Long-Range Transport of Mineral Dust to the Northeast Indian Ocean: Regional versus Remote Sources and the Implications

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ABSTRACT

Synergizing satellite remote sensing data with vertical profiles of atmospheric thermodynamics and regional climate model simulations, we investigate the relative importance, transport pathways, and seasonality of contribution of dust from regional (Thar Desert and adjoining arid regions) and remote (southwest Asia and northeast Africa) sources over the northeast Indian Ocean [i.e., the Bay of Bengal (BOB)]. We show that while over the northern BOB dust from the regional sources contribute more than 50% to the total dust load during the southwest monsoon period (June–September), interestingly; the remote dust sources dominate rest of the year. On the other hand, over the southern BOB, dust transported from the remote-source regions dominate throughout the year. During June, the dry elevated layer (at altitudes between 850 and 700 hPa) of dust, transported across the Indo-Gangetic Plain to the northern BOB, arises primarily from the Thar Desert. Dust from remote sources in the far west reaches the southern BOB after traversing over and around the southern Indian Peninsula. Since dust from these distinct source regions have different mineral composition (hence optical properties) and undergo distinct changes during atmospheric transport, it is important to understand source-specific dust contribution and transport pathways to address dust–climate feedback.

1. Introduction

Several studies have shown that long-range transport of mineral dust from arid and semiarid regions can significantly affect the climate of faraway locations by

impacting radiative balance, air quality, precipitation, cloud formation, etc. (e.g., Rosenfeld et al. 2001; DeMott et al. 2003; Prospero and Lamb 2003; Miller et al. 2004; Prospero et al. 2014). Mineral dust deposited over the ocean surface by the prevailing wind systems is also known to significantly perturb the ocean biogeochemistry (e.g., Fung et al. 2000; Bishop et al. 2002; Jickells et al. 2005; Schlosser et al. 2014; Chien et al. 2016). The Indian Ocean (IO) is subjected to heavy dust deposition. Studies have shown that the dust load over the northern IO is high; second only after that of the North Atlantic Ocean (e.g., Mahowald et al. 2005 and

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the references therein; Tanaka and Chiba 2006). Every year during several days in spring and summer seasons, satellite images show that the northern IO is covered by a thick layer of dust originating from the surrounding arid and semiarid regions of northwest India (the Thar Desert), the Middle East (including the Arabian Peninsula), and northeast Africa (e.g., Li and Ramanathan 2002; Prospero et al. 2002). Based on estimations from several model simulations, magnitudes of dust emission from the Middle East and the surrounding regions vary between 26 and 531 Tgyr⁻¹ and the region contributes 3%–25% of the global dust emissions (Huneus et al. 2011). The importance of mineral dust in modulating the climate over the northern IO has garnered significant attention in the recent decades. Dust over the northern IO is known to perturb the radiative balance (e.g., Satheesh and Srinivasan 2002; Zhu et al. 2007; Das et al. 2013) and atmospheric heating profiles (e.g., Zhu et al. 2007; Satheesh et al. 2008). Model simulations have highlighted and emphasized mineral dust influencing the Indian summer monsoon rainfall by changing the atmospheric heating profile and hence the moisture convergence (Lau et al. 2006; Vinoj et al. 2014; Jin et al. 2014; Solomon et al. 2015; Kim et al. 2016). Understanding these mechanisms and the way they influence the Indian summer monsoon is critical for South Asia since the region depends, directly or indirectly, on the monsoon rainfall.

Most of the studies on dust transport over the northern IO have focused on the Indo-Gangetic Plain (IGP; e.g., Dey et al. 2004; Chinnam et al. 2006; Prasad and Singh 2007; Gautam et al. 2010) or the Arabian Sea (AS), the northwestern part of the IO (e.g., Measures and Vink 1999; Tindale and Pease 1999; Li and Ramanathan 2002; Satheesh and Srinivasan 2002; Zhu et al. 2007), which are in close proximity to the above-mentioned arid regions. However, it is well known that once entrained into the free troposphere, dust undergoes long-range transport and influences places thousands of kilometers away from the sources (Huang et al. 2008; Uno et al. 2009; Creamean et al. 2013).

In the above backdrop, the Bay of Bengal (BOB), the northeastern part of the IO, presents an interesting case. Being surrounded on more than three sides by continental landmass of widely differing natural features and anthropogenic activities, the BOB is found to be under the influence of differing aerosol types controlled by regional and synoptic meteorology (e.g., Moorthy et al. 2003; Moorthy and Babu 2006; Nair et al. 2008; Beegum et al. 2012; Srinivas and Sarin 2013). During the southwest monsoon period (June–September), the prevailing strong southwesterlies lead to enhanced production of sea-salt aerosols (Moorthy and Satheesh 2000; Madhavan et al. 2008). However, recent studies over the

BOB, based on measurements of aluminum concentrations (a proxy for dust) in the water column as well as in the atmosphere, have indicated high dust deposition ranging from around 1 gm⁻²yr⁻¹ over the southern BOB to 6 gm⁻²yr⁻¹ over the northern BOB (Srinivas and Sarin 2013; Vu and Sohrin 2013; Grand et al. 2015). These deposition values over the BOB are quite high and are comparable to those encountered over the North Atlantic Ocean, the North Pacific Ocean, and the Arabian Sea (Mahowald et al. 1999; Measures and Vink 1999; Kohfeld and Harrison 2001). Dust transport within the marine atmospheric boundary layer of the BOB is primarily attributed to the northwesterlies during January–April and is therefore believed to be restricted only to the periods of low-level continental outflow (Srinivas and Sarin 2013; Srinivas et al. 2014). Recent ground-based and aircraft-based lidar measurements (Niranjan et al. 2007; Satheesh et al. 2008, 2009) over the east coast of India (western boundary of the BOB) have pointed to the existence of elevated layers of aerosol dominated by dust, within which the aerosol concentration even exceeded, at times, the values seen in the boundary layer. This indicates that long-range transported aerosol from remote sources could be as important as the locally produced ones and dust transport can take place in multiple layers at different altitudes in the atmosphere. Nevertheless, a clear quantification of the relative dominance of dust from remote sources over that from the regional sources (the Thar Desert and adjoining semiarid regions) is lacking at present. This is particularly relevant since dusts originating from different sources are known to have distinct geochemical and absorptive properties (e.g., Pease et al. 1998; Yadav and Rajamani 2004; Deepshikha et al. 2005; Moorthy et al. 2007) and thus would possibly have different feedback into the climate of a region. In this context, the present paper attempts to explore the relative importance and transport pathways of dust from the Thar Desert versus remotely transported dust over the BOB. To this end, we have synergized results from regional climate model simulations with remote sensing data and atmospheric sounding data with a focus on the period from March to September when dust activity is most prominent over the northern IO and its surroundings. Note that throughout this paper the period from December to February is regarded as the northeast monsoon (NEM), March to May as the spring intermonsoon (SIM), June to September as the southwest monsoon (SWM) and October to November as the fall intermonsoon (FIM) periods.

