GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L20809, doi:10.1029/2006GL027814, 2006

Surface changes in solar irradiance due to aerosols over central Himalayas

U. C. Dumka,[1] S. K. Satheesh,[2] P. Pant,[1] P. Hegde,[1] and K. Krishna Moorthy[3]

Received 10 August 2006; accepted 13 September 2006; published 24 October 2006.

[1] During a comprehensive aerosol field campaign as a part of the ISRO-GBP, extensive measurements of radiative fluxes at the surface were made during December 2004 at Manora Peak, in the Shivalik ranges of the Central Himalayas. The surface radiative fluxes were used to estimate aerosol radiative forcing. Our analysis clearly shows that during the clean atmospheric conditions over Manora Peak, the observed aerosol radiative forcing is in good agreement to those of modeled ones, while for the higher aerosol optical depths (AODs), modeled values are significantly smaller than the observed ones. It was observed that at Manora Peak, the anthropogenic aerosols (from valley below) transported upwards by evolution of boundary layer during the daytime provide an atmosphere conducive for 'mixed' aerosols. Focused efforts are needed to address this issue for which simultaneous observations at high altitude site with those in nearby valley are essential.
Citation: Dumka, U. C., S. K. Satheesh, P. Pant, P. Hegde, and K. Krishna Moorthy (2006), Surface changes in solar irradiance due to aerosols over central Himalayas, *Geophys. Res. Lett.*, *33*, L20809, doi:10.1029/2006GL027814.

1. Introduction

[2] In order to assess the impact of anthropogenic aerosols on Earth-atmosphere system, it is essential to know its radiative forcing. However, the impact of radiative forcing due to aerosols still remains to be one of the largest sources of uncertainties in estimating the effect of anthropogenic aerosol on climate perturbations [*Intergovernmental Panel on Climate Change*, 2001]. This anomaly is primarily due to the large heterogeneity on aerosol properties and scarcity of adequate data. Numerous measurements and impact assessments have been reported from Indian region in recent years [*Moorthy et al.*, 2005; *Satheesh et al.*, 2006; *Pant et al.*, 2006]. However, most of these studies are focused to either urban/semi-urban landmass or oceans adjacent to densely populated coastal belt. Investigations from remote, sparsely inhabited regions have the importance of providing a sort of background against which the urban impacts can be compared [*Pant et al.*, 2006]. In this paper, we report aerosol radiative forcing estimated from radiative fluxes from a high altitude site. These results are compared with those reported for an urban site, Bangalore in southern India and tropical Indian Ocean. The results and implications of these are discussed in the manuscript.

2. Data and Analysis

[3] Aerosol optical depths (AODs) were measured during land campaign-II, conducted by Indian Space Research Organization's Geosphere Biosphere Programme (ISRO-GBP) from 1st to 31st December 2004 at Manora Peak (29.4°N; 79.5°E, 1950 m AMSL), Nainital, located in the Shivalik ranges of Central Himalayas. Further details of location and meteorological conditions are described by *Sagar et al.* [2004] and *Pant et al.* [2006]. The instrument used was a Microtops-II hand-held sun photometer (Solar Light, USA). It provides AOD at 5 channels (0.38, 0.44, 0.50, 0.675, and 0.870 μm) derived from instantaneous solar flux measurements using its internal calibration. A Global Positioning System (GPS) receiver attached with the photometer provides the information for time, location, altitude and pressure. Typical error in AOD measurement using Microtops-II sun photometer is ±0.03. Further details regarding the Microtops-II Sun Photometer, and calibration are described elsewhere [*Porter et al.*, 2001; *Ichoku et al.*, 2002].

[4] The radiative fluxes at the surface were measured at Manora Peak Nainital, in December 2004, using LI-200X Pyranometer (LI-COR Environmental, USA) designed for field measurement of global (direct + diffuse) solar radiation, in the wavelength range from 0.3 to 1.1 μm. The LI-200X features a silicon photovoltaic detector mounted in a fully cosine-corrected miniature head. The current output, which is directly proportional to solar radiation, is calibrated against an Eppley Precision Spectral Pyranometer (PSP) under natural daylight conditions in units of watts per square meter (W m^{-2}). The absolute accuracy of LI-200X Pyranometer under most conditions of natural daylight is about ±3% and is sensitive to 0.2 kilo Watt per square meter per milli volt ($kWm^{-2}mV^{-1}$). Thus, in clear, unobstructed daylight conditions, the LI-COR Pyranometer compares well with the first class thermopile-type Pyranometers.

