A Satellite Observation-based Analysis of Aerosol-cloud-precipitation Interaction during the February 2016 Unseasonal Heatwave Episode over the Indian Region

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ABSTRACT

Aerosol-cloud-precipitation (ACP) interaction during the February 2016 unseasonal heatwave episode over India is analyzed and presented. Moderate Resolution Imaging Spectroradiometer (MODIS) datasets from the Aqua satellite are used to examine the relationship between aerosol and cloud parameters, viz., the aerosol optical depth (AOD), Ångström exponent (AE), cloud fraction, ice and liquid cloud effective radius, cloud optical depth, cloud top temperature, and ice and liquid cloud water path. Furthermore, the Tropical Rainfall Measuring Mission (TRMM) dataset is used to analyze the rainfall during the dissipating phase of the heatwave episode. The prevailing meteorological conditions during the pre-mature, mature, and dissipating phases of the episode are identified by analyzing the near-surface temperature, relative humidity, and vertically integrated moisture flux convergence via 0.25°-resolution ERA-Interim datasets. Back-trajectory analysis is conducted to determine the origin of air masses and transported aerosols. Hot and dry westerly winds dominate during the pre-mature and mature phases, and consequently, significant aerosol transport is observed. The AOD reaches a maximum of 1.6 during the three phases, with the AE being in the range of 0.8–1.7, indicating the presence of both fine- and coarse-mode aerosols. Due to microphysical processes, clouds respond fairly strongly to aerosols in the presence of favorable dynamic and thermodynamic atmospheric conditions. The suppression of precipitation during the pre-mature and mature phases is primarily attributable to weak aerosol-cloud interaction. A major rainfall event in the region comprising northern Odisha, eastern Jharkhand, and most parts of West Bengal, which is situated north of the minimum vertically integrated moisture flux zone, occurs during the dissipating phase. This rainfall event results from the unseasonal transport of moisture from the neighboring Bay of Bengal, the presence of appreciable aerosol loading, and the consequent ACP interaction.

Keywords: Aerosol-cloud interaction; Heatwave; Aerosol optical depth (AOD); Rainfall.

INTRODUCTION

Extreme hot weather is frequent in summer over India. The prevailing warm winds (also known as “loo”) during summer typically bring in heatwave conditions over India during March–June. In some years, maximum daytime temperatures exceed 45°C for many days over north-western, eastern coastal states, central parts and Indo-Gangetic Plain regions of India (Pattanaik *et al.*, 2016). In summer 2015 and 2016, these regions experienced a severe heatwave condition resulting in loss of several human lives, birds, and animals (Pattanaik *et al.*, 2016; Mishra *et al.*, 2017; Oldenborgh *et al.*, 2018).

The summer heatwave conditions over north-central

India result from the anomalous subsidence due to the quasi-stationary Rossby wave-train along the African Jet, generated from stretching of upper-level cyclonic vorticity in the west of North Africa induced by blocking over the North Atlantic (Ratnam *et al.*, 2016). In contrast, summertime heatwave over eastern parts of India is due to the anomalous Matsuno-Gill effect that generates cooling in the Pacific and north-westerly anomalies over adjacent landmasses to reduce the land-sea breeze effect (Ratnam *et al.*, 2016). Furthermore, sufficient local forcing on air temperature may have a substantial role in enhancing the intensity of heatwave conditions (Ghatak *et al.*, 2017). Thus, in a changing climate scenario, such episodes may be sensitive to large-scale dynamic effects as well as local or regional ones.

Heatwaves over India are broadly associated with climatic systems or processes including El Niño-Southern Oscillation (ENSO), and also gradients in the sea surface temperatures over north Indian Ocean (Ratnam *et al.*, 2016). Re-curving tropical cyclones over the Bay of Bengal (BOB)

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usually change the direction of winds, inhibit moisture transport to the continental region, and may consequently lead to heatwave conditions over coastal and inland areas. Although heatwave conditions over India are mostly driven by large-scale forcing (Ratnam *et al.*, 2016), regional effects like the ones mentioned cannot be ignored.

Every year, India experiences several heatwaves during the pre-monsoon months (March, April, May). Several studies suggest that urban areas have experienced a significant number of heatwaves in the last two decades (IPCC 2007; Mishra *et al.*, 2015). The most affected regions over the Indian subcontinent are Andhra Pradesh, Telangana, Punjab, Uttar Pradesh, Odisha, Jharkhand, and Bihar (Mishra *et al.*, 2015). Table 1, derived from Ratnam *et al.* (2016) and originally taken from India Meteorological Department (IMD), shows heatwave episodes occurring over eastern, northern, and central India.

Prevailing heatwaves may increase short-term mortality (Confalonieri *et al.*, 2007). For instance, in 1988, heatwaves caused nearly 1300 deaths (De and Mukhopadhyay, 1998). In 1998 and 2003, about 2042 and 3054 people died (Bhadram *et al.*, 2005), respectively, across India. In 2015, during the pre-monsoon period, heatwaves caused the death of about 2500 people in India (Ratnam *et al.*, 2016). In southern India, including Andhra Pradesh and neighboring areas like Telangana, heatwaves caused more than 1735 and 585 deaths, respectively, in 2015. Other areas in eastern parts of India, including West Bengal, Jharkhand, Bihar, and Odisha, were also influenced by the 2015 pre-monsoon heatwave condition (Bhadram *et al.*, 2005).

Metaxas and Kallos (1980) suggest that the identification of heatwave episodes be based on temperature criteria (i.e., the daily average temperature or the daily maximum temperature must be higher than the average temperature of the corresponding day of past years). The study by Ratnam *et al.* (2016) suggested supplemental criteria by considering IMD guidelines for identifying heatwave episodes during summer:

- (i) A heatwave is not considered until the maximum temperature of the stations reach 40°C for plains and 30°C for hilly regions.
- (ii) When normal maximum temperature of a station

≤ 40°C, a departure of +5–6°C from normal value is considered a heatwave condition.

- (iii) When the normal maximum temperature of a station > 40°C, a departure of +4–5°C from normal value is considered a heatwave condition.
- (iv) When actual maximum temperature ≥ 45°C, irrespective of normal maximum temperature, a heatwave condition is declared.
- (v) For coastal stations, if the maximum temperature ≤ 40°C, a heatwave may be declared.

