

Large Aerosol Radiative Forcing due to the 1997 Indonesian Forest Fire

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[1] During the last decade, the feedback between El Niño and biomass burning caused the Indonesia's forest fire aerosols to be the second most significant source of anthropogenic aerosol over the tropical Indian Ocean after the South Asian Haze. In this paper, the estimates of the radiative forcing during the 1997 Indonesia's forest fire have been obtained by integrating satellite derived aerosol optical depths and cloud cover with in-situ observations of single scattering albedo and a Monte-Carlo Aerosol-Cloud radiation model. The haze reduced the seasonal average solar radiation absorbed by the equatorial Indian ocean by as much as 30 to 60 W m^{-2} during September to November 1997, and increased the atmospheric solar heating by as much as 50% to 100% within the first 3 kilometers. The radiative forcing at the top of the atmosphere (TOA) was in the range of 5 to 15 W m^{-2} under cloudy skies. The significance of such large radiative flux changes to the tropical ocean-atmosphere heat budget and climate needs to be examined with climate models. **INDEX TERMS:** 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); 1610 Global Change: Atmosphere (0315, 0325); 1640 Global Change: Remote sensing. **Citation:** Podgorny, I. A., F. Li, and V. Ramanathan, Large Aerosol Radiative Forcing due to the 1997 Indonesian Forest Fire, *Geophys. Res. Lett.*, 30(1), 1028, doi:10.1029/2002GL015979, 2003.

1. Introduction

[2] The recently completed Indian Ocean Experiment (INDOEX) has identified the northern Indian Ocean to have a high concentration of absorbing aerosols and aerosol radiative heating has been shown in model studies to have substantial climate effects [Ramanathan *et al.*, 2001]. The regional aerosol pollution of anthropogenic origin, also known as the South Asian Haze, is a winter monsoon event affecting the area of the size of United States during December to April. A key feature of the haze is the aerosol single-scattering albedo (SSA) being as low as 0.9 [Ramanathan *et al.*, 2001], which results in nearly twofold increase in the lower troposphere heating rates [Podgorny *et al.*, 2000; Podgorny and Ramanathan, 2001].

[3] Numerical experiments with the National Center for Atmospheric Research (NCAR) Community Climate Model Version 3 (CCM3) revealed important implications of the South Asian Haze for both regional [Ramanathan *et al.*, 2001; Chung *et al.*, 2002] and global climate [Chung *et al.*,

2002; Chung and Ramanathan, 2002]. Specifically, the haze cools the surface and warms the lower troposphere, which have dramatic implications for the hydrological cycle in Asia. As shown in Chung and Ramanathan [2002], the recent drought in Southwest Asia and South Asian Haze may be closely connected. Xu [2001] recently reported a similar climate change in central China and linked it to the aerosol pollution.

[4] The focus of this study is the direct aerosol forcing produced by biomass burning during the Indonesia's forest fires. Indonesia has the third largest area of tropical forest in the world, and by far the largest area in Asia. Large scale burning produces persistent haze over large areas of Sumatra and Kalimantan during every dry season, but the haze normally goes away in September. This did not happen in 1997 when the rain season was delayed by an El Niño event and the haze reached several countries including Malaysia, Singapore, Philippines and Thailand. While El Niño-related droughts occur in Indonesia every two to seven years, the 1997 fires were triggered by the intensification of agriculture and logging over the past two decades and can be attributed to human rather than natural causes [Schweithelm, 1999].

[5] There have been several papers addressing the aerosol radiative forcing in the Indian Ocean region based on an integrated approach (i.e., a combination of in situ aerosol and radiometric observations, and remote sensing). Rajevee *et al.* [2000] used INDOEX data to develop a model for retrieving aerosol optical depth (AOD) from the Advanced High-Resolution Radiometer (AVHRR) data during January–March 1998. Li and Ramanathan [2002] extended the retrievals by Rajevee *et al.* [2000] for the annual cycle using an aerosol model with seasonally adjusted SSA and phase function. A significant increase in AOD has been found over the equatorial Indian Ocean in October 1997 and attributed to the Indonesia's forest fire. In particular, the fire smoke plumes spread westward as far as 60°E and raised the monthly mean AOD to about 0.3 in remote ocean. Finally, Chou *et al.* [2002] presented global retrievals of AOD from Sea-viewing Wide Field-of-View Sensor (SeaWiFS) data based on an absorbing aerosol model and estimated the clear sky forcing in the vicinity of Indonesia during 1997 fire.

