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Multi year changes of Aerosol Optical Depth in the monsoon region of the Indian Ocean since 1986 as seen in the AVHRR and TOMS data

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Abstract. Aerosol Optical Depth (AOD) data based on AVHRR and TOMS was analyzed to find out the changes in the Indian Ocean from 1981 to 2004. Four regions covering Indian Ocean north of 10° S were studied in detail. The results strongly suggest that the mean value of AOD in these regions decreased from 1986–1990 to 1995–1999. The Arabian Sea and Bay of Bengal show increase thereafter whereas in the equatorial part it decreased further, during 2000–2004. The drop in AOD from the first to second period is evident in AVHRR and TOMS in the case of the Arabian Sea (North West Indian Ocean). The decrease in this case is prominent in summer. These results in general agree with the recently reported global decrease in AOD, "global brightening" and also the reversal of trend in some of the anthropogenic emissions.

Keywords. Atmospheric composition and structure (Aerosols and particles) – Meteorology and atmospheric dynamics (Radiative processes)

1 Introduction

The North Indian Ocean and the adjoining land mass are under significant influence of aerosols and mostly are major sources of natural and anthropogenic aerosols. Aerosols have direct and indirect effects on radiation and on clouds that are recognized as important with respect to weather and climate. It was recognized even prior to the MONEX experiment of 1979 that aerosol processes are significant in relation to the Southwest Monsoon. According to Mohalfi et al. (1998) the dust layer over the Arabian Sea warms the middle levels in its vicinity and cools the layer below it, thus intensifying the inversion above the monsoon flow. Later field experiments like the INDOEX in the Indian Ocean have substantially increased our knowledge about the distribution of aerosols and the aerosol processes. Numerical experimentation using data from field experiments and satellite measurements have provided major insights into these processes in different geographical contexts (Ramanathan et al., 2001).

Li and Ramanathan (2002) note that the Northern Indian Ocean is dominated by anthropogenic aerosols during the winter monsoon season whereas mineral dust and sea salt dominate during the southwest summer monsoon. The former is controlled by low level flow from south and southeast Asia, while in summer lower to mid-tropospheric transports from the African continent and the Arabian Peninsula dominate. During winter monsoon, low-level flow from the Indian subcontinent and adjacent regions is particularly important.

In spite of the advances already made, the long term changes in aerosol distribution in the Indian Ocean is poorly understood. Over the Indian sub-continent (land) increasing trend in AOD has been observed in TOMS observations during 1979 to 2000 (Massie et al., 2004). The prevailing view is that it has been increasing over the sea as well (Ramanathan et al., 2001) as a consequence of the increasing anthropogenic emissions from the littoral states and that it also undergoes episodic changes due to volcanic eruptions or forest fires as well as due to weather anomalies of different scales. However recent works relevant to this problem indicate a possible reduction of AOD and an increase in solar radiation reaching the ground over large parts of the globe, noticeable from the beginning of 1990s (Mishchenko et al., 2007a, b, c, Stern, 2006, Wild et al., 2005). In the present work we try to determine in detail the long term changes in AOD in the oceanic areas of the Indian Ocean, north of 10° S.

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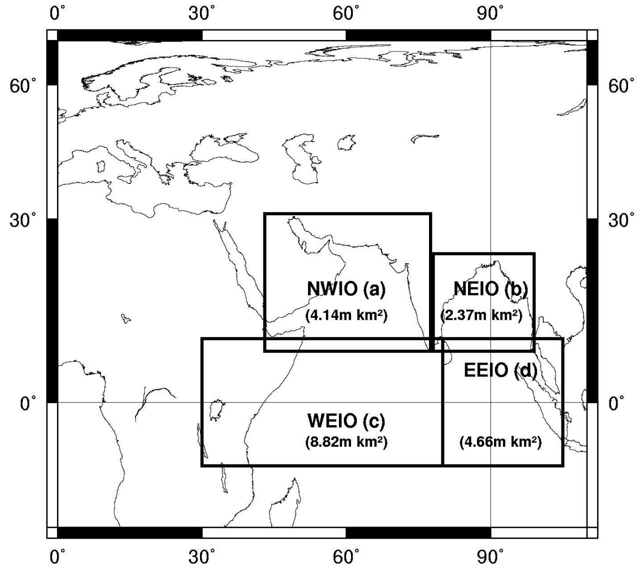

