

# Aerosol optical depths at Mohal-Kullu in the northwestern Indian Himalayan high altitude station during ICARB

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First time observations of spectral aerosol optical depths (AODs) at Mohal (31.9°N, 77.11°E; altitude 1154 m amsl) in the Kullu valley, located in the northwestern Indian Himalayan region, have been carried out during Integrated Campaign for Aerosols, gases and Radiation Budget (ICARB), as a part of the Indian Space Research Organisation–Geosphere Biosphere Program (ISRO–GBP). AODs at six wavelengths are obtained using Microtops-II Sunphotometer and Ozonometer. The monthly mean values of AOD at 500 nm are found to be  $0.27 \pm 0.04$  and  $0.24 \pm 0.02$  during March and April, 2006 respectively. However, their monthly mean values are  $0.33 \pm 0.04$  at 380 nm and  $0.20 \pm 0.03$  at 870 nm during March 2006 and  $0.31 \pm 0.3$  at 380 nm and  $0.17 \pm 0.2$  at 870 nm during April 2006, showing a gradual decrease in AOD with wavelength. The Ångström wavelength exponent ' $\alpha$ ' had a mean value of  $0.72 \pm 0.05$ , implying reduced dominance of fine particles. Further, the afternoon AOD values are higher as compared to forenoon values by  $\sim 33.0\%$  during March and by  $\sim 9.0\%$  during April 2006 and are attributed to the pollutant lifted up from the valley by the evolving boundary layer. Besides the long-range transportation of aerosol particles by airmass from the Great Sahara and the Thar Desert regions to the observing site, the high values of AODs have also been influenced by biomass burning and frequent incidents of forest fire at local levels.

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## 1. Introduction

Aerosols have a direct effect on the atmospheric radiative forcing, as they scatter and absorb solar and infrared radiation in the atmosphere (Charlson *et al* 1992) and indirectly affect the size distribution of cloud droplets (IPCC 2001). Aerosol optical depth (AOD) is an important parameter for assessing the radiative impacts of aerosols in the atmosphere. To understand the effects of aerosols in the atmosphere, it is essential to characterize their properties at as many places as possible since they show high spatial and temporal variations, due to their regional nature and the short lifetime. In the Indian perspective, the study of

aerosols has been carried out mainly through the ground based network stations of Indian Space Research Organization–Geosphere Biosphere Programme (ISRO–GBP) (Moorthy *et al* 1999). Generally, the high concentrations of aerosols in the atmosphere produce narrow spectrum of small cloud droplets and do not allow droplets to grow in size. As a result, rainfall is inhibited. However, if their concentration remains small in the atmosphere, the cloud condensation nuclei (CCN) facilitate the formation of cloud droplets of proper size and precipitate (Jayaraman 2001).

The studies on columnar AODs in the northeastern as well as northwestern Himalayan regions have been very scarce. Tropospheric pollution and

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prevailing humidity conditions have been the major determining factors for the columnar AODs as far as their measurements from the high altitude locations are concerned. With the concerted efforts on the part of ISRO-GBP, such aerosol climatology studies have initiated various programmes to generate a database on AODs throughout the country including the northeastern and northwestern Himalayan regions. For example, the network stations in the Himalayan regions working under ISRO-GBP are Dibrugarh in Assam (Bhuyan *et al* 2005; Gogoi *et al* 2007), Manora Peak, Nainital in Uttarakhand (Sagar *et al* 2004; Pant *et al* 2006a, b; Srivastava *et al* 2006), IIRS, Dehradun in Uttarakhand (Beegum *et al* 2008), GBPIHED, Mohal-Kullu in Himachal Pradesh (Kuniyal *et al* 2006; Beegum *et al* 2008) and Leh (3441 m) and Henle (4517 m) in Jammu & Kashmir (Singh and Singh 2004), where measurements of AODs with the help of Multi-wavelength Radiometers (MWR-SPL make) or Microtops-II (Solar Light Co. USA make) are being conducted.

