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Original Research Paper

Aerosols-Cloud Properties in Dynamic Atmosphere over Kedarnath Sub-Himalayan Region of India: A Long Term Study from MODIS Satellite

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ABSTRACT

The present long term study deals with the aerosol-cloud optical properties carried out during 2003-2012 over Kedarnath (30.73°N, 79.07°E) of the sub-Himalayan region of Uttarakhand, India with a resolution of 1°×1° grid in magnitude. The study was conducted using Moderate Resolution Imaging Spectroradiometer (MODIS) sensor onboard NASA's Terra and Aqua satellites. Interannual and seasonal variations of Aerosol Optical Depth (AOD) are examined in the light of regional synoptic climatic meteorology. Aerosol optical depths have found to be increased >28 % across Kedarnath region of India during the study period of 2003-2012. Annual mean Terra/Aqua AOD values at 550 nm displayed an increasing trend at a rate of ~0.0045/0.0089 per year respectively. Further, seasonal winter means Terra/Aqua AOD values exhibit an increasing trend at a rate of ~0.013/0.006 per year respectively. The results extracted in the present study are compared with the earlier studies as well as with the AOD values over various other Indian regions.

INTRODUCTION

Atmospheric aerosols perturb the Earth-atmosphere energy budget through their direct and indirect effects in terms of incoming and outgoing radiation balance (Singh & Dey 2013, Lee & Penner 2011). Many studies (Wright et al. 2010) have shown that the aerosols may affect the atmospheric general circulation patterns (Pandithurai et al. 2008) and biochemical cycling (Li 2004, Kumar 2011, 2012). Direct interaction of aerosols involves both scattering and absorption of radiation, and the relative importance of these processes depends on their chemical composition, refractive index and size distribution (Lyamani 2008, Pan et al. 2010, Lee & Penner 2011, Kumar 2014) whereas the indirect effect of aerosols on climate occurs by modifying the optical properties (Lee et al. 2009). Recently, a number of ground based aerosol networks such as AERONET were established worldwide, procuring continuous data sets on a variety of aerosol parameters over land and even over oceans (Kumar 2007), which further often suffer from the technical flaws in the instrumentation, lack of skilled manpower and consistent maintenance that can result in gaps in the invaluable scientific database (Niu & Li 2012). Aerosols modify the cloud properties and precipitation through a number of mechanisms with varying and contradicting consequences (Kang et al. 2009, Kumar 2011). Therefore, extensive investigations through satellite remote sensing provide an unparalleled opportunity to advance the understanding of aerosol with climate linkages (Raman 2012, Kumar 2013). It provides an efficient means to characterize the atmospheric aerosols temporally and globally (Rodriguez et al. 2012). The current study uses a scientific climatological database on aerosol optical depth values at 550 nm from the passive MODIS sensor. Recent investigations show that, higher cloud drop concentrations result in the enhancement of cloud concentration nuclei (CCN), which further generate longer lived clouds (Singh & Dey 2012). In terms of urbanization and industrialization, India is one of the densely populated and developing countries with diverse geographic and climatic conditions in Asia (Satheesh et al. 2005). In the present work, a thorough investigation on the long term (2003-12) temporal variation of Aerosol Optical Depth (AOD) has been attempted using satellite data products. Extensive studies were conducted on the various mechanisms of cloud properties through the interaction of atmospheric aerosol particles with cloud parameters which further influences the earth's climate (Kaufman & Koren 2006, Srivastava et al. 2008, Hoeve et al. 2012, Niu & Li 2012). The present study is focused on the long-term temporal variation of AOD at 550 nm over Delhi (28.56°N, 77.11°E, 233 m asl), India, derived from the MODIS (Terra/Aqua version 5.1 level 3) sensor. Secondly, in order to understand the cloud microphysics, regional correlation maps and time scatter variations between AOD and various cloud parameters are presented. The results of aerosol optical depths obtained over Kedarnath sub-Himalayan region of India were compared with that of the other industrial and densely populated parts of India.

