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Study of successive contrasting monsoons (2001–2002) in terms of aerosol variability over a tropical station Pune, India

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Contrasting monsoon study

R. L. Bhawar and
P. C. S. Devara

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

The present study confirms that aerosols play a major role in cloud formation and affect significantly the precipitation over a regional scale. The study here shows that there is a high variability of aerosol index during a bad monsoon year 2002 indicating an extension of cycle to more than 100 days from a normal 50 day cycle of absorbing and non- absorbing aerosols over a tropical urban station Pune. Pre-monsoon 2002 shows a high loading of coarse mode aerosols (absorbing aerosols) which indicates vertical and horizontal temperature variations in turn affecting the seasonal rainfall at a regional scale. Cloud formation highly depends on aerosol concentration, where surface meteorological features are essential to initiate the process. The surface temperatures were high during the pre-monsoon of 2002 as compared to 2001. The effect of wind speed though, complicated to understand, reveal low values in 2002 with high aerosol optical depth and vice versa in 2001.

1 Introduction

The Indian summer monsoon rainfall (ISMR), defined as the cumulative rainfall over continental India during June-July-August (JJA), having important implications for the socio-economic system of the subcontinent. The JJA rainfall in 2002 was only about 78% of the seasonal average (679.2 mm, for the period 1871–2002) (Parthasarathy et al., 1995). This affected the agricultural system by almost a 40% drop in groundnut production according to Agricultural Journal (<http://www.agjournalonline.com>) and a 13% reduction in rice production according to the Food and Agriculture Organization of the United Nations (<http://www.fao.org>). This is one of the highest deficit monsoon rainfall years in the last hundred years.

The tiny particles suspended in the atmosphere known as aerosols play a major role in the cloud formation processes. Aerosols originate from a variety of natural and anthropogenic sources and thus exhibit a great variability in both space and

Contrasting monsoon study

R. L. Bhawar and
P. C. S. Devara

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Contrasting
monsoon study**R. L. Bhawar and
P. C. S. Devara

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

time. They increase the back-scattering of incoming solar radiation and thereby cause surface cooling while absorbing the infrared radiation emitted from the surface and hence results in surface warming. Natural aerosols generally lead to cooling while man-made/anthropogenic aerosols cause warming. Twomey (1977) described that aerosols act as Cloud Condensation Nuclei (CCN) or Ice Nuclei (IN). Their surfaces have the property of wet-ability as they alter the droplet size spectrum, which influences the amount and distribution of precipitation. Clouds and precipitation have long been recognized as important sinks for atmospheric aerosol, with size and solubility-induced selective removal affecting both the aerosol size distribution and chemical nature of the aerosol population (Junge, 1963). Connections between the aerosol conversion/removal processes and precipitation have been studied by numerous investigators (e.g., Changnon, 1980). Perhaps the first to be recognized (and received the most attention) is the albedo or “Twomey” effect – the increase in cloud albedo which in turn is due to an increase in aerosol concentration. For a dynamic forcing that creates a cloud with a given vertical extent and liquid water content, an increase in aerosol concentration going into the cloud can result in the formation of a larger number of smaller droplets as compared to an unperturbed cloud. The end result is an increase in cloud albedo (Twomey, 1974, 1977a).

Although the main component of atmospheric aerosol that is responsible for the generation and maintenance of the hydrological cycle is not yet clear, it is evident that aerosols are effective agents and hence, reliable data as well as, systematic study is needed to understand these complex processes (Devara et al., 2003). Each cloud drop requires an aerosol particle for water vapour to condense upon; clouds could not form otherwise. Moreover, the aerosol optical depth is a measure of radiative forcing at all time and spatial scales, and its mean value at a given location is highly dependent on prevailing environmental/meteorological conditions and altitude. Thus, influence of surface-meteorological parameters, particularly humidity on aerosol composition, play a significant role in the concentration and size distribution of aerosols. A study in this direction has been carried out using the lidar derived aerosol vertical distributions ac-

