GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L06703, doi:10.1029/2009GL042133, 2010

Seminal role of clouds on solar dimming over the Indian monsoon region

B. Padma Kumari[1] and B. N. Goswami[1]

Received 11 December 2009; accepted 4 February 2010; published 18 March 2010.

[1] In contrast to most of the world where solar dimming has changed over to solar brightening since late eighties, dimming continues unabated over the Indian region. This study investigates new insight into the origin of dimming over India. As the insolation at the surface is controlled by aerosols and clouds, we tried to separate out the two controlling factors by examining clear and cloudy sky days. From 1981–2006, the rate of dimming is found to be twice as large during cloudy conditions (~12 W/m^2/decade) compared to that during clear sky conditions (~6 W/m^2/decade). The clear sky dimming is attributed to increasing aerosols. While the rate of dimming by clouds is similar during summer and winter monsoon seasons, the increased contribution to dimming by clouds during summer seems to come from increasingly deeper clouds covering increasingly larger area. During winter, dimming in cloudy conditions appears to be due to indirect effect of aerosols.

Citation: Padma Kumari, B., and B. N. Goswami (2010), Seminal role of clouds on solar dimming over the Indian monsoon region, *Geophys. Res. Lett.*, *37*, L06703, doi:10.1029/2009GL042133.

1. Introduction

[2] Surface reaching solar radiation (S) is a key component of the net radiation balance at the surface determining the regional climate. Tiny particles in the atmosphere called aerosols arising from natural causes as well as human activities have a strong influence on S. While increasing green house gases in the atmosphere is certainly a major concern for the changing climate, the aerosols through their direct and indirect influence on the radiative balance can influence the climate significantly [*Chand et al.*, 2009]. Since the middle of the twentieth century S has undergone decadal variations in many parts of the world leading to global dimming up to 1990 [*Stanhill and Cohen*, 2001; *Liepert*, 2002; *Liu et al.*, 2004] and brightening after 1990 [*Wild et al.*, 2005; *Pinker et al.*, 2005; *Norris and Wild*, 2007]. However, at few regions continuous dimming is observed [*Padma Kumari et al.*, 2007; *Che et al.*, 2005]. It is believed that solar dimming is due to changes in cloud properties and the increased presence of aerosols in the atmosphere, caused by human activities. Some aerosols scatter and others absorb the incoming solar radiation (aerosol direct effect). Also, since aerosols serve as cloud condensation nuclei, an increase in aerosols could generate more clouds with small drop sizes. Clouds have a very high albedo, and thus tend to reflect even more incoming sunlight back into space (aerosol indirect effect). In each case a fraction of radiation would be prevented from reaching Earth's surface resulting in an apparent dimming of the sun as viewed from the planet's surface. But, the processes involved in aerosol-cloud-radiation interactions have not yet been fully understood.

[3] Over India, a significant continued dimming is observed under all sky conditions [*Padma Kumari et al.*, 2007; *Ramanathan et al.*, 2005], where aerosols and clouds together contributed to the annual trend. Decrease in surface solar radiation may lead to decrease in evaporation and slowdown of the monsoon hydrological cycle [*Wild et al.*, 2005; *Ramanathan et al.*, 2005]. This observation of significant decreasing trend of S has important implications on the role of aerosols relative to that of green house gases on the regional monsoon climate especially in the context of observed increasing trend of surface temperatures over the region [*Kothawale and Rupa Kumar*, 2005]. While the aerosol loading of the atmosphere over the region is increasing, is the decrease in S entirely due to direct radiative effect of the aerosols? How much do the changes in the clouds over the region contribute to this trend in S? Are the changes in the clouds entirely due to large scale dynamical forcing? Could some of the changes in the clouds be due to interactions with the aerosols (indirect effect)? A clear understanding of the continued dimming over India is important. Hence, we examine the trends of S separately during summer and winter and during cloud free and cloudy conditions.

