

Chapter 7

Influence of Tropical Storms in the Northern Indian Ocean on Dust Entrainment and Long-Range Transport

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Abstract Ninety five tropical cyclonic events (tropical storms, depressions and cyclones) between 2001 and 2010 were studied to determine their impact on dust outbreaks and long-range transport over the northern Indian Ocean and south Asia. In addition to the winter and summer Shamal Winds, tropical cyclones are an important mechanism of dust entrainment and transport of dust in this region. Elevated dust levels were observed in the northern Arabian Sea during most tropical cyclone events. During the study period, fifteen tropical cyclones migrated close to the dust source areas leading to major dust storms. Anti-clockwise winds associated with these storms were observed to entrain dust and transport it mostly towards the west or south-westerly direction. Tropical cyclones and storms, located further away from dust source areas, significantly alter the dispersal pathways of dust plumes raised by other mechanisms. The Northern Bay of Bengal cyclone events are shown to aid advection of dust plumes from southwest Asia and Thar Desert over highly populated regions of the Indian Subcontinent. Tropical cyclones also play an important role in dispersal of fine-mode aerosols over South Asia and formation of complex aerosol-dust mixtures.

Keywords Tropical cyclones · Mineral dust · Northern Indian Ocean · Aerosols · Dust storms

7.1 Introduction

Tropical cyclones and accompanying strong winds and heavy rainfall cause extensive damage along coastal regions. They normally originate close to the equator where sea surface temperatures are above 26.5 °C and move westwards and eventually towards higher latitudes. As the cyclones migrate pole-wards

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towards the semi-arid regions and deserts located near the Horse-Latitudes, the cyclonic winds can potentially cause major dust outbreaks. However, there are not many studies directly linking tropical cyclones to dust storms. Study of this linkage is important as mineral dust together with anthropogenic aerosols strongly perturb the radiation energy balance of the earth-atmosphere system, and have significant impacts on various terrestrial and marine ecosystems (Arimoto 2001; McTanish and Strong 2007; Ramanathan et al. 2001a; Rastogi and Sarin 2005; Tegen et al. 1996). The nutrients and toxins associated with dust can have a significant impact on ocean chemistry and primary productivity and its capacity to absorb atmospheric carbon dioxide (Duce et al. 1991; Jickells et al. 2005). Furthermore, the intensity and frequency of tropical cyclones are expected to rise in the northern Indian Ocean (Muni Krishna 2009) and for the first time in the Arabian Sea a super-cyclone, Gonu, was recorded in 2007.

Because of the northerly migration of the ITCZ during summer, much of India and Bay of Bengal receives copious rain during the SW monsoon period between June and September. The winter NE monsoon (December–February) is characterized by dry light winds. The Thar Desert in NW India and region west of it, including SW Asia, the Middle-East and Saharan Africa, receives scanty rain and constitutes the largest contiguous source of dust in the world (Goudie and Middleton 2006). Dust from these regions is transported over Middle-East and the northern Indian Ocean mainly by the so called “forty day” summer Shamal Winds and the numerous 3–5 day winter Shamal Winds (Ackerman and Cox 1988, 1989). In addition, convective events and local winds like Aandhi, Loo, Khamsin, etc. cause dust storms during spring-summer (Middleton 1986). The northern Indian Ocean and surrounding landmass is affected by several tropical cyclones which occur mainly before or after the summer monsoon. Though it is known that cyclone winds can cause dust storms, there are not many specific studies raise showing effect of tropical cyclones on dust entrainment and transport. One such study is the effect of the severe tropical cyclone Sidr in 2008 on dust storms in the Thar region (Badarinath et al. 2009). In the present study, the importance of episodic events like tropical cyclones and storms on uplift and dispersal of aerosols in the northern Indian Ocean and surrounding countries between 2001 and 2010 is discussed.

7.2 Data and Methods

7.2.1 Study Area

The entire northern Indian Ocean comes under the influence of the seasonally reversing monsoons. Heating of the Indian subcontinent and the Tibetan Plateau during spring-summer initiates a monsoonal circulation (Das 1968). The Inter-tropical convergence zone (ITCZ) which lies around 10° south latitude during January, migrates northward and reaches a maximum northerly extent in July covering almost the entire Arabian Sea and the Indian subcontinent (Fig. 7.1).

