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Key Points:

- Satellite observations and Meso-NH model simulations are used to investigate an intense dust storm over north India in June 2018
- Dust is mostly confined below 2 km in the monsoon flow over the Thar desert, northwest India and at ~3 km along the Ganges Valley
- The dust was accumulated in an arc-shaped cloud in the convergence zone between the southwesterlies and the northwesterlies: the ITD

Correspondence to:

U. C. Dumka, D. G. Kaskaoutis and D. Francis,
 dumka@aries.res.in;
 ucumka@gmail.com;
 dimitriskask@hotmail.com;
 diana.francis@nyu.edu

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The Role of the Intertropical Discontinuity Region and the Heat Low in Dust Emission and Transport Over the Thar Desert, India: A Premonsoon Case Study

U. C. Dumka¹ , D. G. Kaskaoutis², D. Francis³ , J.-P. Chaboureaud⁴ , A. Rashki⁵ , Suresh Tiwari⁶, Sachchidanand Singh⁷ , E. Liakakou², and N. Mihalopoulos^{2,8}

¹Aryabhatta Research Institute of Observational Sciences, Nainital, India, ²Institute for Environmental Research and Sustainable Development, National Observatory of Athens, Athens, Greece, ³New York University Abu Dhabi, Abu Dhabi, United Arab Emirates, ⁴Laboratoire d'Aérodynamique, Université de Toulouse, CNRS, UPS, Toulouse, France, ⁵Department of Desert and Arid Zones Management, Ferdowsi University of Mashhad, Mashhad, Iran, ⁶Indian Institute of Tropical Meteorology, New Delhi, India, ⁷Environmental Sciences and Biomedical Metrology Division, CSIR-National Physical Laboratory, New Delhi, India, ⁸Environmental Chemical Processes Laboratory, University of Crete, Crete, Greece

Abstract A severe dust storm occurred over north India during 12–16 June 2018 is analyzed using satellite observations, reanalysis, ground-based measurements, and model (Meso-NH) simulations focusing on the dynamic processes that caused the dust-storm generation, uplift, and propagation as well as its impacts on air quality. The initial dust emission was triggered by strong near-surface southwesterlies (~15–20 m s⁻¹) associated with the monsoon flow advancing northward, in response to the deepening of the thermal low over the Thar desert. The convergence between the northwesterlies and the monsoon flow along the Intertropical Discontinuity region caused high dust accumulation over northwest India in an area of weak winds. Convective mixing during daytime favors the vertical transport of dust to higher altitudes above the monsoon flow, but the towering Himalayas and the associated return northerly flow aloft play a blocking role leading to dust accumulation at heights between 1 and 3 km over northwest India. The prevailed northwesterlies in the middle troposphere favor the eastward transport of the dust plumes along the Ganges valley, helping to evacuate the dust toward east India. Based on Meso-NH model simulations, the dust storm was associated with dust loads higher than 30 gm⁻² and AODs higher than 3, in agreement with MODIS observations. The impact of the dust storm on the spatial-temporal evolution of the PM₁₀ and PM_{2.5} mass concentrations is studied using data from 23 air-quality stations over northern India, indicating daily PM₁₀ peaks reaching at ~900 µg m⁻³, implying a severe degradation of air quality.

1. Introduction

Mineral dust is a key atmospheric component, which has serious effects on regional and global climate system via scattering and absorption of solar and terrestrial radiations, on cloud microphysical properties and global biogeochemical cycles, and adverse effects on air quality, socioeconomic factors, and human health (e.g., Behrooz et al., 2017; Goudie, 2014; Mahowald et al., 2005; Martiny & Chiapello, 2013; Middleton, 2017; Nastos et al., 2011; Ramanathan et al., 2001; Schepanski, 2018).

Over the Indian subcontinent, the premonsoon intense dust events may alter the atmospheric stability and heating rates and modulate the Indian summer monsoon (ISM) rainfall (Bollasina et al., 2008; Jin et al., 2014; Kaskaoutis et al., 2018; Lau et al., 2006; Solmon et al., 2015). Furthermore, deposition of the south Asian dust on the Himalayan glaciers leads to acceleration of their melting due to decrease in albedo caused by darkening of the snow surface (Gautam et al., 2013). Another important issue is the severe deterioration of air quality and the very high particulate matter (PM) levels during periods of dust storms, as dust contributes to an already highly polluted atmosphere over northern India (Dey & di Girolamo, 2010; Giles et al., 2011).

The Thar desert is a major dust source in south Asia (Washington et al., 2003; Gautam et al., 2009) and is characterized by hyperaridity (annual mean rainfall <10 mm), absence of vegetation, and fine sediments very prone to aeolian erosion (New et al., 2002; Pokharel et al., 2017). Due to extremely dry conditions and strong winds, northwest India is under the influence of frequent and intense dust storms during the premonsoon (April–June) season. The typical premonsoon dust storms last for several days (~4–7) and the dust

particles are mixed with anthropogenic pollution forming a persistent thick aerosol layer, known as brown clouds, with important climate implications (Lawrence & Lelieveld, 2010; Srivastava et al., 2018). Previous studies, using multiple satellite sensors, ground-based measurements, and reanalysis, agree to an overall decrease in dust loading (~10–20%) over northern India in the premonsoon season during the last ~15 years (Kaskaoutis et al., 2011; Kaskaoutis et al., 2012; Lakshmi et al., 2019; Lodhi et al., 2013). Recent works revealed that this decrease is attributed to an increase in premonsoon rainfall (~27% since 2000), soil moisture (17%–27%), and greenery around the Thar desert that confined the dust activity (Jin & Wang, 2018; Pandey et al., 2017). Dust events over northern India have been examined in numerous studies (Chinnam et al., 2006; Das et al., 2013; Dey et al., 2004; Dumka et al., 2014; Gautam et al., 2010; Hegde et al., 2007; Kumar et al., 2014; Kumar et al., 2015; Pandithurai et al., 2008; Prasad et al., 2007; Prasad & Singh, 2007; Sarkar et al., 2019; Sharma et al., 2012; Sijikumar et al., 2017; Singh et al., 2016; Singh & Beegum, 2013; Srivastava et al., 2014; Tiwari et al., 2019), mostly focusing on the synoptic meteorology and estimation of the radiative impacts of dust storms, but the atmospheric dynamics triggering the emissions and controlling the uplift and transport of dust plumes have not been well documented.

The complexity of dust storms in terms of the initial source (Arabian Peninsula, Iran/Pakistan, or Thar desert), intensity, duration, meteorological dynamics, transport pathways, and vertical distribution makes each event unique. In general, the premonsoon dust events originated from the Thar desert exhibit a curved-like dust plume which propagates from the desert area toward the central/eastern Indo-Gangetic Plains (IGP). However, this curved shape and the triggering dynamics controlling it have not been well examined. In addition, changes in the altitude of the dust plumes transported over the Ganges valley have not been investigated in previous studies, although this issue is very important for the dust-induced radiative effect, atmospheric stability, and mixing processes during the monsoon season (Kumar et al., 2014).

One key feature of monsoon systems is the Intertropical Discontinuity (ITD) region also called Intertropical Front (ITF), which marks the convergence zone at the surface between two flows: the moist and relatively cool south-westerly monsoon flow to the south and the dry and warm north-easterly flow to the north (Bou et al., 2008; Flamant et al., 2009; Hastenrath, 1985; Pospichal et al., 2009). The ITD is embedded in the Intertropical Convergence Zone (ITCZ) and it constitutes the convergence zone on its northward bound, characterized by nearly zero meridional wind and strong updraft due to the horizontal convergence (e.g., Bou et al., 2008; Williams, 2008). The monsoon season starts with the northward propagation of the ITD from over the ocean to the continent during the months of April and May, while the ITD continues to move inland reaching its northernmost position at about 32°N in July and August (Lawrence & Lelieveld, 2010). The ITD position does not move gradually over several months, but there are many processes that impact the ITD at various time scales, from daily low-level jets (Flamant et al., 2009) to multiday pulsations with cycles of about five days (Couvreur et al., 2010). These pulsations are associated with increased meridional low-level winds and transport of additional moisture to the north, helping to onset the monsoon. Furthermore, the ITD has been identified to play an important role in the dynamics of dust outbreaks over the desert areas in Africa during the premonsoon and the early monsoon seasons when the dust activity reaches its annual peak (Engelstaedter & Washington, 2007). It was found that the acceleration of the flows on both sides of the ITD leads to high dust emissions in this area and that the dust remains confined within the ITD for several days due to the strong horizontal convergence and strong updraft in its vicinity (Bou et al., 2008; Bou et al., 2014; Bou Karam et al., 2009; Bou Karam et al., 2009).

Despite its well-known role in dust activity in Africa, only few studies have investigated the role of the ITD and associated winds in south Asia. For instance, Rashki et al. (2019) found that the position of the ITD over the north Arabian Sea facilitated the accumulation of dust along an area of weak winds and favored the uplift of the Iranian dust plumes to altitudes above ~3 km preventing them from reaching the central Arabian Sea (Kaskaoutis et al., 2015; Rashki et al., 2015). To the best of our knowledge, there is no study elucidating the interrelation of the ITD with dust storms over continental India and its role in dust emission, accumulation, and long-range transport. Therefore, the current work aims to explore the interaction between winds in the ITD region and transport of dust from the Thar desert over continental India for the first time.

In this study, we combine observations from satellite sensors like MODIS (Moderate Resolution Imaging Spectroradiometer) and CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations), along with reanalysis-based (Modern-Era Retrospective analysis for Research and Applications

(MERRA-2)) meteorological/aerosol products and Mesoscale Non Hydrostatic Model (Meso-NH) simulations, to explore the atmospheric processes that caused an intense dust storm over northern India in premonsoon (12–16 June 2018). Main emphasis is given on investigating the role of the Indian-Pakistan thermal low and the monsoon flow in dust emissions. The vertical profiles of zonal and meridional winds as well as dust over northwest India and the Ganges valley are analyzed and the role of the ITD and the Himalayan range in the vertical distribution, propagation, and accumulation of dust is highlighted. In addition, particulate matter (PM₁₀ and PM_{2.5}) concentrations from 23 air-quality monitoring stations across north India are used to investigate the impact of dust on air quality. Section 2 describes the data sets and model used in this study, while the Results section is divided into the characteristics of the dust event (section 3.1), the synoptic meteorological patterns (section 3.2), the mechanisms that facilitate the dust emissions and transport (section 3.3), the vertical profiles of wind and dust (section 3.4), and the influence of dust on the PM concentrations over north India (section 3.5). The main findings are summarized in section 4.

2. Data Sets

2.1. Reanalysis Data

Several atmospheric parameters were obtained from the MERRA-2 database at spatial resolution of $0.5^\circ \times 0.625^\circ$ and at 72 hybrid-eta levels from surface to 0.01 hPa (Gelaro et al., 2017). More specifically, 6-hourly or daily data sets from MERRA-2 were used for the near-surface dust concentration and columnar dust loading, as well as for the horizontal wind speed, vertical profiles of the vector, zonal, and meridional winds. MERRA-2 reanalysis has been increasingly available for studying the dust events and their interrelation with meteorology over the globe (Kaskaoutis et al., 2019; Pokharel et al., 2017; Rashki et al., 2019).