2. Data and Methodology

[4] Daily mean surface reaching solar radiation (S) data measured over different stations in India were collected from India Meteorological Department (IMD). Thermoelectric pyranometers were utilized to acquire the radiation data in the wavelength range from 0.3 to 4.0 μm. The absolute accuracy of the standard instrument is about ±0.3%, while the accuracy of the instruments in the network is about ±1%, and the data generated in the network are well within the accuracy limits specified by *World Meteorological Organization* [1983]. The continuous data available from 1981 to 2006 for the stations Trivandrum, Chennai, Goa, Visakhapatnam, Pune, Mumbai, Nagpur, Kolkatta, Ahmedabad, Varanasi, Jodhpur, and New Delhi are used in the present study. These stations (coordinates given in Table 1) are distributed over northern, southern, eastern, western and central India. Although these are urban locations, S averaged over a season would represent values representative of a much larger area around the stations. Hence, the annual mean or seasonal mean S averaged over the 12 stations provides a reasonable estimate of S averaged over the

---

[1] Indian Institute of Tropical Meteorology, Pune, India.

0094-8276/10/2009GL042133

country. In order to support this, it is desirable to include some rural stations. Unfortunately, most of the radiation observatories are located either in a city/town or just outside a city/town. However, to compare the trends in S at urban stations to that at a rural location, radiation data at Kodaikanal (though not continuous) is analyzed, as it is a hill station situated at an altitude of 2133 m high, least affected by industrialization and urbanization.

[5] The daily radiation data records also contain the information on the number of hours of clear, cloudy, hazy and foggy sky. Based on this information, solar radiation time series has been segregated into clear sky (S_{clear}) and cloudy sky (S_{cldy}) composites. The time series of clear sky days includes data for conditions not only clear throughout the day but also hazy days. On the other hand, time series of cloudy sky days includes data for conditions - overcast, cloudy throughout the day or cloudy for more than 2 hrs. NOAA interpolated OLR(Outgoing Long wave Radiation) monthly and daily data over Indian latitudes and longitudes (10–35°N, 65–95°E) (available from http://www.cdc.noaa.gov/) has been used as a proxy for convection.

3. Results

[6] From daily mean S_{clear} and S_{cldy} composites annual means have been computed for all the selected Indian stations. The time series of annual means has been subjected to linear regression analysis and their slopes are presented in Table 1. The linear trends in S_{cldy} during the period 1981–2006 over all the stations are found to be decreasing (statistical significance is shown in Table 1) and varying from −0.29 to −1.89 W/m^2/yr. The average solar dimming observed over all these 12 stations under cloudy sky conditions is found to be ~12 W/m^2/decade or 31 W/m^2/26 years (Figure 1).

[7] Similarly, trends in S_{clear} also showed strong decline (Table 1), except two stations Chennai and Pune (statistical significance is shown in Table 1). The average solar dimming observed over all the 12 stations under clear sky conditions is found to be ~6.1 W/m^2/decade or ~15.86 W/m^2/26 years (Figure 1). This solar dimming under clear sky conditions is likely to be due to increasing trend of anthropogenic aerosols over almost all major locations in India [*Sarkar et al.*, 2006; *Ramachandran and Jayaraman*, 2003; *Sahu et al.*, 2008]. Hence the trends in S_{clear} represent direct effects of aerosols by scattering and absorbing the incoming solar radiation. Kodaikanal (discussed in the above section), considered almost as a rural/remote place, shows high S values compared to other stations. This indicates less aerosol loading at Kodaikanal as compared to other stations. It is interesting to note that Kodaikanal also shows decreasing trend in S for all sky (−1.65 W/m^2/yr) and cloudy sky (−1.84 W/m^2/yr) conditions (see Figure S1).[1] As it is a high altitude station affected by both summer and winter monsoons, the number of clear sky days is limited and does not allow a reliable estimate of the trend during clear sky conditions. However, strong decreasing trend of S during cloudy sky at this station supports our finding based on the other stations. Hence, the annual mean or seasonal mean S averaged over the 12 stations may provide a reasonable estimate of flux averaged over the country.

