4.1 EFFECT OF ATMOSPHERIC COMPOSITION ON RADIATION BALANCE, CLOUD MICROPHYSICS AND INDIAN SUMMER MONSOON RAINFALL

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1. INTRODUCTION

The Asian summer monsoon is a giant feed-back system involving interactions between land, ocean and atmosphere. Efforts to understand its behaviour is scientifically challenging, and dates back to about a century, which have produced large amount of literatures (e.g., Walker 1910; Bjerknes 1969; Lighthill and Pearce 1981; Hastenrath 1988; Pant and Rupakumar 1997; Webster et al. 1998). The Indian summer monsoon rainfall (ISMR), defined by the cumulative rainfall over the continental India during June-July-August (JJA), also has important implications for the socio-economic system of that subcontinent. For example, the domestic crop yield in India has been traditionally linked to the amount of summer monsoon rainfall (SMR) (Parthasarathy et al. 1988); the agricultural sector accounts for 25 percent of India's gross domestic product and 60 percent of the labour force. The JJA rainfall in 2002 was only about 78% of average rainfall amount (679.2 cm, for the period 1871-2002) (Parthasarathy et al. 1995), and that resulted in almost a 40% drop in groundnut production (www.agjournal.com). This is one of the two highly rainfall deficit years, second only to 1972, in the past century.

The dynamical link between below normal rainfall years and the positive phase of El Niño/Southern Oscillation (ENSO) (see a review by Webster et al. 1998) or the negative phases of Indian Ocean Dipole (IOD) have been addressed earlier (Ashok et al. 2001). In these impact studies, only the dynamical aspect of the summer monsoon system (SMS) is considered; so as the statistical ISMR prediction model employed by the Indian Meteorological Department (IMD) (e.g. Gowariker 1991). In contrast, the focus of this study is to analyze the radiation and microphysical aspects of the SMS.

The aerosol particles (with residence time ranging from days to weeks) can absorb or reflect the incoming solar radiation to exert large radiative cooling (21-26 W m^{-2}) at the earth's surface and warming (16-18 W m^{-2}) in the troposphere (Podgorny et al. 2003). Recently, it has also been suggested that different aerosol types of continental origin could affect the growth of cloud droplets and thereby the rainfall intensity over the Amazonian region (Andreae et al., 2004). All the above mentioned processes could coherently effect the SMS by reducing evaporation from sea surface, weakening the pressure gradients between the African high and Tibetan low (transverse monsoon component), and inhibiting growth of cloud droplets.

2. DATA AND ANALYSIS

We have used meteorological (winds, sea surface temperature - SST, outgoing long-wave radiation - OLR) datasets from the NCEP/NCAR reanalysis to depict the mean state of the atmosphere (1979-2002) and deviations during two distinct years of 2002 (deficient ISMR along with a negative IOD phase) and 2003 (surplus ISMR with a positive IOD phase). In addition, the choice of these years is to a great extent restricted by the unavailability of the coherent physical and microphysical data. The aerosol indices are gathered from the Total Ozone Mapping Spectrometer (TOMS) (Herman et al. 1997), and aerosol microphysical properties are derived using the Moderate Resolution Imaging Spectroradiometer (MODIS) measurements (Nakajima and King 1990). ATSR World Fire Atlas is obtained from European Space Agency - ESA/ESRIN via Galileo Galilei, Italy.

Figure 1 shows the ISMR variability for the period 1871-2003 and the ENSO index. Generally is it seen that the deficit ISMR years are more strongly linked to the El Niño events compared to the link between excess ISMR years and La Niña events. Most prominent deviation from this hypothesis occurred in 2002 when a large negative ISMR anomaly was observed during a period of weak El Niño. Further it could be suggested from Fig. 1 that after 1972 the frequency of deficit ISMR years are only loosely connected to El Niño events; only 3 out of 7 ISMR deficit years (10% below normal) coincided with El Niño period. Since the human activities are influencing the chemical composition of Earth's atmosphere, an effect escalated more recently (IPCC, 2001); this break down of ISMR – ENSO correlation could possibly be a manifestation of chemistry-climate interaction in 'anthropocene' era.

