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Continuous observations of synoptic-scale dust transport at the Nepal Climate Observatory-Pyramid (5079 m a.s.l.) in the Himalayas

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Abstract

This study presents two years of continuous observations of physical aerosol properties at the GAW-WMO global station "Nepal Climate Observatory – Pyramid" (NCO-P, 27°57′ N, 86°48′ E), sited at 5079 m a.s.l. in the high Himalayan Khumbu Valley (Nepal). Measurements of aerosol number size distribution, aerosol optical depth (AOD) and single scattering albedo (SSA) are analysed from March 2006 to February 2008. By studying the temporal variations of coarse ($1\,\mu m < D_p \leq 10\,\mu m$) particle number concentration, 53 mineral Dust Transport Events (DTEs) are identified, accounting for 22.2% of the analysed data-set. Such events occurred prevalently during pre-monsoon (for 30.6% of the period) and winter (22.1%) seasons. However, uncommon cases of mineral dust transport are observed even during the monsoon season. The main sources of mineral dust reaching NCO-P are identified in the arid regions not far from the measurement site, i.e. from Tibetan Plateau, and Lot-Thar deserts, which account for 52% of the dust transport days. Moreover, a non-negligible contribution can be attributed to the Arabian Peninsula (17%) and the Indo-Gangetic Plains (16%), as indicated by three dimensional (3-D) back-trajectory analyses performed with LAGRANTO model.

The observed DTEs lead to significant enhancements in the coarse aerosol number concentration (+513%) and coarse aerosol mass (+655%), as compared with average values observed in "dust-free" conditions ($0.05 \pm 0.11\,cm^{-3}$ and $3.4 \pm 3.7\,\mu g\,m^{-3}$, respectively). During DTEs, SSA is higher (0.84–0.89) than on "dust-free" days (0.75–0.83), confirming the importance of this class of events as a driver of the radiative features of the regional Himalayan climate. Considering the dust events, a significant seasonal AOD increase (+37.5%) is observed in the post-monsoon, whereas lower increase (less than +11.1%) characterises the pre-monsoon and winter seasons confirming the influence of synoptic-scale mineral dust transports on the aerosol optical properties observed at NCO-P.

1 Introduction

Mineral dust is one of the main components of tropospheric aerosol and it is able to influence global and regional climate through many complex processes (e.g. Forster et al., 2007). Dust particles affect the radiative budget of the atmosphere by absorbing and scattering the incoming shortwave solar radiation, as well as by interacting with the ongoing long-wave radiation (Dickerson et al., 1997; Lau et al., 2006). Considerable uncertainty still affects current knowledge of the optical properties of mineral dust, and contradictory findings have resulted from both satellite/in situ measurements (Kaufman et al., 2001; Dubovik et al., 2002; Anderson et al., 2003) and modelling studies (e.g. Hess et al., 1998). Predicted and measured SSA values fall within such a wide range as to predict either positive or negative forcing (Lafon et al., 2006). Moreover, dust particles indirectly affect regional and global climate by influencing cloud formation, lifetime, atmospheric radiative properties, as well as the amount of precipitation (Rosenfeld et al., 2001; Sassen, 2002; Zuberi et al., 2002; Mahowald and Kiehl, 2003; Mace et al., 2006). As highlighted by laboratory/model studies (e.g. Hanisch and Crowley, 2003; Bauer et al., 2004) and atmospheric observations (e.g. Fischer at al., 2003; Bonasoni et al., 2004; Umann et al., 2005), mineral dust may strongly affect the balance of tropospheric O_3 (a powerful regional greenhouse gas), thus having a further indirect effect on climate.

Major dust mobilization into the atmosphere occurs in specific arid regions, as evidenced both by satellite data and surface observations (Prospero et al., 2002; Washington et al., 2003; Liu et al., 2008a). North Africa (Sahara desert and Sahel belt), the Arabian peninsula (Arabian desert) and western Asia (Lot and Thar deserts) can be considered the greatest sources of soil dust (Léon and Legrand, 2003; Washington et al., 2003; Prasad and Singh, 2007) able to inject yearly several Tg of dust particles into the atmosphere. The Tibetan Plateau and the arid areas of the Indo-Gangetic Plains are also important dust source regions (Han et al., 2008; Gautam et al., 2009).

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As shown by Ramanathan et al. (2007), mineral dust is one of the main components of the Atmospheric Brown Cloud affecting South Asia, in particular during winter and pre-monsoon seasons. During these seasons dust aerosols from the Arabian peninsula and western Asia are transported by low-level westerly winds into northern India and Nepal, piling up against the Himalayas foothills (Lau et al., 2006; Gautam et al., 2009). The accumulation of desert dust and soot aerosols over the southern slopes of the Tibetan Plateau may contribute to enhance heating in the middle/upper troposphere, leading to a strengthening of the meridional tropospheric temperature gradient and, therefore, the advancement of monsoon rainfall in early summer (Lau and Kim, 2006). In addition, because of the absorbing properties of dust, deposition onto snow and ice surfaces may potentially increase melting rates and, hence, affect the dynamics of seasonal snow cover in the region (e.g. Adhikary et al., 2000; Aoki et al., 2006).

Thus, the need exists to better quantify dust levels and variability in the Himalayan area and provide more accurate estimates of the potential impact of dust on the cryosphere. However, apart from the increasing satellite observations of the Tibetan Plateau and Himalaya-Karakoram regions (Liu et al., 2008b; Huang et al., 2007; Gautam et al., 2009), very few studies have been carried out in relation to continuous in-situ dust observations at high altitudes in the Himalayas (Hedge et al., 2007; Carrico et al., 2003; Kaspari et al., 2009).

The purpose of the present paper is to evaluate and characterise the frequency and intensity of dust transport events and their influence on background atmospheric properties in the high Himalayas. The work is based on the first two years (March 2006–February 2008) of continuous observations performed at the GAW-WMO global station "Nepal Climate Observatory-Pyramid" (NCO-P) located at 5079 m a.s.l. on Southern slope of the Himalayas. The observatory is part of the Ev-K2-CNR SHARE (Stations at High Altitude for Research on the Environment) and UNEP ABC (Atmospheric Brown Clouds) projects, providing continuous measurements of trace gases, aerosol and meteorology (Bonasoni et al., 2010). In-situ coarse aerosol number observations, N_{coarse} ($1\,\mu m < D_p < 10\,\mu m$), considered as a proxy for mineral dust at high altitude remote

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sites (e.g. Carrico et al., 2003; Van Dingenen et al., 2001), and three dimensional (3-D) air-mass back-trajectories have been used together to identify the Dust Transport Events (DTEs) at the measurement site. Seasonal aerosol size distributions from 0.25 to 10 µm, single scattering albedo (SSA) and Aerosol Optical Depth (AOD) for DTEs and "dust-free" conditions, are also discussed. The characterisation of dust events as a function of seasons and air- mass origin is also investigated, furnishing precise indications of the main source areas contributing to mineral dust transport over the Southern Himalayas.