Table 1. Observed Reduction in Surface Reaching Solar Radiation During the Period 1981–2006, for Clear and Cloudy Sky Days Over the Indian Stations[a]

Station	Latitude, Longitude	Clear Sky (W/m^2/yr)	Cloudy Sky (W/m^2/yr)
Trivandrum(SI)	8.48°N, 76.95°E	**−1.05**	**−1.47**
Chennai (SI)	13.0°N, 80.18°E	+0.18*	−0.29
Goa (WC)	15.48°N, 73.82°E	−0.56	**−0.70**
Visakhapatnam (EC)	17.72°N, 83.23°E	**−0.83**	**−2.12**
Pune (IP)	18.5° N, 73.9°E	+0.49*	−0.34
Mumbai (WC)	19.12°N, 72.83°E	−0.05*	**−0.81**
Nagpur (IP)	21.10°N, 79.05° E	−0.60	**−1.10**
Kolkatta (NE)	22.39°N, 88.27°E	**−1.33**	**−1.10**
Ahmedabad (NW)	23.07°N, 72.63°E	*−0.39*	**−1.89**
Varanasi (NC)	25.45°N, 83.02°E	−0.97	**−1.34**
Jodhpur (NW)	26.3°N, 73.01°E	−0.52*	**−1.13**
New Delhi (NW)	28.58°N, 77.20°E	**−1.72**	**−1.83**

[a]The numbers in bold represent significant at 99%, numbers in italics represent significant at 95% and others significant at 90%. Numbers with an * represent not significant. SI, Southern India; WC, West Coast; EC, East Coast; NE, North East; NW, North West; NC, North Central; IP, Interior Peninsula.

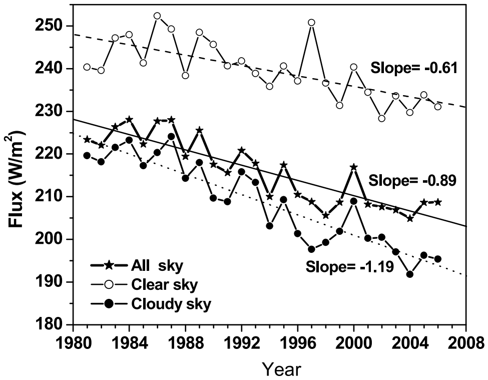

Figure 1. Annual mean (average of 12 stations) surface reaching solar radiation under all sky, clear sky and cloudy sky conditions from 1981–2006. Straight lines represent trend. All the trends are significant at 99%.

[8] The annual mean S under all sky conditions (computed from daily means) is also shown in Figure 1 for comparison. It is interesting to note that the rate of decrease of S during cloudy conditions is twice as large as that during the clear sky conditions. The average of trends during clear and cloudy conditions is consistent with the trend in all sky conditions. Since clouds are the strongest modifiers of S, changes in S under cloudy conditions is expected. However, it is not obvious why it should show a strong decreasing trend. This indicates that clouds play an even larger role in the observed solar dimming than the aerosols. The question is how do the clouds achieve this and why?

[9] To answer this question, we examine seasonal variation (average of May to October (MJJASO) and November to April (NDJFMA)) of S_{clear} (Figure 2a) as well as S_{cldy} (Figure 2b) averaged over all the stations. Consistent with the annual cycle of solar radiation reaching the region, the S_{clear} values observed during MJJASO season are higher than the values observed during NDJFMA season. However, the negative trend observed during NDJFMA is nearly double the negative trend that is observed during MJJASO

---

[1] Auxiliary materials are available in the HTML. doi:10.1029/2009GL042133.