If the heatwave episode happens during a non-summer month, it may be classified as an unseasonal one, like the one that occurred during February 2016 over the Indian peninsula. Here, the temperature may exceed 4 to 6°C compared with the mean maximum temperature. The present study intends to consider this unseasonal heatwave episode for analyzing potential aerosol-cloud-precipitation (ACP) interaction during the different phases of its occurrence. It may be noted that the heatwave condition would certainly create an unstable environment and may induce transport of air masses from neighboring regions, which may contain aerosols as well as moisture. However, it is not understood clearly how ACP interaction takes place over India during an unseasonal heatwave episode. In view of this, the present study attempts to fill a gap that is quite important as far as ACP interaction over this region is concerned.

The primary microphysical variable that is important when evaluating ACP interaction is aerosol size distribution (Dagan *et al.*, 2015; Kant *et al.*, 2017). The presence of greater numbers of cloud condensation nuclei (CCN) in the atmosphere (Patidar *et al.*, 2012) results in smaller cloud droplet size even with diameter < 1 µm (Squires, 1958). Initial size variation of the droplets is the primary factor in determining the effectiveness of condensation processes (Pinsky *et al.*, 2013), and subsequently, it influences the efficiency and beginning of warm rain coalescence and collision processes (Gunn and Phillips, 1957; Warner, 1968; Rosenfeld and Lensky, 1998). The efficiency and magnitude of entrainment also depends upon the amount of aerosol present in convective clouds (Jiang *et al.*, 2006; Xue and Feingold, 2006; Small *et al.*, 2009).

Giant CCN (or GCCN, with diameter > 1 µm) play an

Table 1. List of heatwave episodes over east coast of India, north and central India (Ratnam *et al.*, 2016).

Heat wave events over the east coast of India		
29 May–4 Jun 1983	01–07 May 1985	07–13 Jun 1986
17–23 May 1986	07–13 May 1994	10–17 May 1996
29 May–07 Jun 1997	09–15 May 2002	25 May–13 Jun 2003
15–21 May 2007	14–20 May 2008	26 May–03 Jun 2010
30 May–06 Jun 2012		
Heat wave events over north and central India		
19–30 May 1984	24–30 Jun 1987	08–14 May 1988
26–31 May 1988	11–21 Jun 1992	02–08 May 1993
07–13 Jun 1993	29 May–04 Jun 1994	30 May–10 Jun 1995
21–28 May 1998	07–12 Apr 1999	30 Apr–05 May 1999
16–24 Mar 2004	15–22 Jun 2005	18–27 Jun 2009
18–27 Mar 2010	08–20 Apr 2010	12–16 May 2010
18–24 May 2013		

important role in cloud growth and rain formation. Several studies (Houghton, 1938; Johnson, 1982) show that GCCN have an impact on the collision-coalescence process by developing relatively bigger droplets in convective clouds (Lasher-Trapp *et al.*, 2001). Some studies, like Cheng *et al.* (2009), show that in a relatively polluted environment, GCCN have a bigger impact on the rain rate of convective clouds. This phenomenon can also occur in convective (Yin *et al.*, 2000; Teller and Levin, 2006) and stratiform clouds (Fiengold *et al.*, 1999; Zhang *et al.*, 2006).

Aerosols also have a substantial impact on the microphysical and dynamic structure of stratocumulus and cumulus clouds, and consequently, precipitation formation processes (Segal and Khain, 2006; Pinsky *et al.*, 2008; Khain *et al.*, 2009). Some studies suggest that aerosols suppress rain produced through collision-coalescence process (Albrecht, 1989; Rosenfeld, 1999; Hudson and Mishra, 2007; Niu and Li, 2012; Dagan *et al.*, 2015), whereas some studies suggested concluded enhancement in rain rate (Koren *et al.*, 2012; Niu and Li, 2012; Koren *et al.*, 2014). Some others advocate for the significance of both of these aspects depending upon the prevailing meteorological conditions and geographical location (e.g., Kant *et al.*, 2019a, b). However, some numerical model simulation results show that in a relatively polluted environment, delay in beginning and decrease in the amount of rainfall occurs in convective clouds (Jiang and Feingold, 2006; Altaratz *et al.*, 2008; Xue *et al.*, 2008).

While realizing the complexities involved in ACP interaction discussed above, the present study focuses on analyzing and understanding: (i) relevant meteorological characteristics associated with the February 2016 unseasonal heatwave episode, (ii) prevailing aerosol properties, (iii) associated cloud microphysical properties and (iv) consequent precipitation occurrence and distribution over the study area. The details of the data and methodology adopted for this purpose are briefly discussed in the following section. The results obtained are presented in Section 3, and Section 4 summarizes the findings from this study.

GEOGRAPHICAL LOCATION, DATA AND METHODOLOGY

The present study is primarily focused on the region of the Indian subcontinent, which was impacted by the unseasonal heatwave during February 2016. Central India covers the states of Madhya Pradesh, Maharashtra, and Chhattisgarh. Summer is usually very hot over this region, with daily high temperatures exceeding 42°C. During winter, in contrast, the daily high temperature is below 12°C (Jain and Kumar, 2012). The western part of India lies near the Thar Desert located in the northwest part of the country. The Arabian Sea is to the west and Vindhya Range is located to the north.

The climate of western India is semi-arid and tropical wet/dry. Daily high temperatures over the western part of India during the summer are above 40°C and in winter below 15°C (Jain and Kumar, 2012). The eastern part of

India hosts the states of Jharkhand, Bihar, Odisha and West Bengal. Most of the country's population reside near the eastern part of India and Indo-Gangetic Plain (IGP) region. During summer, the high temperatures exceed 38°C over this part of the country, whereas winter is very cold (temperature below 10°C).

Southern India consists of states like Karnataka, Tamil Nadu, Andhra Pradesh, Kerala, and Telangana. The southern part of India is encircled by the Arabian Sea in the west, BOB in the east and the Indian Ocean in the south. Southern India has a non-arid climate. The maximum daily temperature exceeds 45°C in summer, whereas winter is colder with minimum temperatures below 18°C. During February, the maximum daily average temperature exceeds 30°C, while the minimum daily average value approaches 10°C over Madhya Pradesh (Table 2). The variation in daily climatological temperature is found to be maximum (~16.3°C) over Madhya Pradesh, whereas it is minimum (~10.4°C) over Tamil Nadu during February. The mean climatological total rainfall falls in the range 0.75–24.3 mm (Table 2).