An integrated campaign for aerosol, gases and radiation budget (ICARB) was conducted under ISRO-GBP during March to May 2006. The ICARB was conceived as an integrated campaign comprising of three segments namely the land, ocean, and aircraft. The land segment involved the ground-based ISRO-GBP network stations for the aerosol observations, whereas spatially resolved measurements were made on the moving platforms involving the remaining segments. Further, the main emphasis of this campaign was given to study the physical, chemical, and optical characteristics of aerosols and trace gases as well as their temporal and spatial variations in the regional levels.

## 2. Experimental setup and database

### 2.1 Experimental sites

The present study has been carried out at Mohal (31.9°N, 77.11°E; altitude 1154 m amsl), 5 km south of Kullu, a tourist spot in the Kullu valley of northwestern Himalayas in the state of Himachal Pradesh. The Kullu valley starts from the south at Larji (957 m) in the lower Beas valley up to the Rohtang crest (4038 m) in the upper Beas basin. The Kullu valley is bisected by the River Beas and extends up to 80 km long and 2 km wide. Based on micro-climatic conditions, the whole valley geographically falls into two parts, namely the upper Kullu valley and the lower Kullu valley. Raison is a location, which divides this valley into two parts. The sub-Kullu valley south of Raison falls in a rain shadow zone where the present experimental site, Mohal is

located. Kullu (1219 m), a tourist spot, is close to the present experimental site. Mohal (Kullu) falls under sub-temperate climate and occupies an area of about 7 km<sup>2</sup> with a native population of 18,306 in 2001 (Census of India 2001) having a floating population of about 24,000 visitors per day during the peak of summer season (Kuniyal and Vishvakarma 2006).

Due to rapidly growing urbanization in the recent past, the surrounding environment in the immediate vicinity of the experimental site is dominated by tourism and agro-horticultural activities. Soil dust, vehicular emissions, forest fires and other biomass burning activities mainly for cooking and heating purposes in and around the experimental site have contributed significantly to increase the concentration of different types of aerosols over this region. In addition to this, contributions arise from wind blown dust, aerosols, attributed mainly to the long-range transport of aerosols through airmasses as well as from local sources.

### 2.2 Prevailing meteorology

The prevailing meteorological characteristics have also been examined with the help of Automatic Weather Station (Wind Monitor, WM-251, make Envirotech). Daily meteorological data were collected on an hourly basis. These hourly data were averaged to find the diurnal value of various meteorological parameters. Overall, 2134 hourly samples at Mohal from January to June 2006 were collected to draw a wind-rose. Figure 1(a-f) shows the meteorological conditions at Mohal. The highest temperature recorded during the campaign was 19°C on 24 April 2006 (figure 1a). The relative humidity was lowest with 55.4% on April 15, 2006 followed by 56.1% on March 8, 2006 and 56.8% on April 12, 2006 (figure 1b). The lowest relative humidity at Mohal was recorded with 24% on April 11, 2006. The prevailing wind pattern during the campaign is shown by figure 1(c). The wind at Mohal is under light strong breeze category ranging between  $\sim 14$  and  $\sim 17$  km h<sup>-1</sup> during second and third week of April 2006 (figure 1d). Figure 1(e) shows yearly wind pattern, which is being usually found at the experimental site. The wind-rose reveals that for majority of days the wind is received from the northwesterly direction at the experimental site. During campaign, the maximum rainfall was recorded on March 13, 2006 with about 37 mm followed by about 25 mm on April 15, 2006 and 20 mm on April 10, 2006 (figure 1f).

### 2.3 Aerosol optical depth measurements

The present observations of AODs were obtained by using Microtops-II (Solar Light Co, USA),