[5] During the above-mentioned period of observations the surface solar fluxes were also measured at Bangalore using a Single Detector Rotating Shadow-band Radiometer (Model SDR-1) (Yankee Environmental, USA), which is a field instrument that measures the global (direct + diffuse) solar radiation in the wavelength range from 0.3 to 1.1 μm. The SDR-1 consists of a single cosine-corrected broadband silicon channel that provides fully automatic measurements. This instrument is similar to bolometric/thermopile type radiometers except the spectral response of silicon does not extend as far into the mid infrared. Thermally controlled sensor head eliminates ambient temperature-induced errors.

[1] Aryabhatta Research Institute of Observational Sciences, Manora Peak, Nainital, India.
[2] Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore, India.
[3] Space Physics Laboratory, Vikram Sarabhai Space Centre, Thiruvananthapuram, India.

0094-8276/06/2006GL027814$05.00

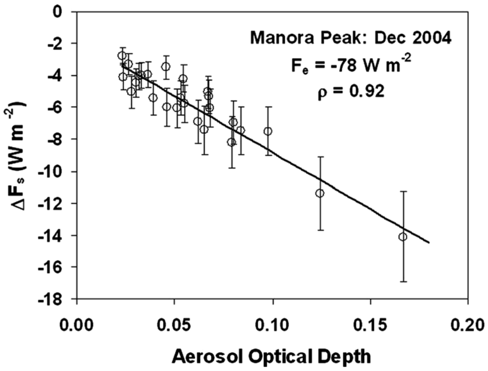

Figure 1. Scatter plot between the aerosol radiative forcing (obtained for Manora Peak, Nainital), at the surface as a function of AOD at 500 nm.

Cosine response of the detector is better than 1% (after correction) for 0–80° solar zenith angles. The absolute accuracy of this instrument is ±3 Wm^{-2}.

[6] For estimation of direct radiative forcing, we need radiative fluxes for clear skies. In December 2004, clear-sky conditions prevailed during most the month except five days. During rest of the period whenever thin cloud patches were present, radiation data was screened to avoid cloud contamination. This was accomplished by using cloud-screening procedure described by *Satheesh et al.* [1999]. Diurnal average fluxes were obtained by fitting the instantaneous clear-sky flux with a diurnal curve obtained from radiative transfer model [*Satheesh and Ramanathan*, 2000]. The aerosol-free flux was obtained using radiative transfer model, which employed measured atmospheric conditions (data from India Meteorological Department radiosondes). Since the station is already at ~2 km altitude, humidity was low even at surface level. More details of methodology employed to estimate diurnally averaged forcing from observed radiative fluxes is provided by *Satheesh and Ramanathan* [2000] and are not repeated here.

3. Results

[7] Aerosol radiative forcing at the surface is the effect of aerosol, both natural and anthropogenic, on the net short-wave radiative fluxes and is defined as the difference between the observed clear-sky net short-wave radiative flux and the net short-wave flux for the aerosol free atmosphere. We employ methods described by *Satheesh and Ramanathan* [2000] for obtaining the aerosol short wave radiative forcing directly from the observed fluxes. The aerosol radiative forcing (ΔF_s), thus obtained (for the wavelength range from 0.3 to 1.1 μm) at Manora Peak is plotted as a function of observed AODs at 0.50 μm (Figure 1). This indicates that the magnitude of ΔF_s increases with increasing value of AOD and slope of this curve yields the aerosol surface forcing efficiency (F_e). The value of F_e multiplied by individual daily value of AOD yields the corresponding aerosol radiative forcing, which is therefore not influenced by instrumental or model offsets. The value of F_e thus obtained in December 2004 for Manora Peak is -78 Wm^{-2}. This agrees within observational uncertainties with the estimated value of F_e as -71 Wm^{-2} by *Pant et al.* [2006] by using the measured aerosol microphysical properties into the radiative transfer model. Thus, the modeled aerosol radiative forcing values agree fairly well with the observed values in these cases. Both, observed and modeled values of F_e at Manora Peak are comparable to the corresponding values of -71 to -82 Wm^{-2} estimated by *Podgorny et al.* [2000], *Satheesh and Ramanathan* [2000], *Conant* [2000], and *Bush and Valero* [2002] over the Indian Ocean during January, February and March 1999.