[6] Given the potential impact of Indonesia's biomass burning on the regional and global climate, focused numerical experiments with NCAR CCM3 are essential for addressing this issue in greater detail. In this study, we develop an aerosol optical model, constrained by SSA observations during the 1997 Indonesia's forest fire, and apply this model to both retrievals of AOD from AVHRR data and aerosol forcing calculations under cloudy skies.

Our ultimate goal is to provide monthly mean maps of heating rates to be used as an input to a coupled ocean-atmosphere model.

2. Aerosol Optical Model

[7] As the 1997 Indonesia's fires were triggered by El Niño, this prevented an advance planning of a dedicated campaign like Smoke, Clouds, and Radiation-Brazil (SCAR-B) [Kaufman *et al.*, 1998]. There have been two observational sites during the fire event operated by Nakajima *et al.* [1999] in Singapore and by von Hovning-Huene *et al.* [1999] in Malaysia as well as observations on a commercial vessel from Tokyo to Singapore by Nakajima *et al.* [1999]. Based on the radiometric observations from these sites, the column SSA was found to be 0.9 at 500 nm and fairly constant in the vicinity of Indonesia [von Hovning-Huene *et al.*, 1999; Nakajima *et al.*, 1999], i.e. nearly the same as SSA observed during INDOEX [Ramanathan *et al.*, 2001].

[8] As we are not aware of any aerosol chemical and microphysical measurements performed at the same time and applicable to deriving an aerosol optical model, we employ standard polluted marine aerosol model of Hess *et al.* [1998], which contains sea salt, sulfate, and soot as components. For sea salt, the same vertical distribution is used as for boundary layer aerosol during INDOEX (uniform distribution up to 1000 m and then exponentially decreasing with a scale height of 800 m), while smoke components (soot and sulfate) are assumed to be uniformly distributed up to 2,000 meters and then exponentially decreasing with the same scale height (see observations by Ross and Hobbs [1998] during SCAR-B). Using the two aerosol vertical distributions and climatological profile of relative humidity as constraints on the model, the species' contributions are adjusted to get the pre-assigned SSA value of 0.9 at 500 nm. In such a way, the contributions of sea salt, soot and sulfate to AOD at 500 nm are 15 % (the same as observed during INDOEX), 11 % and 74 %, respectively. While the Hess *et al.* [1998] model does not include such an important aerosol component as organic carbon (OC), this assumption does not affect the results of this study. First, the observed SSA is used to constrain the aerosol optical model, and, second, phase functions for sulfate and OC were nearly the same during INDOEX [Satheesh *et al.*, 1999].

[9] Dubovik *et al.* [2002] recently reported spectral SSA for various regions of intensive biomass burning around the world, so that comparison can be made with the 1997 Indonesia's forest fire smoke based on the type of vegetation burned. A large proportion of the area that burned in Indonesia was not forest, but rather grass, agricultural wastes, scrub and non-woody swamp vegetation [Schweithelm, 1999]. Based on this information, the 1997 Indonesia's fire smoke should be more absorptive compared to biomass burning smoke in Brazil, and less absorptive than biomass burning smoke in African savanna, and this conclusion is supported by the data of Dubovik *et al.* [2002]. A similar comparison of Angstrom parameter is more difficult to make since it was a highly varying quantity during the 1997 Indonesia's fire [von Hovning-Huene *et al.*, 1999; Nakajima *et al.*, 1999].