2. Data and model

We have used regional climate model and air parcel back-trajectory simulations along with aerosol remote

sensing data and radiosonde data to study the relative contribution of regional and long-range transported dust from remote sources and dust transport pathways. The satellite aerosol data have been used for a period of 15 years to understand the long-term general transport pathways of dust originating from different sources to arrive at the BOB. The model simulations, on the other hand, have only been carried out for a single representative year, that is, the year 2014, to study in detail how dust from regional and remote sources vary in space and time and also how dust transport from different sources takes place in the vertical. The data and the models are described in the following subsections.

a. Regional Climate Model

The Regional Climate Model, version 4.5 (RegCM4.5), has been set up over the domain encompassing the northern IO and its surroundings (13°S – 34°N , 38° – 104°E) at 30-km resolution. Simulations have been carried out for the period 1 November 2013–30 November 2014 with the first month taken as spinup time. The RegCM model has been previously used to study dust transport over India (e.g., Das et al. 2013, 2015; Solomon et al. 2015). It is a hydrostatic, sigma-vertical coordinate, terrain-following model with Arakawa B grid horizontal grid system. The model includes an online dust scheme, in which dust emission is parameterized based on saltation and sand-blasting processes when the model-calculated wind friction velocity exceeds the thresholds for particular soil types (Marticorena and Bergametti 1995; Zakey et al. 2006). Dust size distribution at emission has been modeled based on an analogy to fragmentation of brittle materials (Kok 2011a) and this yields an emission size distribution that is independent of the wind speed (Kok 2011b). Dust transport takes place in four size bins: 0.01–0.1, 0.1–1.0, 1.0–5.0, and 5.0–20.0 μm , and dust is removed via wet (Giorgi and Chameides 1986) and dry (Zhang et al. 2001) deposition processes. The land surface process is modeled using Biosphere–Atmosphere Transfer Scheme (BATS; Dickinson et al. 1993). Only the direct radiative effect of dust that is calculated both for shortwave and longwave regions is included in the model (Kiehl et al. 1996). For simulating dust, soil texture from the Food and Agriculture Organization of the United Nations (FAO; at $0.083^{\circ} \times 0.083^{\circ}$ spatial resolution) as well as soil moisture information from the European Space Agency Climate Change Initiative (ESA CCI; at $0.25^{\circ} \times 0.25^{\circ}$ spatial resolution) is provided. The 6-hourly meteorological boundary conditions (wind, temperature, relative humidity, and geopotential height) have been provided by ERA-Interim ($1.5^{\circ} \times 1.5^{\circ}$ spatial resolution; Dee et al. 2011) and

weekly sea surface temperature (SST) data from Optimum Interpolation SST (OISST; at $1^{\circ} \times 1^{\circ}$ spatial resolution) are used. Since there are important dust sources outside the domain, chemistry boundary conditions have been provided by the Community Atmosphere Model coupled with chemistry (CAM-Chem). For the present study, dust has been allowed to dynamically and thermodynamically interact with the model forcing fields. Some of the important physics options used are Holtslag nonlocal boundary layer scheme (Holtslag and Boville 1993), Emanuel convection scheme for convective precipitation (Emanuel 1991), and the Subgrid Explicit Moisture Scheme (SUBEX) for large-scale precipitation (Pal et al. 2000).

Two sets of simulations have been carried out in order to investigate the relative importance of regional and remote dust sources. In the first set, dust emission is allowed from all dust sources (local plus remote) in the study domain (ALL_DUST runs). In the second set, dust emission from regional dust sources (i.e., the Thar Desert and the central peninsula of India) has been “turned off” (NO_REG runs), which yields the effects of remote sources alone. Figure 1 shows the distribution of dust emission from both local and remote-source regions, with the bold contours enclosing the local sources that are turned off during the NO_REG runs. To minimize the effect of model internal variability on our analysis, 3-member ensemble runs have been carried out for each set by shifting the starting date for each of the runs by ± 5 days. Henceforth, all the RegCM results and discussions are based on the ensemble mean. The dust optical depth τ_{du} from RegCM model at 500-nm wavelength has been compared over land with in situ Aerosol Robotic Network (AERONET) coarse-mode aerosol optical depth τ_c data (Holben et al. 1998, 2001; O'Neill et al. 2003). For this purpose, daily cloud-screened and quality-assured level 2.0 data have been used from eight selected stations spread out in different regions over the study domain (see Fig. 1). Comparison of the modeled τ_{du} over the ocean has been carried out with satellite remote sensing data as explained in section 2c.

b. Air parcel back-trajectory model

The route followed by air parcels to arrive at the northern (represented by 19°N and 90°E) and the southern (represented by 9°N and 90°E) BOB were tracked using the Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT; Draxler and Hess 1998). The 10-day back trajectories starting from an altitude of 3000 m were calculated daily at 0000 UTC (0530 Indian standard time) for June 2014 when dust from both the Thar Desert and the remote sources are

FIG. 1. Dust emission ($\text{mg m}^{-2} \text{day}^{-1}$) in the model domain averaged for the period December 2013–November 2014. The bold contours enclose the regions over which dust emission has been turned off in the NO_REG runs. The open black circles and the filled blue squares indicate the locations of the AERONET and radiosonde stations, respectively.

active [see section 3d(1)]. An altitude of 3000 m is chosen based on RegCM analysis of the arrival height of dust-laden air over the northern BOB [see section 3d(2)]. Also, the arrival time was chosen as 0000 UTC to match the time of radiosonde observations of the vertical profiles of atmospheric thermodynamical parameters (see section 2d). In tune with the boundary conditions used for RegCM simulations, meteorological fields at 6-hourly interval for running HYSPLIT were obtained from ERA-Interim. Dust concentrations along the trajectories were derived based on the position of the air parcels (i.e., latitude, longitude, and pressure level). Along with this, the parts of the trajectories that lie within the RegCM-derived boundary layer were determined. Such portion of the trajectories that resides within the boundary layer over a particular dust-source region indicates the predominant source region from where dust is transported to the northern and the southern BOB.

c. Satellite-derived dust optical depth

To illustrate dust transport over the BOB and also to compare the model results, we have relied on monthly τ_{du} derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) using the algorithm given by Kaufman et al. (2005). For this purpose, MODIS, collection 6, data from *Aqua* (for the period January 2003–December 2015) and *Terra* (for the period January

2001–December 2015) were used together to yield τ_{du} for the period 2001–15. Briefly, τ_{du} is given as

$$\tau_{\text{du}} = [\tau(f_{\text{an}} - f) - \tau_m(f_{\text{an}} - f_m)] / (f_{\text{an}} - f_{\text{du}}), \quad (1)$$

where τ is the MODIS monthly total aerosol optical depth, f is the MODIS monthly fine-mode fraction of aerosol, and τ_m refers to monthly optical depth of maritime aerosol. The variables f_{an} , f_m , and f_{du} refer to the constant values of f for anthropogenic, maritime, and dust aerosols, respectively. Kaufman et al. (2005) have used τ_m as a linear function of wind speed based on the measurements carried out on Midway Island (Smirnov et al. 2003). However, several studies (e.g., Moorthy et al. 1997; Moorthy and Satheesh 2000; Satheesh et al. 2006a) over the IO have shown τ_m to be exponentially dependent on the wind speed. Therefore, we estimated τ_m in this study as

$$\tau_m = \tau_0 [\exp(bW) - 1], \quad (2)$$

where W is the surface (horizontal) wind speed (m s^{-1}), τ_0 is the wind-independent background value of optical depth, and b is the index for wind dependence (s m^{-1}). Here, τ_0 and b have been taken as 0.21 and 0.07, respectively, based on measurements carried out on Minicoy Island in the AS (Moorthy and Satheesh 2000) and during a cruise in the AS and the equatorial IO (Moorthy et al. 1997). The wind speed W is calculated

using the Quick Scatterometer (QuikSCAT; Liu 2002) measurements for the period January 2001–December 2008 and the Advanced Scatterometer (ASCAT; Figa-Saldaña et al. 2002) measurements for the period January 2009–December 2015.