The present study uses 17 days (i.e., 12–28 February 2016) of MODIS (Moderate Resolution Imaging Spectroradiometer) level-3 (version 5.1) data from the NASA Aqua satellite for analyzing ACP interaction during the February 2016 unseasonal heatwave episode. The parameters considered for this purpose include aerosol optical depth (AOD), Ångström exponent (AE), cloud fraction (CF), cloud effective radius (CER), cloud optical depth (COD), cloud top temperature (CTT) and cloud water path (CWP). The grid size of MODIS Aqua satellite retrieved datasets is $1^\circ \times 1^\circ$, and the data are obtained for the 550 nm wavelength. Since the work carried out uses level-3 products, clouds are already removed from the MODIS aerosol data (Remer *et al.*, 2005).

The uncertainty of MODIS AOD over ocean and land, in the absence of undetected cloud contamination, is $0.03 \pm 0.05\tau$ and $0.05 \pm 0.15\tau$, respectively (Remer *et al.*, 2005), where τ is the optical depth. The AE (or “ α ”) shows spectral characteristic features of aerosols and their size distribution.

The liquid water path (LWP in g m^{-2}) used in this study is primarily a derived product of COD and CER (μ), indicating the atmospheric column-integrated amount of liquid or ice water (King *et al.*, 1999). Channel frequencies of 10 to 87 GHz and a vertically polarized channel at 22 GHz (of MODIS) are used to retrieve cloud LWP (g m^{-2}) of non-precipitating and precipitating clouds (Alishouse *et al.*, 1990; Jung *et al.*, 1998). The LWP retrieval uses a unified ocean parameter retrieval algorithm (Wentz and Spencer, 1998), by considering near-surface wind speed, radiative transfer principles, an effective radiative temperature of upwelling radiation, columnar water vapor, rain rate and columnar cloud liquid water content. CF is the portion or percentage of every pixel that is enclosed by the cloud, and is measured by considering the 41×41 km area around the pixel (Varnai *et al.*, 2015). The values of CER (μ) are weighted mean radius of cloud droplets (Bhawar and Devara, 2010). The uncertainty of CER is within 1.0–3.0 μm for

Table 2. Mean climatological variation of near surface air temperature and rainfall for the month of February (as per India Meteorological Department climatological database).

States (No of stations considered)	Climatology Years	Mean Temperature (°C)		Difference between daily maximum and minimum temperature	Mean Total Rainfall (mm)
		Daily Maximum	Daily Minimum		
Andhra Pradesh (9)	1981–2010	32.23	20.87	11.37	6.91
Chhatisgarh (6)	1971–2000	29.25	14.42	14.83	18
Gujarat (10)	1981–2010	30.36	14.95	15.41	0.75
Jharkhand (3)	1981–2010	28.03	13.03	15.00	23.20
Karnataka (16)	1971–2000	30.48	16.53	13.95	12.41
Madhya Pradesh (7)	1971–2000	27.29	10.96	16.33	15.03
Maharashtra (7)	1971–2000	31.41	16.24	15.17	14.63
Odisha (12)	1971–2000	30.23	17.69	12.53	24.27
Tamil Nadu (12)	1971–2000	30.63	20.27	10.36	15.68
Telangana (3)	1981–2010	33.13	18.10	15.03	7.53
West Bengal (6)	1971–2000	27.73	14.10	13.63	21.43

optically thick clouds (King *et al.*, 1997). The standard deviation of MODIS retrieved CER is within $\pm 0.11 \mu\text{m}$ (Remer *et al.*, 2005). The COD is retrieved by merging of water non-absorbing ($0.65 \mu\text{m}$ for land) and absorbing (1.6 , 2.1 and $3.7 \mu\text{m}$) bands of MODIS (Platnick *et al.*, 2003). The uncertainty associated with COD may vary within 10–21% (Minnis *et al.*, 2004; Sayer *et al.*, 2016). CTT (K) values are retrieved using the radiance ratio method (Kidder and Vander Harr, 1995), and can be related to the cloud top pressure (Menzel and Strabala, 1997).

Tropospheric Rainfall Measuring Mission (TRMM) 3B42 (version 6) daily precipitation data are used for rainfall analysis. The grid size of the dataset is $0.25^\circ \times 0.25^\circ$. Furthermore, ERA-Interim global analysis (from European Centre for Medium-Range Weather Forecasts, or ECMWF) data at 12:00 UTC (<http://apps.ecmwf.int/datasets>) with 0.25° spatial resolution are considered for analyzing the prevailing meteorological conditions. For this purpose, meteorological variables like near-surface (at 1000 hPa) temperature, relative humidity (RH) and wind field are considered. The uncertainty in temperature and RH fields from ERA-Interim is up to 0.05 K and 0.4% (Noh *et al.*, 2016). Special attention is given to the air mass transport during an unseasonal heatwave condition by performing back-trajectory analysis using HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) model (Draxler and Rolph, 2003) on a daily basis.

The two-sample Student's *t*-test is performed in this study to analyze the probability (P) value of the datasets for MODIS-derived AOD and cloud parameters. The P-value signifies that datasets are statistically significant at 95% confidence level (Kang *et al.*, 2015). Furthermore, the Pearson correlation technique is adopted in the study for determining the correlation coefficients in a similar manner as that of Sarna and Russchenberg (2017).

In order to analyze ACP interaction over the Indian peninsula during the unseasonal heatwave episode, all of the datasets are considered for the period of 12–28 February 2016. For this purpose, the whole period considered in this study is divided into three phases, (a) pre-mature phase (12–16 February 2016), (b) mature phase (17–22 February

2016) and (c) dissipating phase (23–28 February 2016), based on the prevailing meteorological conditions. Accordingly, the corresponding results are analyzed and presented in the following section.

RESULTS AND DISCUSSION

Prevailing Meteorological Features

The prevalent meteorological features over the study area are analyzed by considering near-surface air temperature, RH and wind field at 1000 hPa. The 1000 hPa mean temperature over the study area at different phases of the unseasonal heatwave scenario superposed with wind field is depicted in Figs. 1(a)–(c), and Fig. 1(d) illustrates the 30-year (1985–2015) climatological mean temperature and wind derived from ERA-Interim data. A comparative analysis is carried out between the climatological mean temperature with that of the different heatwave phases.