[8] A comparison of aerosol radiative forcing efficiency values obtained at Manora Peak, Bangalore and Indian Ocean during INDOEX is shown in Figure 2a. Similarly, in Figure 2b, the aerosol radiative forcing values are shown. Large differences between observed and modeled aerosol radiative forcing and forcing efficiency are clearly observed at Bangalore. *Satheesh and Ramanathan* [2000] found an agreement between model and observations of aerosol radiative forcing and forcing efficiency over Indian Ocean during winter (sec Figures 2a and 2b). However, *Chandra et al.* [2004] reported that over tropical Indian Ocean, during summer monsoon season (June, July and August 1999) modeled surface diffuse radiative fluxes overestimate the observations by ~23 Wm^{-2}. A similar result has also been reported by *Charlock et al.* [2003]. Recently, *Sato et al.* [2003] concluded that the model and observations of aerosol absorption agree only if we increase abundance of aerosol black carbon by a factor of two to three. Several investigators, on the other hand, have found a good agreement between models and observations [*Cess et al.*, 1995; *Kiehl*

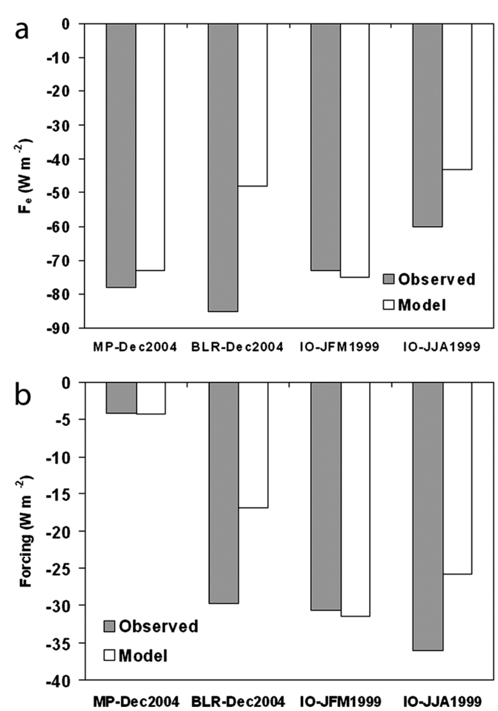

Figure 2. (a) Comparison of modeled and observed aerosol forcing efficiency at Manora Peak (MP), Bangalore (BLR) and Indian Ocean (IO) [during winter months of January, February and March 1999 and summer monsoon months of June, July and August 1999]. (b) Comparison between the modeled and observed aerosol radiative forcing is shown in lower panel.

et al., 1998; *Satheesh et al.*, 1999]. In summary, some studies report excellent agreement between the measured and observed radiative fluxes while other reports indicate large differences. It is important to note that *Halthore et al.* [1998] reported significant discrepancies between observed and modeled fluxes at low altitude stations while showed good agreement at high altitude sites. Over tropical Indian Ocean, measured and modeled radiative fluxes agree [*Satheesh et al.*, 1999; *Satheesh and Ramanathan*, 2000] during winter while they differ significantly in summer monsoon season [*Chandra et al.*, 2004].

[9] The aerosol measurements at Manora Peak, Nainital have shown that AODs is much lower compared to other low altitude locations in India [*Sagar et al.*, 2004; *Pant et al.*, 2006]. It was also observed that the values of afternoon AODs are generally higher than those of the forenoon AODs (see Figure 3 for 500 nm). This was attributed due to the evolution of boundary layer, which transports aerosols from the nearby polluted and valley regions to higher altitude. A gradual increase in aerosol optical depth from forenoon to afternoon can be seen in Figure 3. Due to this forenoon-afternoon asymmetry in AODs, we have examined the measured radiative fluxes separately for forenoon and afternoon hours. Surprisingly, during forenoon hours modeled aerosol forcing slightly overestimate the observations (by 4 Wm^{-2}, which is within instrumental uncertainties) while during afternoon hours, the model underestimate the observations (by $\sim$17 Wm^{-2}). In summary, during afternoon hours aerosols at Manora Peak absorbs more than predicted by radiation model (which incorporate measured aerosol microphysical properties). Our study demonstrate that observed and modeled aerosol forcing agree during clean atmospheric conditions while show a statistically significant difference when the evolving boundary layer brings polluted air from nearby valley below the observational site. It appears that the anthropogenic aerosols (from valley below) transported upwards by evolution of boundary layer during midday and afternoon hours provide an atmosphere conducive for 'mixed' aerosols.