2 Experimental

2.1 Site description

The NCO-P station is located on the south-eastern slope of the Himalayan Range (Nepal, 27°95′ N, 86°82′ E, 5079 m a.s.l.), remote from major regional anthropogenic pollutant sources. A detailed description of the measurement site and experimental set-up is presented in Bonasoni et al. (2008, 2010). The local circulation is affected by a mountain/valley breeze regime, with day-time southerly valley winds and nocturnal reversed flow. The interaction between the synoptic-scale and local/regional circulation leads to the onset and decay of the summer monsoon and winter seasons reported by Bonasoni et al. (2010), which are adopted here to define the seasonal transitions (pre-monsoon, monsoon, post-monsoon, winter) during the 2-year investigation. On the synoptic-scale, NCO-P is mainly affected by a westerly circulation for the greater part of the year, with the exception of the monsoon season, when the air-masses reaching the site usually originate from the Gulf of Bengal and the Indian plains. As NCO-P is located within the large "desert belt" that characterises the Northern Hemisphere sub-tropics (see Prospero et al., 2002 and Fig. 1), it is likely that the seasonal variation of the synoptic-scale circulation can trigger the mineral dust transport from these major desert areas towards the measurement site.

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2.2 Aerosol number concentration and size distribution

Aerosol number concentration and size distribution of particles with diameters between 0.25 and 10 µm in 23 size bins were measured by means of an optical particle counter (OPC) GRIMM 190 with an accuracy of 2% on concentrations over the entire measurement range, as stated by the manufacturer. Such measurements enabled the continuous determination of N_{coarse}, i.e. aerosol particles with diameter between 1 and 10 µm. Assuming spherical particles and an average mineral dust density of 2.5 g cm^{-3} (Xu et al., 2010; Linke et al., 2006; Fratini et al., 2007), the particulate aerosol mass concentration (PM_{1-10}) of N_{coarse} was also calculated. The sampling line, connected with a TSP sampling head, is equipped with a drier system (Naphion© tube) which activates in cases of relative humidity (RH) > 70% in the sampling flow. However, to ensure that there was no influence of humidity on aerosol size, only data recorded with ambient RH < 95% were considered. For the investigated period, OPC measurements (at ambient RH < 95%) were available for 62% of days, the longest data gap due to instrumental failure being recorded from 2 December 2007 to 21 January 2008. This data-set, represents the longest continuous time series of N_{coarse} available at altitudes above 5000 m a.s.l. As for the other in-situ parameters presented in this paper, OPC observations are reported at Nepal Standard Time (NST, i.e. UTC +5.45), while all concentrations refer to STP conditions (273 K and 1013 hPa).

2.3 Aerosol optical properties

Aerosol total and back scattering coefficients at three wavelengths (450, 550 and 700 nm) were derived by an integrating nephelometer (model TSI 3563), installed in March 2006. A $PM_{2.5}$ cyclone at the intake of the nephelometer limits sampling to aerosol particles with aerodynamic diameter of less than 2.5 µm. Measurements are performed at 30 l min^{-1} with a time integration of 5 min, averaged every hour. The procedure leading to the data is described in Marcq et al. (2010).

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The aerosol light absorption at 670 nm was measured with a Multi-Angle Absorption Photometer (MAAP 5012, Thermo Electron Corporation). Additional information on MAAP measurements and calibration procedures are provided by Marinoni et al. (2010).

The Single Scattering Coefficient at 700 nm was calculated as described in Marcq et al. (2010). Over the two-year period, the nephelometer measurements during the winter season were limited to a couple of weeks, and were therefore not considered to be representative of the optical properties of the whole season. For this reason, the SSA winter seasonal value was omitted from the present analysis.

2.4 Aerosol Optical Depth measurements

An automated Cimel 318 sun photometer has been operating at NCO-P since April 2006 as part of the NASA-CNRS Aerosol Robotic Network, AERONET (http://aeronet.gsfc.nasa.gov). The instrument provides measurements of direct sun irradiance at 340, 380, 440, 500, 675, 870 and 1020 nm, allowing the measurement of the Aerosol Optical Depth (AOD). The uncertainty on the AOD is about 0.015 (Eck et al., 1999). Since the mean AOD measured at NCO-P is about 0.04 in the dry season (Gobbi et al., 2010), only direct-sun measurements were used in the present analysis, the inversions of sky radiance being unreliable in such conditions (e.g., Dubovik and King, 2000). Further information on the instrument and its data can be found in Gobbi et al. (2010). The highest quality data (Level 2.0, cloud screened and quality assured) were available only for 2006 and January–February 2007, while for March 2007–February 2008 Level 1.5 (cloud screened) AOD data at 500 nm were considered.

2.5 Air mass back-trajectories and cluster analysis and contributing desert areas

To identify the synoptic-scale dust transport episodes at NCO-P, the path and origin of air-masses reaching the site were identified using the Lagrangian Analysis Tool

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LAGRANTO (Wernli and Davies, 1997), providing 3-D 5-day back-trajectories. Trajectory calculations was based on the 6-hourly operational analyses produced by the European Centre for Medium Range Weather Forecasts (ECMWF). The 3-D wind fields were interpolated onto a horizontal 1° × 1° grid and are available on 60 hybrid vertical levels.

With the aim of identifying synoptic-scale mineral dust transport episodes and of minimizing any influence of thermal valley wind circulation, attention was focused on the night-time back-trajectories (ending at the NCO-P at 23:45 NST and 05:45 NST) which originated or transited over the six selected desert areas reported in Fig. 1: North Africa (NA), Arabian Peninsula (AP), Lot-Thar desert (LT), Indo-Gangetic Plains (IGP), Taklimaklan desert (TAK) and southern Tibetan Plateau (TP). In agreement with the climatological investigation of Liu et al. (2008a), a back-trajectory was considered as indicative for possible catchments of mineral dust, if the travel altitude is below 2–3 km a.g.l. for autumn and winter, or below 4–5 km a.g.l. for summer and spring, over at least one source region.

