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Signatures of Rossby wave modulations in aerosol optical depth over the central Himalayan region

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Abstract. Long-period modulations are shown in aerosol optical depth measured by the Microtops II Sun photometer over a high-altitude site the central Himalayan region (Nainital, 29.4° N, 79.5° E, 1958 m a.m.s.l.) for the first time. Fourier analysis of aerosol optical depth showed dominant 25–45 day oscillations observed in MODerate-resolution Imaging Spectro radiometer data. Further, a Hovmiîler diagram showed westward (northward) propagation at a different longitude (latitude), confirming that the modulations are associated with Rossby waves. It is also shown that the Rossby wave amplitude causes an additional warming of $4.16 \pm 0.98\,\mathrm{W\,m^{-2}}$ over the observational site. Hence, the present study illustrates the importance of wave-induced aerosol dynamics and the corresponding radiative effects.

Keywords. Atmospheric composition and structure (aerosols and particles)

1 Introduction

It is now well known that atmospheric aerosols (both natural and anthropogenic) exhibit large spatial, temporal and spectral variability due to their shorter residence times and diverse sources. Moreover, larger heterogeneity in aerosol properties in the lower troposphere also contributes to intra-seasonal, annual and inter-annual variability (e.g. Devara et al., 1994; Panditurai et al., 1998; Pal and Devara, 2012). In this context, a few recent studies have focused on the modulation of spectral aerosol optical depth (AOD) by short- and long-period oscillations (Tian et al., 2008; Beegum et al., 2009; Das et al., 2011; Manoj and Devara, 2011).

Considering the advances in the morphology of aerosol layers and their contribution to the Earth's radiation budget, recent reports attempted to understand the role of atmospheric waves in the variability of AOD, from fast-moving gravity waves to slow-moving planetary-scale waves. It is also known that the planetary-scale waves are intense in winter in both hemispheres and play a vital role in transporting not only energy and momentum but also atmospheric trace species (Rossby, 1939; Madden and Julian, 1971; Tian et al., 2008; Beegum et al., 2009; Das et al., 2011; Manoj and Devara, 2011). Hence, it is important to understand the variability of aerosols in terms of atmospheric wave modulations, and this discrepancy could be an essential input to the global and regional aerosol models to assess the global and regional aerosol radiative forcing (ARF) and subsequent climatic impacts (Satheesh et al., 2006). Earlier reports on the equatorial and tropical latitudes show modulation by Madden–Julian oscillation (MJO) which dominates the tropical variability on time scales of 30–70 days (e.g. Beegum et al., 2009). However, such studies do not exist over extra-tropical, mid-latitudes or high latitudes showing the effect of planetary scale waves on AOD and quantification of the impact on ARF.

In this context, the present study aims to investigate the planetary wave signatures in AOD from a high-altitude location at extra-tropical latitudes. We also attempt to quantify the atmospheric ARF due to the long-period modulations.

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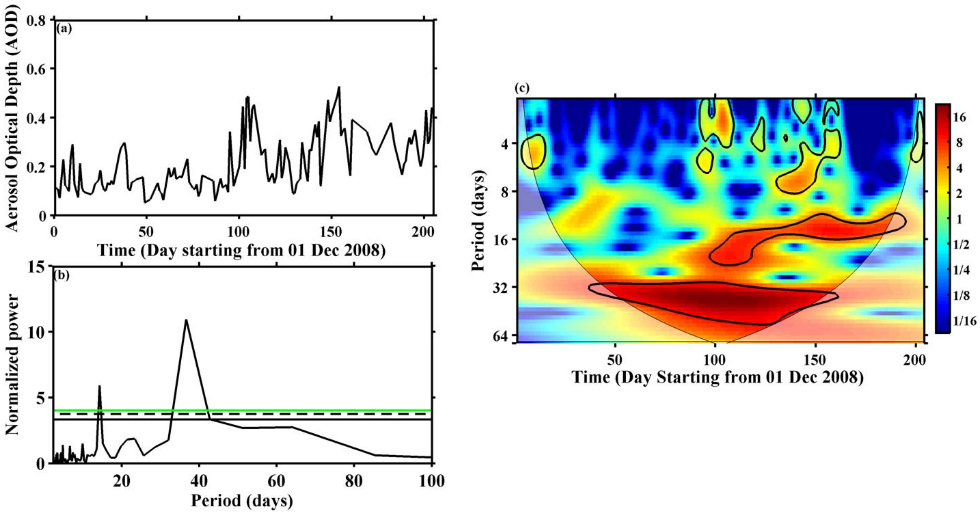

