Impacts of Absorbing Aerosols on South Asian Rainfall

A Modeling Study

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Note: This paper will appear in Climatic Change published by Springer. The original will be available from www.springerlink.com. While the scientific Content would remain same, the final published version may slightly differ from this copy.

Abstract. Anthropogenic aerosols in the lower troposphere increase the absorption and scattering of solar radiation by air and clouds, causing a warmer atmosphere and a cooler surface. It is suspected that these effects contribute to slow down the hydrological cycle. We conducted a series of numerical experiments using a limited area atmospheric model to understand the impacts of aerosol radiative forcing on the rainfall process. Experiments with different radiative conditions under an idealized setting revealed that increasing atmospheric forcing and decreasing surface forcing of radiation causes reductions in rainfall. There was no relationship of top of the atmosphere forcing to the rainfall yield. The model was then used to simulate a domain covering southern part of Sri Lanka, over for the period from November 2002 to July 2003. For a given radiative forcing, instances with lower rainfall yields showed larger fractional reductions in rainfall. The trends in seasonal rainfall observed over the site in past 30 years in a different study confirms this finding. We conclude that the negative impact of increase of anthropogenic aerosols on rainfall would be more severe on regions and seasons with lower rainfall yields. The consequences of this problem on the industries that critically depend on well-distributed rainfall like non-irrigated agriculture and on the general livelihood of societies in low-rain areas can be serious.

Keywords: Aerosols, Radiative Forcing, Precipitation, Atmosphere, Atmospheric Brown Clouds, ABC, Anthropogenic Haze, Global dimming

1. Introduction

Changes in the earth's atmospheric composition due to human activities or other reasons, almost always affects the physical properties and processes in the atmosphere. Some of these changes are relatively slow and persistent over long periods of time. The abundance of greenhouse gases increase the trapping of long wave radiation emitted by the earth surface and causes a systematic change in the temperature of the earth system. In the presence of high systematic (e.g. seasonal) and random variability of many properties of the earth system, these slow changes are not immediately apparent, but becomes clear in long-term trends. Increase of atmospheric aerosol and the resulting changes in the atmosphere, on the other hand, are relatively short-term phenomena due to the short lifespan of particles in atmosphere. The persistence of the aerosols are affected by a number of atmospheric-factors like humidity, winds, precipitation, etc. and the sources of aerosols, and hence the aerosol concentrations often vary seasonally.

Every year polluted air from northern land masses including Indian sub continent interacts with the clean flows from south over the Indian ocean causing high absorbing aerosol concentrations, now known as Atmospheric Brown Clouds (ABCs), hovering in the atmosphere during the period from December to April. Several experimental and modeling studies have indicated that these concentrations show unusually large blocking of solar energy. Later it has been shown that this is not a problem local to the south Asia, but becoming increasingly apparent in many parts of the world. Several researchers have indicated that radiative forcing due to anthropogenic aerosol can cause major changes in the global water cycle (Section 2). However, there are very few studies on the effects of aerosol radiative forcing at local scales (e.g. watershed scale).

In this paper, we describe a series of numerical experiments conducted using a limited area atmospheric model (MM5 of NCAR, see section 3) to investigate the impacts of aerosol radiative forcing on the tropical rainfall. First the effect of different forcing levels were investigated under idealized conditions where all other parameters (e.g. moisture, winds, temperature, topography, landuse) were carefully controlled. The results indicated that the rainfall yields are sensitive to the amount of radiation absorbed by the atmosphere (atmospheric forcing) and the reduction of downward radiative flux at surface level (surface forcing). Under these idealized conditions, an unchanging level of radiative forcing that was equivalent to south asian seasonal haze (Ramanathan et al., 2001a) resulted in about 6% reduction in rainfall. A six-month long series of simulations to cover the period of occurrence of seasonal aerosol concentrations were conducted for the southern part of the island of Sri Lanka, under real-world atmospheric situation, with only radiative properties changed. These results showed that the smaller rainfalls are much seriously affected by increasing aerosol radiative forcing than larger rains.

2. Aerosols and Atmospheric Radiative Transfer

Aerosols directly increase the absorption and scatter of solar radiation by the atmosphere. Additionally, there are several indirect impacts of aerosols on the heat budget of the atmospheric system. Large concentrations of aerosols (particularly the size range between 10^{-2} µm 10^{1} µm diameters known as large aerosols) increases cloud reflectivity (barrier for radiative transfer) by providing more sites for water droplet formation (Hansen et al., 1997). This also increases the lifetime of clouds (Twomey, 1980) – another cause of radiative blocking. The radiative impacts of aerosols are largely limited to short-wave solar radiation, whereas long-wave terrestrial radiation passes largely unaffected.

In the earth atmosphere system, the effect of the changes of radiative properties can be seen in three diagnostic quantities of the radiative budget of the earth-atmosphere system, namely top of the atmosphere forcing (ATMF) – the net effect on the earth-atmospheric system, changes in the heat flux at earth surface (Surface Forcing, SURFF) and as heating tendency of atmosphere (Atmospheric forcing, ATMF). Traditional focus when dealing with global-scale issues like warming due to GHGs was largely on TOAF (Intergovernmental Panel on Climate Change (IPCC), 1995). However, to better understand regional climatic issues like aerosol effect it is necessary to investigate the ATMF and SURFF as well.