2.2. Satellite Observations

Combined Aqua-MODIS AOD₅₅₀ (C006) retrievals from the Dark Target and Deep Blue algorithms are utilized at a spatial resolution of $1^\circ \times 1^\circ$, in order to study the spatial-temporal evolution of the columnar dust loading during the dust event. Errors in MODIS C006 AOD₅₅₀ retrievals are in the range of $\pm(0.05 + 15\%)$ over land and $\pm(0.04 + 10\%)$ over ocean (Levy et al., 2013). In addition, night-time Level 2 version 4.10 retrievals of the extinction and backscatter coefficient profiles at 532 nm over India during 11–16 June 2018 were obtained from Cloud Aerosol Lidar with Orthogonal Polarization (CALIOP) on board the CALIPSO satellite (Winker et al., 2013). In order to investigate the dust contribution to the total-aerosol profiles, the dust extinction coefficient was estimated using the measured depolarization ratio (δ) and the back-scattering coefficient (β), along with a prior information on the dust LiDAR ratio (S_d), depolarization ratio of dust (δ_d), and nondust aerosols (δ_{nd}) as (Lakshmi et al., 2019; Tesche et al., 2009; Vaishya et al., 2018)

$$\sigma_d = S_d \times \beta \times \frac{(\delta - \delta_{nd})(1 + \delta_d)}{(1 + \delta)(\delta_d - \delta_{nd})} \quad (1)$$

Via considering the depolarization ratio for dust (0.2 to 0.3) and nondust particles (0.02 to 0.07), an average of upper and lower bounds, that is, $\delta_d = 0.25$, $\delta_{nd} = 0.045$ (Yu et al., 2015) along with a dust LiDAR ratio of $S_d = 44$ sr were used here to estimate the dust extinction coefficient profiles.

2.3. Ground-Based Measurements

Ground-based PM₁₀ and PM_{2.5} concentrations from 23 stations along the IGP were taken from the Central Pollution Control Board (CPCB) air quality network under the National Ambient Air Quality Monitoring Programme (NAMP), in order to assess the impact of the transported dust plumes on the surface air quality. The PM concentrations are measured via the Tapered Element Oscillating Microbalance (TEOM) method (CPCB, 2011; Kedia et al., 2018).

2.4. Model Simulations

Model simulations for the dust characteristics and spatiotemporal evolution are performed using the Meso-NH (version 5.3.0) atmospheric model (Lac et al., 2018; Lafore et al., 1998), a nonhydrostatic mesoscale atmospheric model with an online dust emission and transport module (Grini et al., 2006). The performance of the Meso-NH model, especially in terms of dynamics that drive dust mobilization, has been well

established, and its ability to simulate dust emission and transport over north and west Africa has been highlighted in several studies (e.g., Bou Karam, Flamant, Knippertz, et al., 2009; Bou Karam, Flamant, Tulet, et al., 2009; Todd et al., 2008; Tulet et al., 2008). Furthermore, the Meso-NH model has been extensively validated using many “aerosol-related” data sets acquired from ground-based platforms (Todd et al., 2008; Tulet et al., 2008), airborne platforms (Bou et al., 2008; Bou Karam, Flamant, Tulet, et al., 2009), and space-borne platforms (Bou et al., 2010; Bou et al., 2014; Bou Karam, Flamant, Knippertz, et al., 2009; Chaboureaud et al., 2011).

In this study, the model was run during seven days from 10 June 2018 at 00:00 UTC to 16 June 2018 at 00:00 UTC over the domain 60°–90°E, 10°–40°N, using a 12-km horizontal grid spacing covering the Indian subcontinent and parts of the Indian Ocean. In the vertical, 72 levels were used (from 10 m to 28 km) with 35 of them within the planetary boundary layer (i.e., below 2 km). The initial and boundary conditions are provided from the ECMWF reanalysis. The model run used a convective mass-flux scheme (Bechtold et al., 2001), a mixed-phase bulk microphysical scheme (Pinty & Jabouille, 1998), a subgrid cloud cover and condensate content scheme (Chaboureaud & Bechtold, 2002, 2005), a turbulence parameterization (Cuxart et al., 2000), a Rapid Radiative Transfer Model parameterization (Mlawer et al., 1997) that takes into account the radiative effect of dust, and a dust scheme (Grini et al., 2006). The latter includes the Dust Entrainment and Deposition (DEAD) scheme (Zender et al., 2003) that calculates dust fluxes from wind friction speeds and the ORganic and Inorganic Log-normal Aerosols Model (ORILAM; Tulet et al., 2005), in which transport, dry and wet deposition, and the radiative properties of three dust particle sizes are parameterized (Bou Karam et al., 2017; Chaboureaud et al., 2016; Francis et al., 2018).

3. Results and Discussion

3.1. Characteristics of the Dust Event in June 2018

The dust activity over north India has a distinct seasonal cycle, which maximizes in premonsoon (approximately April to June), facilitated by the hot and dry conditions and the increased south-westerly/westerly winds (e.g., Kaskaoutis et al., 2014; Prasad & Singh, 2007). Although the dust loading exhibits a significant decreasing trend over the region during the last ~15 years (e.g., Lakshmi et al., 2019; Pandey et al., 2017), June of 2018 was an exceptional dusty month for northern India with dust activity above the climatic mean conditions. Dust surface concentrations, obtained from MERRA-2 reanalysis, in June 2018 are higher than the June climatological mean (1980–2018), with the largest increases (statistically significant) to be detected primarily over the Thar desert and secondarily along the IGP (Figure 1a). More specifically, MERRA-2 reveals surface dust concentrations of $\sim 250 \mu\text{g m}^{-3}$ ($\sim 80\%$) above the June climatological mean over the Thar desert and along the Indian-Pakistan borders, while along the Ganges valley the surface dust concentration was $\sim 100\text{--}150 \mu\text{g m}^{-3}$ ($\sim 130\%$) above the normal value for June, which is considered as an exceptional increase. Furthermore, the MERRA-2 dust loading distribution shows increased values in June 2018 compared to mean June (1980–2018) over northwest India and Pakistan, along the IGP and in the central/north Arabian Sea (Figure 1b). The large increase in dust aerosols over north India in June 2018 is attributed to an intense and long-lasting dust event ($\sim 12\text{--}16$ June). The NPP/VIIRS true-color imagery (Yang et al., 2018) detects thick dust plumes over the Thar desert, started emitting on 12 June 2018, which initially moved to north and then shifted to east along the main axis of the Ganges valley (Figure 2). This mechanism for the long-range transport of dust and the shape of the dust-plume propagation are characteristics for typical premonsoon dust storms originated from the Thar desert (Kumar et al., 2015) and will be analyzed in the following sections.

Figure 3 shows the spatial distributions of the Aqua-MODIS AOD₅₅₀, compared with the Meso-NH simulated AOD during 10–16 June 2018. In general, this comparison reveals a satisfactory agreement during the predusty and dusty days, since the model captures reasonably well the beginning of the dust emissions over the Thar desert on 13 June, as well as the expansion of the thick dust plumes initially to the north and then to the east, along the Ganges valley. When the dust plume reached at the northwest Himalayas, it changed direction and followed an eastward propagation over the Ganges valley, alongside the south face of the Himalayas. From 14 to 16 June, high AODs covered the whole IGP and also affected the north-western Himalayas, as well as the eastern Himalayan range one to two days later, similarly to what was reported in previous studies (Chatterjee et al., 2012; Shao & Dong, 2006; Srivastava et al., 2011). MODIS AOD₅₅₀

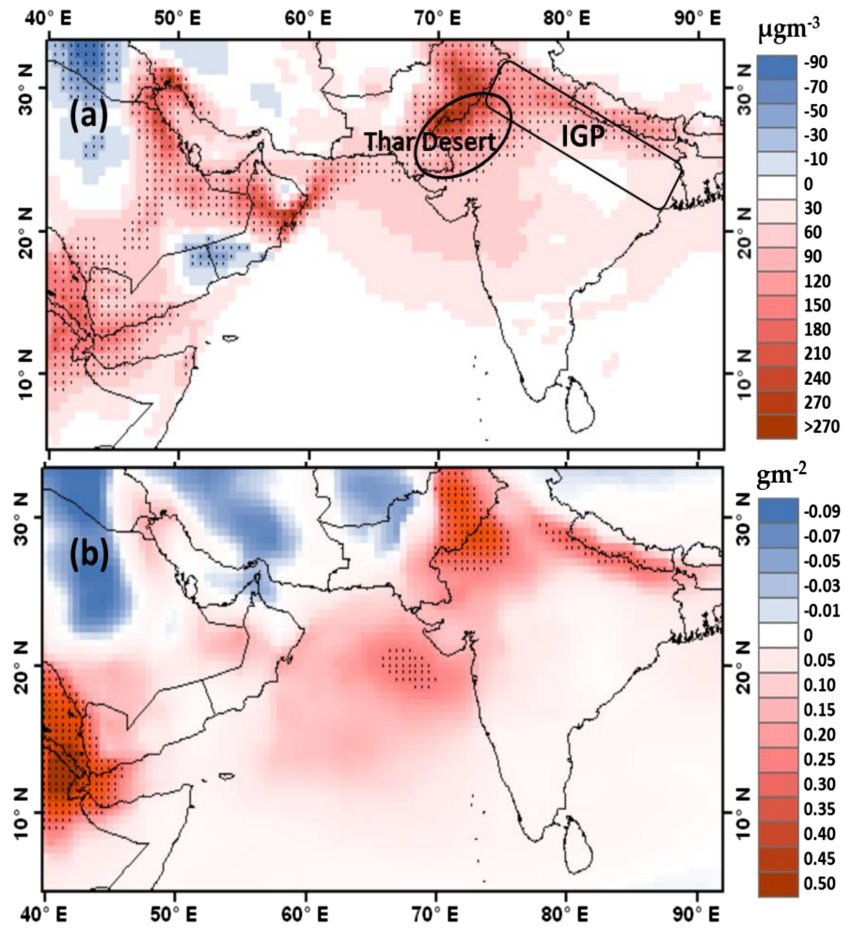


Figure 1. Spatial distribution of the differences in the (a) dust surface concentration and (b) columnar dust loading between June 2018 and mean June (1980–2018) according to MERRA-2. The dots show statistically significant differences at 95% confidence level.

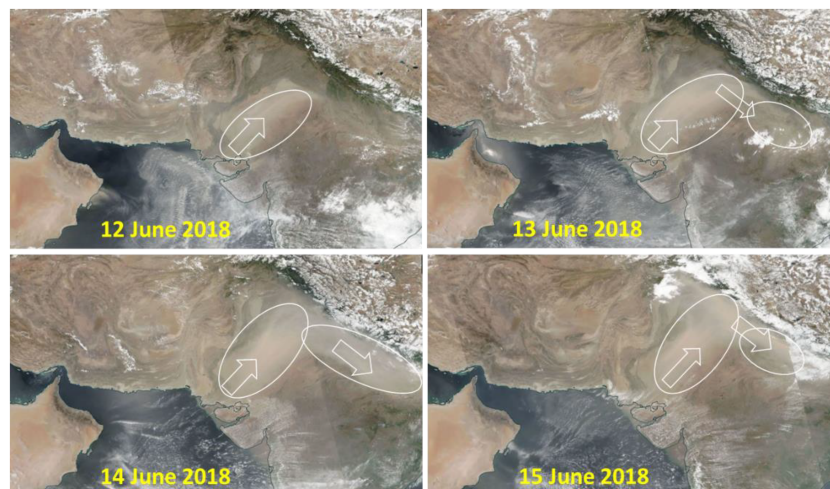


Figure 2. NPP/VIIRS true color corrected images for intense dust storm days (12–15 June 2018) over north India. The circles define the main dust plumes and the arrows show the propagation of the dust storm.