**Contrasting
monsoon study**R. L. Bhawar and
P. C. S. Devara

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

quired over Pune (Devara et al., 1994). Thus till present, aerosols mostly have been considered as a problem of climate change which reduces the global warming by their radiative properties, and in air-chemistry by intensifying the pollution and having possible impacts on clouds and rainfall. Effects of aerosols on atmospheric hydrological cycle in the Asian monsoon region are also investigated by Lau et al. (2006). Anthropogenic aerosol emissions may increase cloud cover by up to 5%, resulting in a substantial net cooling of Earth's atmosphere (Breon, 2006). Aerosols affect precipitation in two ways; the presence of more aerosols leads to formation of smaller cloud droplets resulting in brighter clouds that reflect more solar energy back into space which is the first indirect effect. While numerous smaller cloud droplets tend to reduce precipitation and change the extent of cloud cover (Rosenfeld, 2000).

The contrasting monsoon year is a good opportunity to study the various phenomena involved in monsoon dynamics. In the present study, the importance and behavior of aerosols during two consecutive years of active and weak monsoon activity has been highlighted. The focus will be in terms of aerosol composition, optical and physical properties, derived from coincident ground-based multi-filter solar radiometer and satellite-borne measurements over a tropical urban station Pune and meteorological conditions.

2 Data deduction

The data used in the present study comprise of a MICROTOPS-II solar radiometer (MTP)-observed aerosol optical depth, Total Ozone Mapping Spectrometer (TOMS)-derived aerosol index (AI) and concurrent meteorological parameters recorded during two successive contrasting monsoon seasons of 2001 and 2002 over Pune (18.32° N, 73.51° E, 559 m AMSL), India. The cloud effective radius and cloud optical depth derived from MODIS sensor also has been utilized to study the indirect effect of aerosols. The MTP is a portable, hand-held, multi-channel solar radiometer, which had been operated at the Indian Institute of Tropical Meteorology (IITM), Pune. MTP provides

**Contrasting
monsoon study**R. L. Bhawar and
P. C. S. Devara

columnar: aerosol optical depth (AOD), ozone (TCO) and precipitable water content (TWC) (Morys et al., 2001; Devara et al., 2001). It measures the extinction of solar radiation through atmosphere by aerosols against the incident solar radiation and gives AOD at 380, 440, 500, 675, 870 and 1020 nm. The MICROTOPS-II-derived AODs at different wavelengths were utilized to calculate the size index (ν) parameter and aerosol loading over the station. The satellite based TOMS sensor has been flown aboard since 1978 on various platforms for monitoring global TCO by studying both incoming solar radiation and back-scattered radiation in the UV-region. Space-borne sensors provide a good temporal and spatial coverage. As suggested by Herman et al. (1997) TOMS data also can be used to derive Aerosol Index (AI).

$$AI = -100[\log_{10}(I_{331}/I_{360})_{\text{meas}} - \log_{10}(I_{331}/I_{360})_{\text{cal}}]$$

Where, I_{meas} is the measured back-scattered radiance and I_{cal} is the calculated radiance for a pure Rayleigh atmosphere. The positive AI represents absorbing aerosols while negative AI corresponds to less-absorbing or non-absorbing aerosols. TOMS used the radiance in UV wavelengths as it is advantageous to characterize aerosols over all surface types. MODIS (MODerate resolution Imaging Spectroradiometer) was flown on Terra and Aqua platforms in 1999 and 2002, respectively. It monitors the Earth in 36 discrete bands with a high spatial resolution of 250 m, 500 m and 1 km in different bands. The cloud effective radius derived from MODIS is considered to strengthen the quantification of the aerosol effect on cloud cover (Kaufman et al., 1997).