[10] Aerosol particles are assumed spherical, asymmetry parameter and SSA for aerosol species are computed using

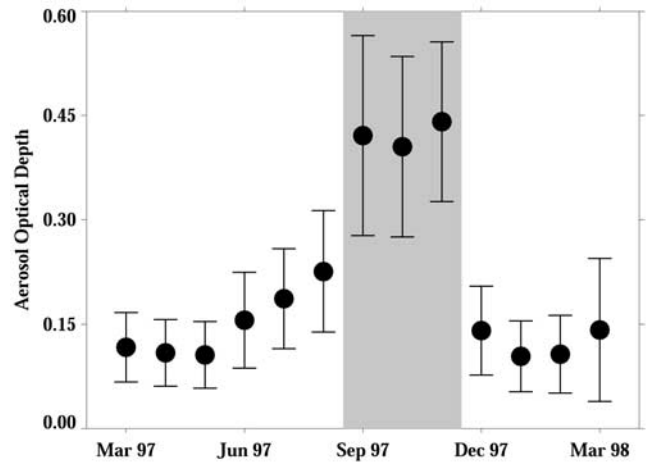


Figure 1. Regional (10°S to equator, 80° to 150°E) average monthly mean aerosol optical depth (AOD) at 630 nm retrieved from AVHRR observations over the Indian Ocean during the 1997 Indonesia's forest fires (shaded region). Vertical bars represent spatial inhomogeneity in AOD distribution.

the OPAC 3.1 software [Hess *et al.*, 1998]. The external mixing approximation used in this study is not critical, since SSA is constrained by observations. Besides, the mixing state has been shown to not affect significantly aerosol forcing over the tropical Indian Ocean based on the INDOEX aerosol model [Satheesh *et al.*, 1999].

3. Aerosol Radiative Forcing Calculations

[11] The monthly mean AOD distributions have been retrieved for 1997–1998 from AVHRR data using aerosol optical model described earlier and a look-up table approach [see Rajeev *et al.*, 2000 and Li and Ramanathan, 2002, for more detail]. The method accounts for multiple scattering by aerosols and absorption due to aerosol, water vapor and ozone. Figure 1 shows regional (10°S to equator, 80° to 150°E) average monthly mean AOD at 630 nm retrieved from AVHRR observations. As a consequence of the 1997 Indonesia's fire event, monthly mean AOD exhibits a distinctive maximum during September to November 1997.

[12] The aerosol radiative forcing is defined in this study as the effect of aerosol, both natural and anthropogenic, on the net short-wave radiative fluxes at the top of the atmosphere (TOA) and surface and on the absorption of short-wave radiation in the atmosphere [Ramanathan *et al.*, 2001, and references therein]. Aerosol forcing calculations also follow an approach described in Ramanathan *et al.* [2001]. Specifically, the diurnal average aerosol forcing as a function of AOD is parameterized using a Monte Carlo radiative transfer model and this parameterization is applied to the satellite derived AOD distributions. The diurnal time averaging is performed by Monte Carlo integration over the range of solar zenith angle representative for a given latitude and time of the year. The forcing over the land is not computed due to the lack of AOD retrievals.

[13] The International Satellite Cloud Climatology Project (ISCCP) data [Rossow *et al.*, 1996] have been used to calculate aerosol forcing for the general case of cloudy

skies. ISCCP data provide diurnal average cloud fractions for low-level, middle-level and high-level clouds at 2.5° by 2.5° grid boxes across the globe, however, the cloud optical thickness is given as the average for the grid box and hence additional information is necessary to partition cloud optical thickness between cloud layers. As we are not aware of such an algorithm, two limiting cases are considered with respect to the magnitude of aerosol forcing under cloudy skies. In the first case, all cloud optical thickness in a given grid box is assigned to the low-level clouds (1–2 km), whereas in the second case, all optical thickness is assigned to middle- (4–6 km) and high-level (8–12 km) clouds and is assumed the same for both cloud types. In such a way, the calculated forcing values are believed to bracket a “realistic” case and provide a measure of uncertainty in computing the forcing. The diurnal mean aerosol forcing is parameterized according to *Podgorny and Ramanathan* [2001] and *Ramanathan et al.* [2001] and then the parameterization obtained is applied to the monthly mean AODs and ISCCP data.