The pre-mature phase indicates that the heatwave was developing and the affected area experienced daily high temperatures from 32 to 36°C (Fig. 1(a)). The maximum 30-year mean temperatures are in the range 34–36°C (Fig. 1(d)). This is a westward shift from the IMD-observed highest value of the maximum temperature (i.e., 33.13°C as mentioned in Table 2) when compared with the spatial distribution of near-surface mean climatological values for February (Fig. 1(d)). In view of this, the pre-mature phase already shows a temperature at par with or above the mean maximum daily value, and a significant area is affected in this stage.

In the mature phase, the heatwave condition had grown and expanded over a relatively large area even up to the northern and eastern part of the Indian peninsula (Fig. 1(b)). Temperatures in some areas over western and south-western parts of the considered region exceeded 36°C (in the range 36–38°C). The area with $> 36^\circ\text{C}$ gradually increased, occupying most parts of the western and south-western region of the Indian peninsula, which is quite evident in the third phase of the event (Fig. 1(c)). Therefore, a significantly large part of the considered area experienced temperatures of more than 32°C and some parts exceeded

Fig. 1. The spatial distribution of 1000 hPa temperature ($^{\circ}\text{C}$, shaded contours) and winds (m s^{-1} , represented by arrows) during (a) pre-mature phase (12–16 February 2016), (b) mature phase (17–22 February 2016), (c) dissipating phase (23–28 February 2016), and (d) mean temperature (1985–2015 during February) of unseasonal heatwave condition over Indian region. Here, ERA-Interim data of 0.25° resolution is considered.

36°C (Figs. 1(a)–1(c)), which is quite unusual ($4\text{--}6^{\circ}\text{C}$ higher) compared to the 30-year mean.

A predominant westerly wind was found over the study area during the pre-mature and mature phases, whereas during the dissipating phase both easterly and westerly winds were observed near the surface (Figs. 1(a)–1(c)). The flow pattern is similar in the 30-year climatology from ERA-Interim data (Fig. 1(d)). Eastern India is dominated by easterly winds, whereas westerly winds dominate in the western part of the study area (Fig. 1). However, central India is dominated by the prevailing northeasterly and/or northwesterly winds, acting like a convergence region. This is a favorable condition for transport and accumulation of aerosols (Panda *et al.*, 2009; Panda and Sharan, 2012) as well as moisture in the central and eastern parts of the country.

RH during the pre-mature phase (Fig. 2(a)) is comparatively low ($20\text{--}40\%$) over inland areas, whereas it is relatively high ($50\text{--}70\%$) over coastal regions. The easterly winds advected more moisture from the neighboring ocean to the coastal areas, as indicated by the spatial distribution of RH in different phases (Fig. 2). Hot and dry westerly winds dominate in the mature phase of the unseasonal heatwave episode, increasing the air temperature over western and southern parts of the inland areas up to $\sim 38^{\circ}\text{C}$ (Fig. 1(b)). However, near the coastal area, the mean temperature remains $\leq 30^{\circ}\text{C}$. Eventually, the heatwave condition supports the flow of easterly winds and associated moisture from the neighboring BOB. Consequently, RH increases (maximum up to 80%) over coastal areas and a relative decrease ($10\text{--}30\%$) is seen over the inland areas (Fig. 2) due to convective scavenging. A surge in RH is seen over coastal West Bengal, including Kolkata, in the dissipating phase of the episode (Fig. 2(c)), thus supporting possible enhanced moist convection.

Convergence of prevalent westerly and easterly winds over the central region may help in the formation of convective clouds through enhanced moisture from the adjoining sea advected to inland regions. It can also increase moisture content over coastal and nearby inland areas. These scenarios may enhance rainfall over some areas of the study region. It is therefore important to understand where the possible occurrence of rainfall takes place. One of the possibilities could be the areas with higher RH (at least $> 50\%$; i.e., in West Bengal and northern parts of Odisha as shown in Fig. 2(c)).

Fig. 3 illustrates the spatial distribution of vertically integrated moisture transport during the three different phases superposed with the near-surface (1000 hPa) wind field. It is computed in a manner similar to Panda *et al.* (2015) by considering the specific humidity between layers 1000 hPa and 500 hPa and corresponding horizontal wind components. A zone of minimum vertical transport of moisture ($1\text{--}2 \text{ kg m}^{-1} \text{ s}^{-1}$) is found in the region extending from south-western India to the north-eastern part, located within longitudes $80\text{--}90^{\circ}\text{E}$, irrespective of the phases of the episode (Fig. 3). Increase ($> 4 \text{ kg m}^{-1} \text{ s}^{-1}$) in vertical transport of moisture in other regions is due to the increased wind variability associated with the prevailing convective activity. Increased wind variability can generate a positive feedback cycle between the near-surface winds and convection, with increased evaporation to support enhanced convection (Felton *et al.*, 2013). Such convective transport activity is supported by stronger vertical winds too in the coastal regions, where moisture availability is substantial (Guha *et al.*, 2017). The resulting convective activity supports the enhanced occurrence of rainfall (Fig. 4) in the regions with higher moisture availability or significant vertical moisture transport (Panda *et al.*, 2015).

Fig. 2. The spatial distribution of 1000 hPa Relative humidity (%; shaded contours) and winds (m s^{-1} , represented by arrows) during (a) pre-mature phase (12–16 February 2016), (b) mature phase (17–22 February 2016) and (c) dissipating phase (23–28 February 2016) of unseasonal heatwave condition over Indian region. Here, ERA-Interim data of 0.25° resolution is considered.

Fig. 3. The spatial distribution of vertically integrated moisture flux convergence ($\text{kg m}^{-1} \text{s}^{-1}$) superposed by 1000 hPa wind field during (a) pre-mature phase (12–16 February 2016), (b) mature phase (17–22 February 2016) and (c) dissipating phase (23–28 February 2016) of unseasonal heatwave condition over Indian region. ERA-Interim data of 0.25° resolution is considered for this purpose. Here, the rectangular box is for NMVMF region ($19\text{--}24^\circ\text{N}$, $80\text{--}90^\circ\text{E}$).