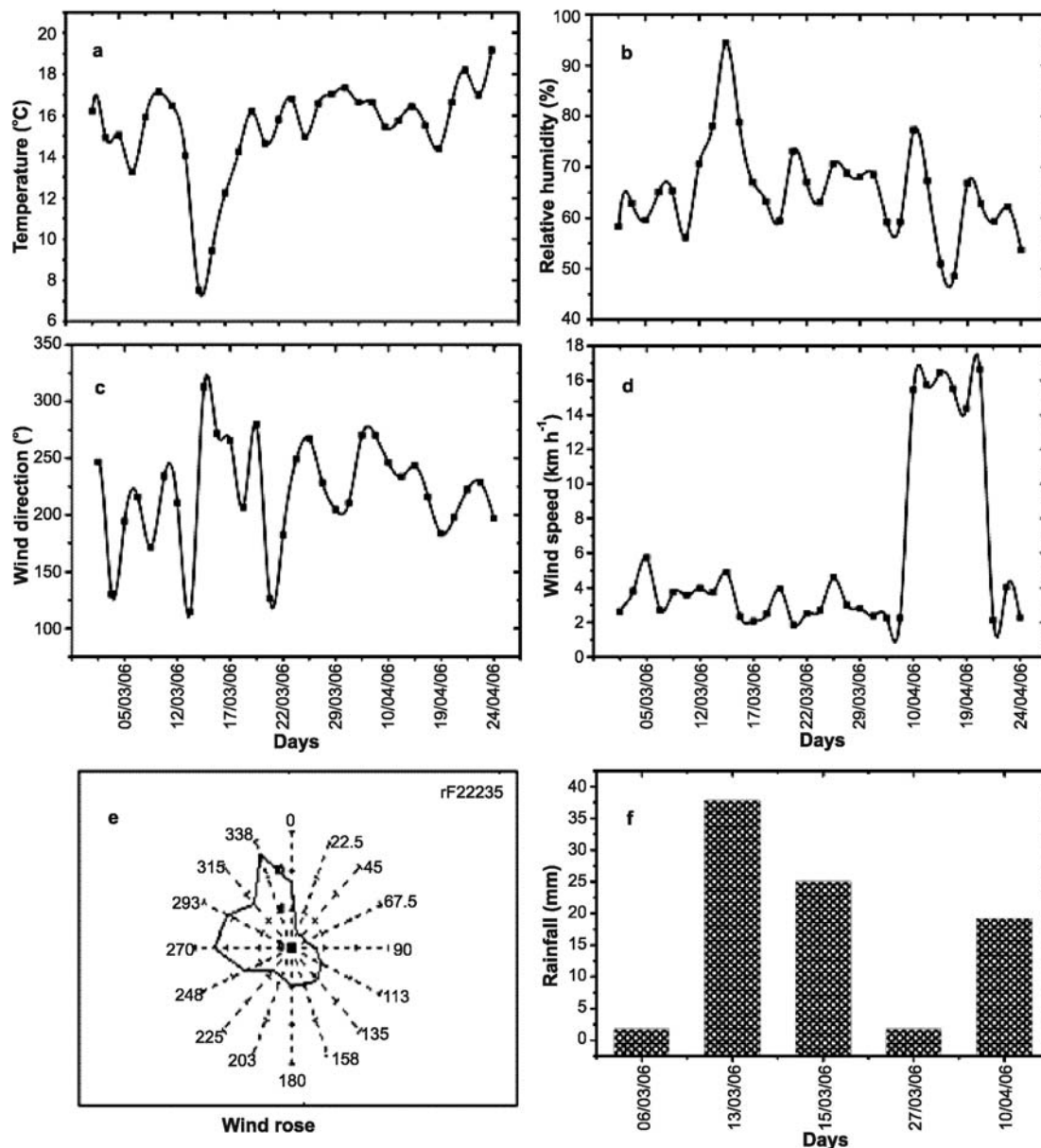


Figure 1. Meteorological parameters at Mohal: (a) temperature, (b) relative humidity, (c) wind direction, (d) wind speed, (e) wind-rose, and (f) rainfall.

Sunphotometer and Ozonometer. These are handheld photometers that measure direct solar radiations and give instantaneous columnar AODs (at six wavelengths centered at 380, 440, 500, 675, 870 and 1020 nm with a bandwidth of 6 to 10 nm), water vapour content (W) and total columnar ozone (TCO) based on their initial calibration. Observations were taken approximately at half an hour interval from sunrise to sunset whenever the sky was clear or partly clear and no visible clouds were present in the neighbourhood of the solar disc. The performance and methodology of data acquisitions with Microtops-II have been described by Morys *et al* (2001) and Ichoku *et al* (2002). The total number of datasets of AOD measurements

were available for 38 days (from March 3, 2006 to April 24, 2006).