The value assigned for f_{an} is 0.90 based on the maximum value of f measured by MODIS in the region of continental outflow over the head BOB and East Asia for the entire period 2001–15. The reason for assigning the maximum value of f to f_{an} is to avoid any contamination of the anthropogenic aerosol signatures with other natural aerosols like dust and sea salts, which are much coarser in nature. The value taken for f_m is 0.60 based on MODIS measurement of f for December–March of each year over the western part of the equatorial IO (5° – 10° S, 50° – 70° E) located to the south of the intertropical convergence zone (ITCZ), where pristine maritime condition is expected to prevail. The standard deviations (SDs) for the values of f_{an} and f_m are 0.01 and 0.02, respectively. Since dust particle size distribution evolves toward finer size from emission to deposition [as the heavier coarse particles would fall off more rapidly; see Mahowald et al. (2014) and the references therein], f_{du} is expected to vary along dust transport paths. For example, studies have shown that during the SIM and SWM season, f is less than 0.20 in northwest India and more than 0.80 in the southeastern part of the IGP (e.g., Jethva et al. 2005; Ramachandran 2007; Ramachandran and Cherian 2008). By separating dust, based on calcium concentration, from the composite aerosols, Misra et al. (2014) have reported an average coarse mode fraction [defined as $(PM_{10} - PM_{2.5})/PM_{10}$] of 0.59 ± 0.22 . Here, we have assumed f_{du} of 0.40, which lies between low fine-mode fractions near dust sources and high fine-mode fractions found away from the sources. Using the Monte Carlo method for error calculation, Kaufman et al. (2005) have obtained error of 10%–15% in τ_{du} . By employing the same method and assuming a 10% variation in the values of f_{an} , f_m , and f_{du} , we obtain here error between 7% and 16% over the BOB.

Additionally, we have also confirmed our results using monthly nonspherical aerosol optical depth τ_{ns} data from Multiangle Imaging SpectroRadiometer (MISR) for the period 2001–15, along with daily τ_{ns} data for the year 2014 (Kalashnikova et al. 2005). The nonspherical aerosol optical depth is calculated as a product of total aerosol optical depth and the nonspherical fraction. Since dust is the predominant nonspherical particle present in the atmosphere, τ_{ns} can be used as a proxy of τ_{du} to study spatial and temporal distribution of dust aerosol over a region. For this purpose we have used the MISR, level 3, products available at $0.5^{\circ} \times 0.5^{\circ}$ spatial resolution.

d. Radiosonde soundings

Profiles of potential temperature θ and relative humidity (RH) from radiosonde ascents have been obtained from the University of Wyoming website (<http://weather.uwyo.edu/upperair/sounding.html>) to study the vertical structure favoring dust transport. Four stations were selected to trace dust transport for June 2014: Riyadh, Saudi Arabia, and Jodhpur, Lucknow, and Kolkata, India (see Fig. 1). The last three stations lie in the western, central, and southern IGP, respectively. All the profiles were obtained between 0000 and 0300 UTC and represent the early morning hours. This choice of time was based on the time of maximum availability of data. Although, local time in Riyadh is around 150 minutes behind the local time of India, we believe that the profiles in Riyadh are as representative of the early morning hours as the profiles over India. The radiosonde profiles were manually screened for any inconsistencies in the values or for any obvious data outliers. Next, the data were gridded vertically for pressure ranges 1000–100 hPa at 25 hPa intervals. These gridded data were averaged for June and their SDs was derived.

3. Results and discussion

We first give an overview of the study area, that is, the BOB and the surrounding regions. This is followed by an illustration of MODIS observation of meridional variation of dust sources over the BOB. We next use RegCM simulations to understand this observed meridional variation by exploring the seasonal cycle as well as the vertical distribution of dust from the Thar Desert and from remote sources. We look into the relative contributions of dust from these sources to the total dust load. The RegCM results are further corroborated by HYSPLIT back trajectories to examine the different dust transport routes for the northern and the southern BOB.

a. Characteristics of the study area during SIM and SWM

The meteorological conditions over the northern IO is shown in Fig. 2 using a combination of satellite and reanalysis data for SIM (Figs. 2a,b; March–May) and SWM (Figs. 2c,d; June–September) periods. Spatially, high values of MODIS-derived τ_{du} are observed over the AS adjacent to the main dust-source regions, while over the BOB, much lower values of τ_{du} are discerned. Nevertheless, τ_{du} over the BOB is much higher in comparison to pristine oceanic regions. For example, near the equator, the average value of τ_{du} can be around 0.1 during the SIM period and around 0.2 during the SWM period. On the other hand, the average value of

FIG. 2. The meteorological conditions and variation in dust loading over the northern IO during (a),(b) SIM (March–May) and (c),(d) SWM (June–September) for 2014. The shading in (a) and (c) represents MODIS-derived dust optical depth and contours are the precipitation (mm day^{-1}) from the TRMM satellite. The shading in (b) and (d) shows the sea level pressure (hPa) and the vectors represent the wind at the 850-hPa pressure level obtained from ERA-Interim.

τ_{du} over the BOB (north of 10°N) is around 0.20 for both SIM and SWM periods. The values can shoot up to 1.50 during the dust episodes. Again, over the AS, average τ_{du} during SWM period ranges from more than 0.60 in the northwest to less than 0.30 toward the southeast. Values of τ_{du} can be well above 2.50 during intense dust storm episodes.

Temporally, dust activity in the arid and semiarid regions surrounding the northern IO starts building up during the SIM to reach a peak during the initial part of the SWM period and subsequently subsides (e.g., Middleton 1986; Prospero et al. 2002; Léon and Legrand 2003; Deepshikha et al. 2006). Lifting of dust over southwest Asia (including the Arabian Peninsula) is accomplished by the northwesterly wind, locally known as shamals, which can be either due to eastward migration of cold fronts originating from the Mediterranean region (winter shamals; Perrone 1979; Vishkaee et al. 2012; Notaro et al. 2013) or due to the pressure gradient

set up between the low pressure over the Indian subcontinent and the surrounding high pressure regions (summer shamals; Rao et al. 2003; Notaro et al. 2013; Yu et al. 2016). Being a transition period between the NEM (December–February) and the SWM period, SIM can experience lifting of dust both because of cold front migrations and setting up of pressure gradient. The anticyclonic circulation over the AS favors the transport of this dust over the Indian mainland and into the northern BOB (see Fig. 2b). Additionally, dust from the Thar Desert as well as from southwest Asia can be transported across the IGP to reach the northern BOB (e.g., Chinnam et al. 2006; Prasad and Singh 2007; Kumar et al. 2008). The southern BOB is still under the influence of the easterlies that are carrying anthropogenic aerosols from East and Southeast Asia during the SIM period (Moorthy et al. 2003; Srinivas and Sarin 2013). With the advent of the SWM, the entire northern IO comes under the influence of the southwesterlies, which

brings copious amount of rainfall over the Indian subcontinent. There are two precipitation hotspots where rainfall exceeds 15 mm day^{-1} : 1) the west coast of India and 2) along the eastern boundary of the BOB. The dust activity during the SWM period is associated with the northerly Levar wind over the Iran–Afghanistan–Pakistan border region (Kaskaoutis et al. 2015; Rashki et al. 2015); northwesterly summer shamals around the Persian Gulf coast; and the southwesterly wind over Somalia, southeastern part of the Arabian Peninsula, and the Thar Desert (Léon and Legrand 2003; Deepshikha et al. 2006; Notaro et al. 2013; Yu et al. 2016).

b. Meridional variation of dust over the BOB

The wind system that characterizes the northern IO can result in complex and multiple pathways of dust transport over the BOB that vary spatially. The north–south variation of MODIS-derived τ_{du} over the BOB is illustrated in Figs. 3a–3d. Over the northern BOB (taken here as 17° – 20°N and 87° – 92°E), τ_{du} peaks during May (Fig. 3a) to attain a value of 0.46 ± 0.13 (where the value appearing after the $\pm$ symbol is the SD) and contributes around 80% of the total τ . With the advent of the SWM season (increasing rainfall), τ_{du} starts to decline, although the SD remains quite high during June–July, showing the large spread in the values. Figure 3b shows the correlation of τ_{du} averaged for March–September (SIM and SWM periods) for each year over the northern BOB with the rest of the northern IO. A significant positive correlation exists over the BOB south to 10°N and to a lesser extent over the northeastern part of the AS. On the other hand, τ_{du} over the southern BOB (taken as 7° – 10°N and 87° – 92°E) peaks during July, reaching a value of 0.24 ± 0.05 and contributing about 68% of τ (Fig. 3c). A similar correlation between τ_{du} for SIM and SWM over the southern BOB and the rest of the northern IO shows that significant positive correlation exists over the southern BOB and the southern AS, extending into the western equatorial IO (see Fig. 3d). However, there is no significant correlation of τ_{du} over the southern BOB with that of the northern BOB. This implies that the dust cycle over the southern BOB is different from that of the northern BOB. Thus, there is a meridional variation in the dust sources and transport routes over the BOB. While the northern BOB is influenced largely by the regional dust sources (located mostly in India), the remote sources of dust become important over the southern BOB.