RESULTS AND DISCUSSION

Spatial variation of mean annual aerosol optical depth:

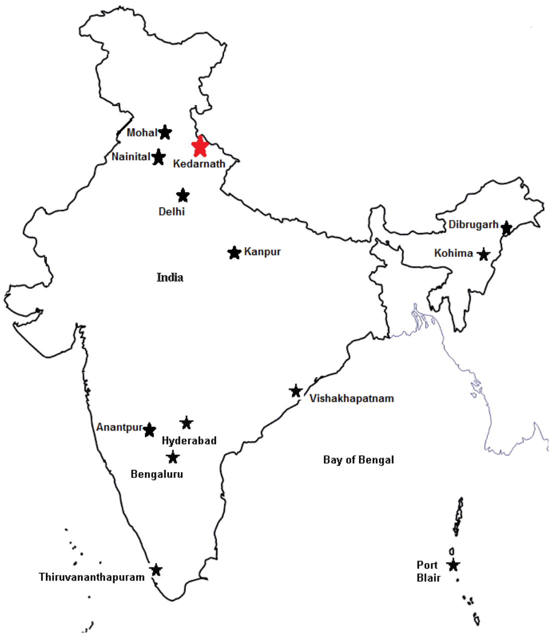

Fig. 1: Geographical location of Kedarnath region of Uttarakhand (red star) along with other Indian sites (black star) over which the AOD data have been used for comparison study.

The spatial variation of the mean annual aerosol optical depth of Terra/Aqua satellite sensors at a wavelength of 550 nm has been plotted over Kedarnath sub-Himalayan region of Uttarakhand, India for the ten year period of 2003-2012 (Fig. 2). Since Uttarakhand zone of Northern India is normally calm and free from any type of dominated industrial areas and anthropogenic activities, therefore, AOD values (>0.39) have been found over Kedarnath sub-Himalayan region of Northern India.

Monthly variations in AOD: The daily mean Terra/Aqua AOD values at 550 nm are grouped into calendar months for the ten year period of 2003-2012 over Kedarnath sub-Himalayan region of Uttarakhand, India. A monthly mean variation of the AOD (Terra/Aqua) values for the study period (2003-2012) is shown as a box and whisker plot in Fig. 3. Solid dots in Fig. 3, within the box, represent the mean values; centre line indicates the median (50 percentile value); the range of the whiskers shows the standard deviation of the mean value. Each of the monthly mean AOD value was obtained from a significant number of daily AOD values. An important gross feature of Fig. 3 is that, both Terra/Aqua monthly mean AOD values and their statistics exhibit similar temporal pattern. The monthly mean AOD value was found to be enhanced up to June with a clear dip in April. However, the range in AOD data values at 550 nm was highest in June. The maximum AOD values at 550 nm were observed during June where as the least value was found in the month of September (Fig. 3). Monthly mean AOD values observed in the present study are very much in agreement with that of Dumka et al. (2008) for the wavelengths close to 500 nm. Their results were based on the ground-based point measurements for the period of 2006 at Nainital, India. They found an increase in the mean AOD towards the summer months that can be attributed to the dry weather conditions. It may be due to the fact that the wet removal processes become insignificant during the summer months due to scanty rainfall conditions (Singh et al. 2004). Further, during these summer months, the solar heating and length of the daytime will be maximum which results in strong turbulent mixing and convective motions, and hence lifting of atmospheric aerosols from the surface (He et al. 2014). Over Bangalore (in India), Satheesh & Moorthy (2005) supported this mechanism using a micro pulse LIDAR. They observed cloud like structures within the aerosol layers during summer due to intense convective mixing of aerosols. All these processes, increase the AOD values during this season (Levy et al. 2007). The monsoon months AOD values are moderate with a peak value in July. The decrease in the AOD value might be due to the washout of aerosols by rainfall (Xiong et al. 2009). The other important and dominant factor (Hoeve et al. 2012) responsible for the higher AOD values during these months is the surface wind speed. The wind speed becomes stronger during this period and it can significantly pick up the soil, dust and biological particles in order to suspend in the atmosphere (Qiu et al. 2005).