Moderate values ($2\text{--}7 \text{ kg m}^{-1} \text{s}^{-1}$) of vertically integrated moisture flux during the mature phase (Fig. 3(b)) indicates that moist convection and consequent convective activity can also be initiated due to the support from prevailing winds and increased near-surface temperature (Figs. 1–3). Regional warm air advection during the mature phase (Fig. 1(b)) presumably provided enough support for

convective activity and subsequent rainfall occurrence mainly during the dissipating phase (Fig. 4(c)). The dominance of stronger easterly winds in the dissipating phase helped moisture transport from the nearby ocean (Figs. 2(c) and 3(c)) and consequently, acted to cool the land surface after the heatwave episode in addition to the cooling effect resulting from rainfall.

Back Trajectory Analysis

There was no significant rainfall occurrence over land during the pre-mature and mature phases of the episode (Figs. 4(a)–4(b)). However, the occurrence of appreciable rainfall ($0.1\text{--}18\text{ mm day}^{-1}$) during the dissipating phase took place in the region located north of the minimum vertically integrated moisture flux (NMVMF) (within $19\text{--}24^\circ\text{N}$, $80\text{--}90^\circ\text{E}$, i.e., mainly over West Bengal, parts of Jharkhand and northern Odisha (Fig. 4(c)). Here, we begin investigation of potential signatures for ACP interaction. Images from MODIS reveal the transport of aerosols along with air masses (in all phases) towards these rainfall areas (Fig. 5). Though this can serve as strong evidence for the presence of aerosols in the designated region, back-trajectory analysis is performed to correlate with substantive potential sources.

Seven days during each phase are considered for the back-trajectory analysis. For this purpose, GDAS (Global Data Assimilation System) data from NOAA is taken, and the trajectories are produced using the HYSPLIT model (Fig. 6). The trajectories attending heights of 500, 1000 and 1500 m AGL (above ground level) are considered. The air mass trajectories indicate that transportation happens mainly from the areas located in western, southern and eastern parts of the region. During the pre-mature phase, the trajectories for 12 and 15 February (Figs. 6(a)–6(b)) indicate the dominance of western Asian or Arabian air masses compared to those of eastern or southern origin. The 15 February satellite image from MODIS Aqua (Fig. 5(b)) shows transport from the western Asian or Arabian Peninsula to the Indian subcontinent. In the mature phase, trajectories from 17 February indicate transport primarily

from the Arabian Peninsula and the Arabian Sea side (Fig. 6(c)) through westerly winds. The likelihood is that corresponding aerosols from these regions would be dust and sea-salts (Gautam *et al.*, 2011).

Trajectories on 27 February show that long-range air mass transportation occurred from the south-eastern side (i.e., BOB) of the Indian subcontinent (Fig. 6(f)) or towards the end of the dissipating phase. This is also seen through MODIS (Fig. 5(d)). The easterly winds help to bring sea salt, and black carbon (BC) and sulfate aerosols produced by biofuel and fossil fuel combustion and biomass burning from south-east Asia (Rajeev *et al.*, 2000; Verma *et al.*, 2008).

Aerosol Characteristics

The spatial distribution and correlation between mean AOD and AE ($0.412\text{--}0.47\text{ }\mu\text{m}$) during the pre-mature, mature and dissipating phases of the unseasonal heatwave episode (Fig. 7) are analyzed for understanding primary aerosol characteristics. During the pre-mature phase, AOD is found to be mostly in the range $0.2\text{--}1.6$, with AE (α) values up to 1.7 over the study area (Fig. 7(a)). The AOD is significantly higher over some parts of the eastern region ($18\text{--}25^\circ\text{N}$, $80\text{--}90^\circ\text{E}$). In the pre-mature phase, α values imply that fine-mode aerosols are relatively significant in the atmosphere over the study region.

The aerosol loading in the atmosphere decreases over the study area with a modified spatial distribution of during the mature phase (Fig. 7(b)). The range of AE remains constant. The prevailing hot and dry conditions in the mature phase likely help in the vertical mixing of aerosols due to convective processes. In the dissipating phase, AOD lies mostly in the range $0.2\text{--}1.4$ with α being

Fig. 4. The spatial distribution of rainfall (mm day^{-1}) during (a) pre-mature phase (12–16 February 2016), (b) mature phase (17–22 February 2016), and (c) dissipating phase (23–28 February 2016) of unseasonal heatwave condition over Indian region. Here, the rectangular box is for NMVMF region ($19\text{--}24^\circ\text{N}$, $80\text{--}90^\circ\text{E}$). TRMM data of 0.25° resolution is considered for illustrating the rainfall variation.

Fig. 5. Transportation of air masses through winds during (a) pre-mature phase (15 February), (b–c) mature phase (17 and 20 February), and (d) dissipating phase (27 February) of unseasonal heatwave condition over Indian region (<http://modisatmos.gsfc.nasa.gov/IMAGES/index.html>).

0.4–1.7 while the easterly winds are dominant (Fig. 7(c)). The easterly winds help in transporting aerosols from south-eastern parts of the area considered (Figs. 5–7) especially to the NMVMF region (Figs. 3 and 7(c)). Thus, it is presumed that the presence of these enhanced aerosols will perturb background CCN for cloud in the designated region (Fig. 7) and likely played a significant role in governing the occurrence of appreciable rainfall during the dissipating phase (Fig. 4(c)).

The spatial correlation between AOD and AE during all phases of the unseasonal heatwave episode is shown in Figs. 7(d)–7(f). White color in the figures signifies missing data. Mostly positive correlation is observed over the NMVMF region during the pre-mature phase (Fig. 7(d)). A negative correlation (–1.0 to –0.2) is observed during the mature and dissipating phases over the region where rainfall occurred (Figs. 7(e)–7(f)). Asterisks in all phases signify that datasets are statistically significant at the 95%

confidence level (which is valid for other figures too). The value of AE may also vary with the ratio in changes of fine- and coarse-mode particles in the atmosphere.

Aerosol-cloud-precipitation Interaction

The previous discussion in Subsections 3.1, 3.2 and 3.3 depicts the presence of aerosols over the NMVMF region (Figs. 3, 5 and 6) where the bulk of observed rainfall occurred (Fig. 4). In order to understand the ACP interaction over the said region, several cloud parameters such as CER (μ), COD, CF, CTT (K), and CWP (g m^{-2}) are analyzed.