Blocking of solar radiation by aerosol abundance is not a new issue. It has been reasonably well established that the increase of atmospheric aerosols (mainly highly reflective sulfate aerosols) due to an impact of a large extraterrestrial body was responsible for a huge blocking of solar radiation known as the ‘impact winter’ (Pope et al., 1997) , which caused a global-scale collapse of the ecosystems including the extinction of many dinosaur species some 65 million years ago (Galeotti et al., 2004). More recently, Benjamin Franklin (1706-1790) hypothesized that the severe winter in Europe in 1783 is related to the increase of aerosols due to Laki volcano eruption in Iceland.

Based on the hypothesis that the most extensive long-lived anthropogenic aerosols are highly reflective sulfates, Hansen and Lacis (1990) indicated that the aerosols have a net cooling effect on the earth and atmosphere – a competing effect with greenhouse gases. The global forcing of anthropogenic aerosols (1-1.5 W/m^{-2}) is smaller than greenhouse forcing(2-2.5 W/m^{-2}). Later Penner et al. (1992) estimated aerosol radiative forcing due to contemporary biomass burning to be around -2 W/m^2, almost equal to the greenhouse forcing in magnitude.

Crutzen and Andreae (1990) estimated the total direct releases of carbon into the atmosphere due to anthropogenic burning related to shifting agriculture, Savannah fires, firewood burning and agriculture is in the range of 1500 – 4000 Tg/year. In comparison to the amounts released by wild-fires and planned burning of forests (150-300 Tg/year) above are very significant sources. Out of total particulate matter released by biomass burning, about 80% is carbonaceous (organic and elemental carbon) and almost 20% is high radiation absorbing black (elemental) carbon (Andreae et al., 1988). Based on these findings Crutzen and Andreae (1990) indicated that increased aerosols due to biomass burning can have significant impacts on cloud microphysical and radiative processes and as a result the tropical rainfall and hydrological cycle may be affected.

The first large-scale experimental study on anthropogenic aerosol plume of South Asia was the INDOEX experiment (Ramanathan et al., 2001b), which involved observations using satellites, aircraft, ships, surface stations and balloons, supplemented by aerosol models to derive regional aerosol radiative forcing. The experiment revealed that the aerosol buildups during the December-April season can reduce the solar heating of the ocean by about 15% (20 to 30 W/m^{-2}). Regionally (and seasonally), this is very much larger than the globally averaged greenhouse forcing values. The Aerosol Optical Depth (AOD) – a measure indicating the difficulty for the light to penetrate atmosphere regularly reached values as large as 0.5 (compared to 0.2 for pristine air). There can be a heating tendency in the atmosphere due to absorbing aerosols (Ramanathan et al., 2001a). They computed that the heating tendency is about 0.4 K/day for an atmospheric forcing about 15 W/m^2. Using the Community Climate Model (CCM3)(Kiehl et al., 1998), Ramanathan et al. (2001b) showed that the rainfall along the Inter-Tropical Convergence Zone (ITCZ) can be increased by about 15% to 30%.

Using the observations of first phase of INDOEX experiment (February to March, 1998) with a multi-scattering Monte-Carlo radiation model, Podgorny et al. (2000) showed that the black carbon content (approx. 10% of aerosol optical depth) in INDOEX aerosols is responsible for about 50% of the solar heat absorption of the clear air. In clear air situations, the average aerosol ATMF was about +12 W/m^2.

Novakov et al. (2000), analyzing INDOEX aerosol observations, showed that the black carbon contents of the Indo-Asian aerosols are comparable with those observed associated with major industrialized countries (e.g. Japan) which are characterized by heavy fossil fuel use. Further the constancy of the black carbon (BC) ratio to total carbon (TC) and organic carbon (OC) indicated that the bulk of the carbonaceous aerosols are from primary terrestrial sources, not from the secondary production of organic carbon aerosols by photochemical reactions (Cooke et al., 1999).

MayolBracero et al. (2002) published a detailed chemical and optical analysis of INDOEX aerosols and reported that on average, 14% of the aerosol mass was BC. Further, using correlation analysis they established that the high absorbing nature of the INDOEX aerosols are due to the high concentrations of BC. On the vertical profile, the largest concentrations of aerosols were on the residual continental boundary layer, rCBL (1.3 to 3.2 km) while smaller concentrations were found on the Marine boundary layer, MBL (∼1.2 km).

While observation or experiment results provide the ultimate test for any scientific hypothesis, in reality, often modeling helps to fill the gaps in experimentation. Further, the prediction of future changes and their impacts can only be successfully done using models. Modeling studies on anthropogenic aerosol impacts on climate have almost always focused on large scale and impact studies on watershed or equivalent level are markedly lacking. The research presented in this paper was an attempt to contribute to fill this gap.