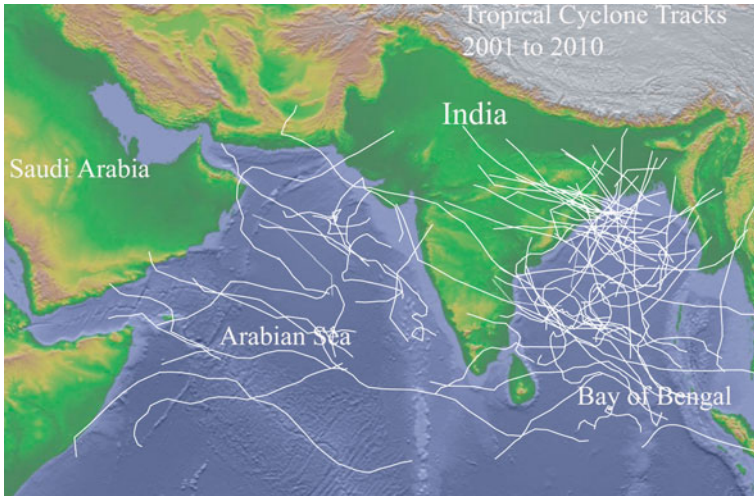


Fig. 7.1 Tracks of tropical cyclones and storms over the northern Indian Ocean between 2001 and 2010

Depressions and tropical cyclones often form in the vicinity of the monsoon trough. The development of tropical cyclones depends on SST's above 26.5 °C, and low wind shear in the upper troposphere. Since a minimum of Coriolis force is required, tropical cyclones do not form over the equator. They also require pre-existing disturbances in atmospheric circulation for initiation. During summer, the sub-tropical jet stream over north India disintegrates and reforms north of the Himalayas over central Asia and around this time a tropical easterly jet stream (TEJ) builds up over peninsular India extending up to Africa. The area south of the ITCZ has winds blowing predominantly from the ocean with consequent high precipitation. During spring-summer a quasi-permanent high is set up at the head of Saudi Arabia and eastern Mediterranean Sea. The strong pressure gradient between the quasi-permanent Arabian High and Asian Low sets up persistent northerlies in the Persian Gulf Area with strong dust laden winds, called Shamal, between May and end of July (Goudie and Middleton 2006). The intensity of the Shamal wind is enhanced by the presence of the Zagros Mountains.

The 3–5 days winter-Shamal Winds are episodic events due to passage of cold fronts between November and March. During this period, the polar jet migrates to lower latitudes and its proximity to the sub-tropical jet enhances disturbances in the Persian Gulf region. Dust storms can occur in the front and rear of the cold fronts. Dust events are seen mainly over Iraq, Iran and Afghanistan region with not much activity being recorded over the Arabian Peninsula. The SW Asian region including Baluchistan, Afghanistan, Iran and Iraq, are characterized by mountain chains and endorheic lakes which derive their water from snowmelt and occasional rain. Winds, intensified by mountain gaps, blowing over dry lake beds and deserts make this region very prone to dust storms. The dust is normally dispersed by the prevailing weak NE monsoon winds.

About 4–12 storms and depressions form in the northern Indian Ocean every year. They originate mostly between 5°N and 15°N latitude in the south eastern part of the Bay of Bengal and Arabian Sea (Fig. 7.1). Few tropical cyclones originating in the west Pacific cross over into the Bay of Bengal. Tropical cyclones of hurricane intensity in the northern Indian Ocean are conspicuous by their absence over areas overlaid by the TEJ because of high vertical wind shear. Though a number of depressions are formed during the SW monsoon they do not develop into severe tropical cyclones.

In the Bay of Bengal, winter cyclonic events move west-northwestwards and hit the Indian Peninsula and Sri Lanka coasts. During April–May, cyclonic events form in the south and central Bay which move initially west, then north and sometimes recurve to the NE and hit the Bangladesh or Myanmar Coast. After the TEJ has set, depressions form in the central or North Bay and move west-northwestwards and hit the east coast of India. Post-monsoon cyclones are mainly formed in the south and central Bay and hit the east coast of India.

In the Arabian Sea, tropical cyclones generally form in southeast Arabian Sea and adjoining central Arabian Sea in the months of May and between October and December. Some of the cyclones that originate in the Bay of Bengal travel across the Indian Peninsula and emerge in the Arabian Sea as low pressure areas. They frequently intensify into cyclonic storms. Most of the storms in Arabian Sea move in west-northwesterly direction towards Arabian Coast in the month of May and in a northerly direction towards India–Pakistan Coast in the month of June. In other months, they generally move initially northwest then north and finally recurve towards northeast affecting the north-eastern part of the Arabian Sea. A few tropical cyclones also move west north westwards towards the Arabian coast.