Seasonal variations in AOD: A plot for the seasonal variation of AOD (Terra and Aqua) at 550 nm for the study period over Kedarnath of the sub-Himalayan region of Uttarakhand, India has been shown in Fig. 4(a,b). Mean AOD at 550 nm along with standard deviation was also determined with the confidence level of 95%. The lowest seasonal mean Terra (Aqua) AOD value is observed with a value of ~0.27±0.075 for winter (0.76±0.17, summer) and confidence level of ~0.027 (0.229) whereas the highest seasonal mean Terra (Aqua) AOD value is recorded during the summer period with a value of ~0.42±0.07 (0.43±0.063) and confidence level of ~0.130 (0.093). The quantities in the parenthesis denote the data values for Aqua sensor. It is clear from Fig. 4 that the mean AOD values at 550 nm increased towards summer reaching ~0.55 ±0.07 (0.55±0.063). The post monsoon season shows relatively low aerosol loadings 0.3±0.054 (0.27±0.061) close to the summer season because rainfall washes out most of the aerosol concentration (Yong et al. 2011). The continuity of trend has been shown in the post monsoon season for AOD distribution over Kedarnath of sub-Himalayan region of Uttarakhand, India. It may be observed that the influence of aerosol particles on monsoon activity mainly depends on the dynamics/microphysics or

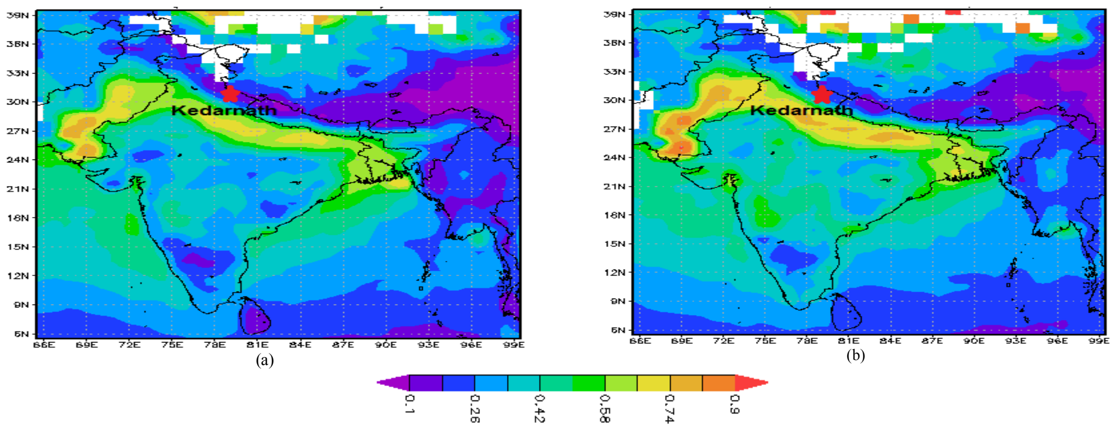

Fig. 2: Terra/Aqua satellite derived spatial distribution of area averaged annual mean AOD over Kedarnath region of Uttarakhand, India for the period 2003-2012.

both (Jones et al. 2009). Therefore, seasonal changes in AOD exist for the selected Kedarnath site in the sub-Himalayan region of Uttarakhand, India, and it may be due to small variations in the automobile, industrial and urban anthropogenic aerosol concentrations (Ramanathan et al. 2001). It is to be stated that rapid enhanced AOD during summer season may cause adverse effects to the agriculture crops and also to the human health (Hoeve et al. 2012). These results are in close agreement with the work of Prasad et al. (2004) where they have reported the similar increase in AOD during summer season for the Indian subcontinent. Singh et al. (2004) presented the seasonal and interannual changes of the aerosol particle properties over an urban industrial site in the Ganga basin of the Indian subcontinent. The aerosol properties over Kanpur were found to show a strong seasonal effect with the maximum variability during the monsoon season. It is due to the fact that the Kanpur region of Northern India is characterized by different types of aerosol mass loadings, which varies seasonally (Srivastava et al. 2008). Further, the diurnal cycle of the local pollutants was also clearly observed during the post monsoon and winter seasons, which was found to be suppressed during the monsoon season over the Kanpur region of India. It may be attributed to the fact that they are the urban stations having high aerosol loading due to industrial and urban domestic activities and some years may be drier with more dust events. However, the enhanced aerosol loading may affect the rainfall over these places which may cause drought conditions. The wind vector plots and back trajectory analysis provide the information about the synoptic circulation pattern and potential pathways of transport phenomenon (Das et al. 2012). The season-wise mean synoptic temperature and wind pattern at 850 hPa for the study period (2003-12) over Kedarnath of Uttarakhand and surrounding regions is shown in Figs. 5 and 6. It is to be noted that North Indian region including the IGP is significantly believed to have high aerosol laden which was due to its dense industrial and urban areas (Hoeve et al. 2012). Further, at the north of Indian sub-continent, orography of the Himalayas act as a natural boundary to the dispersion of aerosols and low temperature conditions in winter leads to the confinement and build-up of aerosol particles (Yong et al. 2011).