A similar signature of different dust sources for the northern and the southern BOB is also revealed by correlation analysis using MISR-observed τ_{ns} values for the period March–September of the years 2001–15 (see Figs. 3f,h). It is important to note that MISR-

observed τ_{ns} values and the contribution of τ_{ns} to the total τ are much lower compared to those from MODIS (see Figs. 3e,g). However, there is a broad similarity between MISR and MODIS observations so far as the peak dust season is concerned. MISR shows τ_n peaking during June over both the northern and the southern BOB. The north–south variation in dust sources over the BOB is further explored in the following sections with the help of simulations performed using RegCM model.

c. Simulation of dust transport over the BOB

As a first step to understand if RegCM is able to simulate the spatial distribution and temporal variation of dust over the northern IO reasonably well, we have tried to assess how well the model is able to capture the observed meteorological fields over the region. For this, we have compared simulated temperature at the 850-hPa pressure level, surface-level wind, and precipitation for SIM and SWM periods for ALL_DUST runs with different sets of satellite data (Fig. 4). We have used temperature obtained from the Atmospheric Infrared Sounder (AIRS; Chahine et al. 2006) onboard the *Aqua* satellite at $1^{\circ} \times 1^{\circ}$ spatial resolution for comparison with RegCM-simulated values. Generally, a negative normalized mean bias (underestimation) in simulated temperature is seen over the ocean and the dust-source regions when compared to the AIRS observation. This can lead to increased stability over the dust-source regions and impact dust emission. During the SWM period, a region of positive normalized mean bias (overestimation) is seen over the east coast of India and extending into the IGP. Comparison of RegCM-simulated surface-level wind with ASCAT observations reveals positive normalized mean bias of the wind speed over the entire region, especially during the SWM period. The difference in wind vectors at surface level over the BOB shows that the model simulates enhanced southwesterlies during the SIM period and enhanced westerlies during the SWM period. While enhanced southwesterlies can lead to less dust transport during the SIM period, the enhanced westerlies during the SWM period can result in increased transport of dust from the northeast Africa and the Arabian Peninsula into the BOB. Furthermore, the model bias in simulating the precipitation has been evaluated against the Tropical Rainfall Measuring Mission (TRMM) 3B42, version 7, data at $0.25^{\circ} \times 0.25^{\circ}$ spatial resolution (Huffman et al. 2007). Large positive bias in precipitation over the eastern part of the BOB extending to the south and large negative bias over India along with the northern and western part of the BOB are seen during the SWM period. This can impact τ_{du} by increasing the wet removal of

FIG. 3. The (left) temporal evolution of dust load and (right) correlation maps for dust transport pathways over the (a),(b), (e),(f) northern BOB and (c),(d),(g),(h) southern BOB. The time series of monthly climatological (2001–15) MODIS-derived dust optical depth and MISR-derived nonspherical aerosol optical depth is indicated by the black curves on the left, and the vertical error bars show their SDs. The gray columns indicate the percentage contribution of dust/nonspherical aerosol optical depth to the total aerosol optical depth. The shading on the right indicates the correlation of dust optical depth averaged for the period March–September over the (b),(f) northern and (d),(h) southern BOB (shown by the dashed boxes) with the rest of the northern IO. The black contours enclose the regions where the correlation is significant at 95% confidence level.

FIG. 4. Comparison of RegCM-simulated meteorological fields for ALL_DUST runs with observations for (left) SIM (March–May) and (right) SWM (June–September) period. Normalized mean bias (%) is shown for temperature at (a),(b) the 850-hPa pressure level and (c),(d) surface-level wind speed (shading) over the ocean. Mean difference is shown for surface-level wind vectors [arrows in (c) and (d)] and (e),(f) precipitation.

dust over the southern bay and enhancing atmospheric lifetime of dust over the northern bay.

We next explore how well RegCM simulates dust aerosol distribution over the study region. At the very outset, it is noteworthy that direct observations of dust aerosol are limited, especially over the northern IO. Although several in situ measurements like time series

at a point or cruise transects exist (e.g., Clemens 1998; Measures and Vink 1999; Tindale and Pease 1999; Kumar et al. 2008; Srinivas and Sarin 2013; Grand et al. 2015), they only give us snapshots of dust aerosols over a limited time period and in a specific location. Often aluminum, which has an average crustal abundance of 8%, is used as a tracer for dust (Measures and Vink

FIG. 5. (a),(b) RegCM-simulated dust optical depth for ALL_DUST runs (shading) and percentage normalized mean model bias (contour) for (a) SIM and (b) SWM seasons. The continuous red lines and the dashed black lines indicate positive and negative percentage normalized mean biases, respectively. Note the different color scales used for (a) and (b). (c),(d) Daily RegCM-simulated dust optical depth (black curves), MODIS-derived dust optical depth (red circles), and MISR-observed nonspherical aerosol optical depth (blue squares) for (c) northern BOB and (d) southern BOB for the period December 2013–November 2014.

2000). Satellite-based observations are widely used to validate model results because of their large spatial and temporal coverage. So far as dust aerosol is concerned, this has to be approached with caution, because, in addition to the uncertainties in the retrieval algorithm, satellites give total τ from which dust component has been separated with additional assumptions (Kaufman et al. 2005; Ginoux et al. 2012). In this study, we have relied on τ_{du} derived from MODIS, τ_{ns} from MISR and coarse mode τ , that is τ_c , from AERONET to compare the modeled τ_{du} with the observations. The inherent assumption here is that if the model can correctly simulate τ_{du} , it can also correctly simulate dust emission and deposition. This is justified by the fact that τ_{du} is the net result of dust emission and deposition and as such represents dust in the atmosphere undergoing transport. As mentioned before, since SIM and SWM periods are the

dustiest periods over the northern IO, validation also considered only these periods.

Figures 5a and 5b shows modeled τ_{du} for SIM and SWM period and normalized mean bias in percentage when compared with MODIS-derived τ_{du} . We have not conducted a similar analysis for MISR τ_{ns} because of the very low number of MISR data points during SIM and SWM periods. Overall, the model has captured the spatial distribution of τ_{du} with high values over the northwest AS and the northern BOB and low values away from the dust sources (see also Figs. 2a,c). Nevertheless, the modeled values of τ_{du} are mostly underestimates compared to MODIS-derived τ_{du} ; the extent of underestimation increases with increasing distance from the dust sources. This is particularly clear when one looks at the pattern of the normalized mean bias during the SWM period. As RegCM does not

FIG. 6. Comparison of modeled dust optical depth (red curves) for ALL_DUST runs with AERONET coarse-mode aerosol optical depth (black dots) for selected AERONET sites. The shading indicates modeled dust optical depth averaged for the period December 2013–November 2014. The numbers in parentheses indicate correlation coefficient, normalized mean bias (%), and the sample size considered.

include dust from anthropogenic sources, it is possible that the simulated total dust load would be always lower than that actually present in the atmosphere. Also, positive bias in precipitation over the southern BOB during the SWM period can lead to the negative bias of dust over this region by increased wet removal of dust.