3. Model

As discussed in the previous section there have been a number of studies using global circulation models to investigate the effect of the aerosols on the atmospheric circulation, heat budget and rainfall. A-GCMs depend on empirical parameterizations to resolve the cumulus cloud development and the resulting rainfall. Careful calibration of the cumulus parameterization is required for these schemes to realistically produce grid-mean values for cumulus process. Often the convective cloud cover is not considered in radiative transfer, due to the inability to explicitly resolve clouds. While limited-area atmospheric models (LAMs) at coarse resolutions also have to resort to cumulus parameterization, at finer resolutions (typically $< 5 \sim 10$ km), it is possible for them to rely reasonably completely on the basic physical processes to resolve clouds and rainfall. Due to this reason, high-resolution models can give a better understanding of the short term effects of aerosols on cloud and rainfall processes.

Another major difference between GCMs and LAMs is that while the former operates in a virtually-closed system concerning the material conservation, and hence only the initial conditions are prescribed (apart from the energy transfer with out side earth-atmospheric system), the latter requires the specification of lateral boundary conditions for the entire duration of simulation. For controlled experiments like the one presented in this paper, the ability to be controlled by lateral boundary conditions is advantageous: Although it is impossible to obtain the exact same behavior during two runs of a model representing a dynamically complex system like atmosphere, it is possible to have a reasonable control for a short duration of a few days. In every pair of numerical experiments we have conducted, we have changed only one model condition (ABCs) while keeping the lateral boundary conditions identical.

We used the fifth generation Pennsylvania State University/National Center for Atmospheric Research mesoscale model, MM5 (Dudhia, 1993; Grell et al., 1996) for the study reported in this paper. Present day's atmospheric models, including MM5 are not sophisticated enough to represent the various effects of aerosols on the transmission of solar radiation through the atmosphere and the cloud microphysics. The cloud-radiation scheme (Dudhia, 1993) used in MM5 model accounts for 1) absorption by atmosphere (Lacis and Hansen, 1974), 2) Rayleigh (small particles like air molecules)and aerosol scattering of clean atmosphere, 3) Cloud absorption and 4) Cloud reflection. Our approach in this study was to modify the short-wave (solar) radiation scheme of the model to parameterize the aerosol impact directly in to the radiative budget. The radiative changes due to aerosol were represented by increasing the absorption (1 and 3) and scattering (2 and 4), each by a factor (hereafter referred to as ABS and SCT). The possible differences of response between atmospheric layers and clouds, to the change in aerosol were not considered, largely due to the unavailability of data on such differences. The scattering and absorption factors were vertically varied (Figure 1) to mimic the common distribution of (particularly anthropogenic) aerosols (ABCs) observed in experimental studies (MayolBracero et al., 2002). While the present modification does neither represent the exact physical processes of aerosol radiative forcing at the microphysical scale nor cover the impact of aerosol increase on cloud microphysics, it provides a convenient means of examining the impact of the radiative forcing on the atmospheric system.

4. Numerical Experiments

4.1. IDEALIZED CASE

Idealized physical simulations can be used to introduce the conditions of actual atmosphere into a numerical model in a controlled manner, thus making it possible to isolate them from the other complexities of the real atmosphere for a closer study. They, therefore provide good platforms to examine the response of atmospheric processes (as they are represented in the model) to different changes in influencing parameters. We used a modified version of MM5 model (Pathirana et al., 2005) to investigate the effects of the changes of radiative properties described in section 3 on the overall radiative budget of the atmosphere and the relationship of those changes to the yield of rainfall. Since the user has the freedom to introduce different boundary conditions in this modeling rig, it is possible to create scenarios with different meteorological conditions. For example, by introducing different moisture contents (while maintaining the physical compatibility of all the properties of air) it is possible to create scenarios with differing rainfall yields. (This is how the 'normal' and 'dry' scenarios that are referred to later in this section were obtained).

The modeling domain was as follows: a 2000 km high Gaussian mountain ridge was subjected to 10m/s steady lateral wind field. The relative humidity of flowing air was nearly-saturated (RH >90%) on layers near the surface and then gradually dropped with height to a value less than 30% above 450 hPa level (See 'normal' condition in table I). The details of this idealized experiment are given in Pathirana et al. (2005). The model was run for 48h period for each experiment with different ATMF and SURFF values. Totally 20 experiments were conducted.

The following quantities were computed for each simulation: 1) The three radiative parameters (TOAF, ATMF and SURFF) averaged over each 24h period and 2) the rainfall accumulated over these periods. Table II shows the correlations of the three different radiative parameters with absorption and scattering factors. In the model, ABS significantly affects SURFF and ATMF while SCT affects TOAF and SURFF. These are expected behaviors of the model. A heating tendency continues to the upper reaches of the atmosphere. The boundary layer shows a small negative response probably due to the cooling effect of ABCs on the surface. The negative change of vertical velocity in the lower reaches indicate increased stability of the atmosphere, while around and above the ABCs peak, there is a positive change (decreased stability). The moisture in the first kilometer from the surface is reduced, but that of the upper reaches are increased. We discuss the possible implications of these findings towards the end of this paper.

Figure 2 looks at the relationship of the three radiative parameters to the change in the accumulated rainfall yield. The atmospheric forcing and surface forcing have clear, strong relationships with the rainfall yield while TOAF does not. It was also clear from the results that SURFF and ATMF are also correlated to each other (correlation coefficient 0.76, coefficient of determination for a liner fit, 0.57, graphs not shown) therefore it is important to determine whether there is an effect on rainfall of one factor independent of the other. We used partial correlation technique to ascertain this and found that both SURFF and ATMF shows statistically significant partial correlations with rainfall yield. (0.58 and 0.38, respectively.) The rainfall variation in SURFF-ATMF space is shown in figure 3. In spite of the irregularity of the relationship, the variation indicates that the rainfall is influenced both by surface forcing and atmospheric forcing. Increasing ATMF and decreasing SURFF results in reduced rainfall.