Inter-annual variations in AOD and comparative study: The inter-annual variations in the mean annual AOD (Terra/Aqua) during the study period (2003-2011) over Kedarnath region of Northern India are shown in Fig. 4. The climatic annual average value of Terra/Aqua AOD for the study period is ~0.36±0.058/0.34±0.065. From the figure it is clear that annual mean AOD over Kedarnath region of Northern India has been showing an increasing variation by nature (Dai et al. 2014). By using the method of the linear least square fit, the estimated increase in Terra/Aqua AOD value per year is ~0.006/0.008 (Cowpertwait & Metalfe 2009, Quass et al. 2010). However, the observed trend is highly dependent on the monthly and yearly data and averaging aerosol particles concentration over distinct datasets for the study location (Eastman et al. 2009, Lee & Penner 2011, Dai et al. 2014). The rapid growth of industrialization and automobile transportation along with the continuous increase in population (Xiong et al. 2009, Hoeve et al. 2012) might be some of the reasons for the increase in AOD values at 550 nm over Kedarnath region of Northern India. Recently, Kaskaoutis et al. (2012) have shown an overall increase in AOD values on a yearly basis over Kanpur, an industrial location in Northern India using AERONET measurements during the period 2001-2010. They critically mentioned that their surface measurement based trends in AOD values are in agreement with those reported by other satellite observations (MODIS and MISR) over northern India (Quass et al. 2010). Ramachandran et al. (2012) based on ten years of MODIS level 2 data have also shown an in-

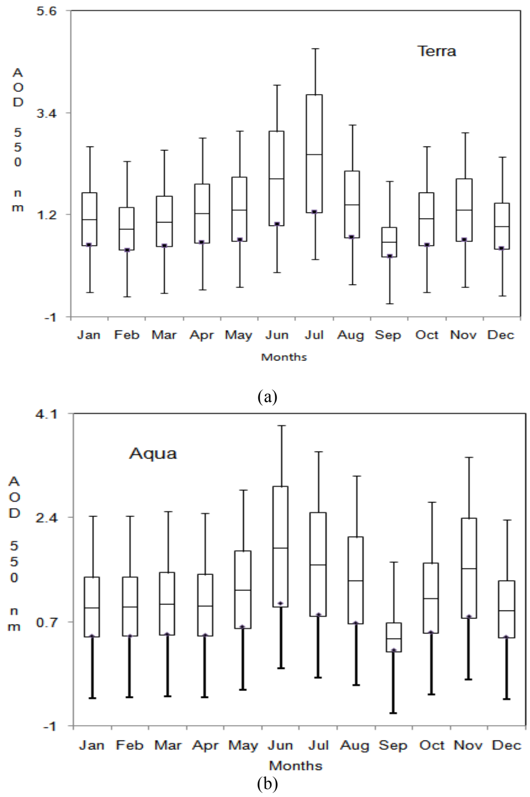

Fig. 3: Box and whisker plot for the monthly mean variation of (a) Terra AOD; (b) Aqua AOD over Kedarnath region of Uttarakhand, India. Solid dots indicate the mean values. The range of the whiskers indicates the standard deviation of the mean value.