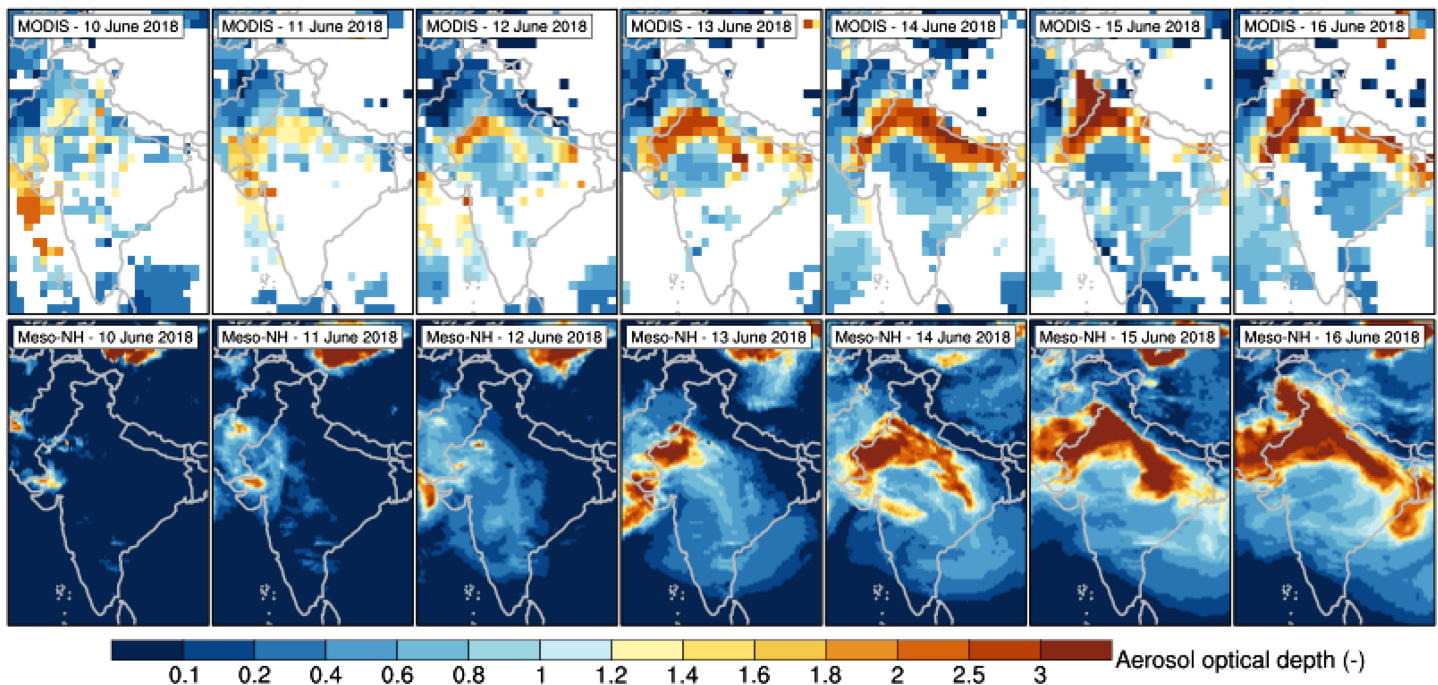


Figure 3. Spatial distribution of the (top) Aqua-MODIS AOD₅₅₀ (13:30 UTC) and (bottom) Meso-NH simulated AODs at 12:00 UTC during 10–16 June 2018. The white areas in MODIS observations correspond to unavailability of data.

reached 4 on some pixels over the Thar desert and IGP (Figure 3), thus approaching the upper limit (5.0) for the MODIS retrievals. The discrepancies between Meso-NH simulations and MODIS observations are mainly detected over the downwind regions and potentially attributed to the fact that the model does not simulate in this case the emissions of anthropogenic aerosols. Averaged Aqua-MODIS AOD₅₅₀ of 1.00 ± 0.51 was reported over Patiala, northwest India, during six dust events (Sharma et al., 2012), while AODs in the range of ~ 1.3 – 1.7 were found in Kanpur, central IGP, during intense dust storms in May (Dey et al., 2004). Spatial-averaged MODIS and WRF-Chem AOD₅₅₀ values over north India (25° – 30° N, 70° – 80° E) were found to be 0.80 ± 0.30 and 0.68 ± 0.28 , respectively, during an intense dust storm originated from the Thar desert in April 2010 (Kumar et al., 2014).

Figure 4 shows the spatial distribution of the columnar dust loading (gm^{-2}) from Meso-NH simulations during the intense dusty period (14–16 June 2018), highlighting the propagation of the dust plume from the Thar desert initially to the north, and then, over the whole IGP. These very high dust loading values ($>30 \text{ gm}^{-2}$) indicate the exceptional-high intensity of the dust storm, which may have important radiative and health impacts. In close agreement with the satellite observations, the Meso-NH simulations verify that the initial dust plume seems to be split into two parts, as the one was accumulated over the northernmost part of India and Pakistan during the afternoon hours of 15 and 16 June, while the other was travelling along the Ganges valley. Remains of the dust plume reached over Bangladesh and northern part of the Bay of Bengal. In addition, the Meso-NH model simulations exhibit high dust loading over the Sistan Basin, east Iran (Rashki et al., 2015), spreading over western Pakistan.

3.2. Synoptic Meteorological Patterns

The atmospheric circulation patterns during the dust-storm event (11–16 June 2018) are examined via synoptic maps of MSLP taken from Meso-NH simulations at high spatial resolution (12-km grid spacing). The MSLP synoptic maps, superimposed by the vector winds at 925 hPa (Figure 5), reveal a progressive deepening of the Indian-Pakistan thermal low core situated at the north edge over the Thar desert from 11–15 June, and a dissipation afterward. The weakening of the thermal low core after 15 June was also associated with less expansion of the low pressure over north India and surrounding regions. The area of the thermal low is characterized by weak to calm winds, while the southern edges of it over the Thar desert are affected

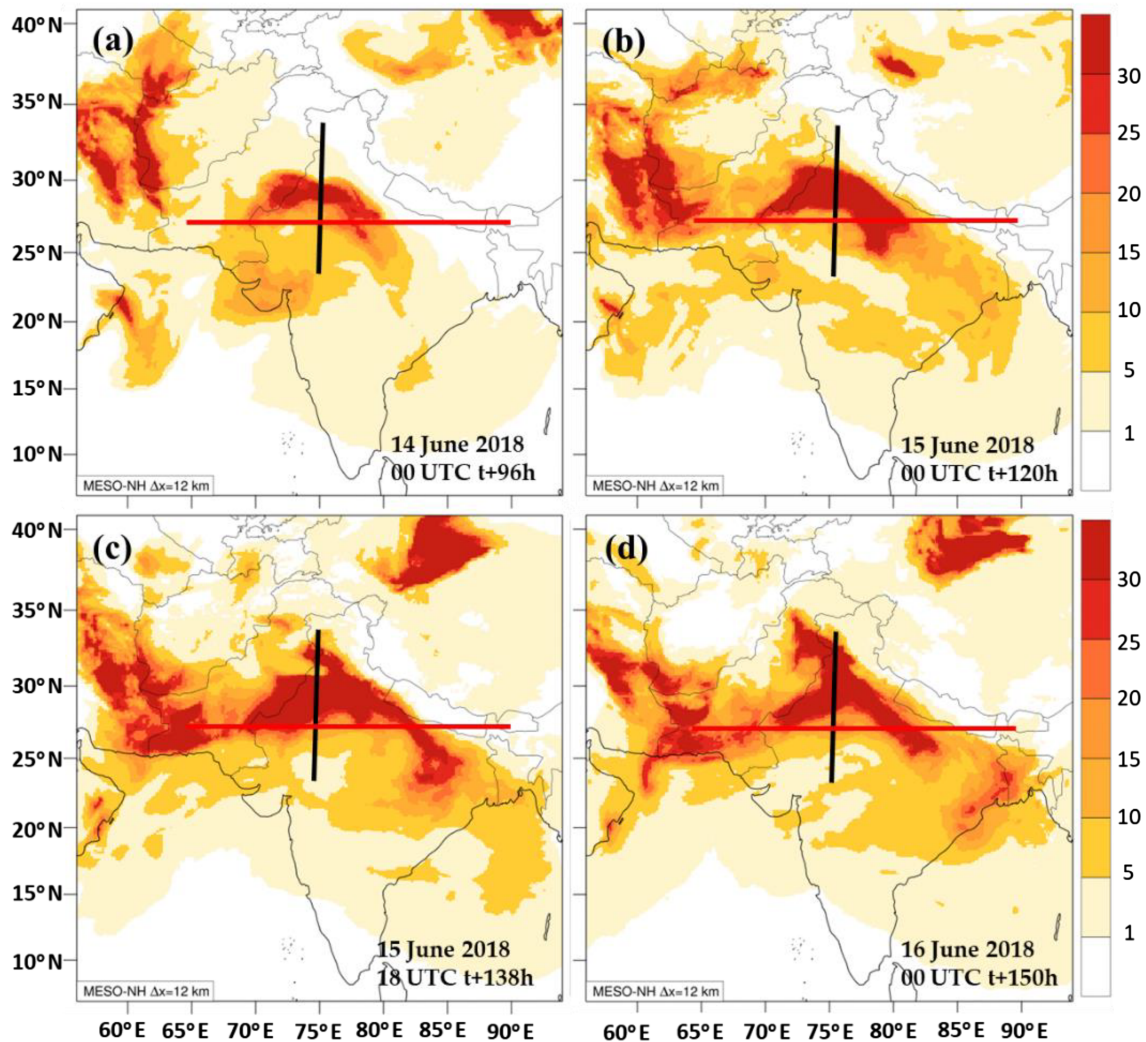


Figure 4. Spatial distribution of the accumulated dust loading (gm^{-2}) for certain hours during 14–16 June 2018 according to Meso-NH model. The black and red lines show the cross sections used for the latitudinal and longitudinal variability of the dust concentration.

by strong southwesterlies associated with the Indian monsoon flow. The large deepening of the core of the thermal low ($\sim 4\text{--}6$ hPa), as well as its expansion toward north India from 11–14 June, plays an important role in triggering strong near-surface winds over the desert, which can initiate dust emissions. The MSLP was also found to exhibit a remarkable diurnal pattern (~ 4 -hPa range) with lower values during noontime. The intense surface heating over the arid/desert areas during daytime deepens the thermal low system and forms favorable conditions for convective turbulence and mixing, resulting in a homogeneous redistribution of dust within the boundary layer as deep as ~ 4 km during daytime (Kumar et al., 2014).

The potential temperature at 850 hPa superimposed by wind vectors at 925-hPa level shows a progressive deepening of the Indo-Pakistani heat low followed by a northward advance and intensification of the monsoon flow characterized by cold air masses and strong winds (Figure 6). Warm air masses are seen over the Thar desert. The potential temperature over the Thar desert increased by more than 14 K from 11 to 15 June (Figure 6) and the pressure dropped by ~ 6 hPa during the same period (Figure 5), indicating a deepening of the thermal low. This deepening facilitated a northward advance of cold air masses from the southwest associated with potential temperature values of 310 K. The northward progression of the monsoon air masses was accompanied by a migration of the heat low (areas of high potential temperature values) progressively to northern latitudes. On 16 June the heat low was still deep (988 hPa and 322 K) but constrained to a much