Fig. 1. **(a)** Time series of Microtops II Sun photometer AOD observed from December 2008 to June 2009 at 500 nm. **(b)** Fourier spectrum showing dominant periodicity at 500 nm for the data shown in **(a)** and **(c)**. Wavelet spectra plotted as a function of day number (starting from 1 December 2008) for 500 nm. Contours in the wavelet spectra represent 90 % confidence level.

2 Data sources

The AOD observations are carried out at Nainital (29.4° N, 79.5° E, 1958 m a.m.s.l.), a high-altitude site in the central Himalayan region (see Sagar et al., 2004, for a detailed site description) by the Microtops II Sun photometer, a hand-held instrument having five channels with central wavelengths at 380, 440, 500, 675 and 870 nm with FWHM (full width at half maximum) of 4 nm for 380 nm and 10 nm for other wavelengths (Ichoku et al., 2002). The filters used at 380 nm have a peak wavelength precision of ± 0.4 nm, while other wavelength channels have a peak wavelength precision of ±1.5 nm. The field of view (FOV) of the Microtops II Sun photometer is ∼ 2.5°, allowing only a small amount of diffused radiation to enter into the optical assembly. The details regarding AOD measurements, error budget and calibration using the Microtops II Sun photometer for the Nainital site are well documented and can be found elsewhere (Porter et al., 2001; Morys et al., 2001; Kumar et al., 2011, and references within). In the present analysis, AOD data of 500 nm during the period December 2008–June 2009 are used to examine the effect of long-period modulations on AOD.

To reconfirm whether the observed modulations are realistic in AOD, data from the space-borne sensor, MODerate resolution Imaging Spectro-radiometer (MODIS) onboard the NASA Earth observing system (EOS) in the Aqua and Terra satellite, are utilized for the period December 2008–June 2009, and AOD cloud screened data is used for the present analysis (Martins et al., 2002). The technical details and retrieval algorithm of aerosol optical properties are given in Levy et al. (2009). In the present study, we have used the MODIS daily AOD Level 3 data (550 nm) in the latitude range of 28–31° N, and to know the zonal propagation of the Rossby wave, we have averaged MODIS AOD data centering our latitude (29.5° N) and taking the whole longitude belt. In order to supplement the observed modulations in MODIS, National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) re-analysis zonal and meridional wind data have also been used. ARF calculations are made by giving the optical properties of aerosols as an input to the Santa Barbara DISORT Radiative Transfer (SBDART) model (see Ricchiazzi et al., 1998, for details) to calculate the radiative fluxes (at 500 nm) over the observational site.

3 Results and discussion

Figure 1a shows the AOD at 500 nm observed by the Microtops II Sun photometer from December 2008 to June 2009. An increasing trend is apparent in AOD from December to June because of high aerosol loading at the site due to forest fire events and long-range transport. Moreover, recent studies also showed a significant increase in aerosol concentration, which presumes the importance of the influence of atmospheric dynamics, which is not only effective in transporting energy and momentum, but also atmospheric trace species from distant locations (Hegde et al., 2007).