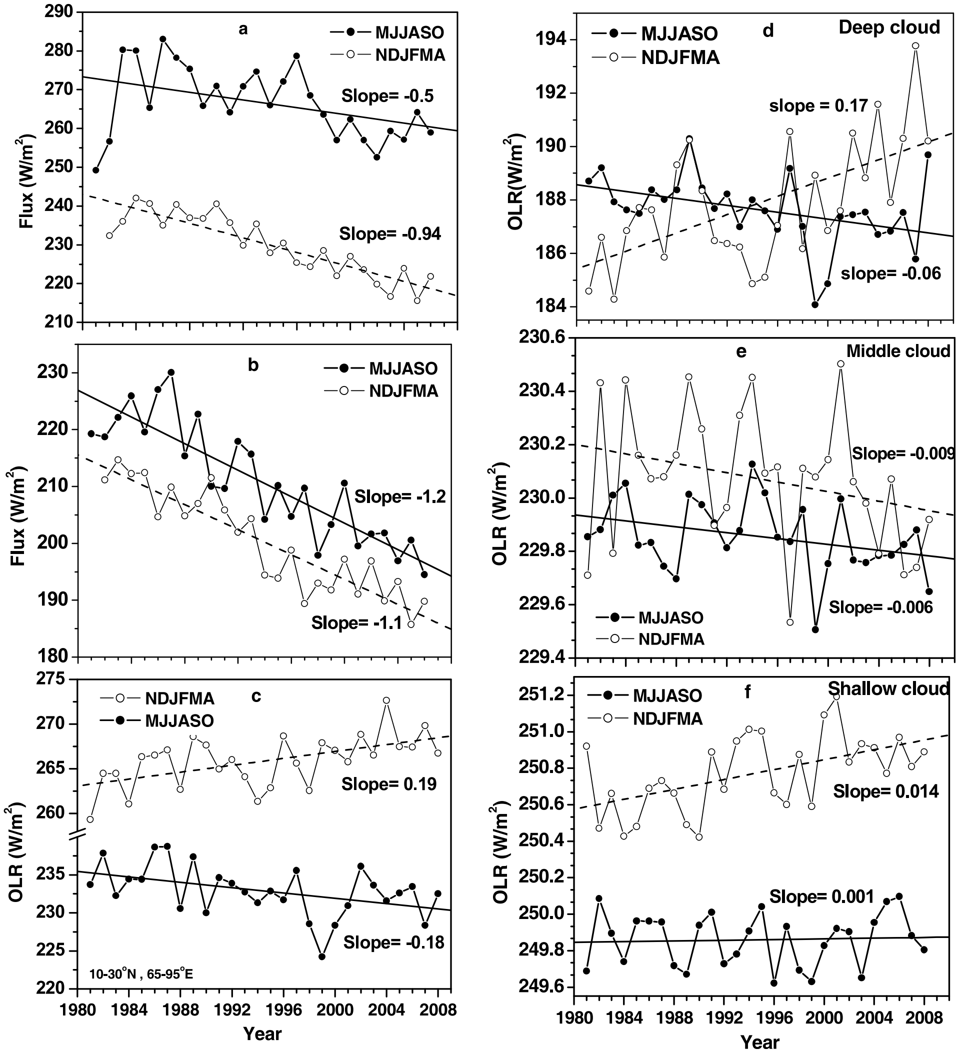

Figure 2. Seasonal variation of surface radiation (S) and OLR over India (10–35°N, 65–95°E) for two seasons MJJASO (May to October) and NDJFMA (November to April). (a) S under clear sky conditions, (b) S under cloudy sky conditions, (c) total OLR, (d) deep cloud (OLR < 220 W/m^2), (e) middle cloud (OLR between 220–240 W/m^2) and (f) shallow cloud (OLR between 240–260 W/m^2). Straight lines represent trend. For Figures 2a and 2b all the trends are significant at above 95%. For deep cloud the MJJASO trend is significant at 95% and NDJFMA trend at 99%. For middle cloud the NDJFMA trend is not significant whereas the MJJASO trend is significant at 90%. For shallow cloud the NDJFMA trend is significant at 99% whereas the MJJASO trend is not significant.