The results indicate that the radiative forcing due to the increased absorption and scattering in the atmosphere and clouds results in a reduction in local rainfall yields. Both the increasing ATMF and decreasing SURFF (the typical effects of increased absorption and scattering due to aerosols) have effects on rainfall in same direction – they cause rainfall to reduce.

We conducted a smaller set of experiments that corresponds to a situation with lower rainfall yield than that of above series of experiments. This was achieved by setting the relative humidity of air to lower values than those of the above experiments (hereafter referred to as ‘dry’ case, see table I) The rainfall yield averaged over the total model domain for normal and dry cases, with no radiative forcing, were 7mm/day and 0.14mm/day, respectively. The relationship between the rainfall reduction and radiative forcing values for these cases, with corresponding ‘normal’ experiments are given in figure 4. This indicates that the aerosol radiative forcing causes much larger fractional reductions in the cases of small rainfall quantities. In the next section we shall examine the effect of radiative forcing on different rainfall yields, using a detailed application of a radiative forcing scenario to a real-world atmospheric situation.

4.2. REAL-WORLD CASE

We applied the changes in radiative forcing explained in the previous section to a real-world atmospheric situation. One objective of this second phase of study was to investigate the impacts of radiative forcing on different rainfall intensities, under more realistic conditions than that of the idealized study reported above. We selected the southern part of the island of Sri Lanka as the candidate area of this simulations and covered a period of six months from November 2002 to July 2003. Southern Sri Lanka is an ideal location to cover a number of tropical rainfall climatologies within an area as small as 30000km^2. During the target period monthly rainfall at locations can range from almost none to more than 600mm. The topography varies from sea level to 2500m. The area was covered with 4km grid size, which made it reasonable to allow only explicit resolving of rainfall without resorting to a convective parameterization scheme in this innermost grid. The initial and lateral boundary conditions were obtained from Final Global Data Assimilation System (FNL) of the National Center for Environmental Prediction, USA. The data resolution is 1^0x1^0 in space and daily in time. In order to economically use the computing resources, a nesting scheme consisting of three levels (36, 12 and 4km grid sizes) was adopted. Figure 5 show the nested domains with the innermost, 4km domain expanded.

Limited-area weather models like MM5 are designed to run over short periods of time like several days. Their skill degrades rapidly with forecasting time due to the chaotic nature of the atmospheric processes. Due to this instability in long-term, the six months period was covered using a series of simulations, each spanning five days period. The model was run under only one radiative forcing condition (ABS=1.5, SCT=1.5). The radiative parameters and rainfall accumulations were calculated for each pixel for 24h periods. The computations were spatially averaged over 3x3 pixel areas (144km^2) before further analysis .

Figure 6 shows the values of TOAF and SURFF observed during the simulations. The average values were 40 and 59 W/m^2, respectively, giving an average ATMF of 19W/m^2. It should be noted that these values are significantly different from some observational studies (e.g. (Ramanathan et al., 2001b)) The maximum ground temperature was reduced by about 2K, whereas minimum (usually night time) temperature was not affected (Figure 7). Under these conditions, the rainfall yield during the six months period was reduced by 18% due to the introduction of aerosol radiative forcing. However, it was clear that this reduction was not uniform over rainfalls different intensities. As figure 8 shows, the small rainfall intensities were much severely affected than heavy rainfalls. Rainfalls of 1-2mm intensity are retarded by 35% on average, while 20-40mm are affected only by 10%.

Figure 5 shows the typical variation of the changes of different atmospheric quantities due to introduction of aerosols. (The example shown in the figure is for the case ABS=SCT=3.0.) All the quantities were calculated as averages over the whole time period of the simulation. First, the most direct impact is the increase of atmospheric radiative heating tendency, whose peak occur several hundred meters above that of the ABCs peak.

5. Discussion

We used a limited area atmospheric model with the short-wave radiative scheme altered, to study the effect of aerosol radiative forcing on rainfall process. The model was modified by introducing two multiplicative factors, ABS and SCT to increase the absorption and scattering of solar radiation, respectively. Two sets of numerical experiments were reported, namely: 1) A series of idealized simulations on the classical problem of flow past a mountain ridge to clarify the relationships between the multiplicative factors, atmospheric radiative forcing parameters and the rainfall yield. 2) A modeling study on a tropical setting (Southern part of the island of Sri Lanka) covering a six months period in order to understand the effect of aerosol radiative forcing on different rainfall intensities.

The factors ABS and SCT, used to mimic the aerosol radiative forcing, are quantities that are meaningful only within the context of the particular radiative forcing scheme used. Therefore, rather than establishing relationships between these quantities and the rainfall, we preferred to derive the three accepted measures of radiative forcing in the atmosphere, namely SURFF, TOAF and ATMF, and related them to the rainfall variations. This approach provides results that can be compared with those of other modeling and experimental studies.