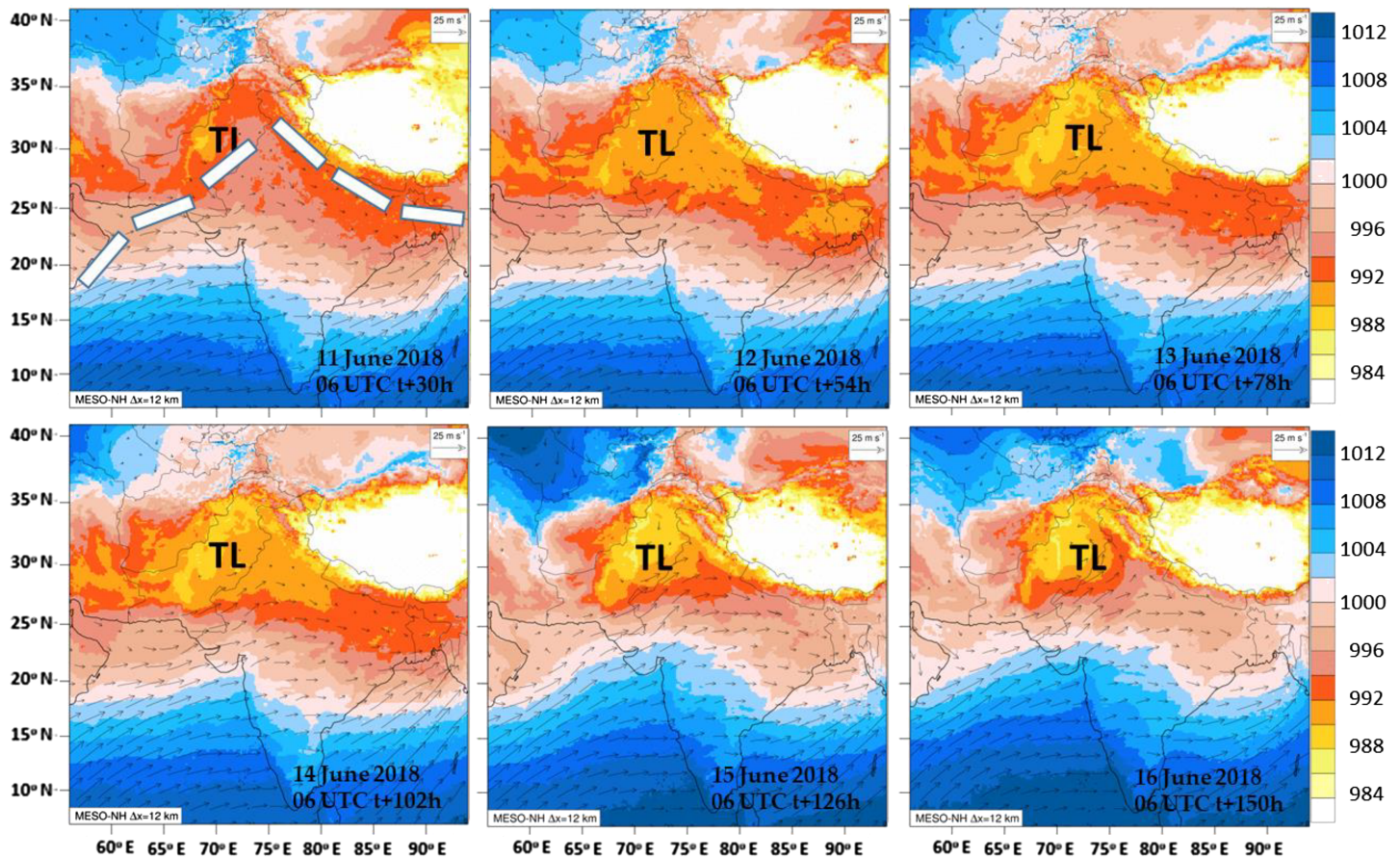


Figure 5. Mean sea level pressure (MSLP) variations over the Indian subcontinent during 11–16 June 2018 obtained from Meso-NH model. The superimposed winds are at 925-hPa level. The positions of the ITD (white) and the Indian-Pakistan thermal low (TL) are defined.

smaller area, which indicates the start of the collapsing phase of the heat low as a result of mixing with cold air masses (e.g., Lavaysse et al., 2009).

The Meso-NH simulations of wind speed and direction at 925 hPa reveal intense southerlies over the Arabian Sea and the Bay of Bengal, associated with the summer monsoon flow (Figure 7). The core of intense winds is seen to advance progressively inland in response to the deepening of the heat low over the Thar desert. The northward advance of the monsoon flow with strong winds reaching $\sim 20 \text{ ms}^{-1}$ over the Thar desert on 13 June, from about 8 ms^{-1} on 11 June, initiate the dust storm. Strong near-surface winds were maintained over this region on the following days as well. Along the ITD, the two opposing wind regimes (southwesterlies and northwesterlies) converged and the area is characterized by weak winds of less than 4 ms^{-1} (Figure 7). The ITD shows a northward shift on 15–16 June associated with a further advance of the monsoon flow. On the other hand, weaker northwesterlies, initially of $\sim 4 \text{ m s}^{-1}$, which increased to $\sim 10 \text{ m s}^{-1}$ on 15–16 June, are seen over the Ganges valley (Figure 7).

In summary, the synoptic situation during 11–16 June indicates a deepening of the Indo-Pakistani heat low, as reflected by the simultaneous decrease in MSLP and increase in potential temperature at 850 hPa. The intensification of the thermal low derived a northward advance of the monsoon flow, which was characterized by strong winds and cooler air penetrating into the warm air masses over the Thar desert, thus initiating the dust emissions. Similar synoptic meteorological patterns characterized by low-pressure systems with cores over the Thar desert and western IGP were observed during several premonsoon dust storms (Kumar et al., 2014, 2015; Sharma et al., 2012), while Kaskaoutis et al. (2014) classified this atmospheric circulation as a specific weather cluster associated with enhanced presence of dust aerosols over the IGP. Dust emissions in the Thar desert are controlled by the synoptic meteorology, local wind regime, precipitation,

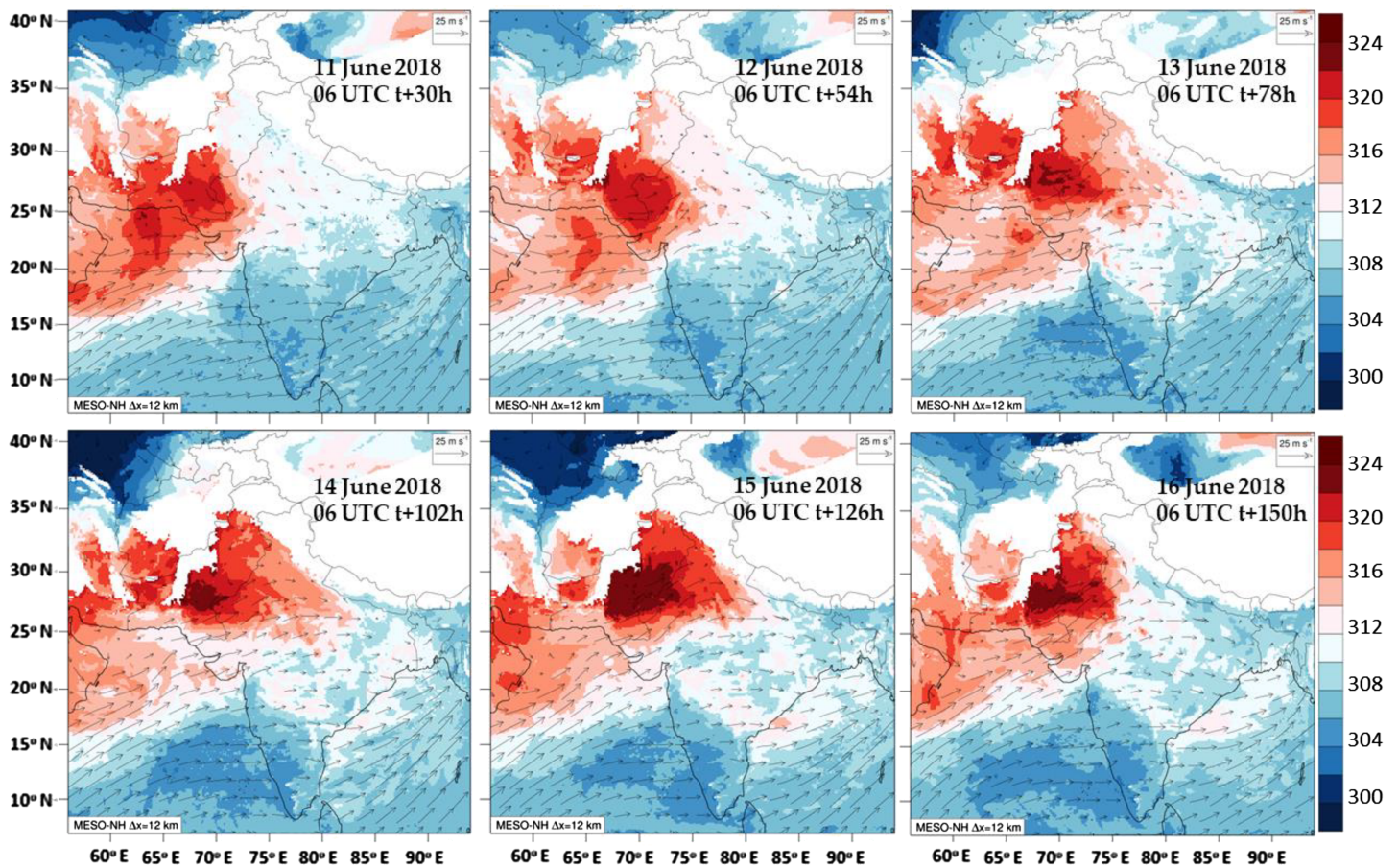


Figure 6. Maps of the potential temperature at 850-hPa level over the Indian subcontinent, superimposed by vector winds at 925 hPa according to Meso-NH model simulations.

and surface characteristics (Parajuli et al., 2016). Strong near-surface winds in the monsoon-flow area cause dust emissions when advancing northward into the Thar desert, as they behave like a density current due to the difference in density between the cold and wet monsoon flow and the dry and warm air over the desert (Bou Karam et al., 2008). The advance of the dense monsoon flow usually intensifies during nighttime and early morning hours, as also shown by Bou et al. (2008) over the Sahara desert, while strong turbulent winds near the surface cause dust emissions. Under these meteorological conditions, the vast majority of the dust events affecting north India originates from the Thar desert rather than the Arabian Peninsula. The long-range transport of dust from Arabia is associated with different synoptic meteorological patterns and mechanisms (e.g., Badarinath et al., 2010; Jose et al., 2016; Singh et al., 2016; Vijayakumar et al., 2016).

3.3. Mechanisms for Dust Emission and Transport: The Role of the ITD

This section elucidates the dynamic processes and mechanisms for (1) the dust emissions over the Thar desert, (2) the vertical transport and accumulation of dust due to convergence at the ITD region, and (3) the long-range transport of dust by the westerlies and the specific role of the Himalayas in creating a return flow and enhancing the dust accumulation over the Ganges valley.

Figure 8 shows the temporal variation of the vector-wind profiles (1,000 to 100 hPa) taken from 6-hr MERRA-2 retrievals over the west (a) and central-east (b) IGP during 10–16 June 2018. Focusing on the Thar desert and west IGP (Figure 8a), the spatial-averaged wind profile shows higher velocities near the surface (up to ~950 hPa), which are intensified on 13–15 June with cores of $\sim 16 \text{ ms}^{-1}$ at ~900 hPa. An important finding is the remarkable diurnal cycle of the low-level winds (below 800–850 hPa), which intensify during the night and early morning hours associated with a fast propagation of the density-current like monsoon flow, which after sunset is turned off by the surface heating. The dust emission over the Thar desert was