Fig. 1. Location map of the regions. Surface area, excluding land surface, is given in million square km in brackets. The regions are NWIO (**a** – North West Indian Ocean 43–78° E, 8–31° N), NEIO (**b** – North East Indian Ocean 78–99° E, 8–24° N), WEIO (**c** – Western Equatorial Indian Ocean 30–80° E, 10° S–10° N) and EEIO (**d** – Eastern Equatorial Indian Ocean 80–105° E, 10S–10° N). The map projection is Cylindrical Equal Area and therefore the areas in the map may be compared.

2 Data and analysis

The commonly available information on aerosols over the oceans is the AOD from satellite measurements. In the present work we examined the data of AVHRR AOD from the Global Aerosol Climatology Project (GACP) and the TOMS AOD data (Total Ozone Mapping Spectrometer data from Ozone Processing Team NASA/GSFC). The following data sets from polar orbiting satellites that are in the public domain were used in this study: (a). The AVHRR mean monthly AOD data at 550 nm, derived and made available by the GACP of NASA. (It is derived from Channel 1 and 2 radiances of AVHRR instruments on board NOAA-7, 9, 11 and 14 and was accessed from ftp://data.giss.nasa.gov/pub/gacp/time_ser/, in September, 2006). The details of derivation, verification and also description of the data are available in literature (Liu et al., 2004, Geogdzhaev et al., 2005). The data is on 1° latitude-longitude grid. It is available for the period August 1981–August 1994 and February 1995–December 2004. AVHRR AOD is available only over oceans. The random error of the data is estimated to be about 0.04 (Mischenko et al., 2007a). (b) The TOMS AOD data (http://toms.gsfc.nasa.gov/aerosols/aot.html) at 380 nm is derived from the NIMBUS-7 observations during January 1979–April 1993 and from Earth Probe observations during July 1996-December 2000. The details of retrieval are available in literature (Torres et al., 2002). The data set consists of monthly average AOD on a 1° latitude-longitude grid and is available for both land and ocean. The random error of this data is estimated to be around +/−0.08+/−0.20 AOD (Jeong et al., 2005). The data is publicly accessible from the above web site (accessed in June 2006). It may be mentioned that TOMS AOD is derived at 380 nm and AVHRR at 550 nm. This wavelength difference explains most of the differences in the mean values between the two data sets reported in this paper.

The data have various sources of errors and biases that are described in the references cited above. The given error estimates of the retrievals, the problems of missing data and breaks in the observations make the study of long-term trends problematic. Neither can one conclude that the data sets can not yield useful information on the long-term trends. We believe that examining the two data sets in combination, and with information external to them, may yield useful inferences on at least certain aspects of the long term changes. It is very essential to do such an examination, if we consider the serious consequences of any trends on various aspects of climate change and also on understanding various climate related processes over the region. It is therefore imperative that we investigate them even when the data has fairly large uncertainties. This is necessary to refine our understanding of the regional aspects of the aerosol problem. Considering the uncertainties in the datasets, only relative and gross changes in AOD are interpreted. Consistency among the AVHRR and TOMS data sets with respect to temporal and spatial changes is also regarded as a factor increasing the reliability of the conclusions. Simple analysis techniques are used so that interpretation is straightforward.

Regional averages (regions are shown in Fig. 1) in this work were computed with latitude weighting. We first computed the regional monthly mean for a region (excluding land) and then calculated the multi-year averages from those values. It may be noted that the accuracy of the computed regional average depends on the number of grid points populated with data and how the data is distributed on the grid. We also expect the uncertainty in the averages to be less than the range of random errors for the monthly mean grid values of AOD given for the data sets.