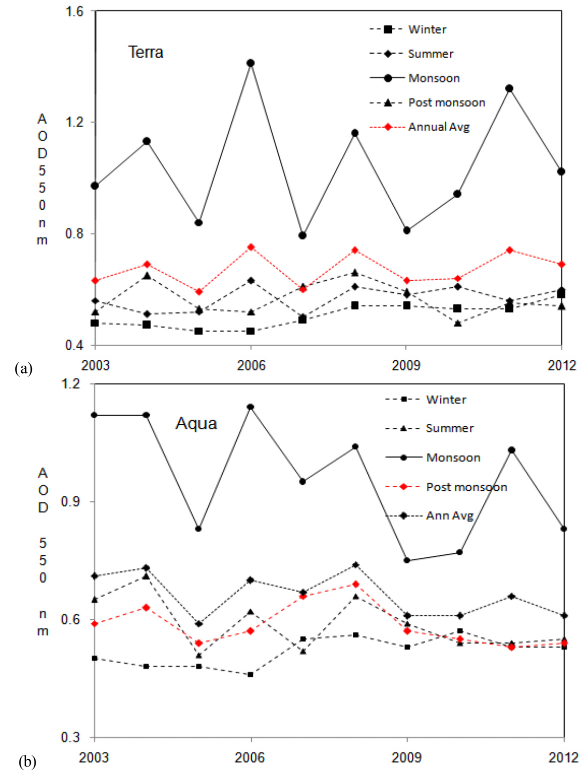

Fig. 4: Seasonal and inter annual variation of area averaged (a) Terra AOD; (b) Aqua AOD at 550 nm over Kedarnath region of Uttarakhand for the period 2003-2012.

creasing trend in the annual mean AOD values over most of the Indian locations including Delhi. They reported an AOD growth of ~0.013 per year which is due to an increase in the urbanization and also an increase in the number of automobiles in Delhi city during the ten year period of study. Further, Kumar (2013) investigated that aerosol optical properties have been found to be increased >15% across North Eastern part of India during the last decade (2001-2010). They also suggested that highest annual mean increase of AOD (>79%) has been found over Shillong, a city of North Eastern part of India. Even the coastal locations like Trivandrum on the west coast recorded higher AOD values as compared to that in Kedarnath region of Uttarakhand. In Dibrugarh, the north eastern location of India, the summer and winter season AOD values (Kumar 2013) are higher, and the rest of the seasons is lower compared to Kedarnath region of Uttarakhand. Gogoi et al. (2009) concluded that the local conditions and the widespread rainfall lead to a more pristine environment during monsoon and retreating monsoon seasons which in turn lead to lower AOD values. It was reported by Singh et al. (2008) that the pre-monsoon/ summer months mean over Patiala of Punjab is somewhat similar to that of Kedarnath region. This is to be noted that Patiala is situated in the Northwest region of India. It is very close to our selected site Kedarnath of Uttarakhand. At Nainital, which is a high-altitude station (~1950 m masl) in the central Himalayas, Pant et al. (2006) reported a very low value of winter time AOD. Since, Delhi is also located at an altitude of ~233 m masl, due to its urban, industrial and cosmopolitan nature, the AOD values at Delhi are far higher as compared to Nainital. It is due to the fact that Nainital, a region of Uttrakhand is surrounded by hilly areas with a number of green trees, small population, less transportation and industrial activities which may cause for lower AOD values at Nainital, a place similar to our selected site Kedarnath of Uttarakhand.

Relationship between AOD and Angstrom exponent value: Angstorm exponent (α) is an exponent that expresses the spectral dependence of aerosol optical thickness with the wavelength of incident light (Sekiguchi et al. 2009). Spatial distribution of area averaged Angstorm exponent has been shown in Fig. 7(a), whereas its seasonal variation is shown in Fig. 7(c) over the Kedarnath region of Uttarakhand for the period 2003-2012. It is clear from Fig. (7c) that Angstrom exponent becomes maximum in winter