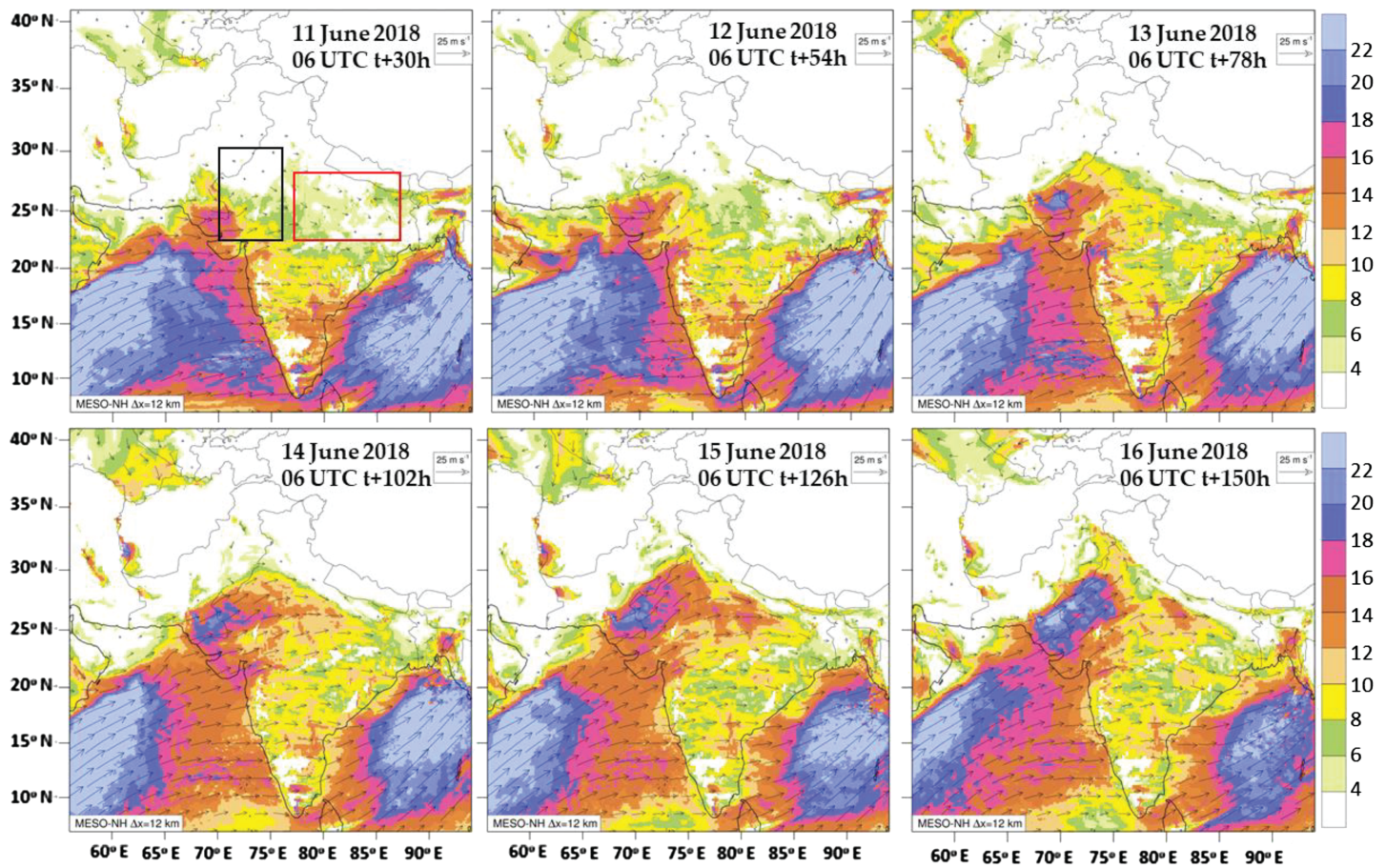


Figure 7. Meso-NH simulations of the wind speed (colored scale) and direction (arrows) at 925-hPa level over the Indian subcontinent during 11–16 June 2018. The black and red boxes correspond to Thar desert-west IGP and to central-east IGP, respectively, where vertical cross sections of the zonal and meridional winds were analyzed.

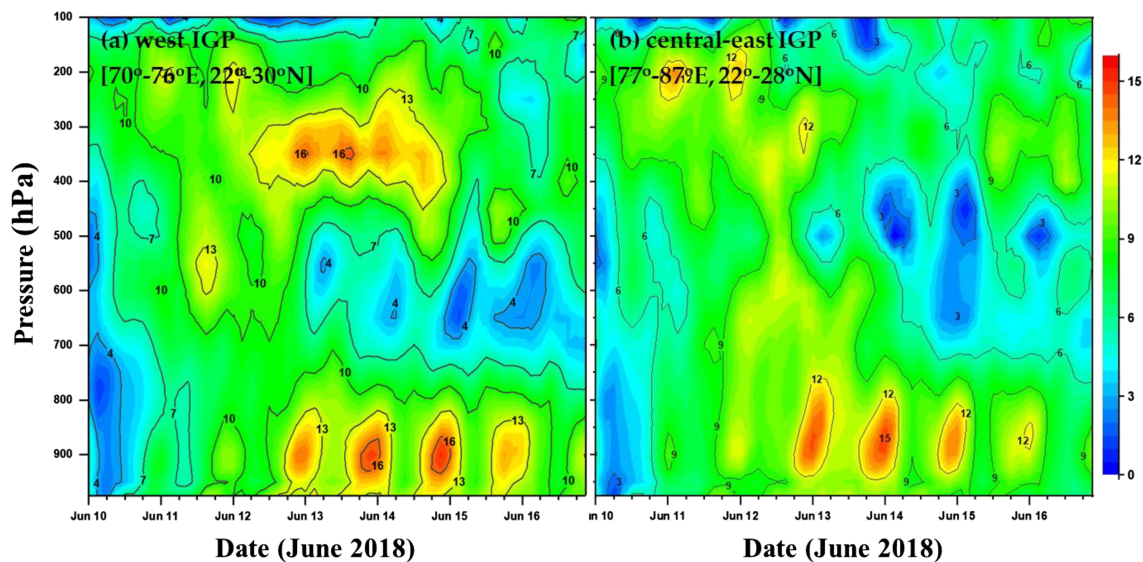


Figure 8. Time-pressure cross sections (1,000–100 hPa) for the vector winds (in ms^{-1}) over the (a) western and (b) central-eastern IGP (black and red boxes in Figure 7, respectively) during 10–16 June 2018 according to 6-hourly MERRA-2 reanalysis.

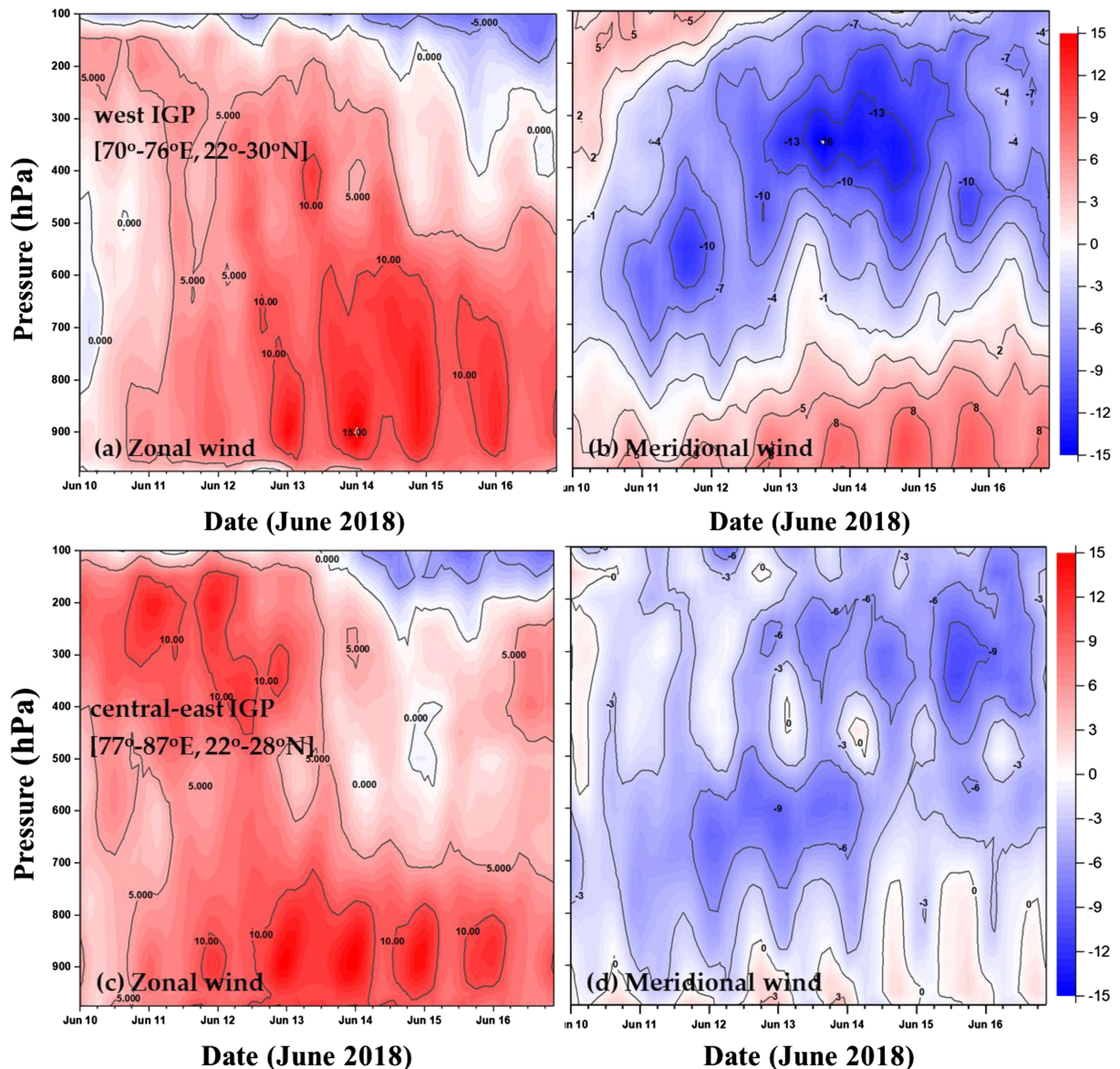


Figure 9. Time-pressure cross sections (1,000–100 hPa) for the (left) zonal and (right) meridional winds (in ms^{-1}) over the (a and b) western and (c and d) central-eastern IGP during 10–16 June 2018 according to 6-hourly MERRA-2 reanalysis. Positive values are for southerlies and westerlies and negative for northerlies and easterlies.

initiated during nighttime by strong near-surface winds in the monsoon flow at the southern side of the convergence zone—ITD. A similar vertical wind profile is shown over the central-east IGP region (Figure 8b), revealing that the core of strong winds reached the surface during nighttime. In both regions, weak winds ($\sim 3\text{--}4 \text{ ms}^{-1}$) occur at 600–700-hPa levels on 13–16 June, indicating that the monsoon layer was confined between the surface and 850 hPa in altitude. Being denser than the atmosphere into which it is advancing, the monsoon flow is found in the lower layers of the atmosphere and propagates fast toward the dry and less dense air above the desert (Bou Karam et al., 2008).

The analysis of the temporal evolution of the zonal and meridional wind profiles over the studied domains in Thar desert-west IGP and central-east IGP is shown in Figures 9a–9d. Over west IGP, strong westerlies (positive zonal-wind values) between the surface and ~ 700 hPa dominated during the dust-storm days, indicating that they play a major role in dust emissions (Figure 9a). Another important finding is the increase in intensity and vertical expansion of the southerlies (positive values of the meridional wind) during the dust-storm days over the northwest IGP, which were maintained at high levels by the end of the examined period