### 3. Results and discussions

#### 3.1 Aerosol optical depths

Daily mean variations of the estimated aerosol optical depths are shown in figure 2. The daily mean of AOD values are higher at shorter wavelengths than at longer wavelengths. Analyzing these AOD for a representative wavelength of 500 nm shows a significant variation in AOD for forenoon (FN) and afternoon (AN) periods of the

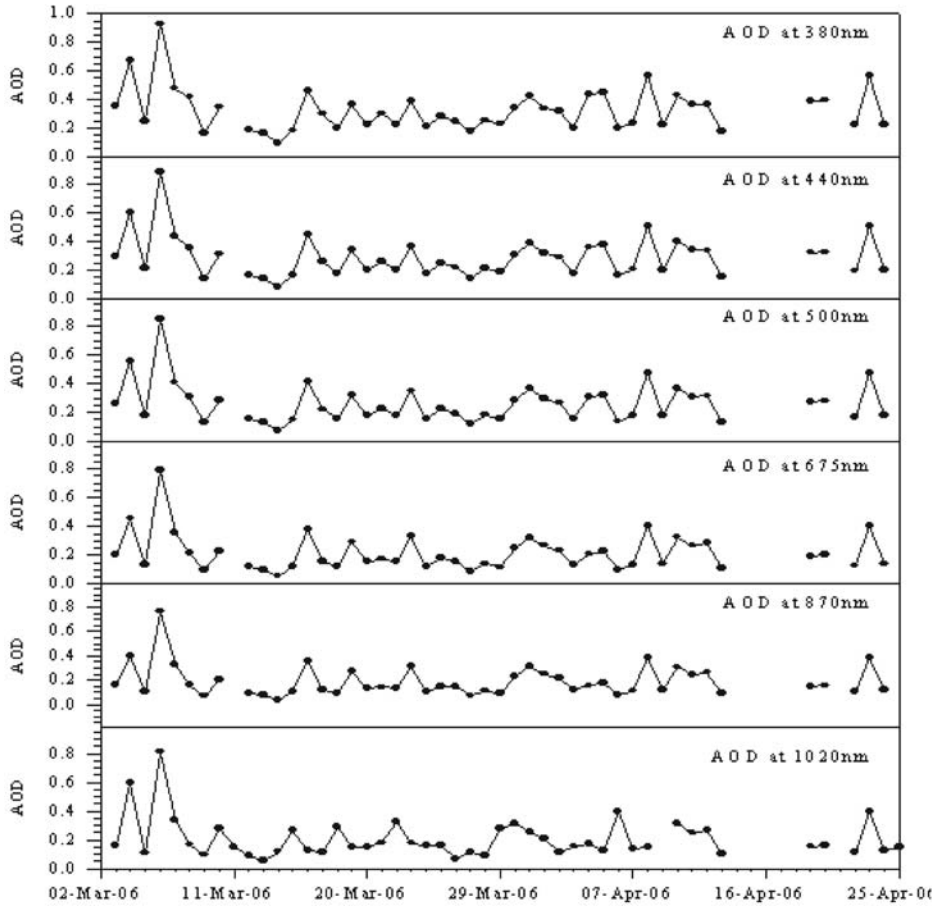


Figure 2. Daily mean variations in AODs at different wavelengths (380–1020 nm).

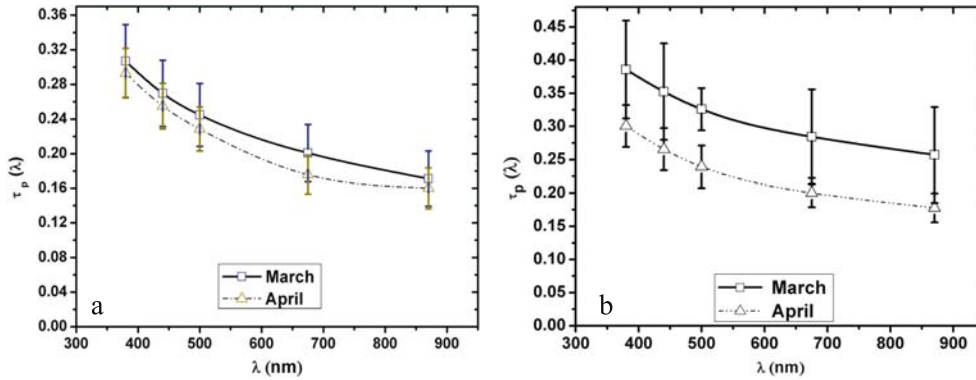


Figure 3. Variations in (a) forenoon (FN) and (b) afternoon (AN) AODs for different wavelengths.