7.2.2 Classification of Tropical Cyclones

Tropical cyclonic events in the northern Indian Ocean are classified as depressions, storms or cyclones depending on the pressure deficiency and associated wind speeds. A seven tier classification adopted by the Indian Meteorological Department (IMD) is given in Table 7.1 (Anon 2012). The size of a tropical cyclone over northern Indian Ocean varies from 50 to 100 km radius to nearly 2,000 km with an

Table 7.1 Classification of tropical cyclones in the northern Indian Ocean (Anon 2012) adopted by the Indian Meteorological Organisation (IMD) and used in this study

System	Pressure deficiency hPa	Associated wind speed Kmph
Low pressure area	1.0	<32 (8.8)
Depression (D)	1.0–3.0	32–50 (8.8–13.9)
Deep depression (DD)	3.0–4.5	51–59 (13.9–16.4)
Cyclonic storm (CS)	4.5–8.5	60–90 (16.4–25)
Severe cyclonic storm (SCS)	8.5–15.5	90–119 (25.0–33.0)
Very severe cyclonic storm (VSCS)	15.5–65.6	119–220 (33.0–61.1)
Super cyclonic storm	>65.6	>220 (61.1)

average of 300–600 km. In the northern Indian Ocean tropical cyclones progress along the sea surface at a rate of 300–500 km a day. The lifetime of a tropical cyclone in the northern Indian Ocean is normally between 3 and 5 days though a few can last up to 10 days (Table 7.2).

7.2.3 Dust Source Areas

The largest contiguous dust source region in the world is the region that extends from NE Africa through the Sahara, Arabian and SW Asia up to the Thar Desert in India (Prospero et al. 2002). The dust from the Sahara, west of the Bodele depression in Chad, is transported predominantly towards the west across the Atlantic towards the Caribbean Islands or northwards across the Mediterranean towards Europe (Prospero 1999; Pye 1987). Amongst African sources only dust from the Nubian Desert and Horn of Africa is transported eastward. The Middle-East and SW Asian dust is transported mainly towards the east (Badarinath et al. 2010). It is seen that the disturbed soils of Iraq, SW Asia and south Asia are major contributors of dust in recent years (Tegen and Fung 1995; Givhechi et al. 2013). The principal dust sources contributing to sediments in the Arabian Sea and region eastward can be classified into six regions.

1. Syrian Desert (Al Jazirah) including Mesopotamia and An-Nafud province which includes the flood plains of the Tigris-Euphrates river Shat-al-Arab and Kuzestan plains of Iran. The desert pavements of the Ad Dahana in Saudi Arabia.
2. The Rub Al Khali, Oman depression and the coastal plains of Saudi Arabian Peninsula.
3. SW Asia which includes the endorheic basins of, Sistan e Baluchistan (Helmand Basin), Mashkel Basin, Jaz Muraian Basin, Dast e Kavir, Lut Basin, Ras Koh, Kerman, and coastal Makaran range. Smaller contributions are from the coastal plains bordering the Persian Gulf, with minor contributions from north Afghanistan and semi-arid regions of Central Asia.
4. Thar Desert including the Thal and Cholistan regions, the Indus and Punjab plains.
5. Nubian and East Libyan deserts, the coastal plains adjoining the Red Sea including the Tokar delta.
6. Horn of Africa including Somalia.

7.2.4 Tropical Storms and Cyclone Data

Data on number of cyclones and storms and related parameters such as maximum wind speed, minimum pressure, tropical cyclone tracks etc. were collected from a number of sources including the Indian Meteorology Department (IMD) reports (<http://www.imd.gov.in/section/nhac/dynamic/cyclone.htm>), and archives of cyclone and storms (<http://weather.unisys.com/hurricane>) and are summarized in

Table 7.2 Details of ninety five cyclone events (tropical cyclones, storms and depressions) in the northern Indian Ocean between January 2001 and December 2010 and their effect on entrainment and dispersal of mineral dust and aerosols