Relationship between AOD and Cloud Fraction

Cloud fraction (f_c) can change with the amount of aerosols present. Several researchers have suggested an increase in f_c (Loeb and Schuster, 2008; Koren *et al.*, 2010), though others suggest a decrease (Small *et al.*, 2009), with the increase in AOD. In this study, f_c lies in the range 0.1–0.7

Fig. 6. Back trajectories reaching the measurement site with altitude 500 m above ground level (AGL) on (a) 12, (b) 15, (c) 17, (d) 20, (e) 22, and (f) 27 February 2016 (http://ready.arl.noaa.gov/HYSPLIT_traj.php).

with maximum values in the NMVMF region where AOD values of 0.6–1.6 are observed in the pre-mature phase (Fig. 8(a)). AOD decreased (range: 0.4–1.2) in this region during the mature phase along with f_c (Fig. 8(b)). The lesser values of f_c signify stronger radiative effects (Koren *et al.*, 2008) during the mature phase over NMVMF region, whereas substantial precipitation occurred in the dissipating phase (Fig. 4(c)). The absorption effects likely suppress the growth and formation of clouds (Adesina *et al.*, 2016) during the mature phase. Absorption of solar radiation by aerosols may lead to evaporation as well. In the post-mature phase, AOD increased to 1.4 in the NMVMF area and f_c values rose to 0.6 during the dissipating phase (Fig. 8(c)). The increase in f_c values with AOD can induce a strong invigoration effect (Niu and Li, 2012), especially in the formation of new and deeper clouds (Small *et al.*, 2009) during the dissipating phase in order to support the rainfall observed.

Mostly positive correlation is observed between AOD and f_c over NMVMF, eastern (Odisha and Jharkhand) and northern parts of the Indian region considered in the pre-mature phase (Fig. 8(d)). In the mature phase, correlations are negative in some parts of NMVMF region but again becomes significantly positive (up to 1) during the dissipating phase (Figs. 8(e)–8(f)). The significantly positive correlations (0.4–1.0) between AOD and f_c may be attributed to

anthropogenic and dust aerosols transported to the region along with prevalent meteorological conditions. The negative correlations are likely resulting from the increase in RH with an increase in AOD, and probably due to more water vapor deposition on the particles (Myhre *et al.*, 2007). The other possible reason could be the radiative absorption effect that is usually dominant with lower AOD and f_c (Kang *et al.*, 2015).

Relationship between AOD and Cloud Effective Radius

Fig. 9 depicts the spatial distribution and correlation between AOD, and ice and liquid CER over India during the pre-mature and dissipating phases of the unseasonal heatwave. Here, only the pre-mature and dissipating phases are considered since most of the clouds are formed in these phases.

Unavailability of data at several places for ice and liquid CER inhibited our ability in determining any significant relationship between them. However, in the dissipating phase, significant values of ice CER (ICER) were found mostly in the range 20–50 μm (Fig. 9(b)), indicating the likelihood of convective clouds. Ice clouds are high-level clouds, and aerosol effects on such clouds are less significant than they are for warm clouds (Jin and Shepherd, 2008). Thus, it becomes important to analyze the variation of liquid cloud effective radius (LCER).

Fig. 7. The spatial distribution (top row) and correlation coefficient (bottom row) between Aerosol Optical Depth (AOD) and Ångström exponent, or AE ($0.412\text{--}0.47\text{ }\mu\text{m}$), during (a and d) pre-mature phase, (b and e) mature phase, and (c and f) dissipating phase of unseasonal heatwave condition over Indian region. The line contours are for AE and the shaded ones are for AOD. Asterisks show datasets are statistically significant at 95% confidence level. Here, MODIS data of 1° resolution is considered.

Fig. 8. The spatial distribution (top row) and correlation coefficient (bottom row) between AOD and cloud fraction (f_c) during (a and d) pre-mature phase, (b and e) mature phase, and (c and f) dissipating phase of unseasonal heatwave condition over Indian region. The line contours are for cloud fraction and the shaded ones are for AOD. Asterisk indicates datasets are statistically significant at 95% confidence level. Here, MODIS data of 1° resolution is considered.

Values of LCER ranged between $12\text{--}16\text{ }\mu\text{m}$ over NMVMF, accompanied by higher AOD values (up to 1.6) during the pre-mature phase (Fig. 9(c)). Moderate to the high amounts ($0.6\text{--}1.4$) of AOD with similar LCER ($12\text{--}16\text{ }\mu\text{m}$) found in the dissipating phase (Fig. 9(d)) indicate a favorable condition for the initiation of precipitation. This

is because enhanced convection has the potential to initiate precipitation (Shepherd, 2005). In such a situation, convective clouds are formed by considering the moisture incursion from neighboring BOB (Fig. 2(c)), encouraged by the land-sea temperature contrast and prevailing wind pattern (Fig. 1; Jin and Shepherd, 2008).

Positive correlation (> 0.4) between AOD and LCER is observed in some parts of NMVMF during the pre-mature and dissipating phases (Figs. 9(e)–9(f)). A positive correlation between AOD and CER during rainfall episodes may signify the presence of slightly soluble organic particles and giant CCN (Yuan *et al.*, 2008). The negative correlation between AOD and CER is due to significant aerosol loading leading to smaller CER (Twomey *et al.*, 1984), which decreases the size of the cloud droplets (Jin and Shepherd, 2008).

Relationship between Cloud Optical Depth and Cloud Top Temperature

The attenuation of light passing through the atmosphere due to absorption and scattering from cloud droplets can be measured as COD. It can indirectly influence the surface and atmospheric radiation budget (Penner *et al.*, 2004; Lubin and Vogelmann, 2011). CTT (K) is a measure of the temperature at the level of cloud top, and it also plays a vital role in determining the net radiation budget of the earth (Adesina *et al.*, 2016). The spatial distribution and correlation coefficient of COD and CTT during the pre-mature and dissipating phases of the unseasonal heatwave is shown in Fig. 10. The values of COD are up to 28 with CTT in the range 280–290°K over NMVMF during the pre-mature phase (Fig. 10(a)). However, in the dissipating phase, the corresponding COD values increase up to 42 without much change in CTT (Fig. 10(b)). Mostly negative correlation (-1.0 to -0.2) is observed between COD and CTT over NMVMF during the pre-mature phase (Fig. 10(c)). During the dissipating phase, the correlation coefficient

ranges between -1.0 to 0.8 over the NMVMF (Fig. 10(d)). The asterisk in Figs. 10(c)–10(d) indicate that the dataset is statistically significant at the 95% significance level.