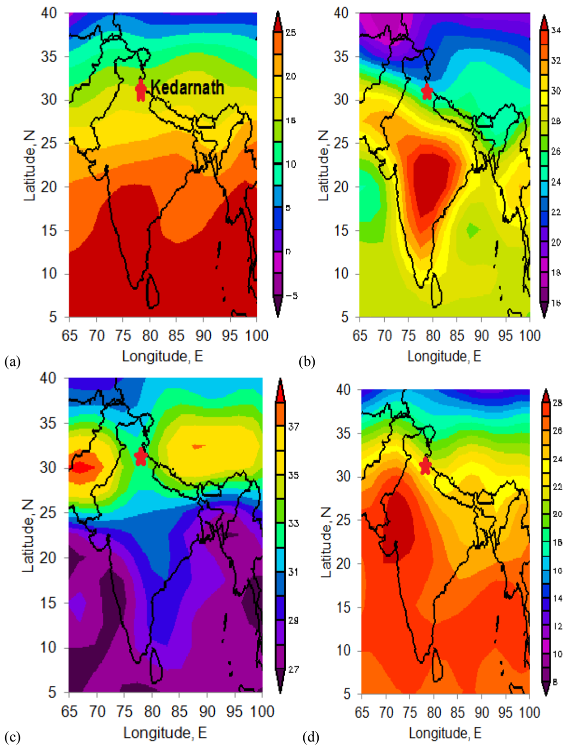

Fig. 5: Mean air temperature at 850 h Pa for various seasons over Kedarnath region of Uttarakhand, India for the period 2003-2012. Red star represents the study location.

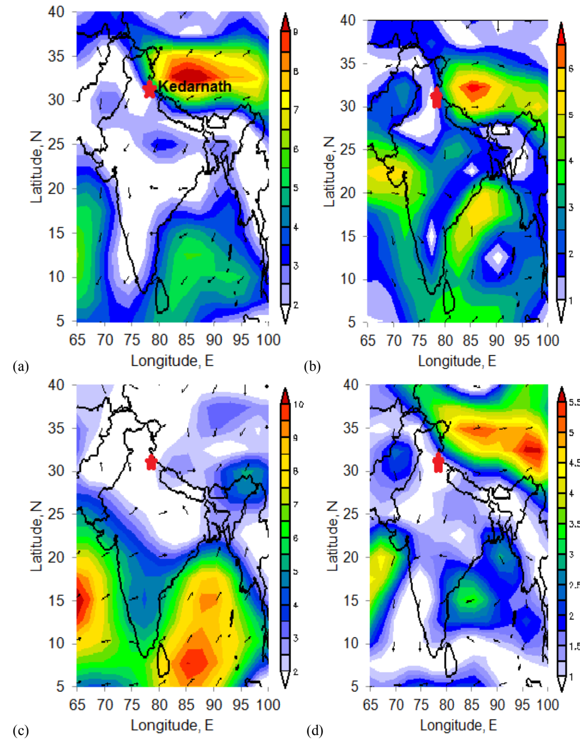

Fig. 6: Mean synoptic vector wind pattern at 850 h Pa for different seasons over various places of South West (SW) region of India. Background colour indicates the magnitude of the wind speed. Red star represents the study location.

season (~1.13±0.092) with its minimum value in summer season (~0.76±0.17). The annual average value of α was found to be observed as ~0.96. Fig. 8(a) shows the time series plot of AOD and Angstorm exponent over Kedarnath region of Uttarakhand for the study period 2003-2012. The statistical correlation plot of AOD versus Angstorm exponent (Fig. 8c) shows that the Angstrom exponent decreases with AOD. It is due to the fact that the swelling of particles due to hygroscopic growth near cloudy areas played a major role in the MODIS data (Pant et al. 2008). The Angstorm exponent may also change if the ratio of the small and course mode particles changes (Kumar 2014). Further this may be due to the fact that a dry particle of anthropogenic origin may have an Angstrom exponent which is 60% higher than a particle with a growth factor of 1.6 (Lyamani et al. 2008). There may be a number of factors which may be responsible for the increase in AOD. Firstly, larger concentrations of atmospheric aerosols may be indeed present near clouds, which would be consistent with the theory (Das et al. 2012). Secondly, it is also possible that AOD may be higher because of the increase in size of humid atmospheric aerosols near clouds (Cowpertwait & Metalfe 2009).