S. No	Start of event	End of event	Duration of event	Number and name of event	Intensity of event	Remarks
1	7-Dec-2010	8-Dec-2010	1	8B	DD	Dust Plume from Makaran to Oman driven by counter-clockwise winds Fine-mode aerosols from India-Pakistan pushed towards Western Arabian Sea
2	2-Nov-2010	12-Nov-2010	10	7B (Jal)	SCS	Fine-mode aerosols from Indus plains pushed towards Western Arabian Sea
3	19-Oct-2010	23-Oct-2010	4	6B (Gir)	VSCS	Fine-mode aerosols from India-Pakistan pushed towards Western Arabian Sea. Dense Haze over Gangetic plains being dispersed
4	13-Oct-2010	16-Oct-2010	3	5B	DD	Dust plumes observed along Makaran Coast. Haze driven from Indian subcontinent towards western Arabian Sea
5	7-Oct-2010	9-Oct-2010	2	4B	D	Dust plumes in Persian gulf, Gulf of Oman and northern Arabian Sea
6	30-May-2010	7-Jun-2010	8	3A (Phet)	VSCS	Cyclone Phet formed in the central Arabian Sea, moved towards Oman and caused a dust event in the Persian Gulf region, then veered towards NE Arabian Sea causing a major dust event in the Thar region
7	19-May-2010	23-May-2010	4	2A (Bandu)	CS	Two cyclones Bandu and Laila formed in the western Arabian Sea and Western Bay of Bengal simultaneously. Major dust events in the deserts adjacent to Red Sea and Persian Gulf. Dust over northern Arabian Sea
8	17-May-2010	21-May-2010	4	1B (Laila)	SCS	Same as above
9	10-Dec-2009	15-Dec-2009	5	8B (Ward)	CS	Counter-clockwise winds of cyclone Ward off Sri Lanka pushes fine-mode particles from Indo-Gangetic plains towards the western Arabian Sea
10	9-Nov-2009	11-Nov-2009	2	7A (Phyan)	CS	Cyclone Phyan in the eastern Arabian Sea pushes fine-mode particles from the Indus Plains and dust from Makaran pushed towards Oman

(continued)

Table 7.2. (continued)

S. No	Start of event	End of event	Duration of event	Number and name of event		Intensity of event	Remarks
				Days	Popular name in brackets		
11	5-Sep-2009	7-Sep-2009	2	6B		DD	Cyclone 6B strikes Bangladesh towards end of SW monsoon. Dust from Afghanistan Margo Desert pushed towards northern Arabian Sea
12	20-Jul-2009	21-Jul-2009	1	5B		DD	Dust from Gulf of Aden, Persian Gulf and Red Sea countries especially Tokar delta traceable to eastern Arabian Sea. Effect of Shamal winds enhanced due to cyclone 5B in the Bay of Bengal
13	25-Jun-2009	25-Jun-2009	1	4A		D	Counter clockwise winds of cyclone 4A in NW Arabian Sea pushing dust from Makaran towards Gulf of Aden
14	23-Jun-2009	24-Jun-2009	1	3A		D	Effects of this cyclone in Bay of Bengal cannot be distinguished from those of 4A in Arabian Sea
15	23-May-2009	26-May-2009	3	2B (Aila)		SCS	Cyclone in northern BOB causing a major dust event in Thar region with a dust plume trailing eastward down the Gangetic plains. Smaller dust events along the Makaran coast contributing to dust over the northern Arabian Sea
16	14-Apr-2009	17-Apr-2009	3	1B (Bijli)		CS	Cyclone in northern BOB pulling dust plumes from the Makaran coast towards the eastern Arabian Sea. Dust storms initiated due to frontal events in the Mesopotamian and Makaran region. Dust storms also seen in the Thar region
17	4-Dec-2008	7-Dec-2008	3	10B		DD	Counter-clockwise winds of Cyclone 10B off Sri Lanka pushes fine-mode particles from Indo-Gangetic plains towards western Arabian Sea
18	25-Nov-2008	27-Nov-2008	2	9B (Nisha)		CS	Cyclone in the SW Bay of Bengal pushes dust from Indian Subcontinent towards central Arabian Sea. Fine-Aerosols mix with dust from Makran Coast
19	13-Nov-2008	16-Nov-2008	3	8B (Khaimuk)		CS	Numerous dust plumes from Makaran coast being pulled southward towards central Arabian Sea and mixing with fine-mode aerosols from Indian subcontinent