There are fundamental differences between the radiative responses of typical Aitken Nuclei like air molecules (diameter 10^{-3}µm which can be explained by Rayleigh scattering) and much larger smoke, dust and haze particles, which are the subject of the present paper. A main one is the selective response of large aerosols to different wavelengths (Mie model). However, the short wave radiative schemes of many LAMs, including the 'cloud radiation schem' of MM5, do not take different wavelengths in to account, but empirically parameterize the fraction of radiation that is absorbed and scattered. It is on this basis that we justified the application of direct multiplicative factors to the absorption and scattering by air and clouds. It is clear that this approach should be further improved in future studies.

The ABS factor shows a strong positive correlation with ATMF and a negative correlation of similar magnitude with SURFF (Table II).

This represents the amount of solar radiation lost to the surface as a result of absorption by air and clouds during the descent though the atmosphere. SCT is negatively affects both TOAF and SURFF, indicating the short-wave radiation lost back to the outer space due to scattering by air and clouds.

The atmospheric conditions in the idealized study were carefully kept constant between experiments and with time (during the same experiment). Therefore the only atmospheric parameters that could affect the model outputs like rainfall yield were the radiative changes. The rainfall yield showed strong correlations with the SURFF and ATMF (figure 2). The significant partial correlations indicate that each of these is strongly related to the rainfall yield, even when accounted for the effect of the other. This indicates possibility of aerosols radiative forcing acting to slow-down the hydrological cycle at two stages: The increased atmospheric heating due to aerosols act to re-evaporate clouds and retard the formation of rainfall. The day-time cooling of surface due to negative SURFF (figure 2) adversely affects the evapotranspiration, making less moisture available for the atmospheric processes. Cooling surface can also affect the convective development by creating highly stable (difficult for the air to rise in the atmosphere) layers near the surface.

The second set of simulations on the real-world case, provided more realistic and variable atmospheric fields (e.g. moisture, winds) providing an opportunity to investigate the effect of aerosol radiative forcing on different rainfall intensities. It should be noted that the atmospheric forcings (Average SURFF, ATMF, 60 W/m^2, 20 W/m^2, respectively) that were applied to this second exercise were somewhat different to the aerosol radiative forcing values reported from past observation studies like INDOEX (SURFF, ATMF approximately 50 W/m^2 and 30 W/m^2).

The study revealed that the rainfalls of different intensities are affected to a deferent degrees making smallest rainfalls being affected most severely. It is interesting to see this result together with the recent trends observed in rainfall of the central Sri Lanka. Reporting an analysis of some 60 rain gauges from the same general area covered in the present modeling study, Herath and Ratnayake (2004) showed that, while the annual rainfall of last three decades did not show any systematic reduction, the inter-monsoon rainfall, which is characterized by small, scattered showers lasting for short duration was significantly reduced. Considering that it is the peak period of the anthropogenic aerosol in the region, the reason for the marked reduction of inter-monsoon rainfall may be the radiative forcing induced by these pollutants in the region. The most definitive approach for examining such a hypothesis would be a long-term observation study on the changes of aerosols, their radiative forcing and the changes in rainfall. While the new remote sensing methods can be an aid in conducting such an exercise, it would definitely be a tremendously expensive and an involved affair. Due to the complexity of the processes and responses of the atmosphere, and the large number of other changes simultaneously taking place in the water-cycle (e.g. landuse, greenhouse gases, inter-annual ENSO and monsoon patterns), isolating the impacts of aerosol radiative forcing would be difficult without the benefit of suitable ‘control experiments’. In this situation, modeling studies provide arguably one of the ‘best-possible’ tools to gain qualitative insights into the effects of aerosol radiative forcing on the hydrological cycle.

The reductions of rainfall indicated by the model study are large. (Up to 12% in case of experiment I and 18% on average, in experiment II) However, these results should be understood in the proper perspective. The aerosol forcing was constant in space and time in the reported experiments, whereas in reality it is hardly so. For example, the south Asian haze is highly seasonal as well as variable at smaller time-scales (Ramanathan et al., 2001b). Further, the rainfall itself acts to cleanse the atmosphere of aerosols (by trapping them during nucleation of cloud droplets) so that rainfall reductions comparable to the magnitude of the present modelings can occur only during the onset of the rainy periods. (This fact may further enhance the difference of aerosol impact on small and large quantities of rainfall in reality, compared to the present results.) While it is possible to consider this in modeling with suitable implementations of aerosol chemistry, the present model did not have that sophistication. Above may be the reasons why the annual rainfall quantities of the south Asia are not significantly affected by recent increase of anthropogenic aerosols.

The surface temperature is reduced due to ABCs. The analysis of the surface heat budget shows that there is a reduction of both incoming short wave radiation and the latent and sensible heat fluxes are reduced. The reduction of short wave energy is compensated on average by about 75% by the decreasing of sensible and heat fluxes. The balance 25% contributes to surface cooling. The length present simulations are not long enough to comment on the long-term stability of the heat budget.

The present results of reduction of rainfall due to aerosol radiative forcing contradicts the impacts indicated by some global model studies while agrees with others. For example Ramanathan et al. (2001b) indicated that the rainfall along the Inter-Tropical Convergence Zone (ITCZ) can be increased significantly due to aerosol radiative forcing. This indicates that the same atmospheric heating tendency due to aerosol absorption can have two opposite effects at two different scales.