Relationship between AOD and SMF: In order to understand the climatic impact of aerosols on clouds, the satellite derived MODIS data consists of a large number of a valuable data set. Since the hygroscopic behaviour of aerosols introduces complications, therefore the aerosol cloud analysis needs to be done by combining various methods. As different cloud parameters in the MODIS data are correlated, therefore care should be taken in this regard. In this section, relationships between the aerosol optical depth (AOD) and small mode fraction (SMF) for the selected Kedarnath region of sub-Himalayan part of India has been presented. A robust relationship between the aerosol optical depth & SMF was found over Kedarnath region. The relationships between AOD at 550 nm and SMF for Kedarnath zone of Indian region were investigated in the present work for the period 2003-2012. This relationship was studied in detail with the help of one tailed distribution single paired *t*-test, trend analysis, and correlation studies. MODIS derived SMF is the ratio of the fine mode aerosol optical depth to the total aerosol optical depth and it can be used as a proxy for delineating fine mode aerosols from coarse mode aerosols (Feng et al. 2013). Fig. 7(b) shows the spatial distribution of area averaged SMF over the Kedarnath region of Uttarakhand for the period of 2003-2012. It is clear from Fig. 7(d) that the annual average value has its maximum (~0.27±0.092) during winter season, whereas, it has mini-

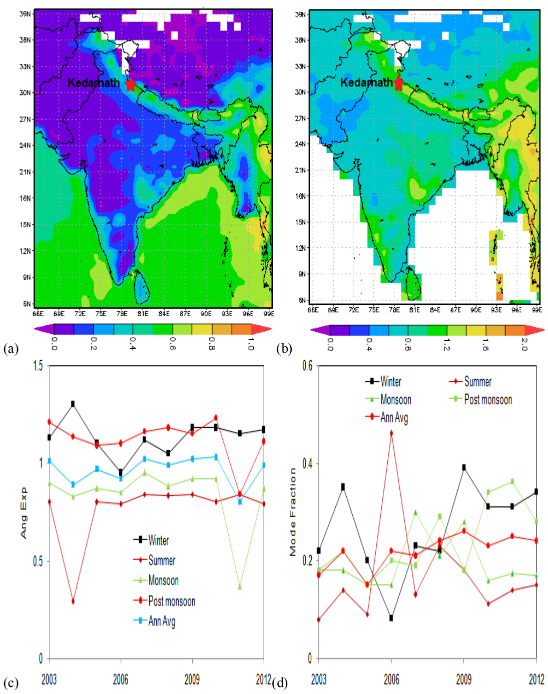

Fig. 7: Spatial correlation map between (a) AOD and angstrom exponent (ANGE), (b) AOD and SMF. The white portion in the map indicate data not available, (c) Seasonal and interannual variation of area averaged ANGE, and (d) Small mode fraction (SMF) over Kedarnath region of Uttarakhand for the period 2003-2012.

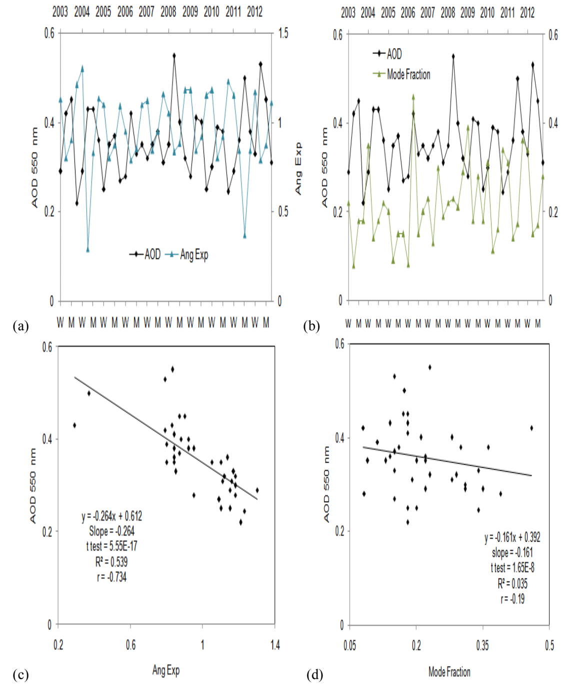

Fig: 8. Time series plot of (a) AOD and ANGE, (b) AOD and SMF, (c) Statistical correlation between AOD & ANGE, (d) AOD & SMF over Kedarnath region of Uttarakhand for the period 2003-2012.