In order to see the manifestation of long-period modulations, we have performed Fourier analysis (Fig. 1b) on daily averaged de-trended (subtracted mean from each point during the observational period) Microtops II Sun photometer AOD data to extract dominant oscillations. Missing data points, though small, are obtained through spline interpolation, which will not have much influence on the long-period modulations. It is interesting to note that 25–45 day

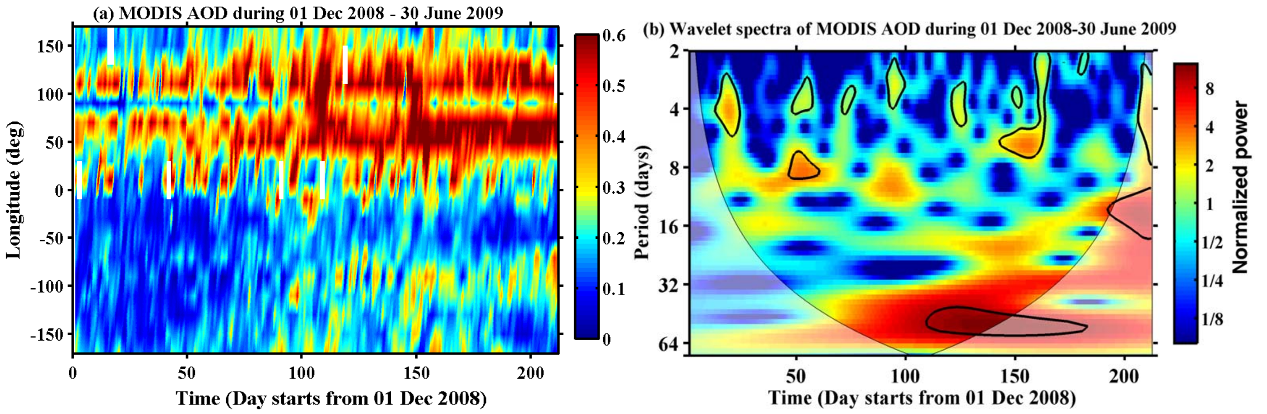

Fig. 2. (a) Time–longitude section of MODIS AOD data obtained during December 2008–June 2009 for 550 nm. **(b)** Wavelet spectra plotted as a function of day number (starting from 1 December 2008) for 550 nm. White patches represent data gaps. Contours in the wavelet spectra represent 90 % confidence level.

periodicity is dominant as compared to 15–25 (quasi 16-day) and significant at 90 % confidence level. These dominant 25–45 day oscillations are effective in modulating accumulation mode aerosols and need to be understood in terms of the lifetime of accumulation mode aerosols. However, our main focus in the present work is to perceive the effect and propagation characteristics of 25–45 day periodicity on aerosol concentration, and the quasi 16-day wave activity during the December 2008–June 2009 period will be taken up as a separate study.

Figure 1c shows the Morlet wavelet spectrum as a function of day number during the period December 2008–June 2009. The Morlet wavelet consists of a plane wave modulated by a Gaussian envelope. The non-dimensional frequency, which gives the number of oscillations within the wavelet itself, is set to six to satisfy the wave admissibility condition. The Morlet wavelet is used in this study due to its simplicity and convenience in investigating wave-like events. The method of Morlet wavelet analysis used in this study is adopted from Torrence and Compo (1998). The spectrum shows the 25–45 day periodicity starting from January 2009 (day number 40) with 90 % significant level. However, shorter periods are dominant around the pre-monsoon season. The main advantage of a wavelet spectrum is that we get the time evolution of particular modulations and it is observed that the longer period modulations are particularly dominant in the first half of the observational period, whereas the shorter periods are dominant in the second half of the observational period.