same day. The range of variations during the whole observation period were from 0.085 (March 17) to 0.787 (March 4) for the FN period and from 0.063 (March 17) to 1.57 (March 6) for the AN period. The highest daily mean of AOD was found to be 0.843 on March 6, 2006. These remarkably higher values of AODs are attributed to the long range transported aerosols due to the airmasses from the Sahara and the Thar Deserts to the observing site. In addition to this, the impact of western

disturbances that are accompanied with the flow of airmasses, which are also prolific in the region during the winter, is considered to be responsible for the frequent variations in AODs during the local winter months. Spectral variations of the mean of FN and AN AODs during March and April 2006 have been shown in figure 3(a and b). The FN value of AOD (at 380 nm) is found to be  $0.31 \pm 0.04$  and  $0.29 \pm 0.29$  during March and April 2006 respectively (figure 3a), whereas the AN

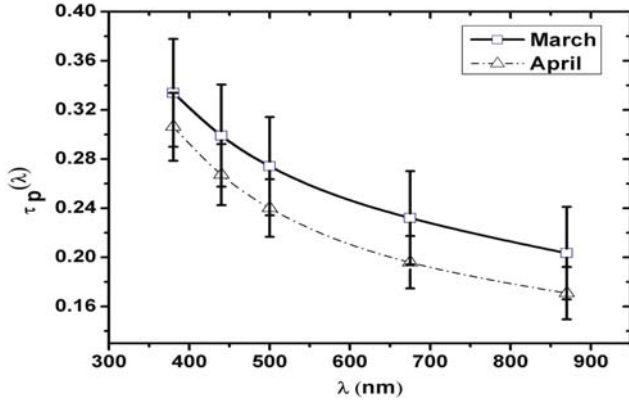


Figure 4. Monthly mean variations in AODs for different wavelengths.

values at the same wavelength showed  $0.39 \pm 0.07$  and  $0.30 \pm 0.03$  during March and April 2006 respectively. Accordingly, this shows an increase of  $\sim 26\%$  and  $\sim 4\%$  from FN to AN during the months of March and April, 2006 respectively. These observations indicate that the FN–AN differences in AOD reduce towards summer months where the afternoon values at the same wavelength remained  $0.33 \pm 0.03$  and  $0.24 \pm 0.03$  during these two months. Similar trends are seen at other wavelengths too. As the observation site is well-elevated, it is possible that during winter months, the AOD measurements are made from above the atmospheric boundary layer, at least during the morning periods. As the solar heating of the land increases, with the advance of the day, convective eddies develop and strengthen. These lift-up the pollutants, including aerosols, from the valley below which eventually break the capping inversion and get distributed to the higher levels, causing an enhancement in the concentration of aerosols in the afternoon. Similar effects are reported from other Himalayan regions also (Pant *et al* 2006b). As summer advances, the minimum land temperature increases and the ABL and even the nocturnal layer deepens, so that the peak would be well within the daytime ABL for most of the time, and the FN–AN difference decreases.

### 3.2 Ångstrom parameters

The spectral variation of aerosol optical depths shows higher values at shorter wavelength and then decreases in accordance with an increase of the wavelengths (figure 4). It complies in harmony with the Mie scattering theory for aerosols distributions.