[10] *Jacobson* [2000, 2001] has pointed out that when smaller aerosols accumulate over larger ones (and forms a mixture) its radiative impact is significantly larger compared to that of external mixture (where various aerosol species exist independently) as also acknowledged by *Chandra et al.* [2004]. Thus it appears that during afternoon hours at Manora Peak existing aerosols and those transported from below valley region enhance absorbing efficiency of aerosol.

4. Conclusions

[11] The main conclusions of our study are the following:

[12] 1. Our study shows that observed and modeled aerosol forcing agrees at Manora Peak during clean atmospheric conditions contrary to the large differences observed while the AOD values are larger.

[13] 2. The value of aerosol radiative forcing efficiency F_e (for the wavelength range from 0.3 to 1.1 μm) is -78 Wm^{-2} at the surface, which is comparable to the Indian Ocean values obtained for winter months of January, February and March 1999 during INDOEX field campaign.

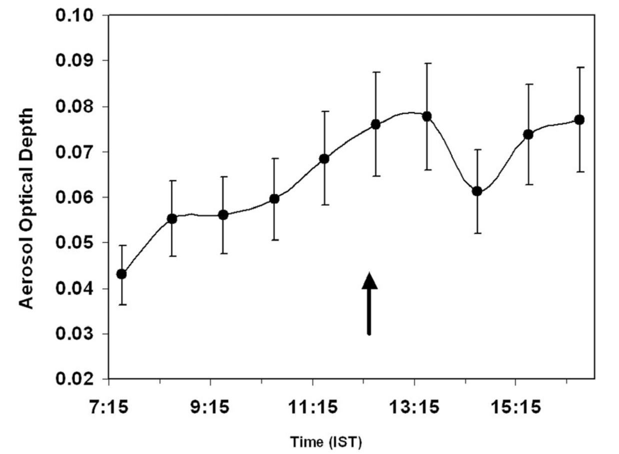

Figure 3. Diurnal variation of aerosol optical depth averaged for December 2004. Hourly mean values are shown in the figure. Vertical bars represent standard deviation. The upward arrow represents local noon.

[14] 3. It was observed that anthropogenic aerosols (from valley below) transported upwards by evolution of boundary layer during daytime provide an atmosphere conducive for 'mixed' aerosols. For such atmosphere, the model aerosol radiative forcing is underestimated in comparison to the observed ones.

[15] 4. Focused efforts are needed to address this issue for which observations at high altitude site simultaneous with those in nearby valley are essential.

[16] **Acknowledgments.** This work has been carried out under Indian Space Research Organization's Geosphere Biosphere Programme (ISRO-GBP) Land Campaign-II. The authors gratefully acknowledge Ram Sagar, A Taori and A. Guharay for fruitful discussions.

References

Bush, B. C., and F. P. J. Valero (2002), Spectral aerosol radiative forcing at the surface during the Indian Ocean Experiment (INDOEX), *J. Geophys. Res.*, *107*(D19), 8003, doi:10.1029/2000JD000020.

Cess, R. D., et al. (1995), Absorption of solar-radiation by clouds—Observations versus models, *Science*, *267*, 496–499.

Chandra, S., S. K. Satheesh, and J. Srinivasan (2004), Can the state of mixing of black carbon aerosols explain the mystery of 'excess' atmospheric absorption?, *Geophys. Res. Lett.*, *31*, L19109, doi:10.1029/2004GL020662.

Charlock, T. P., F. G. Rose, and D. A. Rutan (2003), Validation of the archived CERES surface and atmosphere radiation budget (SARB) at SGP, paper presented at Thirteenth ARM Science Team Meeting, Atmos. Radiat. Meas. Program, Broomfield, Colo, 31 March to 4 April.