The evolution of RegCM-simulated daily τ_{du} over the northern and the southern BOB is compared with MODIS-derived τ_{du} and MISR τ_{ns} in Figs. 5c and 5d, respectively. MISR retrievals are largely absent during much of the SIM and SWM periods. Overall, RegCM is able to capture the summer high and winter low values of τ_{du} as is retrieved by MODIS over the northern BOB. In contrast, over the southern BOB, the high values of modeled τ_{du} are shifted to late winter and spring. It is important to note here that during the SWM period, small number of cloud-free pixels and imperfect cloud screening can influence the overall values of τ . Similarly, biases can be expected in satellite-retrieved total τ during periods of very high or very low aerosol loading

(Sayer et al. 2014). Thus, the satellite-retrieved τ_{du} values during the SWM period have to be treated with caution. However, what becomes immediately evident is the large difference between MODIS τ_{du} and MISR τ_{ns} values with the former showing much higher values. RegCM-simulated τ_{du} values are generally between MODIS and MISR measurements. The departures of the modeled τ_{du} from MODIS values are particularly high during the late SIM and SWM period. The normalized mean biases over the northern BOB when compared to MODIS and MISR are -40% (underestimation) and 45% (overestimation), respectively. Over the southern BOB, on the other hand, the peak values of τ_{du} are seen during the SIM period with a much smaller peak during July. The normalized mean biases over the southern BOB when compared to MODIS and MISR are -85% and -9% , respectively.

The comparisons of τ_{du} with daily τ_c from the selected AERONET stations are shown in Fig. 6. We have not considered MISR τ_{ns} over land because of the much

smaller number of data points (maximum of 30 data points) available per station even after considering $2^\circ \times 2^\circ$ latitude–longitude boxes centered on each station. To avoid inclusion of sea salt within τ_c , the AERONET stations having coastal proximity or island locations have not been considered. Also, inland stations that have data coverage spanning a short period of time have been excluded from the analysis. Unlike MODIS, although limited in spatial coverage, AERONET provides more temporal sampling of τ , and hence the values are much more representative of temporal evolution of aerosol properties. However, there are two caveats of comparing the model-simulated τ_{du} with that of AERONET τ_c : 1) τ_c by AERONET is retrieved based on spectral dependence of τ and not based on actual size criteria (O'Neill et al. 2003) and 2) implicit in using τ_c is the fact that fine-mode dust particles, which are important in long-range transport, are excluded.

Overall, it is seen that modeled τ_{du} curves closely follow the seasonal evolution of AERONET τ_c values. Most of the AERONET stations over the Indian subcontinent have not reported τ_c values during large part of the SWM period, probably because of the cloudy skies prevailing during this period. Nonetheless, the model has captured the summer high and winter low. For all the stations, there is significant correlation between τ_{du} and τ_c at the 99% confidence level. It is seen that the stations located near the dust sources have positive normalized mean bias (overestimations) in τ_{du} compared to τ_c . In general, with increasing distance from the dust sources, the magnitude of positive normalized mean bias decreases and the bias ultimately turns negative (underestimations). The overestimation is particularly high for Jaipur, India, lying to the east of the Thar Desert, and for Mezaira, United Arab Emirates, located in the northern edge of the Rub' al-Khali Desert in the Arabian Peninsula. In case of the latter, the high episodes of τ_{du} in the simulation during February–March are not seen in the observed τ_c . Also, the highest values of τ_c are seen during April–June, while the peak in the simulated τ_{du} occurs in August. For stations located in the advection paths of dust, signs of underestimation are particularly prominent for Lahore, Pakistan; Kathmandu–Bode, Nepal; and Dhaka University, Bangladesh, especially during the SIM and SWM period. Measurements of particulate matter in Lahore have shown that mineral dust consists of $74 \pm 16\%$ of the coarse particle mass ($PM_{10-2.5}$) with maximum contribution during May (Stone et al. 2010), while a mixture of dust and black carbon can also contribute to τ_c , especially during the SIM period over the IGP (Eck et al. 2010; Kedia et al. 2014). Wintertime measurements at Kathmandu–Bode have shown that

soil dust contributes only about 26% of the total PM_{10} mass in the region along with contribution from brick kilns, biomass burning, motor vehicles, and secondary sources (Kim et al. 2015). This indicates that a combination of different aerosol species can increasingly contribute to the coarse-mode fraction of the aerosol optical depth as we move away from the dust-source region. This can explain some of the model underestimations of the dust load.

Thus, the model captures the broad seasonality of dust load over the model domain, while there exist some differences in the details. An overestimation is seen adjacent to the dust sources, while along the transport pathways some signs of underestimations are evident. Some of the underestimates may be due to contributions from other aerosols to the observed optical depths. The underestimation can also stem from the fact that the model does not consider the anthropogenic dust sources. For example, Ginoux et al. (2012) have shown that over the Indian subcontinent anthropogenic sources can contribute up to 45% of the total dust emission and identified IGP as a major anthropogenic-dust-source region. Positive or negative normalized mean bias can also result from bias in modeled meteorological fields. For example, during the SWM period, there is an underestimation of precipitation over the Thar Desert and the Middle East (see Fig. 4f). This can result in enhanced dust emission and overestimation of τ_{du} near the dust sources. RegCM overestimations of the strength of the westerlies can lead to enhanced transport of dust to the BOB. However, the model overestimation of precipitation over Bangladesh can also lead to more wet removal of dust and a negative normalized mean bias of τ_{du} over the Dhaka University AERONET station. This enhanced removal of dust will not impact the variation in dust-source regions over the BOB but will impact the dust concentrations. With this understanding of the model strengths and weaknesses, we next investigate the regional and remote dust transport over the BOB.

d. Regional versus remote dust transport over the BOB

1) SEASONAL CYCLE OF CONTRIBUTION OF REGIONAL AND REMOTE DUST

The contribution of dust from the regional sources in comparison to dust from remote sources can be understood by comparing τ_{du} from NO_REG runs and the difference between ALL_DUST and NO_REG runs, which are shown in Fig. 7. The spatial distribution of τ_{du} averaged for the period December 2013–November 2014 for the ALL_DUST run is shown in Fig. 6 for comparison. As expected, with the regional dust emission turned off, the crescent-shaped region of

FIG. 7. Shading shows the simulated dust optical depth averaged for the period December 2013–November 2014 for (a) NO_REG runs and (b) ALL_DUST minus NO_REG runs. The contours indicate the percentage contribution of dust from the regional sources to the total dust optical depth.

high τ_{du} representing the Thar Desert is no more seen (Fig. 7a). The difference between ALL_DUST and NO_REG runs, which indicates the contribution of the regional dust sources (primarily the Thar Desert), is shown in Fig. 7b. On an annual average, the regional sources contribute more than 60% of dust over the Thar Desert, around 30% over the northern BOB, and down to 10% over the southern BOB. Thus, the Thar Desert and adjoining regions are the main contributors to τ_{du} over the IGP and to a lesser extent over the northern BOB. However, as we move to the southern BOB, long-range transported dust from remote sources predominates, in line with the correlation pattern seen in Fig. 3. That the southern BOB represents a different aerosol regime compared to the northern BOB has also been shown by Satheesh et al. (2006b), who have reported that during the period April–October of 2000–04, the northern BOB was under the influence of air masses from the central and the east coast of India for 50%–60% of the time, and the southern BOB was under the influence of air masses from the AS 70%–85% of the time. We have also carried out additional simulations with the Coordinated Regional Climate Downscaling Experiment (CORDEX; Giorgi et al. 2009) domain for South Asia at 50-km resolution for ALL_DUST and NO_REG cases. The results (not shown) qualitatively agree with the main conclusions derived using our original smaller domain at 30-km resolution (see the discussion above) and indeed point to a north–south difference in dust sources over the BOB.