It is well known that spectral variation of AODs contains information pertaining to their size distribution (Satheesh *et al* 2001). A simple way of expressing the wavelength dependence of AOD is

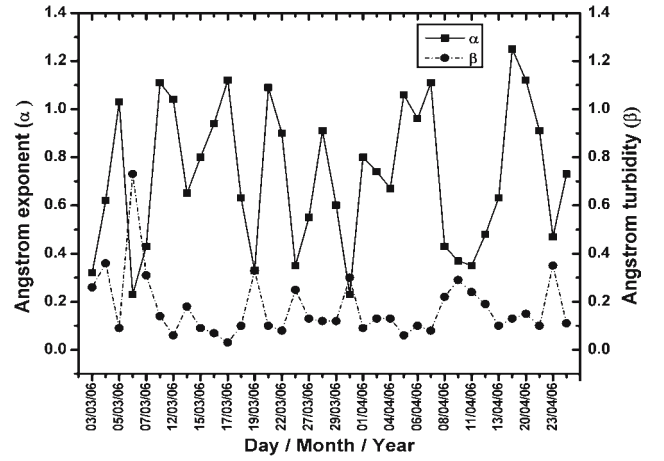


Figure 5. Variations in Ångstrom wavelength exponent ( $\alpha$ ) and turbidity parameter ( $\beta$ ).

through the Ångstrom relation (Ångstrom 1964), expressed as under:

$$\tau_{p\lambda} = \beta\lambda^{-\alpha},$$

where  $\tau_{p\lambda}$  is the spectral AOD as a function of wavelength ( $\lambda$ ),  $\beta$  is the turbidity coefficient representing the total aerosol loading in the vertical column,  $\alpha$  is the Ångstrom exponent related to the size distribution and depends on the ratio of the concentration of small to large aerosols (Ångstrom 1964; Shaw *et al* 1973; Shaw 1976). By evolving an empirical fit of the measured AOD spectra to the Ångstrom power law, the Ångstrom wavelength exponent ( $\alpha$ ) and turbidity coefficient ( $\beta$ ) were estimated (figure 5). The higher values of Ångstrom wavelength exponent ( $\alpha$ ) imply abundance of super micron aerosols (Satheesh *et al* 2001). The values of  $\alpha$  were found to be in the range 0.23 to 1.3 with a mean value of  $0.72 \pm 0.05$ . This is considerably lower than those reported for urban continental region of India and elsewhere, when the mean  $\alpha$  for the period is typically  $> 1.0$ . The low value of ‘ $\alpha$ ’, resulting in a flat AOD spectrum indicating a relatively low abundance accumulation mode aerosols of anthropogenic, due to the remote nature of the site.

### 3.3 Airmass back trajectory analysis using HYSPLIT model

For exploring the possible reasons for the extreme AODs as a consequence of aerosols loading at the site, the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model was followed (Draxler and Rolph 2003). To understand long range transport of aerosols with the airmasses in the region, back trajectories have been able to