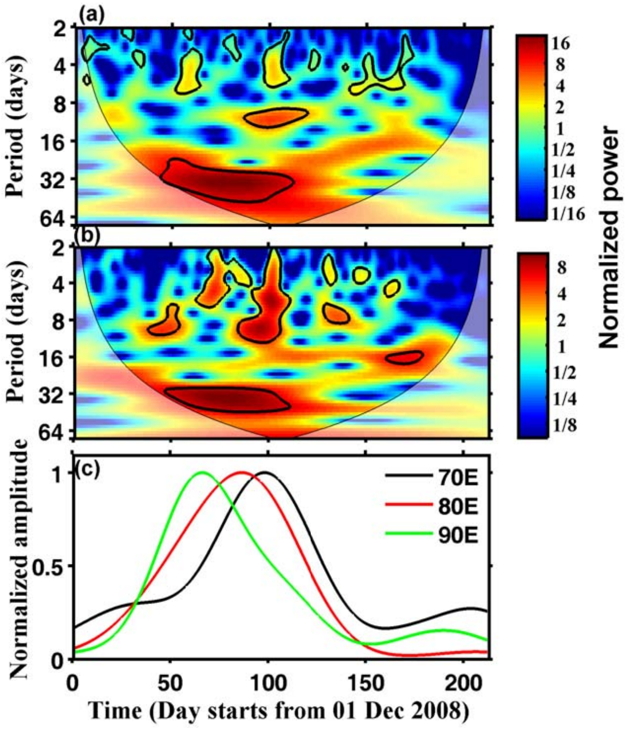

Fig. 3. Wavelet spectra applied for **(a)** zonal and **(b)** meridional wind components of NCEP/NCAR as a function of day number (starting from 1 December 2008) at 600 hPa. **(c)** Normalised amplitude of filtered 25–45 day oscillations for three longitudes, 70, 80 and 90° E, during the observational period. Contours in the wavelet spectra represent 90 % confidence level.

To corroborate whether the observed periodicities are of a global scale, MODIS AOD at 550 nm is utilised during the December 2008–June 2009 period for 28–31° N latitude averaged centering our latitude (29.5° N), taking the whole longitude belt to know the zonal propagation. Figure 2a shows the time–longitude section of the AOD during the period December 2008–June 2009. As expected, high AOD values are seen over the 0–120° E longitude belt (Manora Peak, Nainital; longitude is 79.5° E) as compared to other longitude sectors throughout the observational period (December 2008–June 2009). Noteworthy are the quasi periodic oscillations with westward tilt, which are clearly evident in our longitude belt. Wavelet analysis is applied to the data