3 Results

The regional average values for all four regions for the periods 1986 to 1990 (Period-I), 1995–1999 (Period-II), 2000–2004 (Period-III) in the case of AVHRR (Fig. 2) were calculated. In the case of TOMS, calculations were done only for 1986–1990 and 1996–1999 (Fig. 3) because of paucity of data. The durations of volcanic eruptions do not fall inside the selected time periods.

The mean values clearly show that, in general AOD decreased from Period-I to Period-II in all the regions except in EEIO where it is difficult to make any inference. However

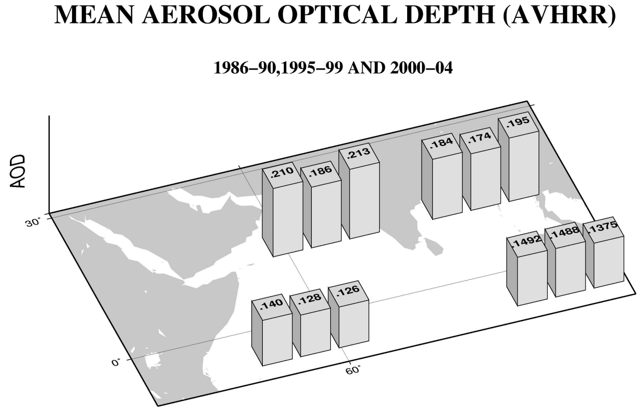

Fig. 2. The mean AVHRR AOD for all four regions for the period 1986–1990, 1995–1999 and 2000–2004. The mean value is written on the top side of the column.

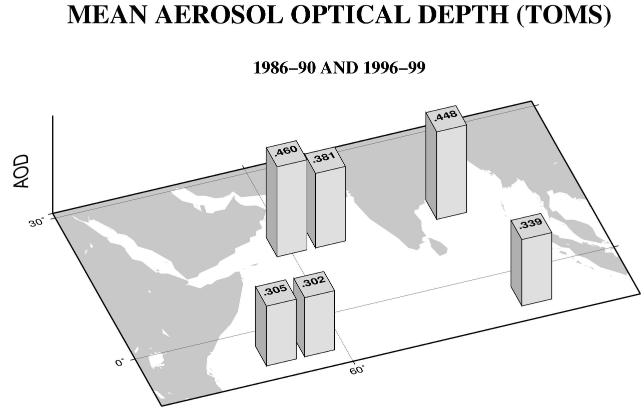

Fig. 3. The mean TOMS AOD. Note the regional differences and the drop in AOD over NWIO. For NEIO and EEIO only the value for 1986–1990 is shown.

the impact of the Indonesian forest fires during Period-II appears to be responsible for the higher AOD values in EEIO. The AVHRR AOD shows that there was an increase from Period-II to Period-III over NWIO and NEIO. However it decreased over WEIO and EEIO. The mean AOD obtained from AVHRR and TOMS show consistent relative magnitudes with respect to all the regions indicating that the observations are capable of capturing the regional variations. Both AVHRR and TOMS show the decrease in AOD from Period-I to Period-II. The annual variation of mean AOD is presented in Fig. 4. It shows that the maximum variation between Period-I to II and from II to III are seen during summer months over NWIO.

Whether the computed differences of mean AOD signify real changes could be answered only by examination of (1) the magnitude of the difference with respect to the standard error of the regional multi year means and (2) the possibility of simultaneous increase and decrease of AOD in two regions being misinterpreted as a long term variation if the spatial sampling is not appropriate. The difference of means that are presented here in the case of AVHRR AOD (Fig. 2) and TOMS (Fig. 3) are statistically significant at 95% confidence interval. We also present the statistics of the distribution of the values for the AVHRR AOD (Fig. 5). It is seen that there is a consistent change in the distribution including the median values that are statistically significant.