(continued)

Table 7.2. (continued)

S. No	Start of event	End of event	Duration of event	Number and name of event	Intensity of event	Remarks
20	25-Oct-2008	27-Oct-2008	2	7B (Rashmi)	CS	Dust plumes from Makaran coast being pulled towards northern Arabian Sea and mixing with fine-mode aerosols from Indian subcontinent
21	19-Oct-2008	22-Oct-2008	3	6A	DD	Cyclone in Gulf of Aden creating dust storms in the Persian Gulf and Red Sea region
22	15-Sep-2008	19-Sep-2008	4	5B	DD	SW monsoon still active so major dust events seen in Mesopotamian and SW Asian region. Cyclone-5B in Bay of Bengal together with a disturbance in NW Arabian Sea leading to huge dust plume in the Persian Gulf being pulled into the Gulf of Oman and northern Arabian Sea
23	9-Aug-2008	9-Aug-2008	1	4B	D	Cyclone in the Bay of Bengal causing dust to be pulled right across the Arabian Sea towards Peninsular India
24	16-Jun-2008	18-Jun-2008	2	3B	D	Cyclone in the Bay of Bengal causing dust to be pulled right across the Arabian Sea towards Peninsular India and up to the western Bay of Bengal
25	5-Jun-2008	6-Jun-2008	1	2A	D	Cyclone 2A off Oman deflected huge dust plumes from Mesopotamian and Arabia peninsula towards Gulf of Aden and western Arabian Sea. Dust plumes also seen in Red Sea
26	27-Apr-2008	3-May-2008	6	1B (Nargis)	VSCS	Large dust event is Persian Gulf region due to Shamal event. The dust plumes pulled by cyclone Nargis across the northern Arabian Sea and over India. Dust events also seen over Thar region
27	11-Nov-2007	16-Nov-2007	5	12B (Sidr)	VSCS	Dust from Central and SW Asia Thar dust and fine-mode aerosols pulled down the Gangetic plains
28	27-Oct-2007	2-Nov-2007	6	11A	DD	Cyclone 11A along the Oman coast raises dust along the Red Sea coast and pulls Makaran Dust and Indus Haze towards northern Arabian Sea
29	27-Sep-2007	29-Sep-2007	2	10B	D	Not much effect because of stronger depression in Arabian Sea

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Table 7.2. (continued)

S. No	Start of event	End of event	Duration of event	Number and name of event		Intensity of event	Remarks
				Days	Popular name in brackets		
30	21-Sep-2007	24-Sep-2007	3	9B		D	Event 9B in the Bay of Bengal and a smaller depression in the north-eastern Arabian Sea occurring simultaneously. Persian Gulf and SW Asian dust pulled towards northern Arabian Sea
31	5-Aug-2007	7-Aug-2007	2	8B		DD	Dust entrained by Shamal winds over Persian Gulf and SW Asia and Red Sea pulled across the Arabian Sea
32	4-Jul-2007	9-Jul-2007	5	7B		DD	Cyclone in Bay of Bengal pulls dust across the Arabian Sea to Peninsular Indian and eastern Bay of Bengal
33	28-Jun-2007	30-Jun-2007	2	6B		DD	Cyclonic storm over the central Bay of Bengal Red pulls dust from Middle-East and SW Asia across the Arabian Sea
34	25-Jun-2007	26-Jun-2007	1	5A (Yemyin)		CS	Cyclone over Bay of Bengal crosses India and moves over to the northern Arabian Sea causing major dust storms over Persian Gulf
35	21-Jun-2007	23-Jun-2007	2	4B		DD	Dust in Red Sea, Gulf of Aden and Persian Gulf traceable across the central Arabian Sea
36	1-Jun-2007	7-Jun-2007	6	3A (Gonu)		VSCS	Super-Cyclone Gonu created major dust events in Middle-East and SW Asia
37	13-May-2007	14-May-2007	1	2B (Akash)		CS	Dust over northern Arabian Sea. Dust over Thar Desert pulled down Gangetic plains
38	3-May-2007	4-May-2007	1	1B		D	Minor dust events in northern Arabian Sea and Indo-Gangetic plains
39	29-Oct-2006	30-Oct-2006	1	12B (Ogni)		CS	Minor increase in dust over northern Arabian Sea from Makaran Coast
40	28-Sep-2006	30-Sep-2006	2	11B		D	Not much effect seen due to this cyclone as it occurred towards end of the SW monsoon
41	21-Sep-2006	24-Sep-2006	3	9B		D	Effect of this cyclone could not be ascertained due to stronger cyclone in Arabian Sea
42	21-Sep-2006	24-Sep-2006	3	10A (Mukda)		SCS	Major dust storms due to this cyclone in SW Asia with dust blown towards SW direction due to counter-clockwise winds