3 Discussion

In addition to the time series of AI for the entire year, both TOMS and MICROTOPS-II data are also grouped under different months and seasons separately for each year. The behavior of optical and physical properties of aerosols in conjunction with concurrent meteorological parameters during 2001 and 2002 is discussed in the sub-sections to follow.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

4 Variations in aerosol composition

Figure 1 illustrates the time evolution of AI over Pune, a fast growing urban station, during 2001 and 2002. The variations in AI exhibit, by and large, bell-shape with maximum (positive AI) during the pre-monsoon and minimum (negative AI) during the winter months for both the years. Broadly, the plot clearly shows the dominance of absorbing aerosols during the pre-monsoon and less- or non-absorbing aerosols during winter. The negative values indicate the non-absorbing aerosols (such as sulphate and sea salt) while positive values indicate absorbing aerosols (such as mineral dust and smoke), and the near-zero values of AI are due to presence of clouds. In 2001 (50 day oscillation) the variation starts with non-absorbing aerosols in winter followed by absorbing aerosols during summer, while in monsoon it has a mixed type of situation with near-zero values indicating mostly the presence of clouds. But for 2002 three prominent cycles each of more than 100 days are observed; it starts with non-absorbing switching to more absorbing aerosols and back to non-absorbing aerosols. The presence of absorbing aerosols in summer months over Pune is mostly due to the transport phenomenon from the semi-arid region (Pandithurai et al., 2004). The absorbing aerosols cause the vertical and horizontal temperature variations during pre-monsoon season, which in turn alter seasonal rainfall over the particular region. They also tend to suppress precipitation under certain meteorological conditions. The dust events lead to enhanced heating rates in the lower troposphere (Pandithurai et al., 2008). Moreover, most important feature that can be seen in the figure is that the variation in AI is significantly large in the year 2002 (drought) as compared to that in 2001 (active monsoon). In order to examine the size distribution of aerosols in 2001 and 2002 the Angstrom parameters α and turbidity parameter β were studied.

Contrasting monsoon study

R. L. Bhawar and
P. C. S. Devara

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



5 Variations in aerosol size distribution

Monthly mean values of α and β obtained from the relation, $\tau = \beta \lambda^{-\alpha}$, where α is wavelength exponent, while β is Angstrom coefficient are seen plotted in Fig. 2 for both 2001 and 2002. The α value is an indicator of size while β indicates the loading of aerosols. The parameters α and β were calculated using the spectral distribution of AOD obtained from MICROTOPS-II. The gap in the data during the monsoon months is due to unfavorable sky conditions under which MICROTOPS-II cannot give reliable data due to presence of clouds. Both plots show larger size index, ($\nu = \alpha + 2$) values indicating greater concentration of sub-micron aerosol particles during the winter and smaller ν values suggesting coarse-mode particles during the pre-monsoon months. Besides the usual behavior of aerosol loading (larger β value) during pre-monsoon months and relatively smaller values during winter, larger values of β and smaller values of α during winter as compared to the pre-monsoon months in certain years are attributed partly due to intense haze formation resulting from trapping of local anthropogenic aerosols. A significant difference is seen between 2002 and 2001. The value of α in pre-monsoon is 0.4 for 2002 as compared to 0.7 in 2001, which implies presence of more accumulation-mode particles in 2001 than in 2002 suggesting more loading of coarse-mode aerosols in 2002 than in 2001 during pre-monsoon. Thus more number of accumulation-mode particles; adequate loading of aerosol amount in atmosphere during pre-monsoon triggered a good cloud formation process in 2001 which yielded a good amount of precipitation. In 2002, the situation was exactly opposite with presence of coarse-mode particles and more loading of absorbing aerosols. The interesting finding is that more absorbing aerosols were present in 2002 the water vapor content was also low by almost 0.5 to 1 cm in 2002 than in 2001 obtained from MODIS satellite data. Large number of absorbing aerosols, heat the lower troposphere but cool surface, and they compete for small amount of water vapor resulting in less amount of rain (Ramanathan et al., 2001). In order to further confirm and strengthen the above point cloud effective radius (CER) for 2001 and 2002 are shown plotted in Fig. 3.