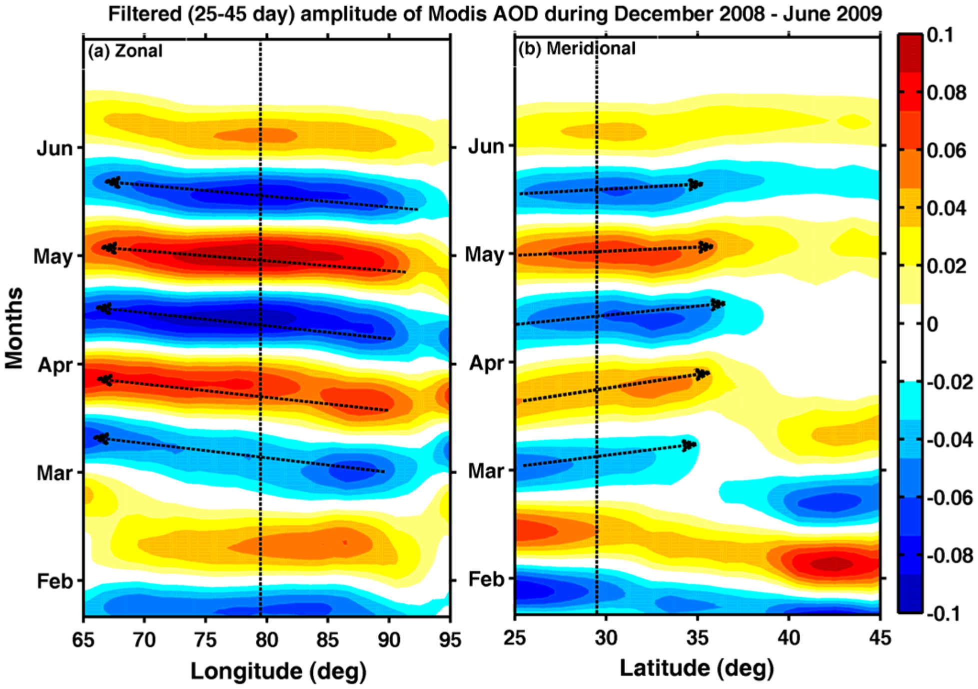

Fig. 4. Time–longitude section of filtered (25–45 day) amplitudes of MODIS AOD from December 2008 to June 2009 for **(a)** zonal propagation (longitude) and **(b)** meridional propagation (latitude). Dotted line represents the longitude and latitude of the observational site and arrows indicate the direction (westward/northward) of propagation.

mentioned in Fig. 2a to see the persistence of long-period oscillations in the MODIS observations also. Similar periodicities of 25–45 days are observed (Fig. 2b) to be dominant, followed by quasi 6.5-day and quasi 16-day periodicities in these space-borne data sets.

Zonal and meridional wind components from NCEP/NCAR re-analysis data at 600 hPa are also analysed for the period December 2008–June 2009 to examine the nature of these long-period oscillations in the wind fields. Note that the 600 hPa level is used for the present analysis, taking the topography around the observational site into consideration.

Figure 3a–b shows the wavelet spectrum of zonal and meridional wind as a function of day number obtained for the December 2008–June 2009 period. It is observed that the 25–45 day oscillations are dominant in both zonal and meridional wind components. In addition to that, shorter period waves (quasi 16-day) are also discernible from the figure. Our observations are during the boreal winter and premonsoon period during which MJO is predominantly eastward along the Equator, with little poleward propagation (Kikuchi et al., 2012). It is generally believed that MJO will be dominant in the zonal wind component and does not show its signature in the meridional wind component. Our observations show significant long-period oscillations in both the zonal and meridional wind components, indicating that these modulations are associated with Rossby-type signatures of extra-tropical latitudes during winter months. To envisage the zonal propagation (whether eastward or westward) of the observed long-period oscillations over longitude (79.5° E), we have chosen 70° E, 80° E and 90° E longitude belts centering our longitude. Figure 3c shows the normalised amplitude of 25–45 day oscillations for the three longitude belts. It is discernible from the figure that long-period waves (25–45 day) propagate westward with a slow-phase speed of 2 m s^{-1}.

Furthermore, to confirm that the modulations in AOD are associated with Rossby waves, we have filtered (band-pass, 25–45 day) the time series of the MODIS-derived AOD at different longitudes (latitudes) to show westward (northward) propagation of Rossby wave modulations. Figure 4a–b shows the longitude/latitude time section of filtered AOD during the period December 2008–June 2009 (a period when wavelet spectra showed maximum amplitude). It is clearly evident from Fig. 4 that the waves propagate westward (northward) at different longitudes (latitudes), as indicated by the arrows. These waves are dominant in 75–85° E longitude (25–30° N latitude) belt during February and moved to 70–80° E (25–35° N) during the March–May 2009 period. However, the modulations fade as we go towards May. Hence this confirms that the wave signatures observed in the AOD are associated with the Rossby waves of extra-tropical latitudes during the winter and spring seasons.

In order to quantify the effect of modulations of aerosols by Rossby waves, radiative flux is estimated based on the