Despite these broad differences, it should be noted that the contribution of the Thar Desert to τ_{du} over the northern BOB is highly seasonal. During the NEM season, the contribution of the Thar Desert to the total τ_{du} is more than 40% over northwest India and around 20% over the IGP. The Thar Desert contributes just $\sim 10\%$ of the total τ_{du} over the northern BOB up to the middle of April (see Fig. 8a). The NEM (Fig. 8b, light

orange shade) and SIM (Fig. 8b, light green shade) are the times of the year when dust from remote sources dominates over both the northern and the southern BOB as is evident from the simulated time of maximum dust emission in the region bordering the northern IO (Fig. 8b). The winter shamals and the Sharav cyclones over the Mediterranean region are the main agents favoring dust emission over southwest Asia during this time of the year (Ganor et al. 1991; Kubilay et al. 2000; Vishkaee et al. 2012; Notaro et al. 2013). Yu et al. (2013) have shown that peak value of τ is encountered over the northern and central Arabian Peninsula during April and May, while over the southern Arabian Peninsula, peak of τ is during June–July. Though their results are not directly comparable with the dust emission used in the present study, since τ is the net result of all aerosols present at all levels in the atmosphere, which would include locally produced as well as transported, these point to the broad similarity between satellite observations and RegCM simulations on the spatiotemporal evolution of dust activity and its seasonality. With the progress of the year, Thar dust activity gains momentum and its contribution to τ_{du} over the northern BOB increases with maximum contribution during June. Over northwest India, dust from the Thar Desert contributes to about 80% of the total τ_{du} , while it decreases to $\sim 60\%$ over the northern BOB and to a mere 10% over the southern BOB (to the south of 12°N). Nevertheless, it is important to note that even during this period, when the local source activity is at its peak, nonlocal sources (like northeast Africa, the southeast Arabian Peninsula, and the region lying in the Iran–Afghanistan–Pakistan border) at times can contribute as much as $\sim 50\%$ to τ_{du} over the northern BOB. Summer shamal is an important agent of dust uplift during this time of the year (see section 3a). About 29 shamal days per year and 10 shamal events per year are reported along the southern

FIG. 8. (a) Shading shows time vs latitudinal variation of the contribution of the Thar Desert to the total simulated dust optical depth over the BOB, and the contours indicate the percentage contribution of the Thar Desert to the same. The latitudinal variation has been obtained by averaging over 87° – 92° E and the time series have been smoothed by employing a 15-day running average. (b) Spatial distribution of the time of maximum dust emission over the study region obtained from RegCM simulation.

coast of the Persian Gulf, with 77% of the shamal days occurring during June–September (Al Senafi and Anis 2015). During July–August, although the absolute value of τ_{du} decreases because of the vigorous monsoon precipitation, the percentage contribution of the Thar Desert to the total τ_{du} increases by 10%. This is possibly due to the combined action of reduction of dust activity over the Arabian Peninsula and the increased wet removal of dust by the monsoonal rains. Note here that the positive bias in precipitation over the southern BOB can lead to increased dust removal and, therefore, can result in underestimation of dust coming from the remote sources. Analyzing shamal weather for the period 1979–2013 over the Arabian Peninsula, Yu et al. (2016) have shown that the onset date of summer shamal is $30 \text{ May} \pm 16$ days and cessation date is $16 \text{ August} \pm 22$ days. The drastic reduction in dust activity in the latter half of August leads to the very low τ_{du} of around 0.02. There is slight recovery during September contributed to primarily by the Thar Desert. From October onward, dust activity is at its lowest and dominated by remote sources. Note that throughout this annual cycle, over the southern BOB (south of 12°N) the remote sources contribute most significantly to τ_{du} .

2) VERTICAL STRUCTURE OF REGIONAL AND REMOTE DUST TRANSPORT

Having discussed the seasonality of the varying contributions of local and remote dust sources to τ_{du} over the northern and southern BOB, we examine the vertical structure of dust transport for June, when both the local and remote dust activities are around their peak and the SWM wind system has established itself over the Indian subcontinent. In Fig. 9, the simulated distribution of τ_{du} coupled with vertical section of dust-mixing ratios

along 70° , 80° , and 90°E show the three-dimensional structure of dust transport across India and into the BOB. The salient characteristics of vertical distribution of dust-mixing ratio along these three longitudes are discussed below.

At 70°E , the highest dust-mixing ratio (in excess of $2000 \mu\text{g kg}^{-1}$) is concentrated at the surface level over the Thar Desert and the mixing ratio decreases with increasing altitude, thereby showing the strong source activity. Interestingly, to the north of 20°N , a 3-layered structure emerges when we quantify the percentage contribution of dust from the Thar Desert to the total along 70°E . At the surface level, the Thar Desert contributes more than 80% of the total dust; most of it being restricted to below the 900-hPa pressure level (source region). Above that, dusts from the remote sources become important. A second region showing comparatively high contribution of Thar dust ($\sim 70\%$) is centered on the 500-hPa pressure level. There can be two possible reasons for the appearance of this secondary region of relatively high contribution from the Thar Desert dust: 1) the irregular shape of the Thar Desert with its southwest-to-northeast orientation favoring intrusion of dust from different sources at different levels when a meridional section is considered. 2) The second reason can be understood by an examination of the simulated wind vectors (Fig. 10), which reveals a cyclonic circulation prevailing over this region at the 850-hPa pressure level. This would draw in some of the dust from southwest Asia and also transport the dust from the Thar Desert both in eastward and northwestward directions. To the southern flank of the cyclonic motion, the northwesterlies from the Persian Gulf are responsible for long-range transport of dust into central India. At the 500-hPa pressure level, the wind is northwesterly

FIG. 9. RegCM simulations of dust transport across India to the BOB during June 2014 from ALL_DUST runs. The black-and-white shade shows dust optical depth over the northern IO and its surroundings during June 2014 and the blue–orange shade shows the latitude vs height (shown as pressure levels) variation of the simulated dust-mixing ratio for 70°, 80°, and 90°E. The black contours indicate the percentage contribution of dust from regional sources to the total dust concentration.

with an anticyclonic curvature. An examination of the vertical velocity field shows descending motion over the eastern part of the Arabian Peninsula with wind entering from the Persian Gulf. Over the Arabian Sea and eastward into the Thar Desert, ascending motion prevails from the surface up to the 600-hPa pressure level, followed by descending motion at upper levels. This setup over the Thar Desert is typical of the heat low type of circulation prevailing over the Thar Desert (Bollasina and Nigam 2011) where there is ascending motion extending into the midtroposphere associated with the intense daytime heating of the surface and descending motion above. The secondary region of high Thar Desert dust is embedded within this region of descent. Thus, the dust from the boundary layer of the Thar Desert that is transported eastward and is lifted up by the cyclonic motion reappears at higher altitude because of the descending motion. Such a circulation gives rise to a complex mixture of dust from different sources in the vertical.