It is not possible to rigorously determine a value for the standard error of the regional multi year means of AOD. We could not find such an estimate in literature. However the standard error of the multi-year mean for a large region like the NW Indian Ocean is expected to be much less than that of the random error of the data used. The maximum decreases are seen in June; 0.125 from Period-I to Period-II and 0.1 from Period-II to Period-III. Both these values exceed the uncertainty from the random error (0.08). In other months also the differences are substantial with respect to the range of the annual variation. The decrease in annual mean AOD from Period-I to Period-II over NW Indian Ocean is 0.024 which is 30% of the uncertainty, if we use the same random error given for the monthly mean observations for a grid square. This however is a fairly large value considering the large number (between 15 000 to 19 000) of observations used, the large area (4.14 million km^2) and the long period of (5 years) over which the averages are calculated. We believe that there is high probability that the observed changes are real.

The influence of spatial distribution of the observations on the mean is expected to be taken care of by averaging over fairly large areas of the size of individual seas. It is also seen that there are consistent changes over individual regions from period I to II (both in AVHRR and TOMS). Further more Mishchenko et al. (2007a, c) show a global (i.e., averaged over the global oceans) reduction in AVHRR AOD during the same time. Therefore it is highly unlikely that the multi-year decrease from Period I to II is because of a redistribution of the aerosols over the Monsoon Region of the Indian Ocean. It is highly probable that it represents a temporal change in the average value.

The global and regional trends in AOD reported by Mishchenko et al. (2007a, b, c) are in agreement with the present results. The works cited above point to the following as possible factors contributing to the observed global changes: decrease in anthropogenic emissions of sulfur (Stern, 2006) and black carbon; increase in vegetation and rain in the Sahel region; changes in other anthropogenic emissions; increased surface wind speed and sea-salt aerosol production in the southern hemisphere mid latitudes. The question of natural variability versus human influence on the changes pointed out here are not clear. It is highly intriguing how the AOD decreased (at least as observed by satellites) in the oceanic area surrounding a rapidly developing industrial region where the aerosol load has been reported as increasing