High amounts of moisture present in the atmosphere results in increased COD over NMVMF (Fig. 10(d)), which depends on the vertical depth and density of the clouds (Alam *et al.*, 2010). The negative correlation is probably due to the presence of absorbing aerosols that encourage evaporation of cloud droplets (decrease in COD) and create relatively thin clouds (Alam *et al.*, 2014). It indicates that cloud droplets are not growing bigger in size and an insufficient amount of water vapor or moisture is present inside the clouds. However, some of the clouds may grow to become relatively large, but might have insufficient liquid water content and thus are not capable of producing rainfall.

COD increases with AOD in the atmosphere and consequently reduces with CER (Fig. 9(c)) since the horizontal and vertical growth of clouds may not happen in the same time, which eventually impacts the cloud lifetime in the atmosphere (Twomey, 1977). In the dissipating phase, it is observed that a relative increase in COD (Fig. 10(b)) corresponds to a moisture incursion in the atmosphere (Fig. 2(c)) over NMVMF, which eventually helps in the formation of convective and precipitating clouds during the dissipating phase. The mature phase related discussion is limited here, due to unavailability of meaningful data.

Relationship between AOD and Cloud Water Path

Cloud water path (CWP) is the column-integrated liquid water inside the clouds. It is also one of the important parameters responsible for transporting energy in the form

Fig. 9. The spatial distribution and correlation coefficient between AOD (shaded) and ice cloud effective radii, or ICER (contours), and liquid cloud effective radii, or LCER (contours), for unseasonal heatwave episode over Indian region during February 2016. AOD and ICER (in μm) for: (a) pre-mature phase and (b) dissipating phase. AOD and LCER (in μm) for: (c) pre-mature phase and (d) dissipating phase. Spatial variation in correlation coefficients between AOD and LCER are depicted in (e) and (f) for pre-mature and dissipating phases respectively. Asterisk indicates datasets are statistically significant at 95% confidence level. Here, MODIS data of 1° resolution is considered.

Fig. 10. The spatial distribution (top row) and correlation coefficient (bottom row) between Cloud Optical Depth (COD) and Cloud Top Temperature (CTT) in °K during (a) pre-mature phase and (b) dissipating phase of unseasonal heatwave condition over Indian region. The line contours represent CTT values whereas the shaded ones are for the COD distribution. Asterisk indicates datasets are statistically significant at 95% confidence level. Here, MODIS data of 1° resolution is considered.

of latent heat in the earth-atmosphere system. Due to the unavailability of sufficient ice CWP (ICWP) data in the pre-mature phase (Fig. 11(a)), it is difficult to establish any relationship between AOD and ICWP. No meaningful relationship is noticed in the case of the mature phase (not shown) as well. In the dissipating phase, over NMVMF, where AOD values were in the range 0.4–1.4, significant ICWP values occurred within the range 200–800 g m⁻² (Fig. 11(b)).

During the pre-mature phase in NMVMF, while AOD values vary up to 1.6, reasonable liquid CWP (LCWP) values in the range 40–120 g m⁻² are observed (Fig. 11(c)). However, the corresponding range of LCWP increases slightly up to 160 g m⁻² over some areas in the dissipating phase (Fig. 11(d)), probably due to the prevailing meteorological condition (discussed earlier in Subsection 3.1). This indicates the increase in liquid water content inside the clouds during the dissipating phase, which probably helps drive precipitation processes, resulting in the major rainfall episode over NMVMF.

In the humid environment, the hygroscopic growth of aerosols is significant, with areas surrounded by clouds producing more numerous smaller cloud droplets (Kant et al., 2019a, b). The increase in aerosol loading may cause a reduction in droplet size, suppressing precipitation during the pre-mature and mature phases before raining out in the dissipating phase. Thus, in the earlier two phases, there is the prevalence of relatively appreciable LCWP. In addition, cloud formation includes both moisture availability and associated thermal and dynamical processes. The response of CWP is determined by the amount of water vapor

present and lower tropospheric static stability (Savane et al., 2015). However, processes like moistening and drying may occur depending upon the variability in CWP with reasonable and favorable aerosol loading. In a low water vapor atmosphere, like that of the pre-mature and mature phases, aerosol loading happens to be undergoing a drying process, which then shifts to moistening in the dissipating phase due to the significant moisture incursion to the NMVMF atmosphere correspondingly enhancing the range and relatively high value of CWP.

It is difficult to draw any conclusion for the correlation between AOD and ICWP due to unavailability of ICWP data. Over NMVMF, mostly negative or slightly positive correlation is observed between AOD and LCWP during the pre-mature and dissipating phases (Figs. 11(e)–11(f)). However, some areas in NMVMF show a strongly positive correlation (up to 1.0) in the pre-mature phase (Fig. 11(e)). The negative correlation between AOD and LCWP during the dissipating phase contradicted the aerosol indirect effect (Alam et al., 2014). Water-soluble aerosols grow due to water uptake and humidity swelling (Storelvmo et al., 2006). This growth depends upon the presence of a reasonable amount of moisture in the atmosphere, and consequently, aerosols become optically thicker (Alam et al., 2014). The mechanism should lead to the positive correlation between AOD and LCWP. Therefore, it is quite challenging to explain this contradictory relationship.

CONCLUDING REMARKS

The aerosol-cloud-precipitation (ACP) interaction over

Fig. 11. The spatial distribution and correlation coefficient between AOD (shaded), ice cloud water path, or ICWP (contours), and liquid cloud water path, or LCWP (contours), for unseasonal heatwave episode over Indian region during February 2016. AOD and ICWP for: (a) pre-mature phase and (b) dissipating phase. AOD and LCWP for: (c) pre-mature phase and (d) dissipating phase. Spatial variation in correlation coefficients between AOD and LCWP are depicted in (e) and (f) for pre-mature and dissipating phases respectively. Asterisks are indicative of datasets with 95% significance. Here, MODIS data of 1° resolution is considered.

the Indian peninsula (Fig. 12) during the three phases of an unseasonal heatwave in February 2016 was investigated by analyzing MODIS, TRMM, and ERA-Interim datasets. Although the temperature was relatively low during the pre-mature phase, the prevailing hot and dry westerly winds eventually gained strength, resulting in a temperature increase over the study region during the mature phase. The maximum temperature and the area it affected gradually increased during the dissipating phase.