mum annual average value during monsoon (~0.2±0.053) season. Fig. 8(b) shows the time series variation of SMF for the period of 2003-2012 over Kedarnath region of India. The SMF satellite data show a strong correlation with AOD having correlation coefficient and R-squared (R^2) values for AOD and SMF as~0.035 and -0.19 respectively (Fig. 8d). It is clear from Fig. 10(c) that SMF decreases with AOD over Kedarnath region of Uttarakhand for the whole study period of 2003-2012. The negative slope of the trend line for the parameters AOD and SMF was found to be (-0.161). It is to be noticed that the significant decrease in the correlation between AOD and SMF might occur for those regions which have more particulate particles due to industrial, transportation and urban domestic activities etc. It may be due to the influence of meteorological conditions. Further, due to increase in aerosol concentrations, cloud cover increases and therefore aerosol concentrations change the cloud properties, because the regions of low atmospheric pressure have more tendencies to create conditions necessary for cloud formation by accumulating aerosol particles and water vapour (Philipp et al. 2006, Sekiguchi et al. 2009). The less correlation coefficient over Kedarnath between AOD and SMF can be compared with Kohima, a remote city covered with mountains and hilly regions of North Eastern India and very close to our study location Kedarnath. The one tailed distribution single paired student's *t*-test between AOD and SMF was estimated to be ~1.65E-8. This particular behaviour of SMF again might be possible because the increasing aerosols number concentration due to anthropogenic, automobile and domestic activities, may change the humidity profiles and thereby change the SMF (Xiong et al. 2009). Moreover, Ramanathan et al. (2001) suggested that since the effective cloud radius increases with the decrease of cloud top pressure and thereby decreasing the SMF with increasing AOD. Hoeve et al. (2012) indicated that most of the AOD versus SMF relationships seen in the satellite data were also carried by such a process, rather than the direct effect of aerosols on the cloud fields themselves. However, during summer, the moderate AOD values and small SMF values support the above argument (Niranjan et al. 2011). It is well known that the sea-salt production is strongly influenced by over-ocean winds and increase exponentially with wind speed (Naud et al. 2007). Also, the wind generated sea spray aerosols will be in coarse size regime (An et al. 2007) and influence the size distribution parameters. In the present work, higher AOD and standard deviation values during this season accompanied with smaller values of SMF hint about the nature of aerosols over the study location. During the post monsoon season, the AOD values slightly dropped off, but the SMF values (~0.24±0.074) increased considerably nearing winter values (Fig. 8b). It is due to the fact that during post-monsoon season, the study region experiences mixed air mass from Indian Ocean/Arabian Sea, Bay of Bengal via Indian subcontinent (Levy et al. 2007).

CONCLUSIONS

Long term ten years (2003-2012) monthly MODIS Terra/Aqua satellite data (Ver 5.1 level 2) have been used to investigate the spatio-temporal climatic variations of aerosol optical depths AOD at 550 nm over Kedarnath region of Uttarakhand, India. MODIS satellite data have also been used to investigate a correlation between aerosol optical depth (AOD) and cloud parameters like Angstrom component, and small mode fraction for the period 2003-12 over Kedarnath region of Uttarakhand. The major findings of the present study are:

1. Aerosol optical depths have found to be increased >32 % across Kedarnath region during the decadal study period of 2003-2012. The mean AOD value was found to be increased up to June with a clear dip in April.
2. The lowest seasonal mean Terra/Aqua AOD value is observed with a value of ~0.27±0.075, winter/~0.76 ± 0.17, summer and a confidence level of ~0.027/0.229 whereas the highest seasonal mean Terra/Aqua AOD value is recorded during summer period with a value of ~0.42±0.07/0.43±0.063 and confidence level of ~0.130/0.093.
3. The post monsoon season shows relatively low aerosol loadings 0.3±0.054 (0.27±0.061) close to the summer season because rainfall washes out most of the aerosol concentration.
4. Yearly mean Terra/Aqua AOD values have shown an increasing trend at a rate of ~0.005/0.009 per year respectively. However, seasonal winter means Terra/Aqua AOD values exhibit an increasing trend at a rate of ~0.012/0.007 per year respectively.
5. Satellite derived AOD values are correlated with SMF. A negative correlation was found for AOD versus SMF (~ -0.19). A small and positive R-squared (R^2) value was obtained for SMF (~0.035) whereas the value of single paired one tailed distribution *t*-test probability has been observed for AOD and SMF (~1.65E-8) which shows that the cloud top temperature was found to remain insensitive with respect to the changes in aerosol particle concentration.

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