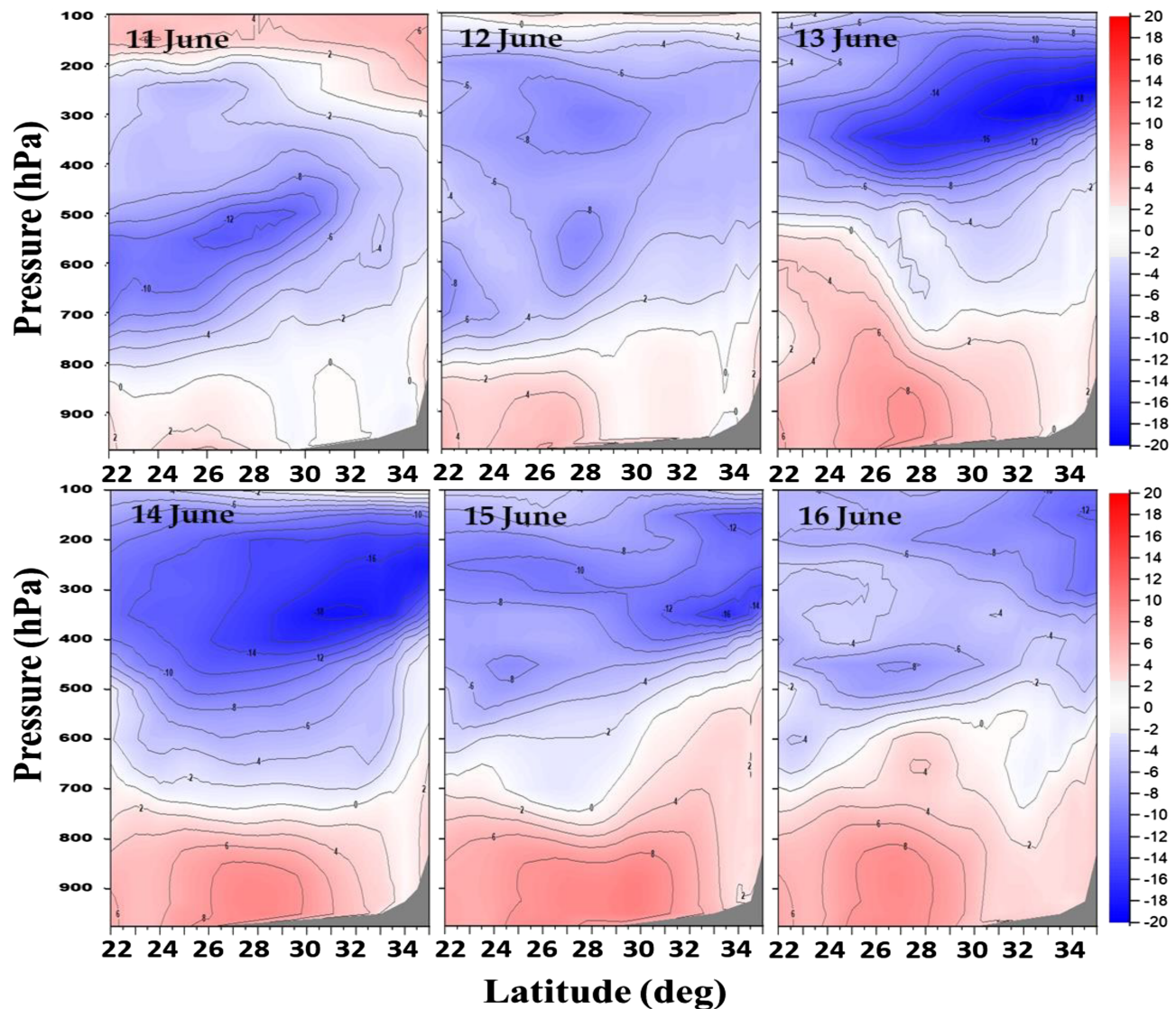


Figure 10. Latitude-pressure cross sections for the meridional wind (in ms^{-1}) over the Thar desert and northwest India (longitude-averaged at 71° – 74°E) at 06:00 UTC (LST = UTC + 5:30) during 11–16 June 2018 according to MERRA-2 reanalysis. Positive values are for southerlies and negative for northerlies.

(Figure 9b). The southern component reached 8 ms^{-1} on these days (spatially averaged values), while a well-defined zone of zero meridional winds associated with the ITD is seen between 900 and 700 hPa. At the upper atmospheric levels, the northerlies (negative values of the meridional wind) dominated (Figure 9b), which, combined with the westerlies (Figure 9a) form the prevailed northwesterly flow over northern India, which transport the elevated dust plumes along the Ganges valley (e.g., Kaskaoutis et al., 2014; Kumar et al., 2015). In the central-east IGP the zonal wind was mainly from western directions, also exhibiting larger intensities near the surface during the dust-storm days, while prior to dust storm the maximum wind intensities were detected near the tropopause (300–200 hPa), defining an upper level jet (Figure 9c). The meridional wind over the central-east IGP (Figure 9d) shows very low values near the surface, defining the position of the ITD, without a clear dominance of northerlies or southerlies. At the upper atmospheric levels, northerlies (~ 6 – 9 ms^{-1}) dominate, while at ~ 500 hPa, the meridional wind reached calm conditions on certain days and hours. The weak meridional winds over the central-east IGP facilitate the dust accumulation over the region, also supported by the weak westerlies ($< 5 \text{ ms}^{-1}$) that transported the dust plumes mostly around the 700-hPa level ($\sim 3,000$ m; e.g., Gautam et al., 2010).

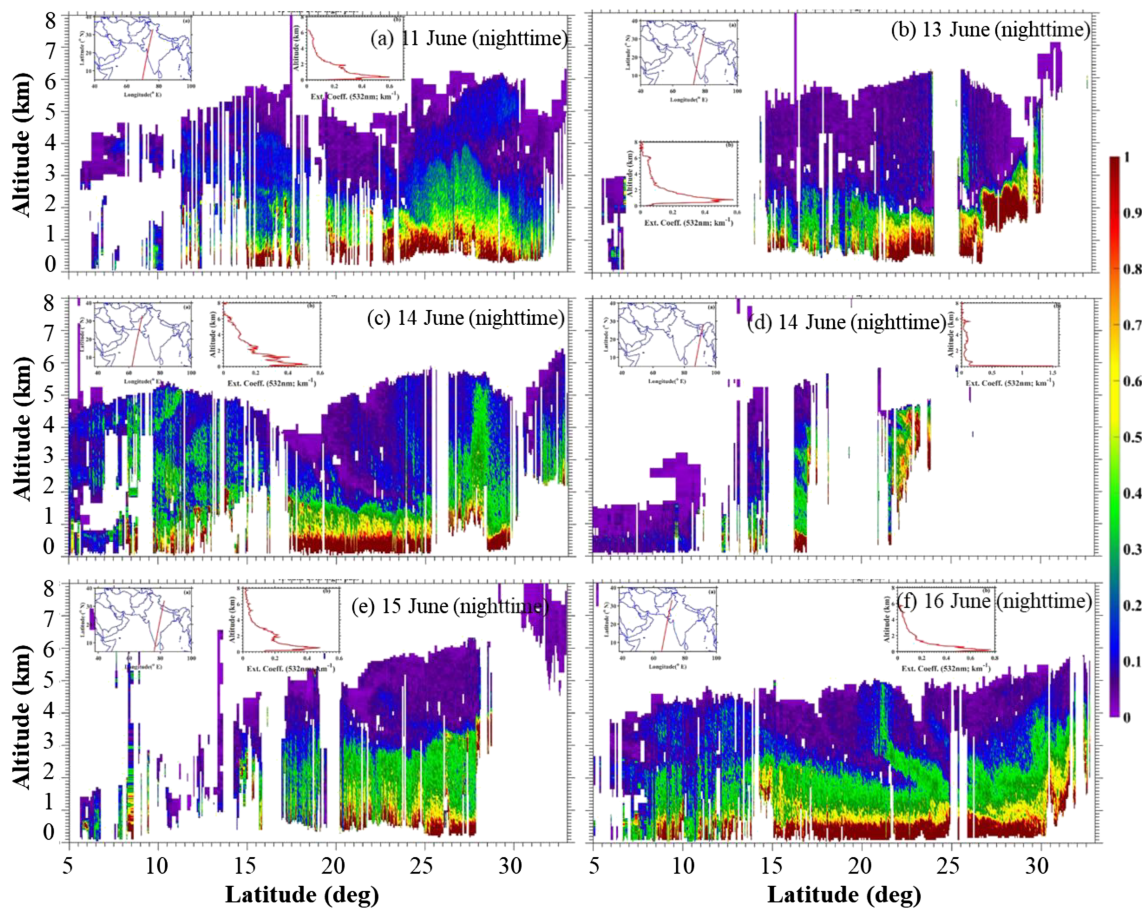


Figure 11. Time-altitude profiles of the extinction coefficient taken from nighttime CALIPSO overpasses (insert maps) over India on 11, 12, and 14–16 June 2018. The insert graphs show the averaged vertical profiles along the CALIPSO overpasses.

Figure 10 shows the latitude-pressure profiles of the meridional wind (longitude-averaged at 71° – 74° E), from 11 to 16 June 2018, according to MERRA-2 reanalysis. During the intense dust emissions on 13 and 14 June, the ITD is well marked (the white isocontours) and a strengthening of the two opposing flows (monsoon flow in red at low levels and northerlies in blue at higher altitudes) occurs. The meridional wind at low levels (below ~ 700 hPa) weakens significantly for latitudes north of 32° N, thus favoring the dust accumulation at the foothills of the Himalayas (see the elevated terrain in grey) over northwest India and Pakistan, as shown from MODIS observations and Meso-NH simulations (Figures 3 and 4). Note also that the ITD can advance or retreat few degrees in latitude in just few days, since a deeper heat low will drive southerlies more strongly. During the examined period, a slight northward movement of the ITD was seen during 14–16 June, justified by the northward advance of the monsoon flow, which moved from 28° N on 12 June to 34° N on 14 June crossing over the Thar desert and causing the dust storm. The monsoon flow advanced almost 6° in 48 hr, highlighting its fast propagation because of the air-density difference between the marine wet air and the hot dry air over the Thar desert. These results are verified from the Meso-NH simulations of the wind speed and direction (Figure 7).

The modeling results highlighted the important role of the ITD on dust accumulation and eastward transport over the IGP, as was also found along the convergence zone between the monsoon flow, Shamal and Levar winds over the central/north Arabian Sea (Rashki et al., 2019). Therefore, the position and movement of the ITD over northwest India may play a crucial role in atmospheric dynamics by trapping the dust along the Himalayan range, leading to increased dust-induced atmospheric warming and related climate implications (Gautam et al., 2010). Furthermore, the highest AODs and dust loading occurred either over the Thar desert on 13–14 June due to increased dust emissions or along the ITD facilitated by the weak winds.

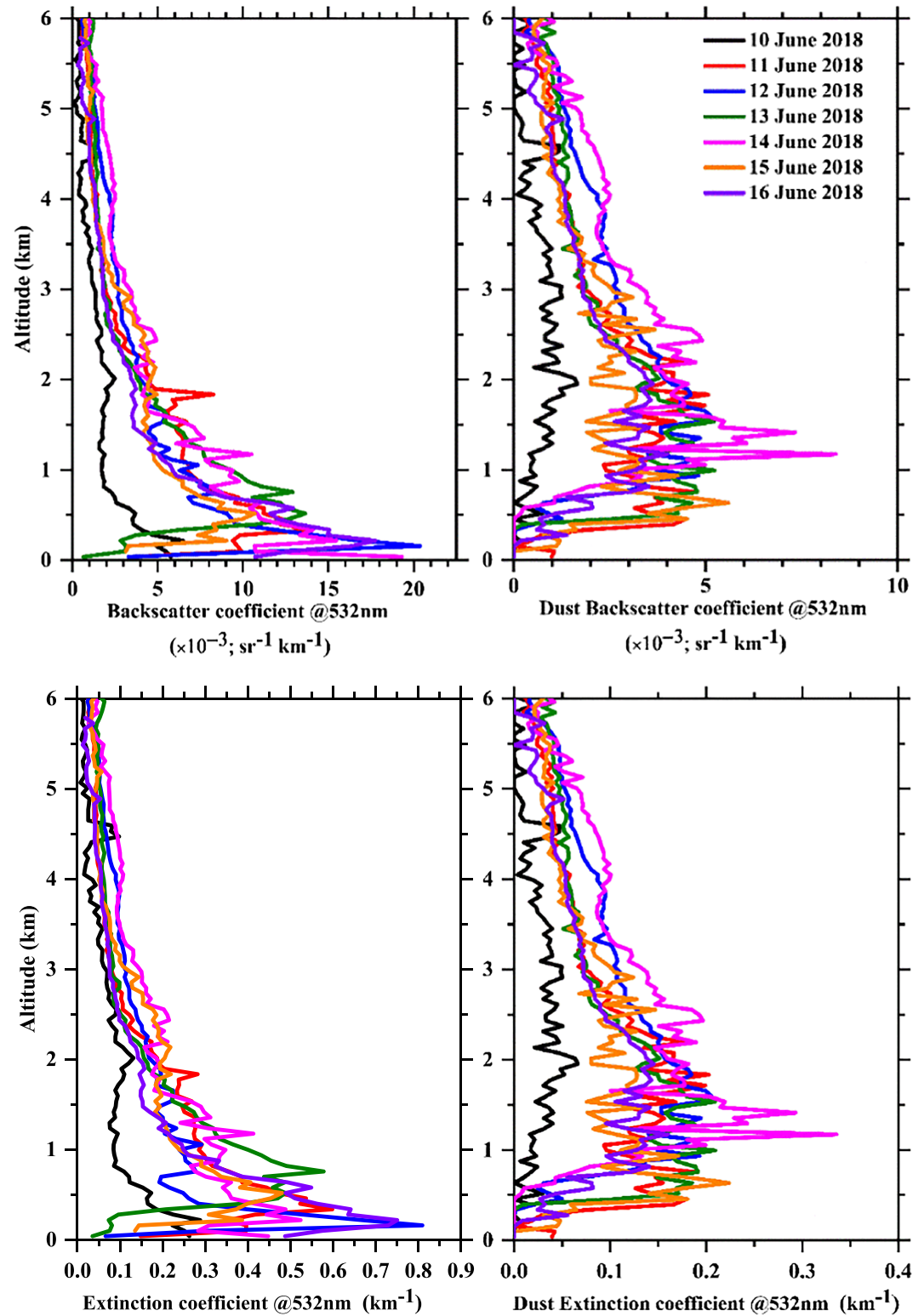


Figure 12. Daily (spatially averaged) vertical profiles of the total and dust backscatter and extinction coefficients during 10–16 June 2018 over northern India (same domains as in Figure 11).