Still it is an open question whether to what degree these two effect compensate with each other and which predominates. The temperature changes (figure 5) indicated by the present paper agrees closely with the GCM study by Ramanathan et al. (2005) (See the web supporting material available at http://www.pnas.org/cgi/content/full/0500656102/DC1). There is also a sinking tendency in the lower atmosphere (1-2.5km) and a rising one in the upper atmosphere (¿2.5km) due to the introduction of ABCs. This is consistent with the recent observation of speeding up of the Hadley-type winter circulation over south Asia and Indian Ocean. (Ramanathan et al., 2005,) has reported that the rainfall reduction occurs due to ABCs.

Perhaps the most significant result of the present study is the relatively larger fractional impact on small rainfall quantities, compared with the larger ones. It can be anticipated that the effects of aerosol forcing would be much predominant with seasons/regions with small rainfall quantities. This makes the aerosol radiative impacts of rainfall a much more important consideration than the average reductions of rainfall seem to indicate. For example, a decrease of surface forcing by 25W/m^2 (Similar to the values observed during INDOEX) would cause 15% reduction of rainfall in dry case whereas normal case was affected only by 3% (Figure 4).

The impacts of the retardation of early onset of rainfall can have dramatic effects on rainfall dependent industries like agriculture. For example a preliminary crop modeling study reported by Herath et al. (2004) indicate that the non-irrigated rice yield in central Sri Lanka can be significantly reduced in response to the reduction of inter-monsoon rainfall, unless the planting season is postponed.

Impacts of the increase of anthropogenic aerosols on rainfall are complex. In the present study we conducted a series of numerical experiments to investigate the impacts of the change of solar radiation distribution between the surface and the atmospheric layers. We found that surface radiative forcing and atmospheric radiative forcing have strong relationships with rainfall yield, whereas top of the atmosphere forcing's effect was insignificant. Further, the fractional reduction of small rainfall quantities were much larger than those of larger rainfall quantities, indicating that seasons and regions with small rainfalls can be more vulnerable for the rainfall reduction due to anthropogenic aerosols. This makes it possible for the aerosol radiative forcing to have severe impacts on rain dependent industries like non-irrigated agriculture.

Acknowledgements

This study was funded partially by a grant from Japan Science and Technology Agency (JST) under JST-CREST project.

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Table I. The moisture profiles for 'Normal' and 'Dry' cases.

P (hPa)	1000	950	850	700	500	400	300	100
'Normal'	95	95	95	95	80	75	50	30
'Dry'	90	85	70	60	50	40	30	30

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Table II. Correlations among ABS, SCT and the radiative parameters. Significant correlation values (based on t-statistic) are bold-faced.

	ABS	SCT	TOAF	SURFF
SCT	0.3			
TOAF	0.3	**-0.6**		
SURFF	**-0.9**	**-0.5**	0.1	
ATMF	**0.9**	0.0	**0.6**	**-0.8**

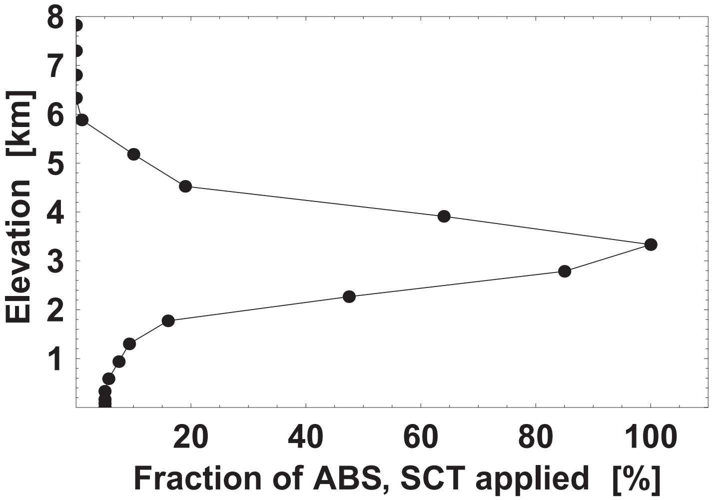

Figure 1. To comply with observed distribution of aerosols, the absorption and scattering effects were varied with elevation. E.g. ABS=1.5 implies that the absorption at 2km and 3km was increased by factors of $(1.5-1)$x20=10% and $(1.5-1)$x100=50%, respectively.