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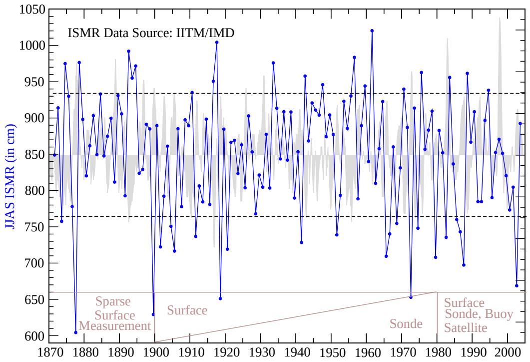
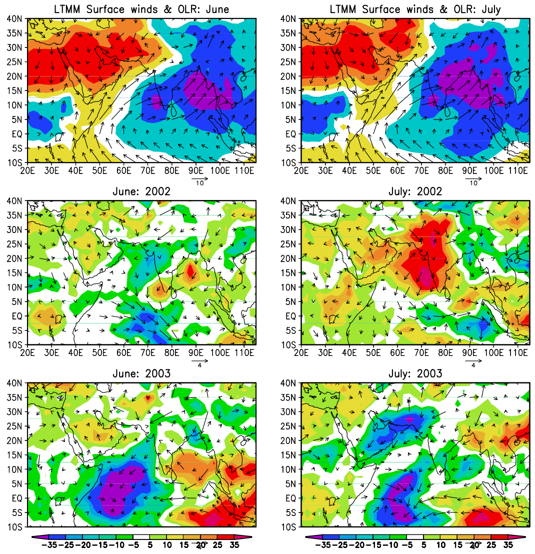


Figure 1: Timeseries of ISMR (JJAS) during 1870-2002 as obtained from the Indian Institute of Tropical Meteorology (www.tropmet.res.in, IITM) and ENSO index according to Japan Meteorological Agency (JMA) SST anomaly (www.coaps.fsu.edu). Positive and negative SST anomalies correspond to El Niño and La Niña, respectively. The types of available atmospheric and oceanic observations for analysis are shown schematically over the bottom axis. In addition a large suite of atmospheric composition observations (*in situ* and remote sensing) is available since the 1970s.

3. RESULTS AND DISCUSSION

Figure 2 illustrates the differences in meteorological conditions (anomalies in OLR and wind) during JJA month in 2002 and 2003. As expected, the positive OLR (clearer sky) values are widespread in JJA months over the western Indian Ocean and the Indian subcontinent, and relatively lower/negative OLR (cloudier sky) values in the eastern Indian Ocean and south-east Asia in 2002. The opposite is true in 2003 with much stronger amplitude. This oscillatory feature over the Indian Ocean is referred to as the Indian Ocean dipole (IOD) (Saji et al. 1999). An examination of surface temperature distributions (not shown) suggests that the centers of surface warming (0.5-1.5^{0}C above average) were located around 80-90^{0}E and 10-15^{0}S during 2002, and the temperatures over the Arabian Sea region were about the climatological average (about 28^{0}C). In June 2003, larger surface temperatures (anomalies greater than +1.5^{0}C) were observed over the Arabian Sea. Unlike in July of 2002, this warming supplies ample energy to the SMS for bringing in heavy rain during July 2003 (~17% more than the climatological average).

The aerosols (Fig. 3), shielding the incoming visible solar radiation, produce a negative radiative forcing (RF) near the surface and positive RF at various levels of the troposphere above the aerosol layer. The negative RF near the earth's surface leads to reduction in surface temperature over the land and ocean. That over the Arabian Sea in June 2002 (ref. Fig. 2) is of particular interest to this study, which weakens the 'heat engine' for activating the SMS over India. The higher AI values in June 2002 are suggested to be one of the reasons for Arabian Sea and West Indian Ocean surface temperature cooling, apart from the IOD dynamics. The warming of lower-middle troposphere over continental Africa (aerosols without cloud) and cloud-top cooling over India (lesser convective heating) would weaken the transverse monsoon circulation between the Tibetan low and African high (ref. Webster et al., 1998).


LTMM Surface winds & OLR: June

LTMM Surface winds & OLR: July

June: 2002

July: 2002

June: 2003

July: 2003

Figure 2: Long-term monthly means (LTMM) and anomalies in the NOAA interpolated outgoing long-wave radiation and wind vector from the NCEP/NCAR reanalysis dataset. The climatological mean are taken for the period 1979-2002 and anomalies are calculated for the June (left panels) and July (right panels) of 2002 and 2003.