(Figure 2a). India receives maximum rainfall during south west monsoon (June–Sept.). After rainfall the atmosphere looks clean as the pollutants get washed off, hence the incoming radiation increases. In spite of the washout effect, the negative trend of S during clear sky conditions in MJJASO is an indication of increasing aerosol loading from local emissions as well as long range transports. High concentration of fine mode particles observed during winter (Dec–Jan–Feb) is attributed to increasing anthropogenic emissions, and high aerosol optical depths observed during Apr–May are attributed to large dust loading in the atmosphere [*Gautam et al.*, 2007]. Hence during NDJFMA season anthropogenic aerosols as well as dust particles play important roles in reducing the incoming radiation.

[10] On the other hand, S_{cldy} (Figure 2b) shows strong decreasing trend during both the seasons. Interestingly, the flux values during MJJASO period are more compared to the values during NDJFMA. To understand the cloud effect on S_{cldy}, we examine seasonal mean outgoing long wave radiation (OLR) constructed from monthly mean OLR data averaged over India (Figure 2c). It may be recalled here that OLR is strongly linked with the cloud top temperature and hence low OLR represents more cloud amount or deeper clouds while high OLR represents shallower clouds or no clouds. The decreasing trend in OLR during MJJASO period indicates increasing cloud amount, which is in agreement with the decreasing trend in S_{cldy} shown in Figure 2b. The increasing trend in OLR during NDJFMA period seems to indicate increasing shallower clouds. As during winter, fine mode aerosol loading is high and hence fog/low cloud formation will be high [*Gautam et al.*, 2007]. Thin high clouds may also be present and may contribute to the trend.

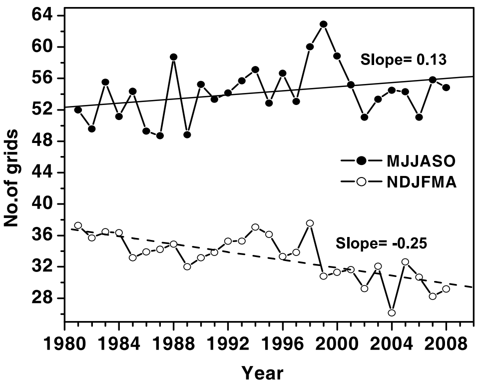

Figure 3. Seasonal variation of average number of grids covered by deep clouds (OLR < 220 W/m^2) over India (10–35°N, 65–95°E) (constructed from daily gridded OLR data) for MJJASO (trend significant at 90%) and NDJFMA (trend significant at 99%).

However, at present we are unable to estimate it and remain an area of uncertainty. Thus, during cloudy days, the changes in S_{cldy} and their trends are attributed to be due to direct cloud effect during MJJASO period and may be due to aerosol indirect and cloud effects during NDJFMA period.

[11] To further understand the role of aerosols in cloud formation, daily OLR data has been segregated into three types as shallow clouds (OLR between 240–260 W/m^2), middle clouds (OLR between 220–240 W/m^2) and deep clouds (OLR < 220 W/m^2). The seasonal averages of OLR over India for the above three different types of clouds are shown in Figures 2d–2f. It is interesting to note that during summer (MJJASO) higher frequency of deeper clouds is leading to low average OLR while during winter (NDJFMA) smaller frequency of deeper clouds is leading to higher average OLR in recent years. To gain further insight, the area covered by deep clouds during the two seasons is examined from the average number of grid cells covered by deep clouds in a day (Figure 3). While the area covered by deep clouds during summer (MJJASO) is increasing, it is decreasing during winter (NDJFMA). The large difference in the area covered by deep clouds during summer and winter is consistent with the fact that the summer south-west monsoon covers most of the country explaining 75% of annual rainfall, while the winter north-east monsoon covers only a small area in the south-east peninsular region and a small area in the northwest India [*Gadgil*, 2003].