[14] Figure 2 presents the average forcing for the equatorial Indian Ocean. Under clear skies (i.e., assuming that optical thickness of clouds is infinitesimally small), the ratio of the surface to TOA forcing is about 3.3 in magnitude, which is nearly the same as the values observed during INDOEX [*Podgorny et al.*, 2000; *Satheesh and Ramanathan*, 2001] and indicative of absorbing aerosols. Since the low-level clouds (located between 1 and 2 km) are embedded in the absorbing aerosol, they tend to increase aerosol-induced absorption in the troposphere, while decreasing the magnitude of aerosol forcing at the TOA [e.g., see *Podgorny and Ramanathan*, 2001]. The middle- and high-level clouds tend to attenuate the aerosol forcing at the TOA and in the atmosphere by reducing the amount of solar energy reaching the lower troposphere. As seen from Figure 2, the presence of clouds reduces the magnitude of the TOA forcing significantly for both cloud cases considered, but has a relatively limited impact on the surface and atmospheric aerosol forcing, and aerosol contribution to the heating rates in the lower troposphere.

4. Regional Distributions of Aerosol Forcing

[15] Finally, we report regional distributions of aerosol forcing at the TOA and surface, and heating rates in the lower troposphere (Figure 3). To this goal, the cloud effects on aerosol radiative forcing are taken into account as an average of low and middle-high cloud cases (see previous section for more detail). The vertical distributions of heating rates for a polluted, pristine and cloudy atmospheres over the tropical Indian Ocean are presented in *Podgorny and Ramanathan* [2001]. As seen from Figure 3, the reduction of solar radiation at the surface reaches values as high as 30 to 50 W m^{-2} (15% to 25% of the climatological values) and the smoke induced atmospheric heating rates of 0.6 to 1 K/day are about 50% to 100% of the climatological [see *Podgorny and Ramanathan*, 2001] solar heating rates for this layer.

[16] We conclude with a brief discussion of the expected accuracy of the aerosol forcing results. Based on the sensitivity studies reported earlier [*Podgorny and Ramanathan*, 2001], the TOA forcing is most responsive to the errors in both cloud and aerosol optical properties. Rela-

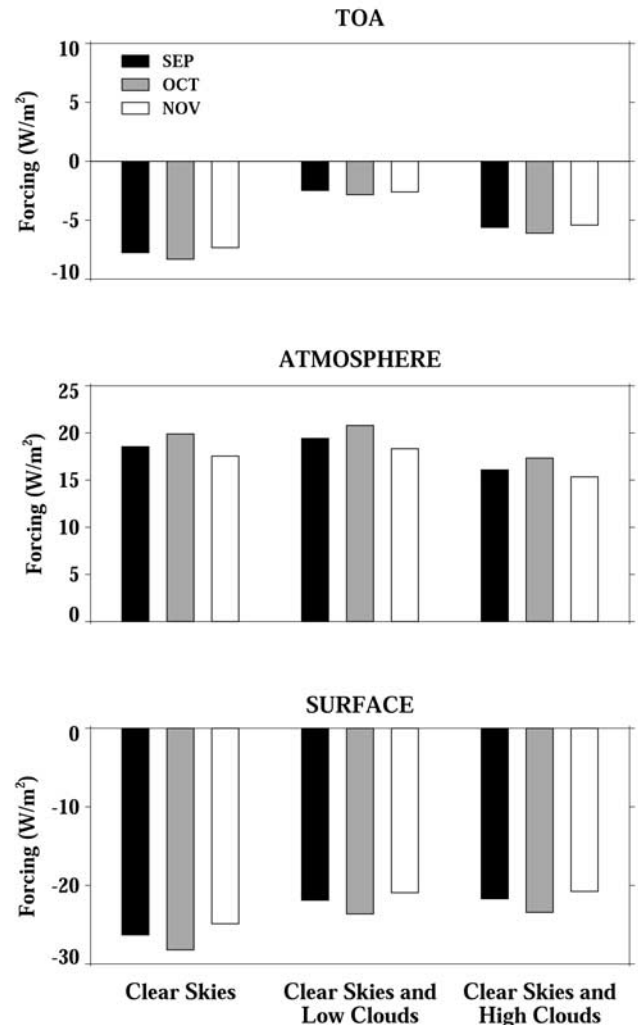


Figure 2. Regional (10°S to 10°N , 40° to 160°E) average aerosol radiative forcing during September to November 1997 calculated for clear sky and two limiting cases of low and high clouds.