The vertically integrated moisture flux convergence was low over a distinct region extending from the south-western to the eastern areas of India during all three phases, despite the expectation of active convection. A moderate to maximum vertically integrated moisture flux was identified in the area to the north of the minimum vertically integrated moisture flux (NMVMF) located in north-eastern and eastern India (basically, northern Odisha, eastern Jharkhand, and most of the adjoining parts of West Bengal). During the dissipating phase, high relative humidity (RH) was observed near the coastal regions, especially the NMVMF (19–24°N, 80–90°E), due to the incursion of moisture from the neighboring Bay of Bengal (BOB), which was aided by easterly and south-easterly winds arising from the land-sea temperature contrast. The moisture flux convergence over the NMVMF indicates favorable conditions for instability and thus the convective initiation processes required for cloud growth, specifically, stronger updrafts that drag the supplied moisture upward, leading to increased cloud droplet size (Fig. 12). The favorable meteorological conditions, convection within the atmospheric boundary layer, and prevailing characteristics of the underlying land surface

help produce warm air advection, resulting in a specific regional circulation pattern (Panda *et al.*, 2009; Panda and Sharan, 2012; Li *et al.*, 2016). The collective effect is accelerated convection (Banacos and Schultz, 2005) over the study area, which may enhance the formation of convective clouds and promote the initiation of precipitation over the NMVMF (Fig. 12).

MODIS satellite images and back trajectory analysis indicate that westerly winds transported aerosols from the western side of Asia and the Arabian Sea to India (Tripathi *et al.*, 2005). Since aerosols can play a substantial role in determining cloud characteristics and the consequent rainfall, the aerosol characteristics and cloud parameters were analyzed along with the relevant meteorological parameters.

Over the NMVMF, the cloud fraction (f_c) increased (decreased) with the aerosol optical depth (AOD) during the pre-mature (mature) phase, suggesting strong radiative or semi-indirect effects from aerosols (Koren *et al.*, 2008), and the absorption of solar radiation by cloud droplets, which consequently suppressed precipitation. On the other hand, the significantly positive relationship between the f_c and the AOD during the dissipating phase indicates an invigorating effect (Niu and Li, 2012) that encourages the formation and growth of larger cloud droplets due to sufficient moisture. The liquid cloud effective radius (LCER) over the NMVMF increased with the AOD during the dissipating phase. Increased CCN aid the convective precipitation process. The relatively high values of the LCER during the dissipating phase, supported by the moderate to high AOD values, promoted convection and moisture incursion through a regional dynamical process

Fig. 12. Schematic diagram representing aerosol-cloud-precipitation interaction during February 2016 unseasonal heatwave episode that occurred over India.

that favors rainfall. The positive AOD-LCER relationship over parts of the NMVMF during the pre-mature and dissipating phases indicates the significant role of dynamical, thermo-dynamical, and microphysical effects on cloud droplets (Kang *et al.*, 2015). This anti-Twomey effect over the cloud effective radius (CER) may be due to the complex composition of aerosols and the flaws in satellite retrieval methods (Li *et al.*, 2011; Wang *et al.*, 2014). However, a negative AOD-CER relationship, irrespective of meteorological conditions with greater aerosol presence, leads to a smaller CER over some land areas (Twomey *et al.*, 1984), which is congruous with the Twomey effect (Twomey, 1977). Thus, aerosols tend to experience either the Twomey or the anti-Twomey effect over land during unstable conditions (Wang *et al.*, 2014).

The lower cloud optical depth (COD) over the NMVMF during the pre-mature phase suggests that optically thinner clouds (Alam *et al.*, 2014) form when aerosols are present, possibly because of the enhanced evaporation of cloud droplets (a semi-direct effect of aerosols). During the dissipating phase, the COD increased without noticeable change in the cloud top temperature (CTT), and the negative COD-CTT relationship that had been observed during the pre-mature phase became positive over some areas.

Aerosol loading may have decreased evapotranspiration or the microphysical effects (Niu and Li, 2012), resulting in reduced liquid cloud water content during the pre-mature phase. However, during the mature phase, hot and dry westerly winds increased the near-surface temperature, thereby strengthening convectively driven liquid water updrafts in the atmosphere—the invigorating effect (Niu and Li, 2012)—and promoting cloud droplet growth. Therefore, sufficient liquid water content supplied to the convective clouds (shown by the liquid cloud water path (LCWP)) during the dissipating phase over the NMVMF was probably responsible for the occurrence of precipitation. A contradictory aerosol response to the cloud water path (CWP) was detected over the NMVMF, partly due to insufficient ice CWP data and to the mostly negative AOD-LCWP relationship.

The clouds' response to aerosols during the February 2016 unseasonal heatwave episode reveals the combined effects of dynamic, thermodynamic, and microphysical processes (Fig. 12). Due to the prevalent dynamic and thermodynamic atmospheric conditions, the observed cloud characteristics cannot be completely attributed to the presence of aerosols. Hence, it is difficult to distinguish the role of aerosols from that of meteorology in determining

cloud properties and precipitation over India during an extreme weather event, and more case studies, including a significant amount of observation as well as a better understanding of relevant physical processes, are required.

ACKNOWLEDGMENTS

The authors are obliged to NOAA-ARL for HYSPLIT transport and dispersion model for computing the back trajectory; the datasets are taken from Aqua-MODIS (<http://giovanni.sci.gsfc.nasa.gov/giovanni/>), Wyoming Weather Web (<http://weather.uwyo.edu>), ERA-Interim portal (<http://apps.ecmwf.int/datasets>) and air mass transport image (<http://modisatmos.gsfc.nasa.gov/IMAGES/index.html>) for the analysis purpose. Special thanks go to our friends Sudhansu Sekhar Rath, Kasturi Singh and Bijay Kumar Guha for their valuable support during my work. We are thankful to the reviewers for their valuable feedback that helped in the overall improvement of the manuscript.

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Received for review, April 25, 2018

Revised, August 9, 2018

Accepted, February 26, 2019