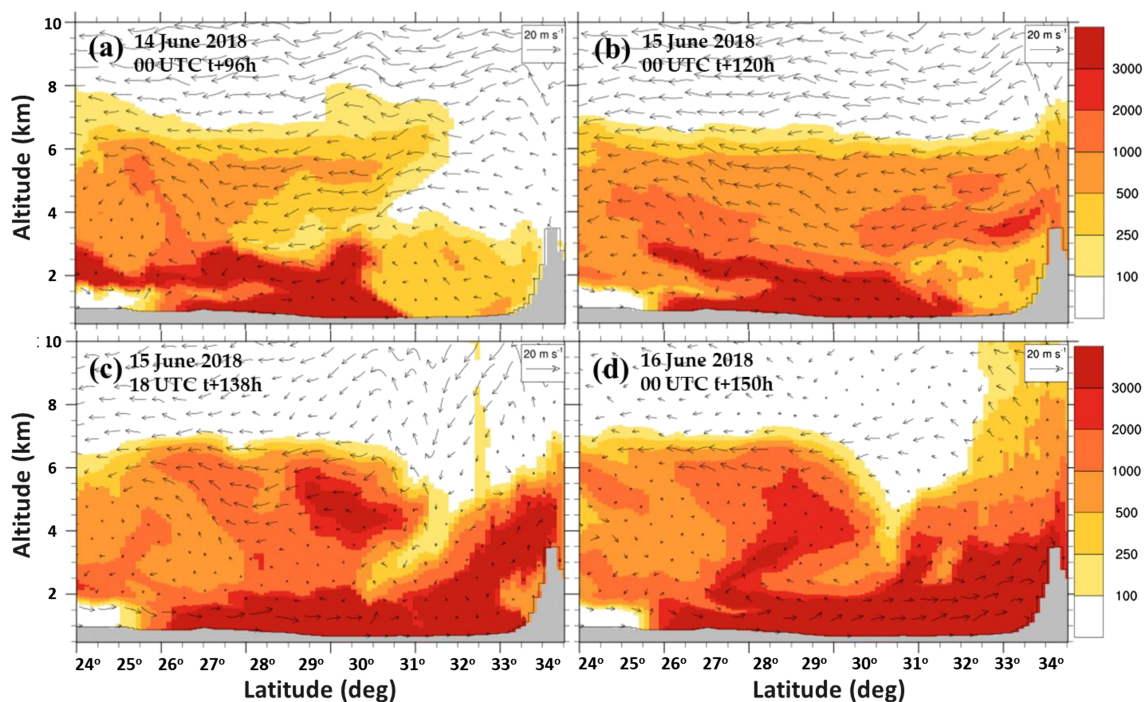


Figure 13. Vertical cross sections for Meso-NH dust concentration (in $\mu\text{g m}^{-3}$) from 24°N to 34°N along 75°E (black line in Figure 4) for certain hours during 14–16 June 2018. The wind speeds along the cross sections are superimposed in vectors (LST = UTC + 5.30).

The analysis revealed that beside the surface parameters (soil moisture and texture, greenness, roughness), the dust-emission processes over the Thar desert are strongly related to the advance of the monsoon flow, whereas the vertical transport of dust is facilitated by the convective mixing due to surface heating as well as to vertical wind shear and atmospheric instability. Because of the convergence along the ITD and the blocking effect of the Himalayas, the uplifted dust was accumulated for few days over the Ganges valley before being able to evacuate eastward by the northwesterlies.

3.4. Vertical Distribution of Dust

Analysis of the vertical dust-aerosol profiles is especially important for understanding the altitudinal variations and vertical mixing of dust over north India due to serious effects on atmospheric heating rates and the ISM rainfall (Dumka et al., 2016; Gautam et al., 2009). The CALIOP vertical profiles of the extinction coefficient at 532 nm from nighttime overpasses are analyzed for certain dusty days (Figure 11). It should be noted that the extinction-coefficient profiles were cloud screened following previous studies (Mishra et al., 2014; Winker et al., 2013). The latitude-altitude cross sections (Figure 11) reveal that the aerosols (mostly dust) are mainly confined from near the surface up to about 2 km over northern India (latitude 20°–25°N), while for latitudes north than 27°N there is a tendency for uplift of the dense dust-aerosol plumes as they are approaching to Himalayas. This feature is more pronounced on 13 June 2018, when the nighttime CALIPSO overpass crossed the central IGP. Elevated dust layers up to 3–4 km are also shown on 15 and 16 June 2018 for latitudes above 27°N. This indicates that after the initial emission and the northward movement of the dust storm, which is mainly confined at altitudes below 1.5 km, the northwest to southeast propagation of the dust plume along the Ganges valley takes place at higher altitudes (~3 km; ~700 hPa) and is mainly driven by the dominant westerlies/northwesterlies at this height level (Figures 8 and 9). The dust transport at different altitudes between the Thar desert-west IGP and over the Ganges valley can modulate in a different way the radiative forcing, the temperature profiles, the planetary boundary layer, and surface-atmospheric fluxes between these regions (Kedia et al., 2018; Kumar et al., 2014).

The spatial-averaged extinction coefficients at 532 nm along the CALIPSO overpasses showed rather high-rate decreases from surface (~0.5–0.7 km^{-1}) to 3 km (~0.2 km^{-1}), while the backscatter coefficients generally follow the same pattern (Figure 12). Despite the very high extinction and backscatter coefficient values

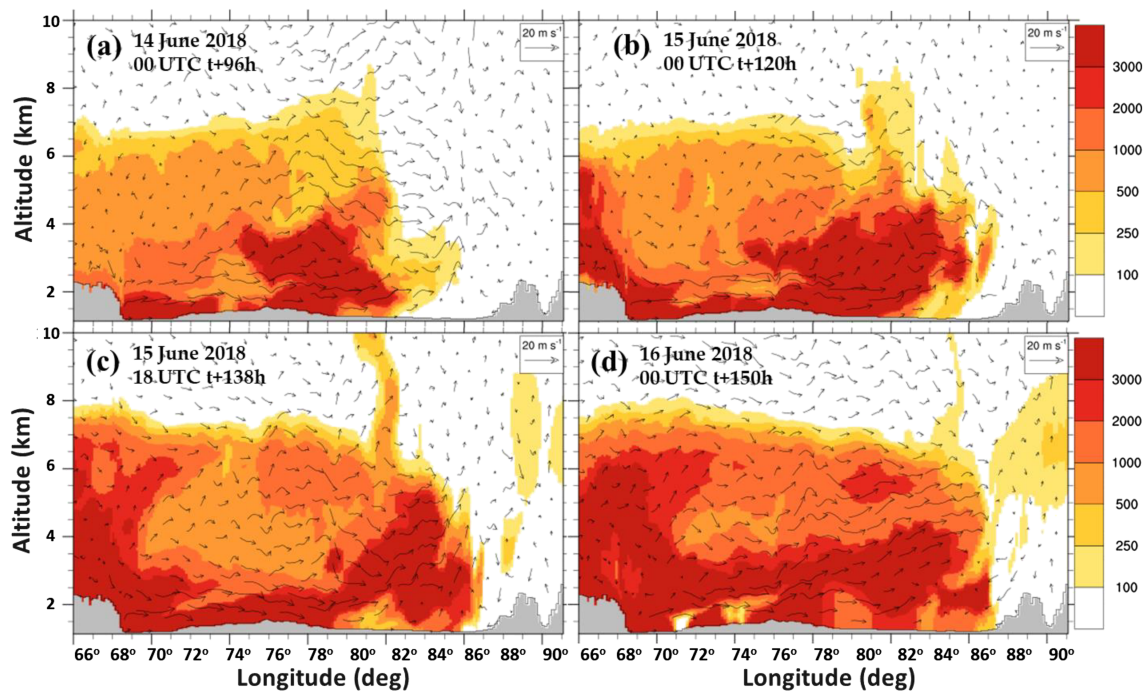


Figure 14. Vertical cross sections for Meso-NH dust concentration (in $\mu\text{g m}^{-3}$) from 66°E to 90°E along 27°N (red line in Figure 4) for certain hours during 14–16 June 2018. The wind speeds along the cross sections are superimposed in vectors (LST = UTC + 5.30).

below 1 km, the respective profiles for dust aerosols show nearly constant values from ~ 1 to 3 km (Figure 12), indicating that the dust plume is mostly transported above the near-surface anthropogenic pollution, also interacting with it within the boundary layer, which may reach to ~ 4 km over north India in premonsoon (Kedia & Ramachandran, 2008). Kumar et al. (2015) reported similar backscatter coefficient values in the range of $0.04\text{--}0.06 \text{ km}^{-1} \text{ sr}^{-1}$ over northwest India during dust storms. The particle depolarization ratio is defined as the ratio between the perpendicular and parallel components of the light extinction from the lidar signal at 532 nm and represents the degree of particle irregularity. The large ($\sim 0.3\text{--}0.4$) depolarization ratio values that were found between 2 and 4 km (not shown) verify the dominance of dust particles at the upper levels of the boundary layer and in the free troposphere.

The latitude-altitude cross sections of the dust concentration and wind speed are examined over Thar desert-west IGP (Figure 13) for the same days and hours as in Figure 4. The Meso-NH simulations reveal important findings regarding (i) the northward propagation of the dust plume along the monsoon flow area at lower altitudes (< 2 km), (ii) the uplift of the dust plume when it approaches the Himalayan range, and (iii) the return flow associated with elevated dust layers at 4–6 km. The wind profiles are in considerable agreement with MERRA-2 reanalysis (see Figure 8), revealing a layer of weak winds at 2–3 km, a dominant southern monsoon flow below, and an overturning circulation (northerlies) above. This northerly flow, which is warmer, drier and, therefore, less dense, travels over the monsoon flow and seems to contribute to the accumulation of dust over a large area along the north Indian borders (see Figures 3 and 4). Because of the opposite directions of these two flows, the horizontal and vertical shears are high and, as a result of the shear, the two layers get mixed where they meet and that is how the dust goes up escaping from the monsoon flow (Bou Karam et al., 2008). On the other hand, the convection due to orography is very characteristic for the dust uplift at elevated layers over the northern latitudes, as also observed from the CALIPSO profiles. It is also important to emphasize on the enhanced emissions due to the advance of the monsoon flow, especially during nighttime, and on the vertical mixing within the boundary layer during daytime, where some of the dust was able to detach and be subjected to long-range transport by the northwesterlies along the Ganges valley. The strong surface heating during daytime and the very hot conditions ($> 40^{\circ}\text{C}$) over northwest India in June, facilitate convective mixing into a very thick (~ 4 km) boundary layer.