3 Results and discussion

3.1 Dust transport event characterisation

In order to identify DTEs related with synoptic-scale air-mass transport and to minimize the interference of valley breeze transport, days characterised by significant night-time (00:00–06:00 NST) N_{coarse} increases were selected, deduced by applying the Kolmogorov-Zurbenko filter (Zurbenko, 1986). In particular, days characterised by night-time N_{coarse} peaks and air-masses having origin or path above one or more the six dust source regions reported in Fig. 1, were classified as Dust Transport Days (DTDs). A total of 101 DTDs were identified, representing 22.2% of total investigated period (454 days). On the basis of temporal contiguity and similar air-mass transport path, these DTDs were grouped into 53 DTEs, (Table 1): 30 events were identified as

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single-day and 23 multi-day events (11 two-day event, 6 events of 3–4 days, and a few long events up to 9 days). This analysis therefore suggests that the synoptic-scale transport of mineral dust can greatly affect the coarse aerosol number and mass concentration at the NCO-P (Fig. 2). In fact, over the 2-year investigation, the average N_{coarse} and PM_{1-10} values increased by 513% and 655% during the DTEs, with respect to "dust-free" conditions (average values: $0.05 \pm 0.11\,cm^{-3}$ and $3.4 \pm 3.7\,\mu g\,m^{-3}$, respectively).

The frequency of DTD occurrence at NCO-P was characterised by a clear seasonal cycle. The highest seasonal frequency of DTDs was observed in the pre-monsoon (30.6% of the period) and winter (22.1%) seasons, with lower values for the monsoon (12.6%) and post-monsoon (11.0%). The results are in good agreement with previous studies, which indicated pre-monsoon and winter as the seasons more affected by mineral dust transport to South Himalayas (e.g. Carrico et al., 2003; Kaspari et al., 2009; Gautam et al., 2009; Decesari et al., 2010).

3.2 Identification of source dust areas and contribution to NCO-P aerosols

The analysis of 3-D LAGRANTO back-trajectories was carried out in order to identify, among the most important desert regions (Fig. 1), the principal source areas of the mineral dust transported to NCO-P. As indicated in Table 1, a single DTE can be characterised by different source regions, depending on air-mass transport and dust emissions. As shown in Fig. 3, TP and LT represents the most active source areas, accounting for 28% and 24% of DTDs, even if not-negligible contributions were also attributed to AP and IGP, accounting for 17% and 16% of DTDs. To make a rough estimate as to the contributions of the identified source regions to the dust concentrations at NCO-P, the N_{coarse} values during DTEs were analysed (Table 2). Throughout the investigation period, air-masses arriving from the "regional" deserts of TP, LT and TAK were characterised by the highest N_{coarse}, thus pointing to the important role of the nearest deserts in influencing the aerosol properties over South Himalayas. This is also testified by the occurrence of a long-lasting DTE in connection with air-mass

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transport from TAK and TP, as shown by LAGRANTO transport analysis and MODIS (Moderate Resolution Imaging Spectroradiometer) data (Fig. 4, upper plate). The said DTE, which occurred from 11 to 19 April 2007, was characterised by an average N_{coarse} of $0.63\,cm^{-3}$ (about 8 times higher than the seasonal "dust free" value) and the highest average PM_{1-10} ($15.1\,\mu g\,m^{-3}$) ever observed during the 2-year period.

As shown by Bonasoni et al. (2010), during the pre-monsoon season the synoptic disturbances along the Subtropical Jet Stream (SJS) can favour the transport of air-masses from the LT or TP regions, where high dust activity was observed by Liu et al. (2008b) and Han et al. (2008). In fact, for the pre-monsoon, TP and LT represent the most frequent dust sources, accounting for 10.3% and 7.3% of DTDs, respectively. For the pre-monsoon, Decesari et al. (2010) showed that PM_{10} samples collected during DTEs from LT and TP were characterised by enhanced calcium content (up to $487\,\mu g\,m^{-3}$), with respect to "dust free" conditions (average concentration: $0.039\,\mu g\,m^{-3}$). The Ca/Al (average 0.6) and Fe/Al (average 0.7) ratios fall in the same ranges as those found by Wu et al. (2010) in insoluble dust snow, with principal sources from the Tarim and Junggar Basins (TAK area). This was in agreement with Rastogi and Sarin (2009) and Cong et al. (2007), who identified these regions as the main source of calcium-rich particles over the Himalayas. Furthermore, apart from the nearest source regions, high N_{coarse} values were also experienced with air-masses from the AP. This confirmed the possibility that mineral dust transported from far regions can also contribute to increasing the aerosol loadings that characterise the Atmospheric Brown Cloud along the Himalayan foothills, as previously suggested by Ramanathan et al. (2007) and Gautam et al. (2009).

During the summer monsoon, due to the northward shift of the SJS, the prevalent southerly "wet" circulation is not favourable to the transport of air-masses from active dust source regions and only a few DTEs were observed at the NCO-P. Such events were mainly related to air-masses coming from IGP and LT, with a limited increase of N_{coarse}. Only when large-scale shifts of the summer monsoon circulation affected the measurement site, were significant amounts of mineral dust transported by air-mass

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coming from LT, IGP, TAK and TP. This occurred during 14-19 June 2006, when high average N_{coarse} (1.08 cm^{-3}) and PM_{1-10} (12.6 µg m^{-3}) were observed at NCO-P. Compared with the seasonal "dust-free" conditions (Table 1), the lower relative increase of PM_{1-10} with respect to N_{coarse} reveals a predominant concentration of small coarse particles, probably due to the efficient gravitational settling during long-range transport and the contribution of polluted air-masses rich in black carbon (Bonasoni et al., 2010; Marinoni et al., 2010). In fact, as deduced from the LAGRANTO analysis and MODIS data (Fig. 4, bottom plate), a huge amount of aerosol moved westward from Pakistan and north-western India, extending over the heavily polluted IGP. During this event the AOD measurements also showed one of the highest values ever recorded at NCO-P (0.172).

For the post-monsoon season, DTE occurrence still remained low, even though a prevalently westerly circulation was re-established over South Himalayas. According to Bonasoni et al. (2010), about 60% of air-masses reaching the measurement site originated or transited over arid regions (i.e. LT, IGP, TP). However only few of these air-masses were characterised by significant dust contents at NCO-P (Table 2). This result appears to be in good agreement with the low dust contributions estimated by Carrico et al. (2003) during the 1998–2000 post-monsoon at the mountain site of Langtang (Nepal Himalayas), clearly indicating that the post-monsoon represents the transition period from the wet (and relatively clean) summer monsoon to the dry (and aerosol richer) winter.