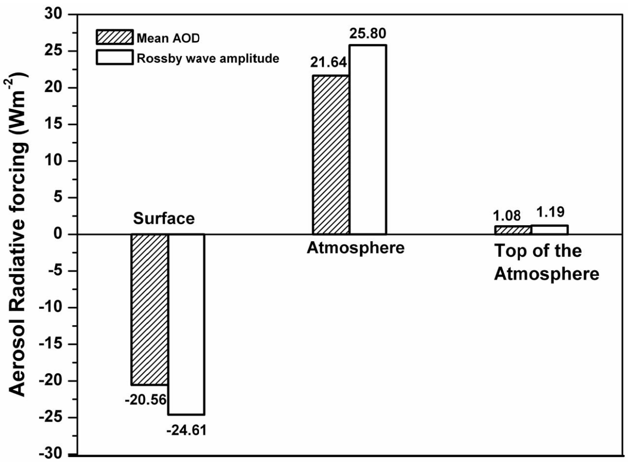

Fig. 5. Diurnally averaged shortwave direct aerosol radiative forcing for surface, top of atmosphere and atmospheric forcing for mean AOD (dashed bars) and Rossby wave amplitudes (non-dashed bars) during the observational period.

optical properties of aerosols like AOD (mean AOD = 0.22 ± 0.01) from December 2008 to June 2009 and Rossby wave amplitude (0.042) obtained by performing Fourier analysis for 25–45 day oscillations), single-scattering albedo (SSA), asymmetry factor and Ångstrom exponent taken from the sun photometer given as an input to the SBDART model. To estimate the ARF over the observational site, we have used the model atmosphere assumed to be tropical and surface reflectance to be a mixture of vegetation (80 %) and sand (20 %) (Kumar et al., 2011). Moreover, concentration of ozone and water vapour is used as per the standard atmospheric model. The hourly estimated ARF are averaged for 24 h to get daily averaged radiative forcing values (see Pant et al., 2006 and Kumar et al., 2011 for details).

Figure 5 shows the ARF effect calculated for mean AOD (0.22) and Rossby wave amplitude ($0.22 + 0.042 = 0.262$) for the surface and top of the atmosphere, respectively. It is interesting to note that the surface and top of the atmosphere for Rossby wave amplitude (mean AOD) are $-24.61\,\mathrm{W\,m^{-2}}$ ($-20.56\,\mathrm{W\,m^{-2}}$) and $1.19\,\mathrm{W\,m^{-2}}$ ($1.08\,\mathrm{W\,m^{-2}}$), respectively. Atmospheric forcing defined as a net variation in the surface and top of the atmosphere turns out to be $\sim 21.64\,\mathrm{W\,m^{-2}}$ and $\sim 25.8\,\mathrm{W\,m^{-2}}$ for mean AOD and Rossby wave amplitude, respectively. It is to be noted that an additional warming of $4.16 \pm 0.98\,\mathrm{W\,m^{-2}}$ is due to Rossby wave amplitude and will be different based on the phase of Rossby wave amplitudes and inter-annual variation (see Beegum et al., 2009).

It is also apparent from the earlier reports that the aerosols are modulated by short-period gravity waves (Manoj and Devara, 2011) and long-period modulations like planetary-scale waves (Beegum et al., 2009). Moreover, Beegum et al. (2009) showed that 30–50 day oscillations are effective in modulating longer wavelengths and attributed their modulations to an association with the MJO. However, it is to be noted that their observations were from a tropical semi-arid location in India. In addition to that, sporadic events like dust storms can transport aerosol particles from western arid regions and they become a source for triggering the gravity waves in the middle atmosphere (Das et al., 2011). In this context, the present study from an extra-tropical high-altitude location showed for the first time the dominant long-period 25–45 day oscillations westward (northward), propagating Rossby waves effective in modulating shorter wavelengths (accumulation mode aerosols) in winter and the pre-monsoon season (Dumka et al., 2008) from eastern arid regions observed over our site. Moreover, Dumka et al. (2008) studied the seasonal variation of aerosol particles over the site, showing that the dominance of accumulation mode aerosols (winter and spring season) could possibly explain the observed variation in the present report. The plausible dominance of Rossby wave features in shorter wavelengths could not only give an indication of lifetime of accumulation mode aerosols, but might also show the seasonal variation in transported dust and typical morphology of the aerosols over the observational site. It is also noted that the slow speed of Rossby waves ($\sim 2\,\mathrm{m\,s^{-1}}$) can take about a month to transport the aerosol particles from eastern locations to the site, also evident from small-phase delay between winds and AOD.