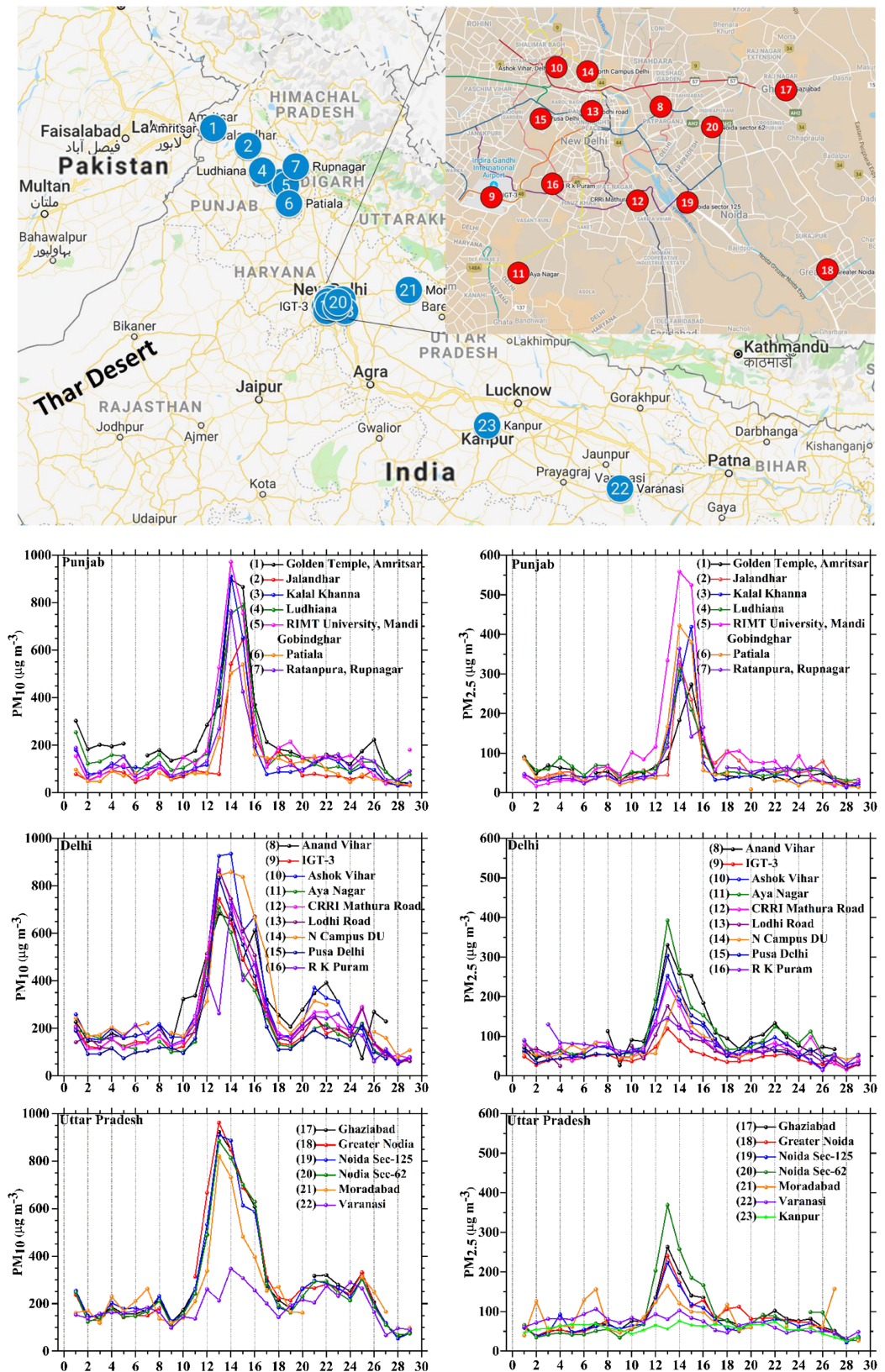


Figure 15. Daily PM₁₀ and PM_{2.5} concentrations at various stations (numbered) over northern India during June 2018.

The longitude-altitude cross sections of the dust concentration and wind speed for the same days and hours as above are shown in Figures 14a–14d. These graphs reveal the propagation and the vertical profiles of dust starting from West Pakistan and the lower Indus Basin and through the Thar desert end up in the eastern Ganges-Brahmaputra valley (see the red line in Figure 4). In general, a large quantity ($>3,000 \mu\text{g m}^{-3}$) of dust is transported from the Thar desert toward central-eastern IGP, driven by enhanced ($\sim 10\text{--}15 \text{ m s}^{-1}$) near-surface winds, which significantly weaken above $\sim 3 \text{ km}$ (Figure 14). The dust is transported from near-surface to about 4 km , while it exhibits a tendency for uplift as the distance from the source increases (central and eastern parts of the Ganges valley). In synopsis, the Meso-NH model simulations and CALIPSO observations are in satisfactory agreement regarding the latitudinal and vertical distribution of dust over north India, as both revealed transport of dust below 2 km with a tendency for uplift when it meets the Himalayan range and/or along the central-east Ganges valley.

Previous modeling studies using WRF-Chem and RegCM4.1 models agreed that the dust is mostly transported between 850 and 700 hPa over north India (Das et al., 2013; Kedia et al., 2018), similarly to our results. A recent study (Xu et al., 2018) investigated the important role of the Himalayan range and the Tibetan plateau in the long-range transport of the west Asian dust in the upper atmosphere, also highlighting the key dynamic of the southern monsoon flow and the overturning circulation that enables the accumulation of dust over northern India. Furthermore, certain atmospheric dynamics control the transport of the Taklimakan desert dust over the Tibetan plateau in spring and summer (Yuan et al., 2019). Therefore, the influence of the meteorological dynamics and thermal forcing on the transport of the Thar desert dust over the Himalayan foothills and along the Ganges valley is a very challenging scientific issue that needs further investigation in the future.

3.5. Influence of Dust on PM Concentrations

This section examines the influence of the intense dust storm on the surface PM_{10} and $\text{PM}_{2.5}$ concentrations over several stations located in Punjab, Delhi, and Uttar Pradesh states in north India (Figure 15). The PM_{10} and $\text{PM}_{2.5}$ daily variations show that June 2018 was influenced by one intense dust-storm event with a duration of about five to six days, which increased dramatically the PM_{10} (mostly) and $\text{PM}_{2.5}$ concentrations over north India. The daily-mean PM_{10} concentrations reached at $\sim 900 \mu\text{g m}^{-3}$ at stations in Punjab, Delhi, and west Uttar Pradesh (stations at the eastern Delhi outskirts). In contrast, in the east Uttar Pradesh (Varanasi; $\sim 700 \text{ km}$ far from the Thar desert), the maximum daily PM_{10} concentrations were much lower ($\sim 300 \mu\text{g m}^{-3}$), indicating less influence of dust and nearly negligible effect on the $\text{PM}_{2.5}$ concentrations, which vary between ~ 50 and $100 \mu\text{g m}^{-3}$ (highly polluted urban levels). Note also that the dust plume was transported at elevated layers over the central IGP (Figure 14), so its signal on surface PM_{10} and $\text{PM}_{2.5}$ concentrations is lesser. The influence of the dust storm seems to be temporally limited over the Punjab stations compared to Delhi, due to larger distance from the Thar desert, while Punjab is mostly affected by the fine dust particles (increased $\text{PM}_{2.5}$ concentrations), likely associated with the accumulation of dust over northwest India. The PM_{10} concentrations sharply increased at stations within the Delhi metropolitan area on 13 June, reaching at peaks of above $1,000 \mu\text{g m}^{-3}$ (in hourly basis), while they started decreasing on 16 June 2018. In the Punjab stations, the PM_{10} concentrations maximized one day later (14 June 2018). This indicates that Delhi was primarily affected by the dust storm, which was propagating to northern latitudes (Punjab state) on the next day, while it affected the central Ganges valley (Varanasi station) two to three days after its initial emission. The background PM_{10} levels at the examined stations ranged from ~ 100 to $200 \mu\text{g m}^{-3}$, on average, indicating a fourfold to sixfold increase during the dust-storm days. The dust storm was found to contribute $410 \mu\text{g m}^{-3}$ on average, ranging from 113 to $562 \mu\text{g m}^{-3}$ between the stations, to the background pollution levels over north India. The average contribution of the dust storm to the $\text{PM}_{2.5}$ concentrations was found to be $118 \pm 73 \mu\text{g m}^{-3}$ ($9.2\text{--}331 \mu\text{g m}^{-3}$), corresponding to $\sim 29\%$ of the mean dust effect on the PM_{10} levels. Such high PM_{10} daily levels are comparable to those reported during intense dust storms over the global deserts and downwind areas (e.g., Behrooz et al., 2017; Kaly et al., 2015; Saeed et al., 2014), while their persistence for several days cause serious respiratory and health impacts to the about 800 million habitats of the IGP.

4. Conclusions

This study analyzed the characteristics of an intense dust-storm occurred over north India in June 2018, elucidating the synoptic meteorology, and dynamic processes that controlled the whole dust life cycle, from the initial emissions to uplift, accumulation, long-range transport, and final dissipation. The dust storm was emitted from the Thar desert and highly impacted the whole Indo-Gangetic Plains (IGP) for about five to six days. High-resolution Meso-NH model simulations revealed a satisfactory agreement with MODIS regarding the spatial distribution of the AOD. The Meso-NH simulations, supported by the MERRA-2 reanalysis, revealed that the dust emissions over the Thar desert were triggered by the density-current like southwest monsoon flow ($15\text{--}20\text{ m s}^{-1}$), which was propagating over the desert area from 12 to 15 June 2018. The deepening of the Indo-Pakistani heat low facilitated the northward migration of the monsoon flow. The dust emissions occurred south from the Intertropical Discontinuity (ITD), which was at around 30°N over northwest India in late premonsoon. Along the ITD region very weak meridional winds dominated due to the strong horizontal convergence, while north from the ITD northwesterlies occurred extending toward the Ganges valley. This wind pattern, consisted of two opposing wind fields that converged at the ITD, caused strong vertical upward and dust accumulation along the ITD and modulated the dust-plume propagation. On the other hand, the near-surface monsoon flow exhibited a remarkable diurnal cycle with highest intensity during the nighttime that caused larger dust emissions, while the intense solar heating during daytime and the associated convective mixing helped the dust to reach at higher altitudes ($3\text{--}4\text{ km}$). Apart from the important roles of the thermal low, the monsoon flow, and the ITD, the towering Himalayas also have a large impact on dust life cycle. The intense dust plume travelling to the north was blocked by the Himalayas and accumulated along their foothills in an area of weak winds associated with the ITD. The blocking by the Himalayas created a return flow in the upper atmosphere (northerlies) enhancing the accumulation of dust and preventing its evacuation. The steep orography of the Himalayas favored the uplift of dust at about $3\text{--}4\text{ km}$ and the northwest winds prevailed north from the ITD spread it over the Ganges valley. The combined effects of these mechanisms resulted in a curved shape of the dust plumes, extending from the Thar desert to nearly the whole IGP, thousands of kilometers downwind. The vertical profiles of the meridional wind over northwest India revealed presence of southerlies at the lower levels, a zone of calm winds at $\sim 700\text{ hPa}$, and dominance of a return flow (northerlies) above. The wind profiles along the Ganges valley were dominated by enhanced near-surface westerlies, which weakened at higher levels and a very low meridional component near the surface, which shifted to northerlies at upper levels. The Meso-NH model showed that the dust plumes were transported at different altitudes over the Thar desert—northwest India ($<2\text{ km}$) and over the Ganges valley ($\sim 3\text{ km}$). These simulations were in satisfactory agreement with CALIPSO vertical aerosol profiles, which also revealed a tendency for uplift of the dust plumes as they were approaching the Himalayas. The dust storm had a remarkable effect on PM_{10} ($\sim 900\text{ }\mu\text{g m}^{-3}$; daily means) and $\text{PM}_{2.5}$ concentrations at several stations over north India, leading to a fourfold to sixfold increase during the dust-storm days. Significant impact of dust on air quality was detected even at 700 km away from the source, signaling hazardous conditions for the millions of people living in the IGP.

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