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Table 7.2. (continued)

S. No	Start of event	End of event	Duration of event	Number and name of event		Intensity of event	Remarks
				Days	Popular name in brackets		
43	3-Sep-2006	4-Sep-2006	1	8B		D	Effect of this cyclone could not be ascertained due to stronger cyclone in Arabian Sea
44	29-Aug-2006	1-Sep-2006	3	7B		D	A frontal system passes over SW Asia creating dust events. Dust plumes pulled eastwards by cyclone towards northern Arabian Sea and India
45	16-Aug-2006	18-Aug-2006	2	6B		D	High AOD over western Arabian Sea and Gulf of Oman. Extensive cloud cover western and central Arabian Sea prevents dust from being transported further eastward
46	12-Aug-2006	13-Aug-2006	1	5B		D	Two low pressure centers in Bay of Bengal and Arabian Sea. Dust from Middle-East and SW Asia pulled towards eastern Arabian Sea
47	2-Aug-2006	5-Aug-2006	3	4B		DD	Large dust plumes seen over northern, and central Arabian Sea, Red Sea and Persian Gulf
48	2-Jul-2006	5-Jul-2006	3	3B		DD	Large dust events seen in Red Sea and Persian Gulf due to Shamal winds. The deep depression in the Bay helps in transport of dust from Gulf of Aden to central Arabian Sea
49	25-Apr-2006	29-Apr-2006	4	2B (Mala)		VSCS	The severe tropical cyclone pulls down dust from the Thar region down the Gangetic plains and central India
50	13-Jan-2006	14-Jan-2006	1	1A		DD	Deep depression in the SE Arabian Sea blows fine-mode aerosols towards central Arabian Sea
51	15-Dec-2005	22-Dec-2005	7	12B		DD	Winter cyclone near Sri Lanka pushes aerosols from Indio-Gangetic plain towards northern Arabian Sea
52	6-Dec-2005	10-Dec-2005	4	11B (Fanoos)		CS	Winter cyclone near Sri Lanka pushes aerosols from Indus plains towards northern Arabian Sea

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Table 7.2. (continued)

S. No	Start of event	End of event	Duration of event	Number and name of event	Intensity of event	Remarks
53	28-Nov-2005	2-Dec-2005	4	10B (Baaz)	CS	Winter tropical storm in southern Bay of Bengal pushes aerosols from Indo-Gangetic plain towards northern Arabian Sea
54	20-Nov-2005	22-Nov-2005	2	9B	D	Winter depression in southern Bay of Bengal pushes aerosols from Indo-Gangetic plain towards northern Arabian Sea
55	26-Oct-2005	29-Oct-2005	3	8B	DD	Winter depression in southern Bay of Bengal pushes aerosols from Indo-Gangetic plain and minor dust from Makaran coast towards northern Arabian Sea
56	2-Oct-2005	3-Oct-2005	1	Name 3B	D	Depression in northern Bay disperses fine-mode aerosols over north India
57	17-Sep-2005	21-Sep-2005	4	7B (Pyarr)	CS	Cyclonic storm in Bay of Bengal pulls dust from Makaran coast to northern Arabian Sea and from Red sea and PG towards western Arabian Sea
58	14-Sep-2005	16-Sep-2005	2	6A	D	Two cyclones over Arabian Sea and Bay of Bengal affects dust plumes over Persian Gulf and Makaran coast
59	12-Sep-2005	16-Sep-2005	4	5B	D	Same as above
60	29-Jul-2005	31-Jul-2005	2	4B	DD	Deep depression over central Bay pulls dust from Saudi Arabian Peninsula across Arabian Sea into peninsular India
61	27-Jun-2005	5-Jul-2005	8	3B	D	Depression over central Bay pulls dust raised by Shamal winds over Saudi Arabia, Red Sea Area and SW Asia across Arabian Sea into peninsular India
62	21-Jun-2005	22-Jun-2005	1	2A	D	Depression over northeastern Arabian Sea causes a dust events over Makaran coast and also pulls dust from Persian Gulf into the northern Arabian Sea
63	13-Jan-2005	17-Jan-2005	4	1B (Hibaru)	CS	Winter storm SE of Sri Lanka pushes fine-mode aerosols from India to eastern Arabian Sea