Contrasting monsoon study

R. L. Bhawar and
P. C. S. Devara

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Contrasting
monsoon study**

R. L. Bhawar and
P. C. S. Devara

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

There were three epochs seen in Fig. 3. In 2001 and 2002 the CER goes on increasing from pre-monsoon to monsoon months as during the monsoon months the cloud formation starts, with a further decrease of CER in winter months. But the CER in 2002 during the monsoon months is less as compared to 2001 which suggests that the cloud formation was less in 2002 as opposed to 2001. Rather we can say clouds formed but dissipated in less time.

It is observed at Pune, that after the onset of monsoon in June, there is more rain in July and August in the normal years and then intensity decreases in September. It is evident in the CER plot that there is a decrease in CER in 2002 for the July and August months. Larger the CER, more the size of cloud droplet and more chances for rain occurrence, while less CER leads to cloud dissipation and hence less rain. Figure 4 shows monthly mean variation in cloud optical depth (COD) during 2001 and 2002. As suggested by Storelvmo et al. (2006), COD directly correlates with rainfall. In the present study, as the CER increases COD also increases and more COD results in more rainfall and vice-versa. It is distinctly seen from the Fig. 4 that in the month of July, when maximum rainfall occurs in Pune COD was less in 2002 as compared to 2001 and amounts to rainfall of 118 mm in 2001 and 26 mm in 2002. As the processes responsible for these differences have an important taking, of what is going on in the regional atmosphere the local meteorological conditions are also important, which are discussed, below.

6 Variations in concurrent meteorological parameters

The normal weather at the experimental site during the pre-monsoon season (March, April, May) is very hot with mostly gusty surface winds and the dust content in the atmosphere is at a maximum. The air flow in the lower troposphere is predominantly westerly during the south-west (SW) monsoon season (June, July, August, September), which brings a large influx of moist air from the Arabian Sea. Fair-weather conditions with clear skies, light surface winds and very low humidity exist during the winter

season (December, January, and February). Low-level inversions during the morning and evening hours, and dust haze during the morning hours occur during this season (Devara et al., 2005).

The daytime diurnal variations in temperature range which is difference between maximum and minimum temperature for the pre-monsoon, post-monsoon and winter months of 2001 and 2002 are shown plotted in Fig. 5. A significant annual variation in all the above three parameters with maximum AOD in pre-monsoon months and relatively minimum in winter months is quite clear from the figure. The high convective activity and frequent occurrence of dust storms are responsible for the higher AODs during the pre-monsoon. Subsequently, the AOD values attain minimum due to cloud-scavenging and rain-washout processes during the monsoon and post-monsoon and thereafter they slowly build-up during post-monsoon and winter months (due to haze) and becomes maximum again in summer. The influence of temperature on AOD is quite clear from the figure. Normally, increase in temperature causes lifting of aerosols that effects size distribution and results in higher AOD. The variations in AOD at 380 nm and concurrent surface-level temperature range for 2001 and 2002 seem to follow each other. In the 2001 plot for variations of AOD with temperature range during the pre-monsoon there is a steep decrease in temperature from 23°C to 8°C. From the post-monsoon to winter there is again an increase in temperature from 8°C to 28°C. Correspondingly there are large AOD variations associated with temperature variations. The plot for AOD and temperature range for 2002 shows a drastically different behavior. There is very less variation in temperature range between 16°C to 24°C throughout the pre-monsoon, post-monsoon and winter. The high value of temperature in the pre-monsoon supports the presence of absorbing aerosols from the AI values of TOMS. The temperature is high during 2002 compared to 2001, and AOD also shows a rise in 2002 than in 2001. The data gaps during the south-west monsoon (June–September) in the plot are due to unfavourable sky conditions, and many times due to rain during that period.