As shown in Fig. 3, during the winter season more than 50% of the selected days related to dust transport from far western desert regions (NA and AP). Large N_{coarse} increases were also associated with these source regions, indicating that the large-scale circulation effectively favoured the transport of mineral dust from remote western regions to South Himalayas, strongly influencing the atmospheric composition in this region (Table 2). As shown by Decesari et al. (2010), the PM_{10} chemical composition characterising the winter DTEs was characterised by iron values of up to 0.59 µg m^{-3}, more than 4 times the average value (0.129 µg m^{-3}) observed in "dust- free" conditions.

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Moreover, as reported by Decesari et al. (2010), the winter Fe/Al (1.1) is much higher than during the pre-monsoon season, reaching greater values than the ones that are typical for dust coming from central Asia deserts (Wu et al., 2010). According to Kaspari et al. (2009) these results further attest to the importance of mineral dust contributions from far-off western regions, indicating that NA can significantly contribute to the injection of soil dust into the free troposphere also during wintertime, when this area is a less active dust source (Liu et al., 2008a).

3.3 Seasonal aerosol size distribution variations during DTEs

Seasonal number size distribution and number concentration were calculated in order to obtain a clear picture of aerosol variability during DTEs and "dust-free" conditions (Fig. 5). In "dust-free" conditions, the seasonal number aerosol size distributions show a shape typical of background areas (Nyeki et al., 1998; Seinfield and Pandis, 1998), with the highest OPC particle concentration observed during the pre-monsoon ($0.37\,cm^{-3}$) and the lowest in the monsoon ($0.07\,cm^{-3}$). The seasonal variations can be explained by the dry and relatively polluted pre-monsoon conditions at NCO-P due to the efficient transport of Atmospheric Brown Cloud pollutants (Bonasoni et al., 2010) and the wet scavenging of aerosol during the monsoon (Marinoni et al., 2010). Compared to other seasons, the high pollution levels that can affect the high altitudes of the Himalayas during the pre-monsoon, are reflected by a higher fraction of accumulation particles (Fig. 5): this pollution can also be mixed with mineral dust during DTEs.

For DTEs, the highest values of N_{coarse} occurred in the pre-monsoon season ($0.38 \pm 0.24\,cm^{-3}$) and winter ($0.15 \pm 0.12\,cm^{-3}$). Neglecting the DTE observed on June 2006, monsoon and post monsoon seasons both show the lowest frequency and lowest intensity of DTEs, with a value of N_{coarse} equal to $0.03 \pm 0.01\,cm^{-3}$ and $0.07 \pm 0.03\,cm^{-3}$, respectively. The corresponding PM_{1-10} seasonal mean concentration during DTEs shows analogous behaviour: high seasonal mass concentrations were

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observed in the pre-monsoon ($6.6 \pm 6.3\,\mu g\,m^{-3}$) and winter season ($2.9 \pm 3.5\,\mu g\,m^{-3}$), while lower values were found for the monsoon ($0.4 \pm 0.3\,\mu g\,m^{-3}$) and post-monsoon ($0.5 \pm 0.4\,\mu g\,m^{-3}$).

Compared with "dust-free" conditions, a change in the seasonal size distribution shapes was evident at $D_p \sim 1.0\,\mu m$, indicating different sources of aerosol in accumulation and coarse mode during DTEs (Fig. 5). During the post-monsoon, winter and, to a lesser extent, pre-monsoon seasons, a further variation in size distribution was also discernible at D_p between 2 and 3 µm, due to a reduced decrease in the number of particles with larger diameters, possibly related to mineral dust transported from the closest sources (e.g. Hedge et al., 2007). This is reflected by the significant differences between size distributions for DTEs and for typical "dust-free" conditions, especially in pre-monsoon and winter seasons (Fig. 5). In the latter two seasons, during DTEs, N_{coarse} increased by a factor 9.4 and 12.3, respectively, with respect to "dust-free" conditions, while in the monsoon (neglecting the episode of June 2006) and post-monsoon seasons the increase is limited to a factor of 4.5 and 2.3, respectively. Such seasonal variations reflect on the variability of DTE contributions to PM_{1-10} at NCO-P (Fig. 2 and Table 1). In fact, pre-monsoon PM_{1-10} increased by 750% with respect to "dust-free" conditions, while the lowest DTE influence was found during the post-monsoon (27% increase).

The seasonal trend is consistent with observations at other sites in the Himalayas (Nagarkot, 2150 m a.s.l.; Langtang, 3920 m a.s.l.) as well as on the Indo-Gangetic Plains (Kanpur, 142 m a.s.l.), as reported by Carrico et al. (2003) and Dey et al. (2004).

3.4 Seasonal variation of aerosol optical properties during dust transport events

As shown in previous sections, the synoptic transport of mineral dust can greatly affect the coarse aerosol number and mass concentration at NCO-P. During such events it is therefore reasonable to expect a significant change in the aerosol optical properties,

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possibly to the extent of determining a direct influence on the radiative properties of atmosphere. For this reason, in order to estimate the effects induced by the occurrence of DTEs on the optical aerosol properties at NCO-P, changes of aerosol optical properties were investigated in terms of SSA and AOD. The analysis concerns only the early morning AOD measurements from sunrise to 09:45 NST, which, by minimizing the influence of valley breeze circulation, can be considered more representative of the night-time synoptic-scale transport at the site.

The seasonal average of AOD daily maximum showed similar behaviours for DTEs and "dust-free" conditions, with the highest values characterising the monsoon season (Table 3). The presence of mineral dust in the troposphere is usually associated with an increase in the observed AOD values (Dey et al., 2004; Prasad and Singh, 2007; Sagar et al. 2004). This is confirmed at NCO-P, where AOD increases were observed during DTEs in the post-monsoon and, to a lesser extent, in pre-monsoon and winter seasons (Table 3). In the latter two seasons, when the Atmospheric Brown Cloud is present over South Asia and the Himalayan foothills (Bonasoni et al., 2010), the polluted aerosols transported by thermal winds in the free troposphere can attain a longer lifetime, possibly accumulating in night-time residual layers (Marinoni et al., 2010), thus explaining the relatively high values of AOD observed at NCO-P during "dust-free" conditions, which were comparable to DTE values (Table 3).