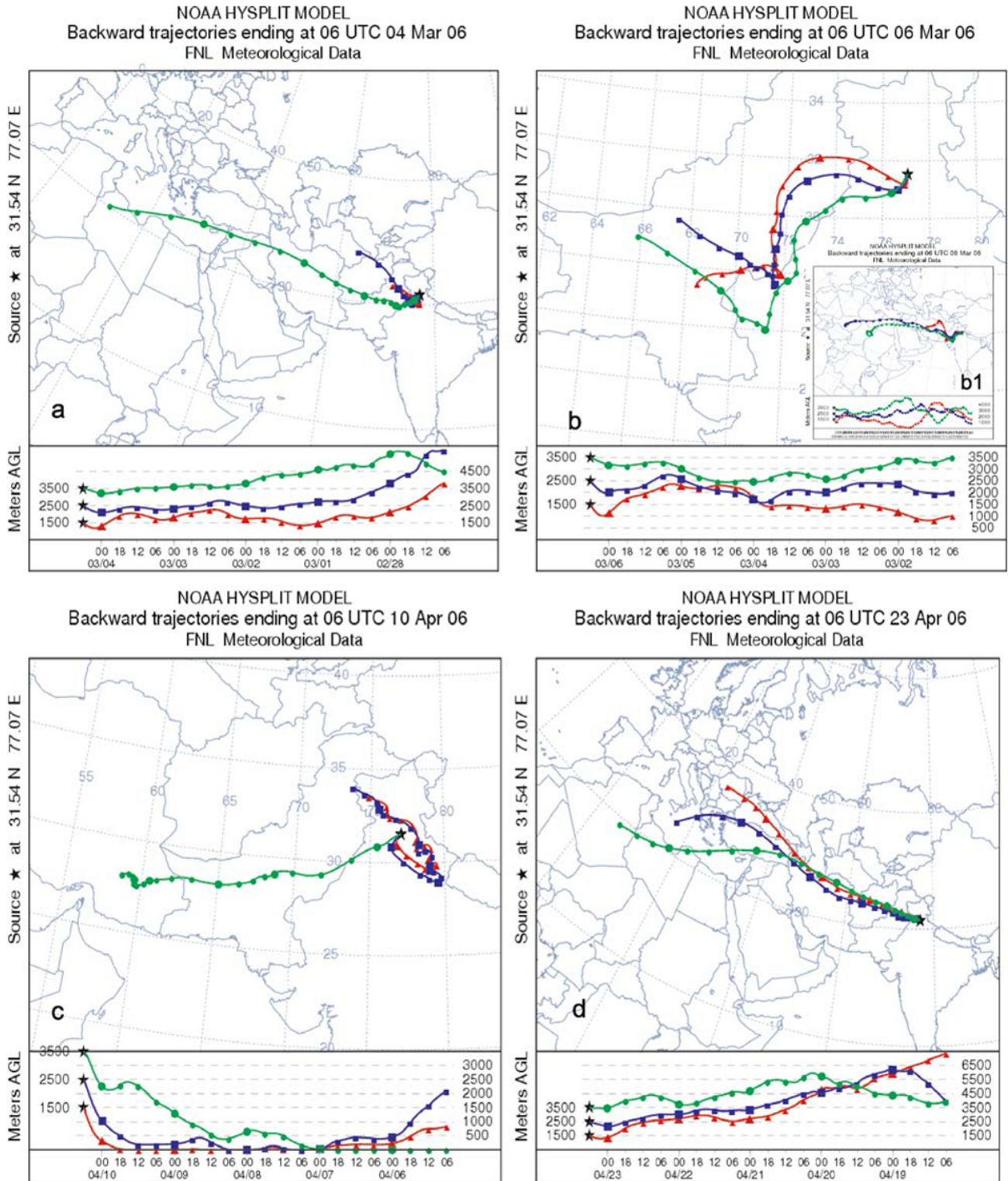


Figure 6. Backward trajectories ending at 06 UTC at Mohal on: (a) March 4, 2006, (b) March 6, 2006, (c) April 10, 2006, and (d) April 23, 2006.

indicate the original sources of air masses. Five days back trajectories ending at Mohal at 1130 IST at different altitudes of 1500, 2500 and 3500 m above the ground level (AGL) were analyzed for March 4 and 6, 2006 and April 10 and 23, 2006 (figure 6). On these days, the observed AODs were exceptionally

high. Most of the back trajectories coming to the experimental site seem to be air mass flow from Sahara, sub-Saharan regions and Great Thar Desert region of Rajasthan. These air masses bring the fine dust particles in the high altitude regions of Mohal, which are mainly responsible for a significant rise

in AOD values and lower value of ' $\alpha$ '. One of the back trajectories at 1500 m (AGL) was almost less than 400 m above the height of the experimental location at Mohal. This height is almost within the mixing height boundary layer for most of the time, influencing the concentration of aerosols in the region.

#### 4. Conclusion

The observations of spectral AODs during ICARB are carried out for the first time from a sparsely inhabited region at Mohal in the Kullu valley of Himachal Pradesh. It is located in the north-western part of Indian Himalayan region. During the campaign, the monthly mean AOD values at 500 nm have been found as  $0.27 \pm 0.04$  and  $0.24 \pm 0.02$  for the months of March and April 2006 respectively. Temporal variations in the spectral AOD values are found to be higher in March in comparison to April 2006 at all wavelengths. The moderately higher AODs during March 2006 seem to be largely influenced by anthropogenic aerosols at local level and also by the long-range transported dust from the outside regions into the experimental site. In this perspective, the airmass back trajectory analysis also shows that the major source of fine aerosols that are transported to the observing site are from the Sahara as well as the Thar Desert regions.

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