The variations in daily mean AOD at 380 nm and relative humidity during pre-

Contrasting monsoon study

R. L. Bhawar and
P. C. S. Devara

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Contrasting
monsoon study**R. L. Bhawar and
P. C. S. Devara

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



monsoon, post-monsoon and winter seasons of 2001 and 2002 are depicted in Fig. 6. Condensation of water vapor takes place on the aerosols with increasing relative humidity and evaporation of water vapor present on the aerosols takes place with decreasing relative humidity. In general, increase in relative humidity leads to particle growth and an associated increase in AOD. Thus the aerosol particles grow as relative humidity increases and shrink as relative humidity decreases. But the rate of growth in response to increase in relative humidity is not equal to rate of shrink in response to decrease in relative humidity.

Due to growth of particle the surface area increases and in turn reflects in high AOD. As the relative humidity increases the AOD also increase for hygroscopic aerosols, which are observed mostly during March and April months of 2001. In 2001 plot, for AOD and surface relative humidity there is a rise of relative humidity from 20% to about 60% in pre-monsoon and post-monsoon while it drops down to 20% in winter. In 2002, the surface relative humidity during pre-monsoon is between 20% and 30% with a high aerosol loading, while in post-monsoon and winter it varies between 35% and 50%. During winter months the relative humidity is less and AOD shows an increase which is due to the presence of haze in atmosphere.

Figure 7 displays the daily mean variations in concurrent AOD and surface wind speed during pre-monsoon, post-monsoon and winter months of 2001 and 2002. The influence of wind speed on aerosol optical depth in the whole atmospheric column is complex (Platt and Patterson, 1986; Villevalde et al., 1994; Smirnov et al., 1995; Moorthy et al., 1997; Kusmierczyk-Michulec et al., 1999). The correlation between wind speed and aerosols also depends on the size of aerosols. Different wind speed affects different size of particles (Smirnov et al., 2003). Overall comparison of surface wind speed for pre-monsoon of 2001 and 2002 shows higher surface wind speed values in 2001 varying from 4 m/s to 10 m/s than in 2002 from 1 m/s to 6 m/s. The variation in surface wind speed for post-monsoon and winter is same in both the years. The association between AOD and wind speed is complicated, because it may either remove aerosols from or may bring in fresh aerosols to the experimental site. The correlation

**Contrasting
monsoon study**R. L. Bhawar and
P. C. S. Devara

between aerosol concentration and wind speed are relatively high in lower altitudes, indicating that the effect of wind speed on aerosol concentration is more significant at lower altitudes (Parameswareen et al., 1995). Whenever the wind speed is high the AOD value is low and whenever wind speed is low AOD is high. Thus high wind speed values are associated with removal of aerosols and low wind speed with addition of aerosols in both the years. Thus compared to 2001, 2002 was associated with slightly more aerosol loading. In 2001 pre-monsoon though the surface wind speeds are high the AOD is not as high as expected which indicates the removal of aerosols from the experimental site. While in the post-monsoon and winter there is a build up of aerosol loading with low surface wind speed values indicating inflow of aerosols from the neighboring areas. There is an opposite correlation between AOD and wind speed in 2002 same as seen in 2001. In 2002 pre-monsoon wind speed is not as high as it was in 2001 but AOD is high as compared to 2001. There is also high aerosol loading throughout post-monsoon and winter months.

7 Conclusions

The role of aerosols was considered in the hydrological cycle but not studied in detail; this study proves the importance of aerosols. The present study proves the importance of aerosols in the hydrological cycle on a regional scale over a tropical station, Pune, India. The cycle of absorbing and non-absorbing aerosols during a normal monsoon is of about 50 days but during a weak monsoon the cycle extends to over more than 100 days as observed from this study. Large variation in the aerosol index values during 2002 than in 2001. As estimated from the angstrom coefficient more aerosol loading of coarse mode particles in 2002 as compared to 2001. The temperature also shows an increase in 2002 indicating warmer atmosphere due to absorbing aerosols. Thus, resulting in less CER which in turn indicated less cloud formation or early dissipation of clouds and giving less precipitation.