4 Summary and conclusions

The main findings of observed modulations in the AOD are summarised below:

- Fourier analysis of AOD showed dominant 25–45 day oscillations with less dominant quasi 16-day oscillations at 90 % confidence level. Wavelet analysis showed the dominance of long-period modulations from January to May 2009.

- Zonal and meridional wind components also showed dominant 25–45 day oscillations at 90 % confidence level.

- Normalised amplitudes of filtered 25–45 day oscillations clearly showed westward (northward) propagation, confirming for the first time that the modulations are associated with Rossby wave type of oscillations with a slow-phase speed of $\sim 2\,\mathrm{m\,s^{-1}}$.

- Filtered 25–45 day oscillations in MODIS AOD also showed clear westward propagation over the longitude belt, confirming that the modulations are intense over our region.

- For the first time, it is shown that inclusion of the Rossby wave modulation in AOD can induce an atmospheric forcing with an additional warming of $4.16 \pm 0.98\,\mathrm{W\,m^{-2}}$.

The most important conclusion drawn from the present study is the role of wave dynamics in modulating aerosols and corresponding radiative effects because of the long-period modulations.

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References

Beegum, S. N., Krishna Moorthy, K., Babu, S. S., Reddy, R. R., and Gopal, K. R.: Large scale modulations of spectral aerosol optical depths by atmospheric planetary waves, Geophys. Res. Lett., 36, L03810, doi:10.1029/2008GL036509, 2009.

Das, S. K., Taori, A., and Jayaraman, A.: On the role of dust storms in triggering atmospheric gravity waves observed in the middle atmosphere, Ann. Geophys., 29, 1647–1654, doi:10.5194/angeo-29-1647-2011, 2011.

Devara, P. C. S., Raj, P. E., Sharma, S., and Pandithurai, G.: Lidar-observed long-term variations in urban aerosol characteristics and their connection with meteorological parameters, Int. J. Climatol., 14, 581–591, 1994.

Dumka, U. C., Krishna Moorthy, K., Satheesh, S. K., Sagar, R., and Pant, P.: Short- period modulations in aerosol optical depths over the central Himalayas: role of mesoscale processes, J. Appl. Meteorol. Climatol., 47, 1467–1475, doi:10.1175/2007JAMC1638.1, 2008.

Hegde, P., Pant, P., Naja, M., Dumka, U. C., and Sagar, R.: South Asian dust episode in June 2007: Aerosol observations in the central Himalayas, Geophys. Res. Lett., 34, L23802, doi:10.1029/2007GL030692, 2007.

Ichoku, C., Levy, R., Kaufman, Y. J., Remer, L. A., Li, R. R., Martins, V. J., Holben, B. N., Hassan, N. A., Slutsker, I., Eck, T. F., and Pietras, C.: Analysis of the performance characteristics of the five-channel Microtops II Sun photometer for measuring aerosol optical thickness and precipitable water vapour, Geophys. Res., 107, AAC5.1–AAC5.17, doi:10.1029/2001JD001302, 2002.

Kikuchi, K., Wang, B., and Kajikawa, Y.: Bimodal representation of the tropical intra seasonal oscillation, Clim Dynam., 38, 1989–2000, doi:10.1007/s00382-011-1159-1, 2012.

Kumar, R., Naja, M., Satheesh, S. K., Ojha, N., Sarangi, T., Pant, P., Dumka, U. C., Hegde, P., Venkataramani, S.: Influences of the springtime northern Indian biomass burning over the central Himalayas, J. Geophys. Res., 116, D19302, doi:10.1029/2010JD015509, 2011.

Levy, R. C., Remer, L. A., Tanré, D., Mattoo, S., and Kaufman, Y. J.: Algorithm for Remote Sensing of Tropospheric Aerosol Over Dark Targets from MODIS: Collections 005 and 051: Revision 2, MODIS algorithm theoretical basis document, 2009.