During the monsoon season, the smaller number of measurements available at the NCO-P lead to consider very carefully the fact that the AOD is higher when the measurement site is not affected by synoptic-scale transport of mineral dust.

The SSA can provide useful information on the optical properties of aerosols, being a key parameter for deriving local estimates of direct aerosol radiative forcing (Hansen et al., 1997; Wang et al., 2009). The seasonal average values of the SSA for both DTEs and "dust free" conditions at NCO-P are reported in Table 3, where no values for winter season are shown, due to the few data available. During "dust free" conditions, the highest SSA value is for the pre-monsoon (seasonal average, 0.83 ± 0.08) and the lowest value is for the monsoon season (0.75 ± 0.15). The values probably reflect a more

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efficient scavenging of hygroscopic aerosol particles with respect to less-hygroscopic absorbing aerosol (such as BC) during the monsoon (Marinoni et al., 2010; Marcq et al., 2010). At NCO-P, higher SSA values characterised DTEs with respect to "dust free" conditions for all the seasons, indicating a more efficient scattering of dust particles and resulting in a relative weak contribution of mineral dust to the mean absorption coefficient. Similar findings were obtained for mineral dust by Dubovik et al. (2002) using eight years of worldwide data from the AERONET network of ground based radiometers. Additionally, an influence of particle size can possibly lead to a further increase of SSA, as found by Collaud Coen et al. (2004), who showed higher SSA values at Jungfraujoch (3576 m a.s.l., Swiss Alps) during episodes of Saharan dust transport. At NCO-P, the highest SSA value (0.89 ± 0.06) was recorded during pre-monsoon DTEs, when the highest frequency and intensity of synoptic-scale mineral dust transport were also observed. Such high SSA values have important implications concerning the direct effects of aerosol on climate. In fact, as pointed out by Hansen et al. (1997), a change in SSA of 0.1 can often change the sign of the direct effect, depending on the albedo of the underlying surface and the altitude of the aerosol layers.

4 Conclusions and discussion

To obtain a better knowledge of the transport of mineral dust to the South Himalayas, and its influence on the aerosol background properties (size distribution and optical proprieties), the present work has analysed the first 2 years (March 2006–February 2008) of coarse aerosol concentrations (N_{coarse}, $1\,\mu m < D_p < 10\,\mu m$) observed at the Nepal Climate Observatory-Pyramid (5079 m a.s.l.), a global GAW-WMO station. The identification of synoptic-scale dust transport episodes at this high mountain site has been carried out taking into account the analysis of night-time data (not influenced by thermal valley breeze) together with three dimensional back-trajectories originating over 6 selected desert areas. A total of 101 dust transport days (DTDs), grouped into 53 dust transport events (DTEs), have been identified, thus indicating that 22.2% of the

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investigated period was influenced by such events. Depending on both the large-scale circulation and the strength of dust source regions, the highest seasonal frequency of DTDs was observed during the pre-monsoon (30.6% of the period) and winter (22.1%). The results have further indicated that the high Himalayas are systematically affected by dust transport, in agreement with other studies (e.g. Carrico et al., 2003; Kaspari et al., 2009; Gautam et al., 2009; Decesari et al., 2009; Gobbi et al., 2010).

The identification of mineral dust source areas has indicated that, on an annual basis, TP and LT are the predominant dust sources (28% and 24% of DTDs, respectively), even if not-negligible contributions have been traced-back to AP (17%) and IGP (16%). In particular, the pre-monsoon period was mainly affected by dust transport from TP and LT, while the winter season showed a strong influence from far western desert regions, such as NA and AP. As also deduced by the analysis of specific case studies (e.g. 14–19 June 2006), during the monsoon season a significant dust transport has been observed at NCO-P only when large-scale shifts in summer monsoon circulation affect the measurement site,. Throughout the period of investigation, air-masses coming from the "regional" Asian deserts of TAK, LT and TP were characterised by the highest N_{coarse} ($0.53 \pm 0.27\,cm^{-3}$; $0.36 \pm 0.34\,cm^{-3}$; $0.38 \pm 0.30\,cm^{-3}$, respectively), thus pointing to the role of the nearest dust sources as major contributors to the aerosol properties at NCO-P. During the pre-monsoon, alongside the said source regions, high N_{coarse} ($0.42 \pm 0.23\,cm^{-3}$) were also experienced with air-masses arriving from AP. This indicates that mineral dust transported from western regions probably also contribute to the large aerosol loading characterising the Himalayan foothills during the pre-monsoon season, when the Atmospheric Brown Cloud extends over IGP up to NCO-P (Ramanathan et al., 2007; Gautam et al., 2009; Bonasoni et al., 2010).

As deduced from continuous measurements at NCO-P, DTEs can strongly influence the aerosol physical and optical properties over the high Himalayas, leading to significant variations in aerosol size distribution, PM_{1-10} concentration and SSA. Over the 2-year period, the observed DTEs led to large average enhancements in N_{coarse} (+513%) and PM_{1-10} (+655%), as compared to the average values found in "dust-free"

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conditions ($0.05 \pm 0.11\,\mathrm{cm}^{-3}$ and $3.4 \pm 3.7\,\mu\mathrm{g\,m}^{-3}$, respectively). In particular, DTEs have been associated to N_{coarse} average values ranging from $0.03 \pm 0.01\,\mathrm{cm}^{-3}$ (during the monsoon, excluding the June 2006 episode) to $0.38 \pm 0.28\,\mathrm{cm}^{-3}$ (during the pre-monsoon), corresponding respectively to a 2.4–4.7-fold increase, with respect to "dust-free" conditions. Similarly, during the pre-monsoon and monsoon DTEs, PM_{1-10} was characterised by average values of $6.6 \pm 6.3\,\mu\mathrm{g\,m}^{-3}$ and $0.4 \pm 0.3\,\mu\mathrm{g\,m}^{-3}$, indicating that, on a seasonal basis, the synoptic-scale transport of dust aerosol increased the average PM_{1-10} by a factor ranging from 1.3 to 8.9.

Dust particles, because of their absorption properties, may deeply impact the Earth's radiative equilibrium, even though the estimation of aerosol radiative forcing including mineral dust remains uncertain (Kaufman et al., 2002; Engelstaedter et al., 2006). In particular, recent studies by Wang et al. (2009), suggested that the role of mineral dust in absorbing solar radiation can be equal to the anthropogenic absorbing aerosols, especially over Indian subcontinent and nearby regions. Thus, the characterization of the DTEs effects on the aerosol optical properties at NCO-P can be considered an important contribution to better understand the critical role of mineral dust in determining the atmospheric radiative budget.