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[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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Contrasting monsoon study

R. L. Bhawar and
P. C. S. Devara

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Contrasting
monsoon study**R. L. Bhawar and
P. C. S. Devara

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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ACPD

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Contrasting monsoon study

R. L. Bhawar and
P. C. S. Devara

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



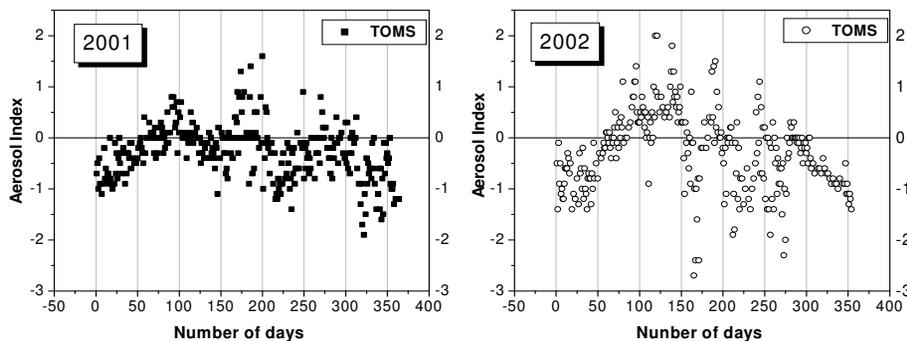
**Contrasting
monsoon study**R. L. Bhawar and
P. C. S. Devara

Fig. 1. Aerosol index variations during two contrasting monsoon years, 2001 and 2002.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

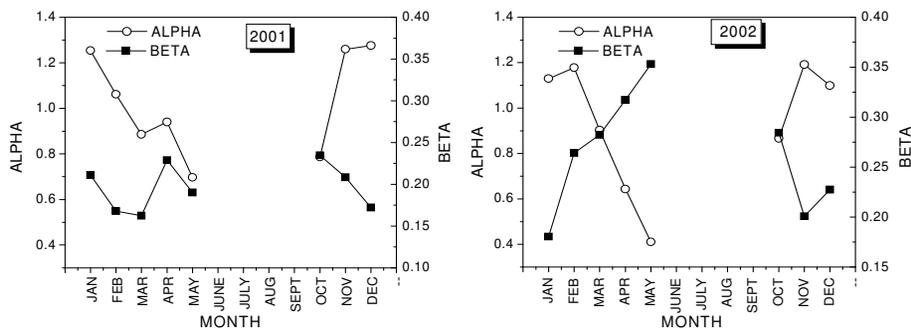
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Fig. 2. Monthly mean variation in α and β observed during 2001 and 2002.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



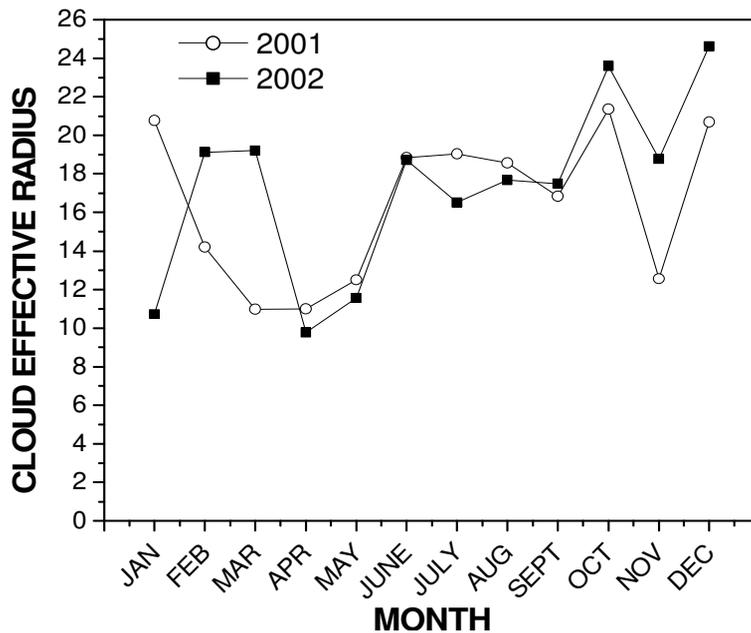
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monsoon study**R. L. Bhawar and
P. C. S. Devara

