with a mean of ~0.95 for the former and ~0.70 for the latter. Thus, the air of Tainan during the winter is highly polluted, and the aerosols are moderately absorbing.

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