At NCO-P higher SSA values were found during DTEs than in "dust-free" conditions, clearly reflecting the influence of synoptic-scale transport of mineral dust on aerosol optical properties over South Himalayas. On seasonal basis, a significant AOD increase (+37.5%) was observed during DTEs in the relatively clean post-monsoon season, whereas lower increases (less than +11.1%) characterised the pre-monsoon and winter seasons when polluted air masses transported by valley breezes up to the measurement site (Bonasoni et al., 2010; Marinoni et al., 2010) can determine relatively high AOD values also during "dust-free" conditions.

The results presented in this work indicates that considerable amount of mineral dust is systematically transported toward the Himalayas leading to notable changes in the aerosol properties during the observed DTEs. Thus, improving the investigation of interaction between optically active dust, tropospheric ozone and soot particles in

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the glacier areas of the Himalayas represents a mandatory action for a more accurate estimation of the possible influence on the thermal equilibrium of the lower atmosphere and on the variability of Himalayan snow cover and glacier dynamics. Also with this aim, further work will be necessary to evaluate the inter-annual variability of mineral dust transport over the high Himalayas and the possible interaction between large-scale, regional and valley breeze circulation.

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Table 1. List of DTEs with average N_{coarse}, PM_{1-10} and the identified source region. For comparison purposes, the average seasonal N_{coarse} and PM_{1-10} are also reported (change in grey colour indicates seasons transition).

Starting dates	Duration (days)	Source regions NA	AP	LT	IGP	TAK	TP	N_{coarse} (#/cm³)	Seasonal "dust free" N_{coarse} (#/cm³)	PM_{1-10} (µg/m³)	Seasonal "dust free" PM_{1-10} (µg/m³)
11/03/06	1				■			0.08		0.73	
13/03/06	2	■		■	■			0.09		0.50	
27/03/06	1	■			■			0.11		0.66	
29/03/06	3			■	■		■	0.17		1.48	
16/04/06	2	■	■	■				0.18	0.08	1.45	0.53
27/04/06	2	■	■			■	■	0.91		11.8	
30/04/06	1					■	■	0.26		2.07	
07/05/06	1					■	■	0.22		1.18	
14/05/06	2			■	■	■	■	0.39		2.84	
14/06/06	6			■	■			1.08	0.06	12.62	0.59
06/10/06	1				■		■	0.09		0.54	
08/10/06	1				■		■	0.09	0.03	0.61	0.18
16/10/06	1		■	■				0.08		0.45	
18/10/06	2		■	■	■			0.08		0.43	
21/11/06	2	■	■	■				0.11		1.10	
24/11/06	2		■	■				0.07		0.50	
28/11/06	1	■	■	■				0.30		3.83	
11/12/06	1	■	■	■	■			0.07		0.55	
26/12/06	1		■					0.28	0.03	3.22	0.24
30/12/06	1	■	■	■				0.56		8.34	
01/01/07	1	■	■					0.18		2.60	
10/01/07	1		■					0.17		4.53	
14/01/07	1	■	■					0.07		1.43	
20/01/07	2	■	■	■				0.05		0.62	
02/02/07	1						■	0.05		0.70	
06/02/07	1	■	■	■	■			0.10		1.50	
27/02/07	1	■		■	■			0.09		0.61	
04/03/07	1		■					0.15		1.85	
12/03/07	2	■	■		■			0.16		2.04	
17/03/07	3	■	■	■				0.24		5.32	
27/03/07	3	■					■	0.28		5.79	
04/04/07	1		■					0.31	0.08	7.57	1.06
11/04/07	9	■	■	■			■	0.63		15.05	
26/04/07	2			■	■	■	■	0.76		10.47	
28/04/07	4		■				■	0.56		10.30	
05/05/07	1					■	■	0.47		6.50	
13/05/07	1			■				0.52		6.81	
16/05/07	1						■	0.32		4.29	
23/05/07	4			■	■			0.37		6.02	
29/05/07	5		■	■				0.38		6.11	
12/07/07	1				■			0.02		0.19	
20/07/07	1				■			0.02		0.64	
23/07/07	1				■			0.02	0.01	0.23	0.05
12/09/07	1				■			0.03		0.30	
17/09/07	4					■	■	0.04		0.42	
22/10/07	2	■	■	■			■	0.05		0.32	
25/10/07	1			■				0.05	0.03	0.73	0.30
05/11/07	1						■	0.04		0.51	
22/11/07	1						■	0.06		0.99	
24/11/07	3	■	■	■			■	0.06		0.89	
06/02/08	3				■			0.17	0.03	5.26	0.49
12/02/08	1	■						0.24		8.08	
17/02/08	2	■	■	■				0.20		5.72	

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Table 2. Average and standard deviation of night-time (00:00–06:00 NST) N_{coarse} (cm^{-3}) for "dust-free" conditions and DTEs, also split as a function of different dust source regions (NA = North Africa, AP = Arabian Peninsula, IGP = Indo-Gangetic Plains, TAK = Taklimaklan Desert, LT = Lot-Thar Desert, TP = Tibetan Plateau).

			Source regions					
Periods	"dust-free"	DTE	NA	AP	IGP	TAK	LT	TP
All seasons	0.05 ± 0.11	0.29 ± 0.29	0.25 ± 0.22	0.29 ± 0.24	0.21 ± 0.24	0.52 ± 0.27	0.36 ± 0.34	0.38 ± 0.30
Pre-monsoon	0.08 ± 0.06	0.38 ± 0.24	0.31 ± 0.24	0.42 ± 0.24	0.27 ± 0.25	0.59 ± 0.22	0.41 ± 0.22	0.51 ± 0.25
Monsoon	0.04 ± 0.22	0.34 ± 0.56	–	–	0.19 ± 0.34	0.05 ± 0.00	1.16 ± 0.49	0.04 ± 0.01
Post-monsoon	0.03 ± 0.01	0.07 ± 0.02	0.05 ± 0.00	0.06 ± 0.01	0.08 ± 0.01	–	0.06 ± 0.01	0.07 ± 0.02
Winter	0.03 ± 0.02	0.15 ± 0.12	0.17 ± 0.15	0.17 ± 0.12	0.15 ± 0.05	–	0.15 ± 0.16	0.06 ± 0.01

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Table 3. Aerosol optical depth and single scattering albedo during mineral dust transport events (DTE) and during periods not influenced by mineral dust transport (dust free). The SSA represent night-time (00:00–06:00 NST) average value. The AOD values for AERONET NCO-P station are Level 2.0 for March 2006–February 2007 and Level 1.5 for March 2007–February 2008.