Fig. 3. Monthly variation in cloud effective radius for 2001 and 2002.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

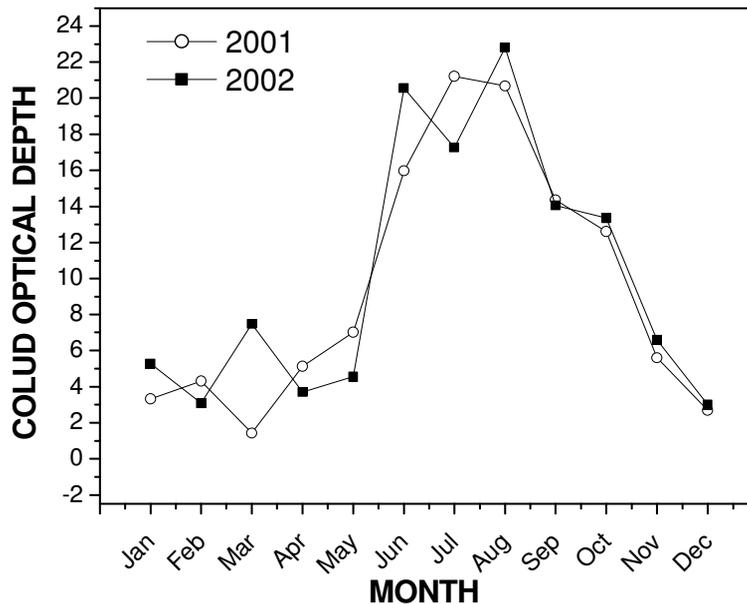
**Contrasting
monsoon study**R. L. Bhawar and
P. C. S. Devara

Fig. 4. Monthly variation in cloud optical thickness for 2001 and 2002.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

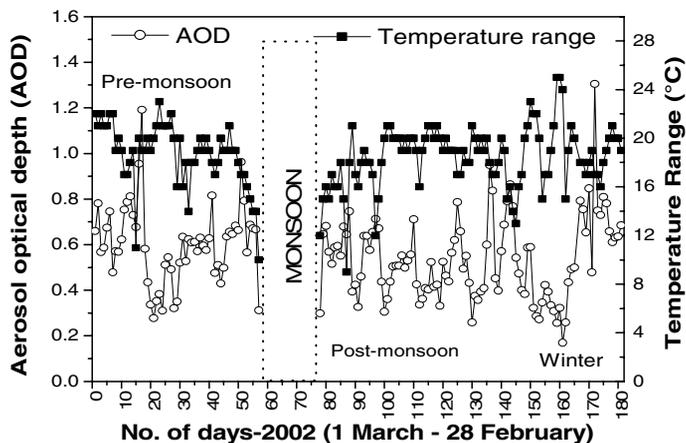
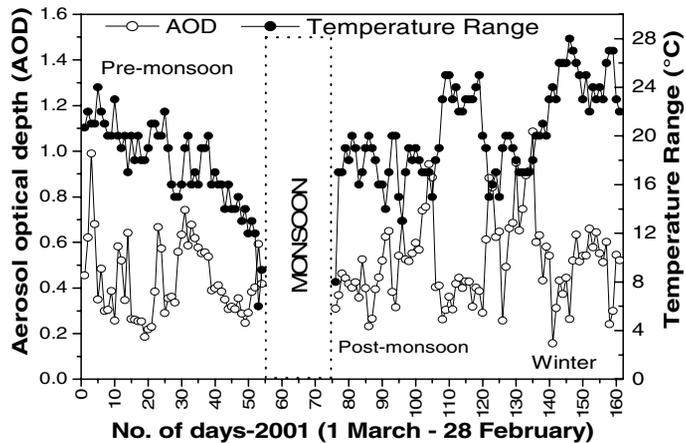
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P. C. S. Devara