4. Conclusions and Discussions

[12] As expected from the significant decreasing trend of S over India, the evaporation over continental India indeed shows a significant decreasing trend [*Jaswal et al.*, 2008]. Further, the monsoon rainfall during the period shows only a weak decreasing trend [*Ramanathan et al.*, 2005; *Goswami et al.*, 2006]. Hence, the monsoon hydrological cycle is indeed weakening over the past three to four decades. Therefore, it is important to understand the process(s) responsible for the decreasing trend of S. Towards this end, daily mean S data has been segregated into clear (S_{clear}) and cloudy (S_{cldy}) sky composites and annual means have demonstrated that the solar dimming (averaged over 12 stations) observed under clear sky conditions is ~6 W/m^2/decade and under cloudy sky conditions it is almost double ~12 W/m^2/decade. S_{clear} shows higher negative trend during NDJFMA period than during MJJASO period. Hence the decreasing trend in S_{clear} is mainly due to direct radiative effect of increasing amount of aerosols. However, clouds contribute nearly twice as much as the direct effect of the aerosols. The seasonal variation of S_{cldy} shows strong decreasing trend during both the seasons, which might be due to aerosol indirect and other cloud effects. The seasonal variation of OLR shows decreasing trend during MJJASO period indicating increasing cloud amount, which is in agreement with the decreasing trend in S_{cldy}. A significant decreasing trend of OLR (<220 W/m^2) during MJJASO indicates deep clouds are increasing also the area covered by deep clouds is increasing as compared to other types of clouds. However, during NDJFMA the amount of deep clouds as well as the area covered by them is decreasing. Thus, during NDJFMA decreasing trend of S_{cldy} can not be explained by deep clouds. This may be an indication of the fact that in winter decreasing trend of S_{cldy} is due to indirect effect of aerosols possibly by increasing the amount of thin shallow clouds.

[13] The increasing trend of amount of deep clouds during summer is the major contributor to the solar dimming. What is responsible for this increasing trend of deep clouds? We believe that it is largely due to increased moistening of the atmosphere [*Trenberth et al.*, 2005] due to global warming leading to increased instability of the atmosphere [*Mani et al.*, 2009]. This is consistent with increased frequency of occurrence and intensity of extreme rainfall events over the region [*Goswami et al.*, 2006]. However, there is a possibility that aerosols could indirectly influence increase in deep cloud through increase in effective convective available potential energy [*Rosenfeld et al.*, 2008] during monsoon season. However, with the available observations, it is not possible to estimate this effect currently and highlights the need for additional observations. The increased amount of deep clouds covering increased area would indicate an increase in the water vapor greenhouse effect over the region and may explain why the surface temperature is increasing in the backdrop of decreasing S.

[14] **Acknowledgments.** The authors are grateful to IMD for providing radiation data and NOAA for OLR data. Also would like to thank Vijay Kanawade for extracting OLR data. IITM is funded by Ministry of Earth Sciences, Government of India.

References

Chand, D., R. Wood, T. L. Anderson, S. K. Satheesh, and R. J. Charlson (2009), Satellite-derived direct radiative effect of aerosols dependent on cloud cover, *Nat. Geosci.*, *2*, 181–184, doi:10.1038/ngeo437.

Che, H. Z., et al. (2005), Analysis of 40 years of solar radiation data from China, 1961–2000, *Geophys. Res. Lett.*, *32*, L06803, doi:10.1029/2004GL022322.

Gadgil, S. (2003), The Indian monsoon and its variability, *Annu. Rev. Earth Planet. Sci.*, *31*, 429–467, doi:10.1146/annurev.earth.31.100901.141251.

Gautam, R., N. Christina Hsu, M. Kafatos, and S.-C. Tsay (2007), Influences of winter haze on fog/low cloud over the Indo-Gangetic plains, *J. Geophys. Res.*, *112*, D05207, doi:10.1029/2005JD007036.

Goswami, B. N., V. Venugopal, D. Sengupta, M. S. Madhusoodanan, and K. X. Prince (2006), Increasing trend of extreme rain events over India in a warming environment, *Science*, *314*, 1442–1445, doi:10.1126/science.1132027.