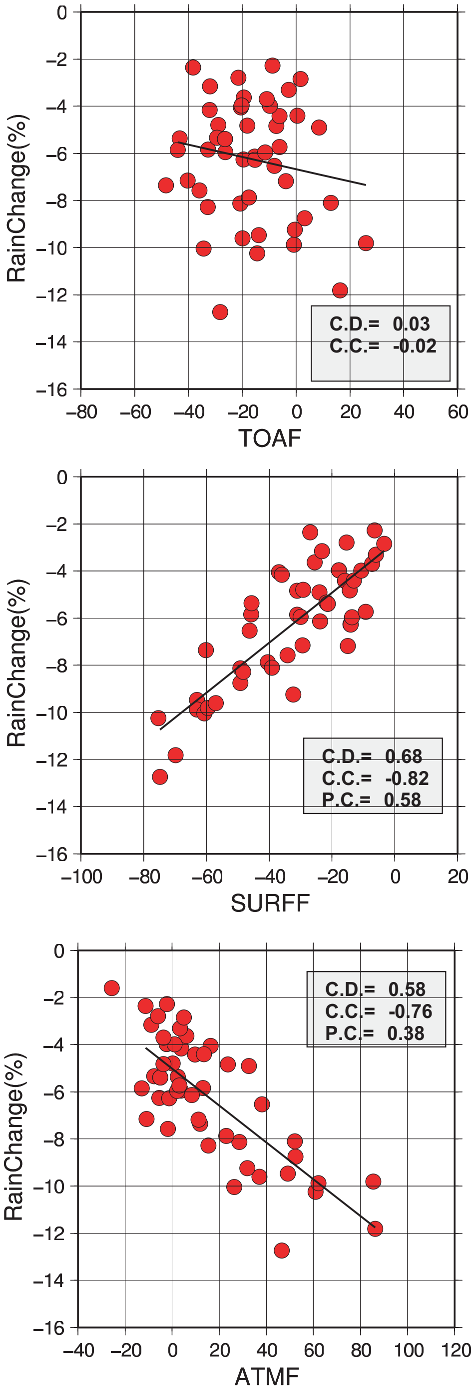

Figure 2. Influence of three radiative parameters on the rainfall change. C.D. - Coefficient of determination. C.C. - correlation coefficient. P.C. - partial correlation of ATMF and SURFF controlling for SURFF and ATMF, respectively.

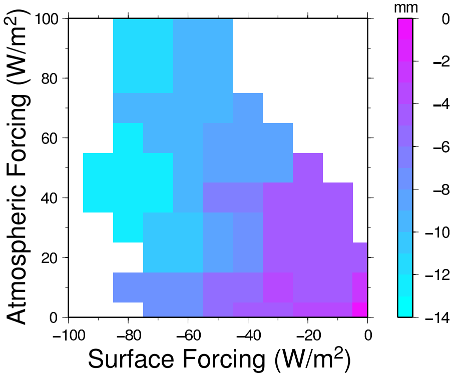

Figure 3. The sensitivity of rainfall yield to Surface forcing and atmospheric forcing. The clear area is not covered by the results.

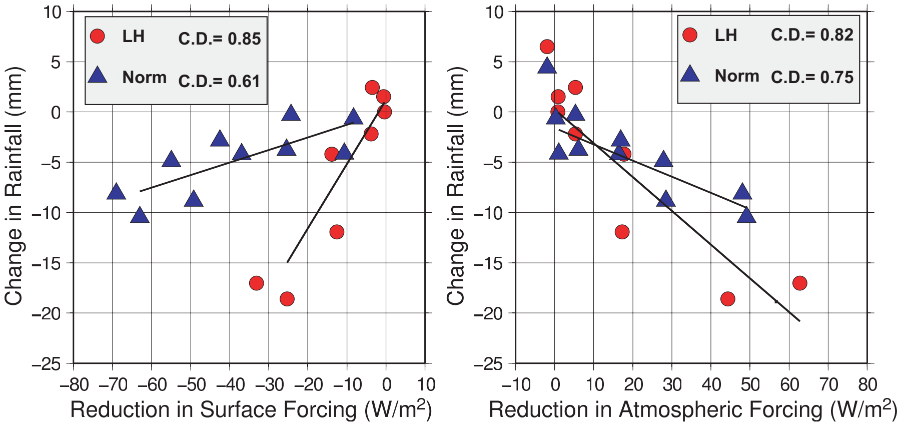

Figure 4. Low rainfall situations showed much larger fractional reduction of rainfall for a given radiative forcing.

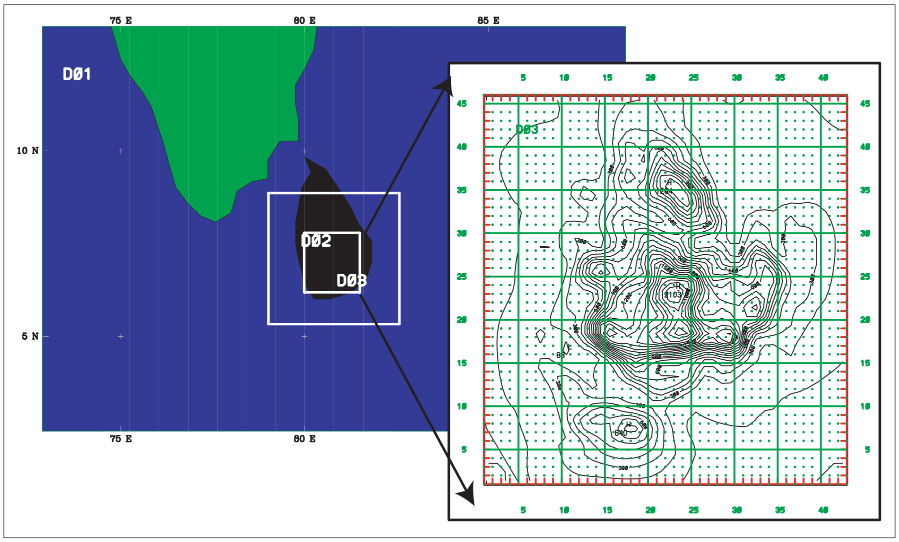

Figure 5. The model domain used for the simulations in Sri Lanka. There were three nested domains and the innermost (4km) grid (shown expanded with topography) was used for further analysis.