Fig. 5. Day-to-day variations in both AOD and temperature range during pre-monsoon, post-monsoon and winter seasons, of 2001 and 2002.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

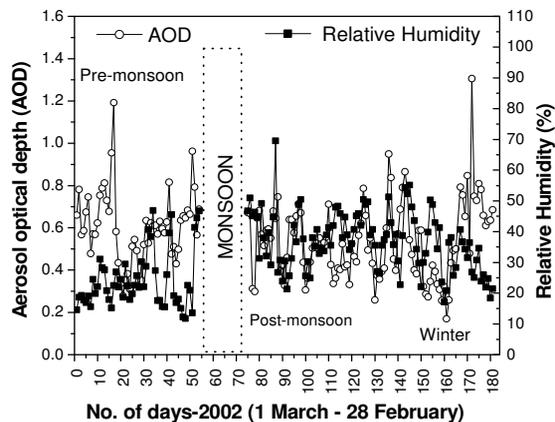
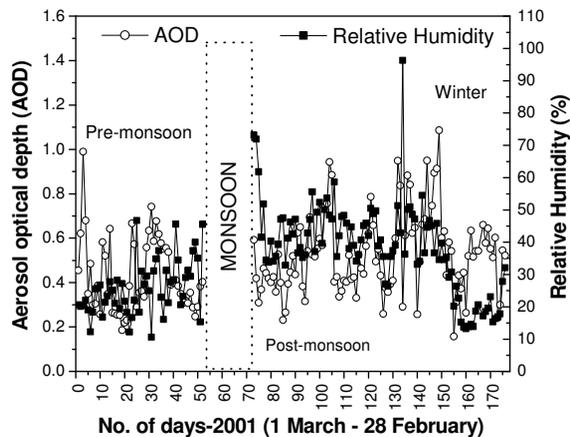
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P. C. S. Devara

Fig. 6. Day-to-day variations in both AOD and relative humidity during pre-monsoon, post-monsoon and winter seasons of 2001 and 2002.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



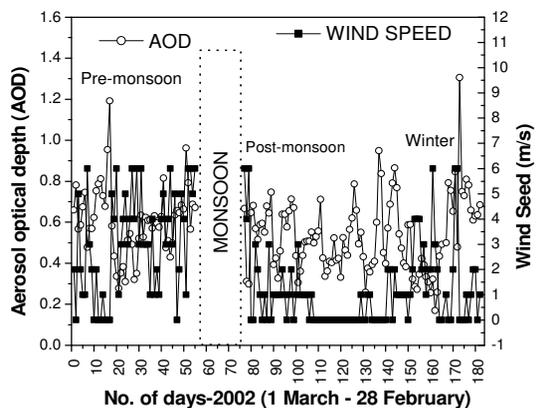
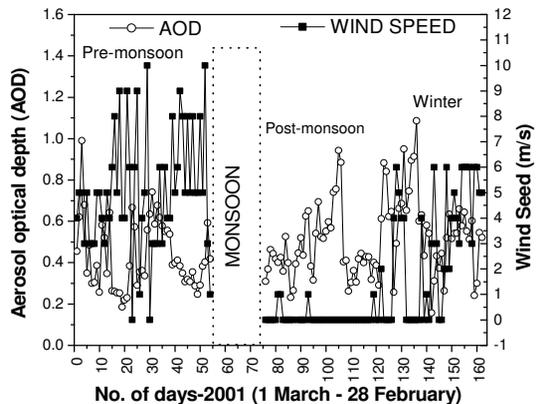
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Fig. 7. Day-to-day variations in both AOD and wind speed during pre-monsoon, post-monsoon and winter seasons of 2001 and 2002.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)