Jaswal, A. K., G. S. Prakasa Rao, and U. S. De (2008), Spatial and temporal characteristics of evaporation trends over India during 1971–2000, *Mausam*, *59*, 149–158.

Kothawale, D. R., and K. Rupa Kumar (2005), On the recent changes in surface temperature trends over India, *Geophys. Res. Lett.*, *32*, L18714, doi:10.1029/2005GL023528.

Liepert, B. G. (2002), Observed reductions of surface solar radiation at sites in the United States and world wide from 1961 to 1990, *Geophys. Res. Lett.*, *29*(10), 1421, doi:10.1029/2002GL014910.

Liu, B., M. Xu, M. Henderson, and W. Gong (2004), A spatial analysis of pan evaporation trends in China 1995–2000, *J. Geophys. Res.*, *109*, D15102, doi:10.1029/2004JD004511.

Mani, N. J., E. Suhas, and B. N. Goswami (2009), Can global warming make Indian monsoon weather less predictable?, *Geophys. Res. Lett.*, *36*, L08811, doi:10.1029/2009GL037989.

Norris, J. R., and M. Wild (2007), Trends in aerosol radiative effects over Europe inferred from observed cloud cover, solar dimming and solar brightening, *J. Geophys. Res.*, *112*, D08214, doi:10.1029/2006JD007794.

Padma Kumari, B., A. L. Londhe, S. Daniel, and D. B. Jadhav (2007), Observational evidence of solar dimming: Offsetting surface warming over India, *Geophys. Res. Lett.*, *34*, L21810, doi:10.1029/2007GL031133.

Pinker, R. T., B. Zhang, and E. G. Dutton (2005), Do satellites detect trends in surface solar radiation?, *Science*, *308*, 850–854, doi:10.1126/science.1103159.

Ramachandran, S., and A. Jayaraman (2003), Balloon-borne study of the upper tropospheric and stratospheric aerosols over a tropical station in India, *Tellus, Ser. B*, *55*, 820–836, doi:10.1034/j.1600-0889.2003.00069.x.

Ramanathan, V., et al. (2005), Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle, *Proc. Natl. Acad. Sci. U. S. A.*, *102*, 5326–5333, doi:10.1073/pnas.0500656102.

Rosenfeld, D., et al. (2008), Flood or drought: How do aerosols affect precipitation?, *Science*, *321*, 1309–1313, doi:10.1126/science.1160606.

Sahu, S. K., G. Beig, and C. Sharma (2008), Decadal growth of black carbon emissions in India, *Geophys. Res. Lett.*, *35*, L02807, doi:10.1029/2007GL032333.

Sarkar, S., R. Chokngamwong, G. Cervone, R. P. Singh, and M. Kafatos (2006), Variability of aerosol optical depth and aerosol forcing over India, *Adv. Space Res.*, *37*, 2153–2159, doi:10.1016/j.asr.2005.09.043.

Stanhill, G., and S. Cohen (2001), Global dimming: A review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences, *Agric. For. Meteorol.*, *107*, 255–278, doi:10.1016/S0168-1923(00)00241-0.

Trenberth, K., J. Fasullo, and L. Smith (2005), Trends and variability in column-integrated water vapor, *Clim. Dyn.*, *24*, 741–758, doi:10.1007/s00382-005-0017-4.

Wild, M., et al. (2005), From dimming to brightening: Decadal changes in surface solar radiation, *Science*, *308*, 847–850, doi:10.1126/science.1103215.

World Meteorological Organization (1983), Measurement of radiation, in *Guide to Meteorological Instruments and Methods of Observation*, 5th ed., *WMO Publ.*, *8*, chap. 7.

B. N. Goswami and B. Padma Kumari, Indian Institute of Tropical Meteorology, Dr. Homi Bhabha Road, Pune, Maharastra 411 008, India. (goswami@tropmet.res.in)