The pathway for dust transport from southwest Asia across India into the BOB is further explored with the help of θ and RH profiles obtained from radiosonde data for June (Fig. 11). Over Riyadh (46.71°N, 24.93°E), RH is less than 20% below the 700-hPa pressure level, indicating the presence of dry desert air mass. The θ curve shows the nighttime inversion occurring at about the 950-hPa pressure level. This is followed by very little gradient in θ with increasing altitude up to the 600-hPa pressure level, showing a convectively unstable regime

with low RH representing the warm and dry air mass formed because of dry convection over the desert region during daytime. This air mass would lift dust to higher levels in the atmosphere, which would be subsequently incorporated into long-range transport by the prevailing wind. Over Jodhpur (26.30°N, 73.01°E), a station that lies to the east of the Thar Desert, the profiles of θ and RH are complicated because of mixing of moisture-laden monsoonal winds with the dust-laden air and as such represent a combination of features seen during May and July. Here, the surface RH value from radiosonde ($\sim 40\%$) is higher compared to Riyadh, and the θ curve is much smoother. Note, again, that the profiles are obtained over India during local early morning hours. Over Jodhpur (Fig. 11b), the following features are discernible in the θ and RH curves: 1) a very shallow nocturnal boundary layer associated with the dry desert location, in which θ and RH are altitude invariant; 2) an enhancement in RH above this layer up to the 850-hPa pressure level associated with synoptic moist monsoonal wind that arrives from across the Arabian Sea; and 3) a dry air centered around the 700-hPa pressure level where RH is less than 35%, followed by a slight recovery in the RH to more than 40% centered around the 550-hPa pressure level. RegCM simulations also show profiles (Fig. 11b, inset) that are in tune with the radiosonde profiles, although there are some differences in the altitude at which these features are present. Interestingly, the second region of lowest RH in the vertical (centered on 850 hPa in RegCM simulations) coincides with the

FIG. 10. RegCM-simulated wind vectors over India and surroundings for June 2014 at the (a) 850- and (b) 500-hPa pressure level. The red box encloses the region where cyclonic circulation prevails at the 850-hPa pressure level that helps in recirculating dust from the Thar Desert. (c) Shading indicates the longitude vs height variation of the vertical velocity and the vectors indicate the prevailing circulation along 23°N. Negative values indicate upward motion. Vertical velocity has been multiplied by 5000 to represent by the same shadings.

location where dust from remote sources dominates, indicating the intrusion of Middle Eastern dust from the west at intermediate altitude over northwest India. Thus, the modeled RH profile together with radiosonde profile over Jodhpur gives further support to the 3-layered structure seen over northwest India in Fig. 9.

At 80°E, maximum dust concentration of more than $80 \mu\text{g kg}^{-1}$ is located at the 850-hPa pressure level forming an elevated layer over the Gangetic Plain (see Fig. 9). This is primarily constituted of dust from the Thar Desert (regional sources), transported by the north-westerlies, which contributes more than 60% in the altitude range of the 900–600-hPa pressure levels. Several studies using ground-based and spaceborne lidars have documented the presence of an elevated aerosol layer over the IGP during SIM (March–May) and SWM (June–September) periods where the top of the aerosol

layer height can go up to 5 km (~ 500 hPa-pressure level) close to the Himalayan foothill regions (e.g., Misra et al. 2012; Mishra and Shibata 2012; Gautam et al. 2010). It has been shown that during SIM and the early part of SWM (June) this elevated layer can contribute from more than 40% to about 70% of the total columnar value of τ (Mishra and Shibata 2012; Sarangi et al. 2016). The signature of this dust transport is also seen in the radiosonde profiles over Lucknow (26.8°N, 80.9°E) located in the central part of the Gangetic basin (Fig. 11c). There is a fall in the RH at 900 hPa accompanied by very little change in RH with height between the 900- and 550-hPa pressure levels, which is indicative of prevalence of dry air mass.

Farther to the east, at 90°E, maximum dust concentration is about $46 \mu\text{g kg}^{-1}$ and this maximum concentration is centered at an altitude of around the 850-hPa level (see Fig. 9). This altitude of maximum dust

FIG. 11. Radiosonde profiles of θ (red) and RH (blue) averaged for June. The red horizontal bars and the blue-shaded regions indicate the SDs of θ and RH, respectively. In the inset RegCM-simulated RH (black curve) and percentage contribution of regional dust to the total (red curve) for Jodhpur is shown.

concentration increases to the 700-hPa pressure level over the northern BOB, forming an elevated aerosol layer. For example, at 20°N, dust residing at altitudinal range between the 850- and 600-hPa pressure levels contributes about 57% to the total dust load. Using airborne lidar, [Satheesh et al. \(2009\)](#) have shown that aerosol above 1 kilometer contributes around 75%–85% of the column optical depth over the east coast of India. They have also shown that within 50 km from the coast, the altitude of maximum aerosol extinction is about 3 km (around the 700-hPa pressure level), which is in line with our results. Similarly, ground-based lidar measurements in coastal locations along the western BOB have reported elevated layers associated with advection of dusty air masses from northwest India and southwest Asia ([Niranjan et al. 2007](#); [Rajeev et al. 2010](#)). Analysis of RegCM-simulated wind direction shows that there is a 2-layered structure: southwesterly at the surface level bringing maritime air mass from the BOB and prevailing northwesterlies in the upper-level favoring

advection of dust from the west. Radiosonde profiles over Kolkata (22.5°N, 88.5°E), located about 100 km inland, show a smooth θ curve and a much less pronounced dry layer located between the 800- and 650-hPa pressure level (see [Fig. 11d](#)). This station largely comes under the influence of maritime air mass. The contribution of the Thar Desert to the total dust concentration ranges from 62% at 26°N, about 38% over northern BOB (at 20°N) and 15% south of 12°N (see [Fig. 9](#)). Interestingly, about half of the dust loss between 80° and 90°E takes place within the layer dominated by dust from the Thar Desert in the region lying to the north of 24°N. This explains why the contributions from remote sources of dust become increasingly conspicuous over the northern BOB.

3) MERIDIONAL VARIATION IN TRANSPORT PATHWAYS OVER THE BOB

Based on the arrival height of the dust-laden air over the BOB determined from RegCM simulations in the

FIG. 12. The 10-day back trajectories of air parcels arriving at the 700-hPa pressure level for (a),(c) the northern BOB and (b),(d) the southern BOB for June 2014. The colors indicate the (a),(b) dust mixing ratio along the trajectories and (c),(d) pressure level at which transport takes place. The dust emission regions are shaded gray and the black contour encloses the Thar Desert. The light-blue-colored part of the trajectories in (c) and (d) indicate where the trajectories lie within RegCM-derived boundary layer.

previous section, back trajectories of air parcels over the northern and southern BOB at the 700-hPa pressure level (~ 3000 m) for June have been analyzed and shown in Fig. 12. Additionally, back-trajectory analysis of air parcels arriving at 847 hPa (1500 m) and 520 hPa (5500 m) are shown in Fig. S1 in the online supplemental material. These back trajectories have been derived using HYSPLIT based on ERA-Interim data. The dust-mixing ratios at the corresponding pressure levels along the trajectories are indicated.

Analyses of these trajectories show that at the surface level, large parts of the trajectories lie over the oceanic regions and follow the southwest monsoon wind (see Figs. S1a,b). They mostly carry pristine maritime air. With increasing height in the atmosphere, the back trajectories become more northwesterly and are conducive to carrying dust from the major dust sources. Almost all the air parcels arriving at the northern BOB (represented as 19°N and 90°E) pass over India with about 53% of the trajectories passing over the Thar Desert (Fig. 12). There is only one trajectory that arrives at northern BOB from the south. Discounting this

trajectory, the rest of the trajectories can broadly be divided into two types: 1) those that originate below the 800-hPa pressure level over the western part of the IO and follow the synoptic (SWM) wind system, and 2) those that come from the northwesterly direction. While the former trajectory group is initially the pristine maritime type, it starts picking up dust after crossing the equator. The second type of the trajectories is dust laden throughout. Analyzing the portion of these trajectories that reside within the boundary layer over the dust emission regions gives an indication of the main dust-source regions for the northern BOB. The most important dust-source regions for the northern BOB are northeast Africa (Somalia), the southern part of the Arabian Peninsula (Yemen and Oman), the Iran–Afghanistan–Pakistan border region, and the southern part of the Thar Desert. Of the total number of trajectories passing over the Thar Desert, 56% lie within the boundary layer while around 50% of the trajectories passing over other dust sources are within the boundary layer. The trajectories passing over these source regions have dust-mixing ratios in excess of $100 \mu\text{g kg}^{-1}$; going up

to more than $1000 \mu\text{g kg}^{-1}$. The rest of the trajectories lie above the boundary layer and indicate long-range transported dust or dust picked up through mixing with other dusty air parcels. These trajectories passing over the Thar Desert are located between the 650 and 800-hPa pressure levels, which corresponds well to the region of very low RH seen from radiosonde profile over Jodhpur (Fig. 11).