Parameter	Pre-monsoon	Monsoon	Post-monsoon	Winter
AOD (500 nm) – DTE	0.041 ± 0.021	0.110 ± 0.058	0.077 ± 0.069	0.030 ± 0.016
AOD (500 nm) – Dust free	0.040 ± 0.026	0.134 ± 0.125	0.056 ± 0.053	0.027 ± 0.021
SSA – DTE	0.89 ± 0.06	0.84 ± 0.13	0.84 ± 0.04	–
SSA – Dust free	0.83 ± 0.08	0.75 ± 0.15	0.82 ± 0.07	–

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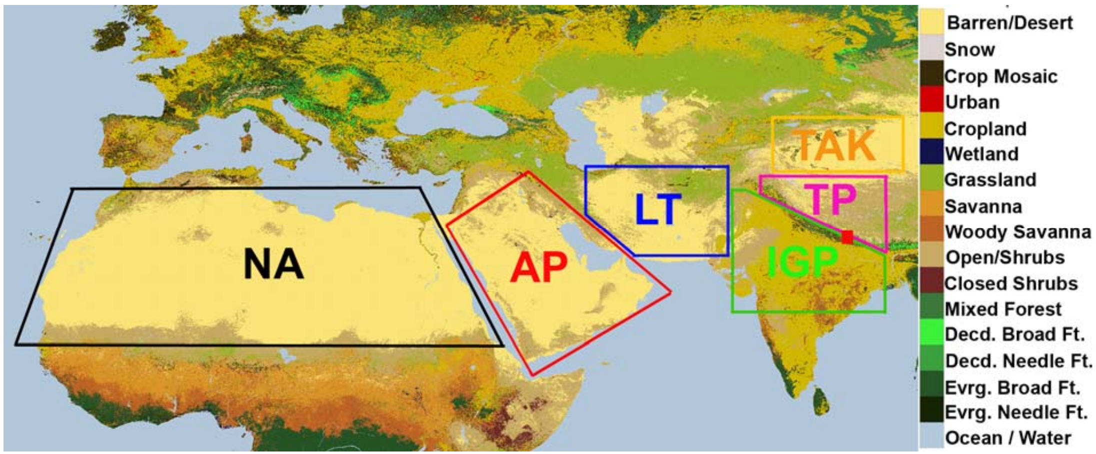

Fig. 1. NCO-P location (red square) together with the boundaries of the six selected mineral dust source regions: North Africa (NA), Arabian Peninsula (AP), Lot and Thar desert (LT), Indo-Gangetic Plains (IGP), Taklimaklan desert (TAK) and southern Tibetan Plateau (TP). Global MODIS Land Cover from NASA Images (www.nasaimages.org).

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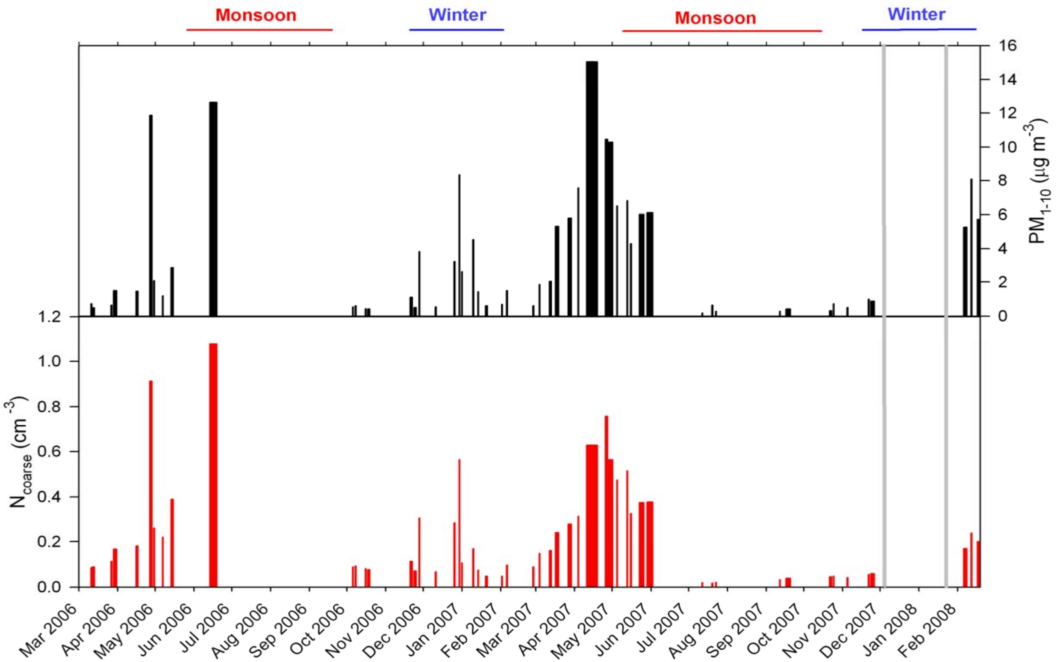

Fig. 2. N_{coarse} (red bar) and PM_{1-10} (black bar) during the Dust Transport Days (DTDs) identified at NCO-P from March 2006 to February 2008. Grey bars delimit the period without measurements available (2 December 2007–21 January 2008).

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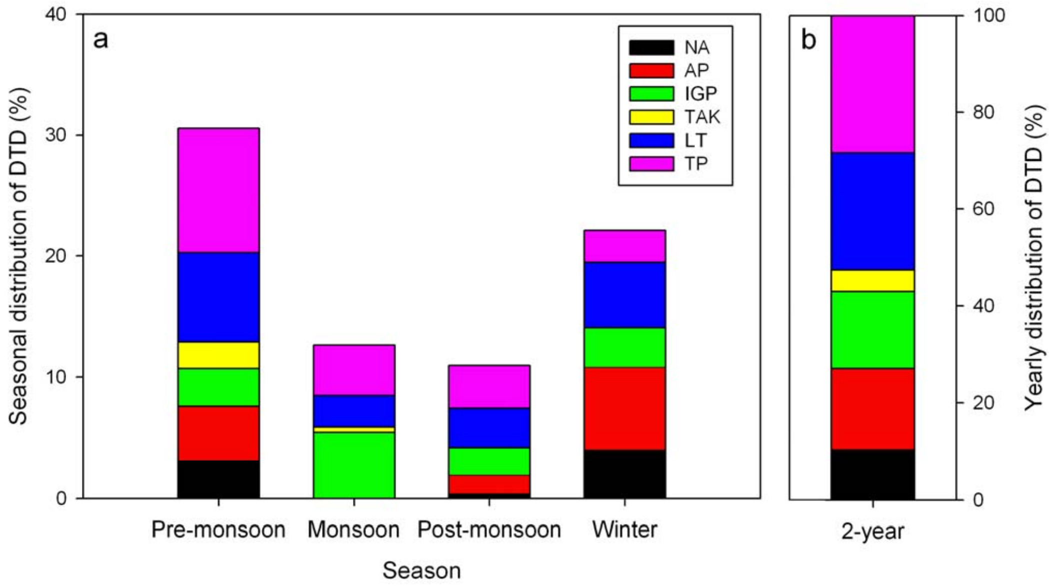