Conant, W. C. (2000), An observational approach for determining aerosol surface radiative forcing: Results from the first field phase of INDOEX, *J. Geophys. Res.*, *105*(D12), 15,347–15,360.

Halthore, R. N., S. Nemesure, S. E. Schwartz, D. G. Imre, A. Berk, E. G. Dutton, and M. H. Bergin (1998), Models overestimate clear-sky surface irradiance: A case for excess atmospheric absorption, *Geophys. Res. Lett.*, *25*, 3591–3594.

Ichoku, C., et al. (2002), Analysis of the performance characteristics of the five-channel Microtops II Sun photometer for measuring aerosol optical thickness and precipitable water vapor, *J. Geophys. Res.*, *107*(D13), 4179, doi:10.1029/2001JD001302.

Intergovernmental Panel on Climate Change (2001), *Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton et al., Cambridge Univ. Press, New York.

Jacobson, M. Z. (2000), A physically based treatment of elemental carbon optics: Implications for global direct forcing of aerosols, *Geophys. Res. Lett.*, *27*, 217–220.

Jacobson, M. Z. (2001), Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols, *Nature*, *409*, 695–697.

Kiehl, J. T., et al. (1998), The National Center for Atmospheric Research Community Climate Model: CCM3, *J. Clim.*, *11*, 1131–1149.
Moorthy, K. K., S. S. Babu, and S. K. Satheesh (2005), Aerosol characteristics and radiative impacts over the Arabian Sea during the intermonsoon season: Results from ARMEX field campaign, *J. Atmos. Sci.*, *62*, 192–206.
Pant, P., P. Hegde, U. C. Dumka, R. Sagar, S. K. Satheesh, K. K. Moorthy, A. Saha, and M. K. Srivastava (2006), Aerosol characteristics at a high-altitude location in central Himalayas: Optical properties and radiative forcing, *J. Geophys. Res.*, *111*, D17206, doi:10.1029/2005JD006768.
Podgorny, I. A., W. C. Conant, V. Ramanathan, and S. K. Satheesh (2000), Aerosol modulation of atmospheric and surface solar heating over the tropical Indian Ocean, *Tellus, Ser. B*, *52*, 947–958.
Porter, J. N., M. Miller, C. Pietras, and C. Motell (2001), Ship-based Sun photometer measurements using Microtops Sun photometers, *J. Atmos. Oceanic Technol.*, *18*, 765–774.
Sagar, R., B. Kumar, U. C. Dumka, K. K. Moorthy, and P. Pant (2004), Characteristics of aerosol spectral optical depths over Manora Peak: A high-altitude station in the central Himalayas, *J. Geophys. Res.*, *109*, D06207, doi:10.1029/2003JD003954.
Satheesh, S. K., and V. Ramanathan (2000), Large differences in the tropical aerosol forcing at the top of the atmosphere and Earth's surface, *Nature*, *405*, 60–63.
Satheesh, S. K., V. Ramanathan, X. Li-Jones, J. M. Lobert, I. A. Podgorny, J. M. Prospero, B. N. Holben, and N. G. Loeb (1999), A model for the natural and anthropogenic aerosols over the tropical Indian Ocean derived from Indian Ocean Experiment data, *J. Geophys. Res.*, *104*(D22), 27,421–27,440.
Satheesh, S. K., K. Krishna Moorthy, Y. J. Kaufman, and T. Takemura (2006), Aerosol optical depth, physical properties and radiative forcing over the Arabian sea, *Meteorol. Atmos. Phys.*, *91*(1–4), 45–62.
Sato, M., et al. (2003), Global atmospheric black carbon inferred from AERONET, *Proc. Natl. Acad. Sci. U.S.A.*, *100*, 6319–6324.

U. C. Dumka, P. Hegde, and P. Pant, Aryabhatta Research Institute of Observational Sciences, Manora Peak, Nainital 263129, India.

K. Krishna Moorthy, Space Physics Laboratory, Vikram Sarabhai Space Centre, Thiruvananthapuram, Kerala 695022, India.

S. K. Satheesh, Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore, Karnataka 560 012, India. (satheesh@caos.iisc.ernet.in)