In contrast to the above scenario over the northern BOB, only around 20% of the trajectories arriving at the southern BOB pass over the Thar Desert. More than 60% of the trajectories arrive from Somalia and the Arabian Peninsula (mostly the eastern part), which is in line with the earlier simulation results indicating the dominance of remote dust sources over the southern BOB (also see Fig. 8a). Around 50% of the trajectories coming from the Thar Desert reside within the boundary layer. Other dust-source regions for the southern BOB, based on the residence of the trajectories within the boundary layer, are Somalia and Rub' al-Khali in the Arabian Peninsula. Initially, these air parcels carry a substantial amount of dust, which is comparable with those carried by the air parcels arriving at the northern BOB. However, after crossing 75°E , there is a drastic reduction in the dust-mixing ratio due to high precipitation over this region during the SWM period, which leads to the removal of dust via wet deposition. This is also true for the trajectories originating within the Thar Desert boundary layer, which experience a drop in the dust-mixing ratio upon entering the BOB. With further increase in height in the atmosphere, dust concentration itself reduces (Figs. S1c,d). Thus, the layer between 850 and 700 hPa is the optimal region for dust transport across the Indo-Gangetic Plain and into the northern Bay of Bengal. It is important to mention here that although this analysis has been carried out for a short period of time, the main results are consistent with the inferences drawn out from long-term MODIS and MISR observations (in section 3b).

e. Climate implications

The impact of long-range transported aerosol on the climate of a region has been of concern in the recent decades. Over the northern IO, understanding the climatic impact of dust is complicated by the fact that the region receives dust from different sources, and each of these sources has different mineral compositions and hence different optical characteristics. For example, several studies have shown that dust over the Thar Desert is much more absorbing compared to that over the Middle East (Deepshikha et al. 2005; Moorthy et al. 2007) because of different soil mineralogy and mixing of dust with other absorbing aerosol species (e.g., Singh et al. 2004; Chinnam et al. 2006). This becomes very

pertinent since dust from the Thar Desert is the main contributor to the elevated layer of dust over the northern BOB, as has emerged from our study (discussions in section 3d). Absorption by such elevated aerosol layer has been shown to heat the atmosphere by about 1.5 K day^{-1} over central India with as much as 70% of total aerosol extinction coefficient contributed by aerosol above cloud (Satheesh et al. 2008). Such elevated layer of aerosol heating near the foothills of the Himalayas is shown to have feedback into the monsoon system by acting as an “elevated heat pump” and drawing in more moisture-laden air (Lau and Kim 2006; Lau et al. 2006). More recent works have also shown that the impact of dust on the Indian monsoon is sensitive to dust-absorptive properties and the sign of dust-induced precipitation change can shift from negative to positive as dust becomes more absorbing in nature (Das et al. 2015; Jin et al. 2016).

The other significance of long-range transported versus regionally derived dust lies in the biogeochemical implications. For example, numerous studies have shown that Saharan dust transported across the Atlantic Ocean fertilizes the ocean as well as the Amazon forest (e.g., Lenes et al. 2001; Koren et al. 2006; Schlosser et al. 2014; H. Yu et al. 2015). When dust particles travel long distances, their size distribution evolves toward finer particles, with larger particles rapidly settling down (Mahowald et al. 2014 and references therein). These small-sized particles provide a larger surface area to undergo processing by different chemical species in the atmosphere (Siefert et al. 1999; Baker and Jickells 2006). Atmospheric processing of iron has shown to increase iron solubility in the remote oceans away from the continents (e.g., Duce and Tindale 1991; Hand et al. 2004). Over the northern IO, the chemical processing of dust aerosol and the derivation of dissolved iron is complicated by the presence of dust from different sources and the mixing of dust with anthropogenic aerosols. For example, the solubility of iron in the dust from the Middle East is around 0.02%–0.4% because of the high amount of calcium carbonate in the soil around the Persian Gulf region (Srinivas et al. 2011). However, over the BOB, solubility of iron in dust is increased to 1.4%–24%, owing to acid processing of dust during its transit over the IGP (Kumar et al. 2010; Srinivas et al. 2011). Thus, while our study shows that dust from the Middle East and northeast Africa contributes a large fraction of the total dust load over the BOB, the amount of dissolved iron that can be derived depends on the transport route as well as the total mass.

In recent years, it is being increasingly recognized that several of the dust-source regions are undergoing climate-related shifts in the source characteristics. For

example, there are reports of reduction in precipitation and increasing frequency of droughts over southwest Asia and northeast Africa because of changes in the strength of the Walker circulation (Barlow et al. 2002; Funk et al. 2008). This has resulted in increasing dust activity over these regions (Rashki et al. 2013; Notaro et al. 2015; Y. Yu et al. 2015). There are also indications of a decrease in dust activity over the Thar Desert (e.g., Kaskaoutis et al. 2012; Babu et al. 2013). Added to this, new dust sources are being created outside of the “traditional” deserts by anthropogenic activities (Ginoux et al. 2012; Stanelle et al. 2014). In this context, how these varying trends of dust in different regions will translate into variability of the level of dustiness over the BOB and its associated climate feedback remains a challenge.

4. Conclusions

We have examined in this paper the relative importance and transport pathways of dust from the regional dust source (the Thar Desert) and remote sources (southwest Asia and northeast Africa) over the BOB using a combination of model simulations and aerosol remote sensing observations along with radiosonde profiles of θ and RH. We find a major contribution of dust from remote sources over the entire BOB, except over the northern part, where dust from regional sources becomes important during the SWM period, peaking during June. Hence, we have largely focused on June. While dust from both the regional and remote sources reaches the northern BOB after transiting over the IGP, dust from the remote sources is transported to the southern BOB after passing over or around the southern peninsula of India. This transport and distribution of dust from regional and remote sources over the BOB is primarily orchestrated by the SWM wind at various pressure levels, leading to a complex structure in the vertical. The most striking feature of this complex structure is seen over the Thar Desert, in the western end of the IGP, where a 3-layered structure is formed. While at the surface level, dust from the Thar Desert constitutes more than 80% of the dust-mixing ratio, there is a second layer of Thar dust centered on the 500-hPa pressure level with an intervening region of remote dust. Such a structure in the vertical probably results from ascending motion at the lower levels over the Thar heat low, followed by descending motion at the upper level. Over the eastern end of the IGP, the dusty air reaches the northern BOB in an elevated layer centered on the 700-hPa pressure level with more than 60% of dust in this layer being contributed by dust from the Thar Desert. The signature of dust transport across the IGP is also evident by a drop in RH values in the vertical. In this way,

the warm and dry dusty air overrides the cold and moist monsoon air and form a stable upper layer.

The present study has been carried out using satellite observations for 15 years and a regional climate model simulation for one year, that is, 2014. It is important to note here that while both satellite observations and model simulations show north–south variation in dust sources over the BOB, large-scale phenomena like El Niño/La Niña and the Indian Ocean dipole have significant impact on the meteorology of the northern IO, which can in turn effect dust production, transport, and removal. In this case, 2014 is characterized by low values of the oceanic Niño index and the dipole mode index before and during the peak dust season. For the years with high values of these indices, the relative contribution of dust from different sources over the BOB can change significantly and can impact the feedback of dust into climate of the region.

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