tively small changes in low-level cloud fraction and SSA may result in significant changes in the magnitude and even the sign of the TOA forcing. As the aerosol absorption in the atmosphere is approximately a linear function of AOD and SSA, typical errors in satellite-derived AOD [15% according to *Rajeev and Ramanathan*, 2001] and ground-based derived SSA [about 0.01 according to *Ramanathan et al.*, 2001] would result in 15% and 10% relative errors in aerosol contributions to heating rates, respectively.

5. Conclusion

[17] Indonesia has experienced forest fire disasters before, but the worst of them occurred in the fall of 1997 during the dry weather fostered by El Niño. We show in this study that the smoke from this fire spread over most of the equatorial Indian Ocean and resulted in a large decrease in the solar flux at the ocean surface which was accompanied by a significant enhancement in the atmospheric solar heating. These results raise the possibility that biomass burning in Indonesia may be a significant factor affecting

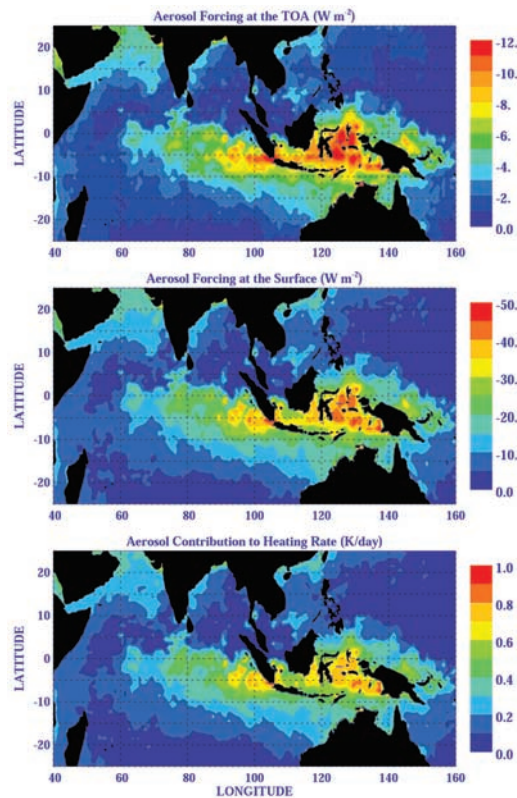


Figure 3. Regional distribution of aerosol forcing at the TOA (top panel) and surface (middle panel), and aerosol contribution to the heating rates in the lower troposphere (0–3 km) (bottom panel) under cloudy skies averaged over September to November 1997.

the regional climate, at least during years when El Niño amplifies the effects of biomass burning, as it did in 1997. In what follows we speculate on the potential impacts of the Indonesia's forest fire aerosols.

[18] The large reduction (15 to 25%) in the seasonal mean solar radiation absorbed by the equatorial Indian ocean when combined with the thermal inertia of the mixed layer (about 6 to 18 months depending on the mixed layer depth) suggests that the climatic effects of the smoke will linger at least for a year or longer. Ocean heat transport reduced evaporation or enhanced long-wave radiation from the warmer lower atmosphere can balance the reduction in sea surface solar radiation. Furthermore, as shown by Chung *et al.* [2002] and Chung and Ramanathan [2002], the large increase in solar heating (0.6 to 1 K/day) by the smoke within the atmosphere may be balanced by enhanced adiabatic cooling which, in turn, implies increased precipitation over the smoke region (largely ocean in this case) and compensating subsidence over most of the low latitudes. Thus a redistribution of tropical rainfall (i.e., droughts in some regions and flooding in others) may be one of the consequences. Indeed, Xu [2001] suggested similar effects for the China region resulting from the absorbing haze. These dynamical responses to the smoke forcing can also feedback on the El Niño phenomenon. The next step is to explore the importance of these effects with a coupled ocean-atmosphere model.

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