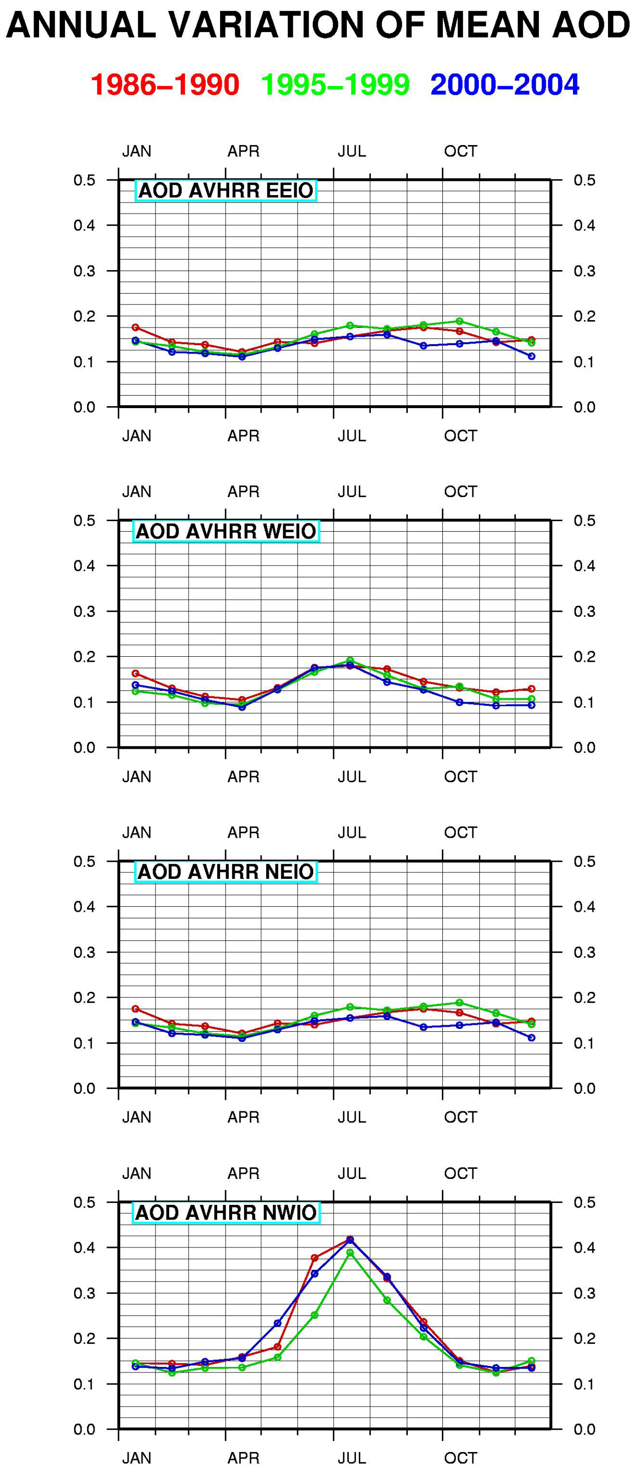

Fig. 4. Mean monthly AVHRR AOD averaged over the periods. Note the high AOD in the NWIO during summer and the low AOD in NEIO and EEIO. The multi annual variations are of a magnitude significant in comparison to the annual range of the variation. The differences in June for the NWIO exceed the uncertainty associated with the random error of measurement.

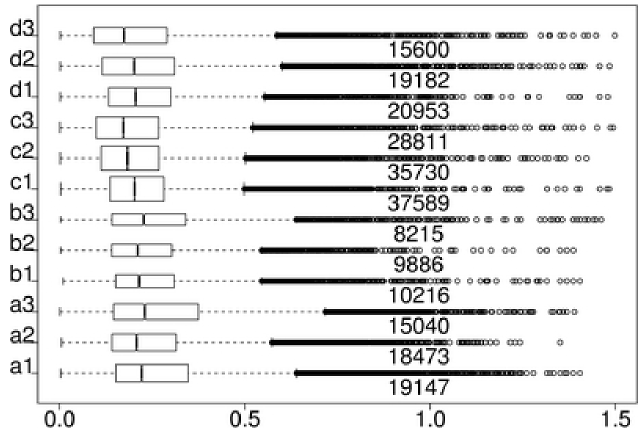

Fig. 5. Box Plots showing the distribution of AVHRR AOD (the letters a, b, c, d correspond to the regions shown in Fig. 1, the numbers in the X Axis denote the AOD). The left side of the box indicates the first quartile (25% of the sample lie left of it), the median is indicated by the middle line (with notches showing 95% confidence interval, in this case too narrow to be seen), the right side of the box indicates the third quartile (75% of the data lie left of this value). The two short vertical lines are drawn at 1.5 times the inter-quartile distance from the median. The circles are out-lier data (appearing in the plot as thick dark line because of crowding). The width of the box is proportional to the sample size (given in figures also). The box plots are identified as a1, a2, a3, etc corresponding to the periods 1986–1990,1995–1999 and 2000–2004 respectively. The plots show that the median value as well as the other important characteristics of the AOD show consistent behavior as the drop in means shown in Fig. 2.

by the same TOMS data set used in this analysis (Massie et al., 2004). The results of Mishchenko et al. (2007b, c) indicate a discontinuity in the long-term changes in global AOD beginning around 1991. The rapid reduction (by half) of industrial emissions from the east European countries during this period is a well documented event that requires attention. It is known that there was substantial decrease in AOD during the corresponding period over the whole of Russia (Gorbarenko et al., 2006). The relative proximity of the Arabian Sea to this region requires that attention is paid to the problem of possible connections between these changes.

4 Summary

The results given in the previous section show that there is a clear decrease in the AOD over the North Indian Ocean from 1986–1990 to 1995–1999 and then a rise from 1995–1999 to 2000–2004 especially in the NWIO. In the equatorial Indian Ocean the lowering appears to be continuous up to 2000-2004. Detailed examination including numerical simulation using transport models is required to definitely characterize these changes and also find out how these changes took place.

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