Figure 4 shows the interannual variation in ISMR during May-September period along with several other physical-chemical parameters obtained from TOMS and MODIS instruments in the period 2000-2003. In general, 2000 and 2001 represent a fairly normal summer monsoon condition (JJAS rainfall deficit smaller than 10%), 2002 was a highly rainfall deficit year, and 2003 being excess rainfall year. In general, the lowest rainfall years of all the monsoon months (June 2003, July 2002, August and September 2001) coincides with the highest TOMS aerosol index over continental India (Fig. 4 a & b). However, the effects of aerosols on radiation balance and cloud microphysics would, to a large extent, depend on their chemical properties. An analysis of daily TOMS-AI suggests that the main source of aerosols over the Indian region during the summer is originated from the Middle-east and northern Africa region (available at www.jamstec.go.jp). The ATSR World Fire Atlas (http://dup.esrin.esa.int/ionia/wfa/) shows constant fire activity around the Persian Gulf region, which is likely to add some biomass burning byproducts during the transport of aerosols. Though the interannual variability in the fire counts is not significant, the amount of carbonaceous aerosols transported to the Indian region will vary significantly due to the changes in transport patterns associated with the dynamical oscillations.

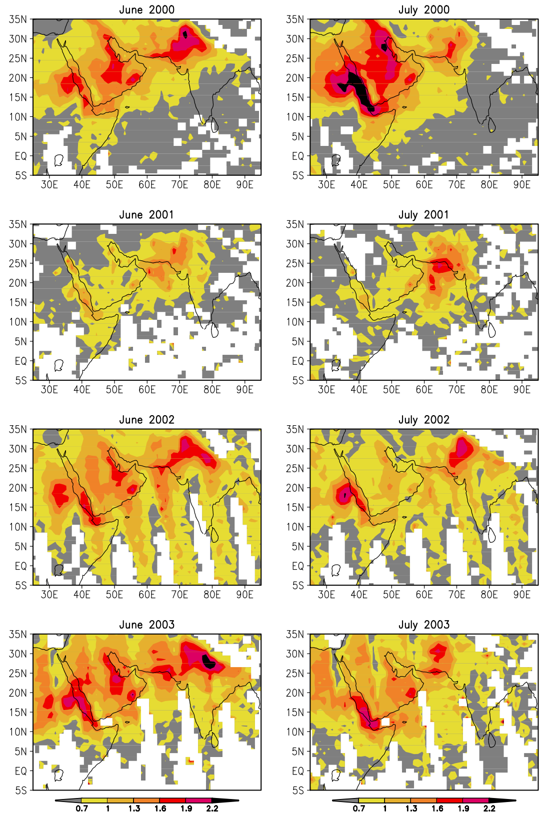


Figure 3: Distributions of TOMS Aerosol Index for June (left column) and July (right column) are shown for the period 2000-2003. TOMS-AI is a measure of the wavelength-dependent reduction of Raleigh scattered radiance by aerosol absorption relative to a pure Raleigh atmosphere. The aerosol properties are classified in the following way: positive AI: desert dust, biomass burning smoke, and volcanic ash; negative AI: haze and volcanic sulfate aerosols neutral AI: clouds or a mixture of absorbing and nonabsorbing aerosols. The daily AI values more than +0.4 are only considered in constructing the monthly aerosol distributions for this plot.

It could be further noted that July, the month most important for agriculture in India, of 2002 and 2003 were the most distinct for all the depicted parameters. In July 2002, the ISMR was only about 46% of climatological average, the AI was highest, CER was smallest, and COT and WVC were lowest over the Indian region. On the contrary, July 2003, which observed 17% excess rainfall, 2000 and 2001 all the physical-chemical parameters were found to be out of phase with that of 2002 values (Fig 4 c-f). The reduction of cloud droplet growth in July 2002 is believed to be an affect of the aerosols on the cloud microphysical properties. Rosenfeld et al. (20001) and Andreae et al. (2004) have clearly demonstrated that the aerosols of desert dust and biomass burning origin would inhibit the cloud droplet growth; thereby an increase in the droplet residence time, i.e., lower probability of warm rain and the cloud droplets attaining higher altitude.