Fig. 3. Seasonal distribution of source areas of mineral dust at NCO-P, expressed as frequency of DTDs.

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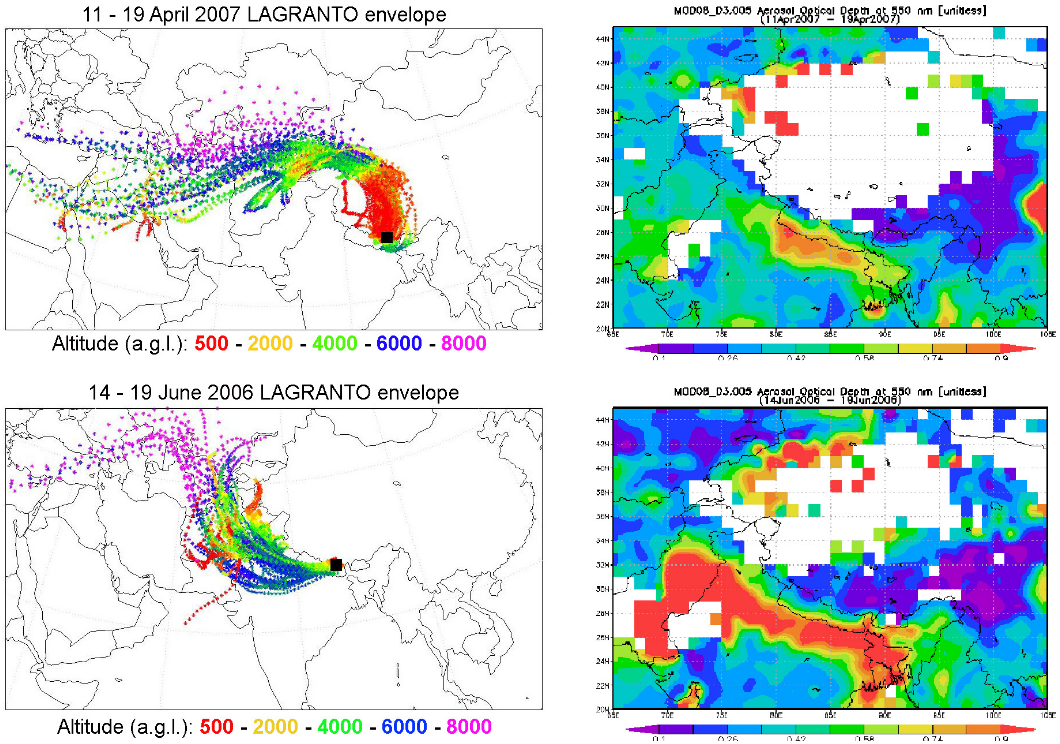

Fig. 4. Left: envelopes of the calculated back-trajectories showing the synoptic circulation affecting NCO-P during 11–19 April 2007 (upper plate) and 14–19 June 2006 (bottom plate). Right: averaged MODIS AOD at 500 nm for the same periods.

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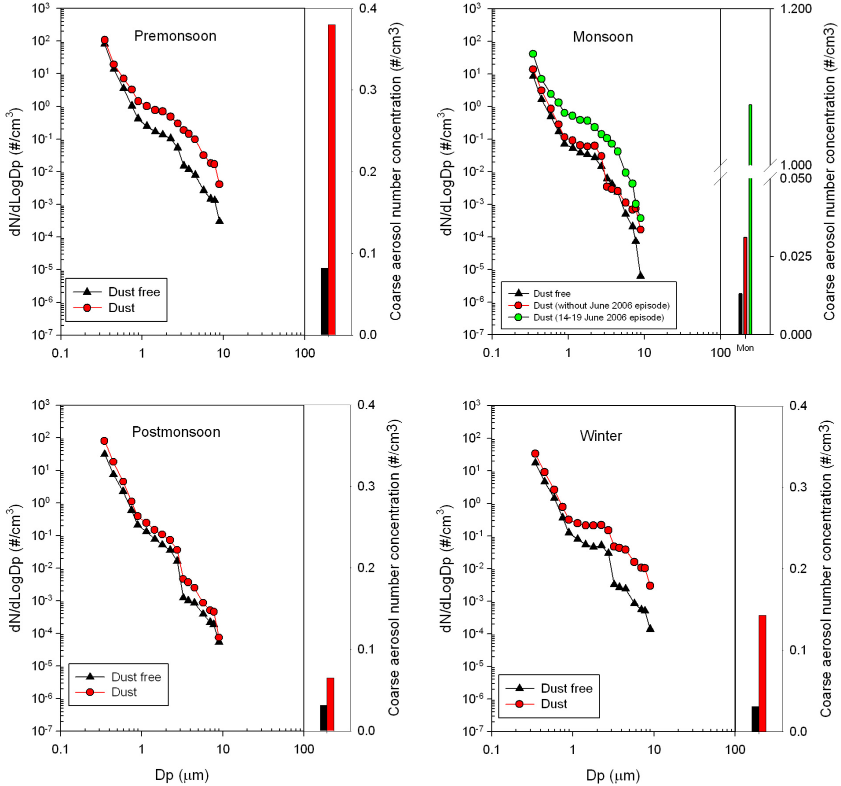

Fig. 5. Night-time (00:00–06:00 NST) seasonal average aerosol size distribution for DTEs (red circles) and "dust free" conditions (black triangles). For the monsoon season, the green circles represent the average aerosol number distribution during the 14–19 June 2006 "special event". On the right, the mean N_{coarse} for the "dust" and "dust free" conditions (respectively, red and black columns) are reported.

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