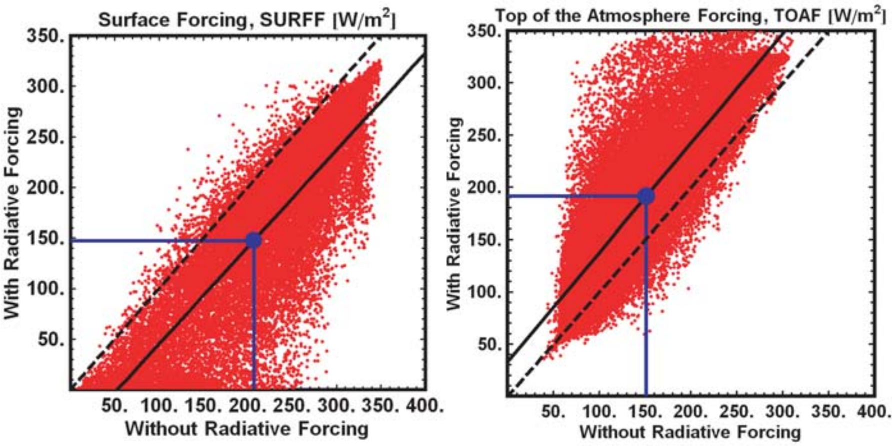

Figure 6. Radiative forcing values during the simulation.

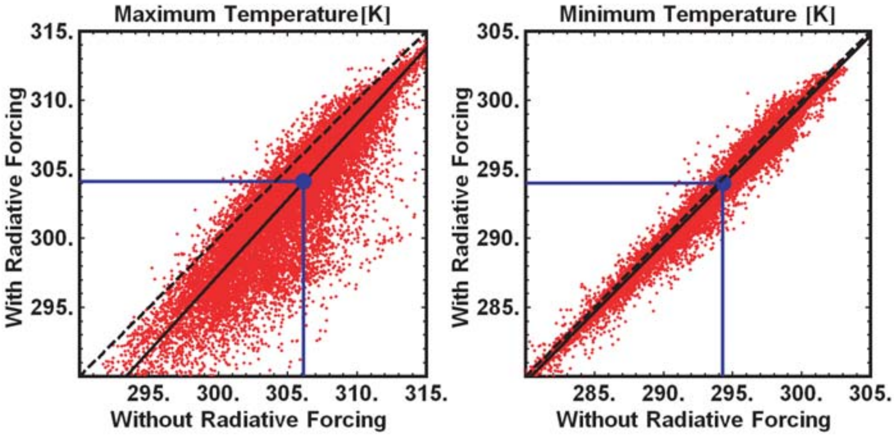

Figure 7. Maximum and minimum ground temperature values during the simulation.

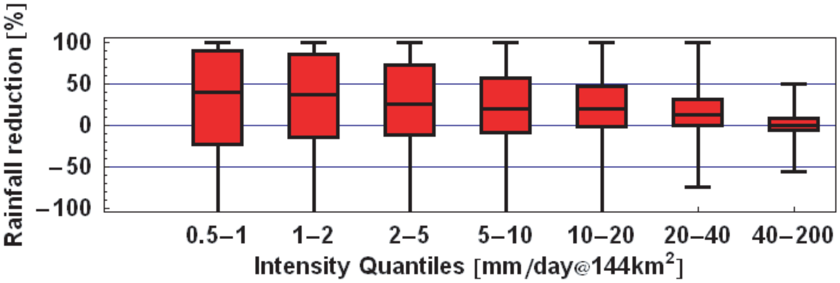

Figure 8. Percentage reduction of rainfall for different intensities. Box and Whiskers represent 25% and 75% quantiles, respectively.

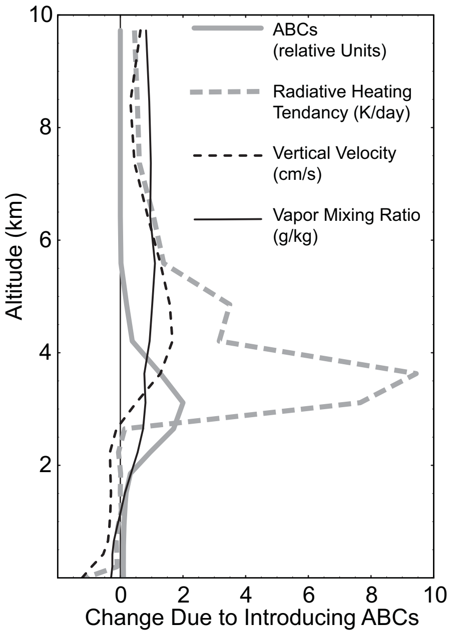

Figure 9. Radiative heating tendency change in the atmosphere due to the introduction of aerosols closely follows that of aerosol forcing (This is a case with ABS=SCT; Indicated as ABCs in the graph.). Vertical velocity is increased above the absorbing layer and decreased below. Moisture is reduced at the boundary layer, but is increased in the absorbing layers and above.