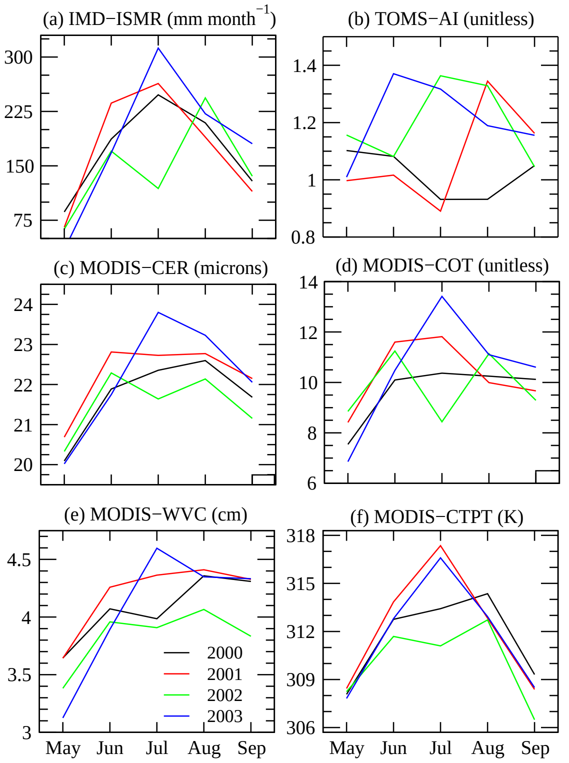


Figure 4: Monthly-mean time series for May-September months in the period 2000-2003 of (a) ISMR, regionally averaged TOMS aerosol index (AI) over India (b), and MODIS derived (c) combined phase cloud effective radius (COT), (d) cloud optical thickness (COT), (e) water vapour column (WVC) and (f) cloud top potential temperature (CTPT) are shown. The MODIS aerosol parameters are averaged over 0–30^0N, 65–90^0E region. The TOMS-AI values more than 0.7 are included in the averaging over a stricter Indian domain (10-35^0N, 70-90^0E). The MODIS/Terra aerosol product and daily TOMS AI are taken from lake.nascom.nasa.gov/www/ and toms.gsfc.nasa.gov, respectively.

The CTPT plots (Fig. 3f) suggest that the heating of middle troposphere (650-500 hPa height) due to convective precipitation over India was lowest in 2002, and this would further weaken the monsoon-Hadley circulation (a positive feedback process for sustenance of the SMS). As discussed earlier, the convective precipitation amount depends on the strength of monsoon circulation (heating gradients) and warm rain cloud formation. However, in the case of July 2002 the cloud top pressure was about 55-85 hPa lower over the Indian domain, indicating larger role of weaker convective activity.

The above observations on atmospheric dynamics, chemical compositions, and radiation budgets mainly during 2002 and 2003, led us to suggest that all the three components interactively control the ISMR. A quantitative estimate of their relative contribution, due to severely restricted observational data (e.g., aerosol chemical composition), can only be studied with the help of general circulation model that includes cloud microphysics.

Several important questions can be raised here; whether the lower amount of water vapour column (WVC) or cloud microphysical properties in July 2002 led to the formation of smaller cloud particles, and as a result the rainfall deficit over India. Our comparison, however, suggests that though the WVC values for July 2000 and 2002 were not very different there is a significant reduction in COT and CER from June to July in 2002, while COT and CER continued to increase from June to July in 2000. Secondly, the change in radiation budget caused by aerosols over Indian monsoon domain should be quantified, and is already receiving due attention (e.g. Babu et al. 2004). This work can be extended further for radiation budget calculations and aerosol characterization as soon the as the SeaWiFS (Sea-viewing Wide Field of view Sensor) aerosol optical depths (AODs) and Angstrom coefficients are processed for the Indian summer monsoon domain using the newly developed technique (Hsu et al. 2004). Further analysis of synoptic scale variability in AI or AOD, SST, and spatial of distribution of ISMR would provide greater insight of the underlying processes involved in the SMS.

Our result on aerosol induced reduction of rainfall over India during the summer can be a critical piece of information for the late monsoon rainfall prediction models. We also suggest here an indirect role of dynamical oscillations in regional rainfall patterns and thus the total impact is larger than that was thought previously.

4. CONCLUSIONS

We have used the meteorological data to show the distinct oscillation pattern in 2002 and 2003 owing to the Indian Ocean dipole and its impact on changing the circulation around the Indian subcontinent. We found that heating of the Arabian Sea surface is reduced due to larger aerosol index in June 2002 and increased for smaller AI in June 2003 compared to the climatological mean leading to deficient July rainfall in 2002 and surplus in July 2003, respectively. The associated increased heating of lower-middle troposphere over Africa by the aerosols and reduced heating of the middle troposphere over India due to lesser convective clouds weaken the monsoon-Hadley circulation, argued to be important for the sustenance of the monsoon activity. We believe that the analyses of cloud microphysical parameters support the study of less efficient cloud droplet growth under the influence of aerosols of non-oceanic origin. As demonstrated here, the weakening of monsoon circulation and inefficient cloud droplet growth generated an anomalously weak all-India rainfall in July 2002. The conditions in July 2003 are just opposite leading to an excess ISMR.

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