Madden, R. A. and Julian, P. R.: Detection of 40–50 day oscillations in the zonal wind in the tropical Pacific, J. Atmos. Sci., 28, 702–708, 1971.

Manoj, M. G. and Devara, P. C. S.: Quasi-periodic oscillations of aerosol backscatter profiles and surface meteorological parameters during winter nights over a tropical station, Ann. Geophys., 29, 455–465, doi:10.5194/angeo-29-455-2011, 2011.

Martins, J. V., Tanre, D., Remer, L., Kaufman, Y., Mattoo, S., and Levy, R.: MODIS cloud screening for remote sensing of aerosols over oceans using spatial variability, Geophys. Res. Lett., 29, 1619, doi:10.1029/2001GL013252, 2002.

Morys, M., Mims III, F. M., Hagerup, S., Anderson, S. E., Backer, A., Kia, J., and Walkup, T.: Design, calibration and performance of Microtops II hand-held ozone monitor and sunphotometer, J. Geophys. Res., 106, 14573–14582, 2001.

Pal, S. and Devara, P. C. S.: A wavelet-based spectral analysis of long-term time series of optical properties of aerosols obtained by lidar and radiometer measurements over an urban station in Western India, J. Atmos. Sol.-Terr. Phys., 84–85, 75–87, doi:10.1016/j.jastp.2012.05.014, 2012.

Panditurai, G., Devara, P. C. S., Maheskumar, R. S., Raj, P. E., and Dani, K. K.: Investigations of QBO in lidar-observed boundary layer aerosols over an Indian urban station, J. Aerosol Sci., 29, Suppl. I, S673–S674, 1998.

Pant, P., Hegde, P., Dumka, U. C., Sagar, R., Satheesh, S. K., Moorthy, K. K., Saha, A., and Srivastava, M. K.: Aerosol characteristics at a highaltitude location in central Himalayas, J. Geophys. Res., 111, D17206, doi:10.1029/2005JD006768, 2006.

Porter, J. N., Miller, M., Pietras, C., and Motell, C.: Ship-Based Sun Photometer Measurements Using Microtops Sun Photometers, J. Atmos. Ocean. Tech., 18, 765–774, 2001.

Ricchiazzi, P., Yang, S., Gautier, C., and Sowle, D.: SBDART: A research and software tool for plane-parallel radiative transfer in the Earth's Atmosphere, B. Am. Meteorol. Soc., 79, 2101–2114, doi:10.1175/1520-0477(1998)079<2101:SARATS>2.0.CO;2, 1998.

Rossby, C. G.: Relation between variations in the intensity of the zonal circulation of the atmosphere and the displacement of the semi-permanent centers of action, J. Mar. Res., 2, 38–55, 1939.

Sagar, R., Kumar, B., Dumka, U. C., Moorthy, K. K., and Pant, P.: Characteristics of aerosol spectral optical depths over Manora Peak: A high-altitude station in the central Himalayas, J. Geophys. Res., 109, D06207, doi:10.1029/2003JD003954, 2004.

Satheesh, S. K., Krishna Moorthy, K., and Srinivasan, J.: Spatial and temporal heterogeneity in aerosol properties and radiative forcing over Bay of Bengal: Sources, role of aerosol transport and implications to regional climate, J. Geophys. Res., 111, D08202, doi:10.1029/2005JD006374, 2006.

Tian, B., Waliser, D. E., Kahn, R. A., Li, Q., Yung, Y. L., Tyranowski, T., Geogdzhayev, I. V., Mishchenko, M. I., Torres, O., and Smirnov, A.: Does the Madden-Julian Oscillation influence aerosol variability?, J. Geophys. Res., 113, D12215, doi:10.1029/2007JD009372, 2008.

Torrence, C. and Compo, G. P.: A practical guide to wavelet analysis, B. Am. Meteorol. Soc., 79, 61–78, doi:10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2, 1998.