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Table 7.2. (continued)

S. No	Start of event	End of event	Duration of event	Number and name of event		Intensity of event	Remarks
				Days	Popular name in brackets		
64	8-Jan-2005	10-Jan-2005	2	Name 01B	D	Western disturbance creates minor dust event in Makaran coast. Winter depression SE of Sri Lanka pulls the dust towards central Arabian Sea	
65	29-Nov-2004	2-Dec-2004	3	10A (Agni)	SCS	A winter frontal system creates a major dust event over SW Asia and Thar region. The counter clockwise winds associated with cyclone Agni pushes the dust towards northern Arabian Sea and Oman	
66	2-Nov-2004	7-Nov-2004	5	9B	DD	Deep depression over Bay along with small depression in western Arabian Sea pushes fine-mode aerosols from Indo-Gangetic plains towards northern Arabian Sea	
67	4-Nov-2004	7-Nov-2004	3	Name 04A	D	Same as above	
68	10-Oct-2004	10-Oct-2004	1	No name	D	Two cyclones one in the Bay and other in the NE Arabian Sea. The Arabian Sea depression is closer to dust sources and deflects the dust from SW Asia and Makaran coast towards Oman. Fine-mode aerosols from Indus plains also deflected towards SW	
69	7-Oct-2004	8-Oct-2004	1	8B	D	Same as above	
70	2-Oct-2004	4-Oct-2004	2	7B	D	Two simultaneous cyclones one in the Bay and other in the Arabian Sea. The Arabian Sea cyclone Onil caused a minor dust event along Makaran Coast	
71	30-Sep-2004	4-Oct-2004	4	6A (Onil)	SCS	Same as above	
72	12-Sep-2004	15-Sep-2004	3	5B	D	Dust over Afghanistan Helmand Basin deflected towards northeastern Arabian Sea by depression in Bay	
73	11-Jun-2004	14-Jun-2004	3	4B	DD	Deep depression in northern Bay pulls Oman and Afghan dust eastward towards India	

(continued)

Table 7.2. (continued)

S. No	Start of event	End of event	Duration of event	Number and name of event	Intensity of event	Remarks
74	10-Jun-2004	13-Jun-2004	3	3A	DD	Counter clockwise winds of a deep depression in Eastern Arabian Sea pushes mineral dust from SW Asia and Thar towards western Arabian Sea and Oman
75	16-May-2004	19-May-2004	3	2B	VSCS	A pre-SW monsoon very severe cyclone in Bay of Bengal influences the Shamal dust event in Saudi Arabian and pulls the dust plume towards the eastern Arabian Sea
76	5-May-2004	10-May-2004	5	1A	SCS	A large pre-monsoon cyclone in eastern Arabian Sea pushes dust from Thar Desert towards Arabian Sea
77	11-Dec-2003	16-Dec-2003	5	7B	SCS	A combination of frontal system in SW Asia and cyclone in southwestern Bay of Bengal pulls huge amounts of dust towards SE Arabian Sea
78	12-Nov-2003	15-Nov-2003	3	6A	SCS	A frontal system in SW Asia creates a dust plume. The cyclone in southern Arabian Sea has weak influence on this plume. Dust plume pulled towards northern Arabian Sea
79	26-Oct-2003	28-Oct-2003	2	5B	DD	A post monsoon cyclonic event crosses the Bay of Bengal. Fine aerosols from India pushed towards Arabian Sea and Bay of Bengal
80	6-Oct-2003	9-Oct-2003	3	4B	D	Depression in the northwestern Bay disperses fine aerosols from Indian sub-continent over Arabian Sea. Miner dust plumes along Makaran coast dispersed towards northern Arabian Sea
81	27-Aug-2003	28-Aug-2003	1	3B	D	SW monsoon depression in central Bay pulls dust from Middle-East towards central Arabian Sea
82	25-Jul-2003	28-Jul-2003	3	2B	DD	SW monsoon depression in central Bay pulls dust from Middle-East towards eastern central Arabian Sea
83	10-May-2003	19-May-2003	9	1B	VSCS	Convective winds create major dust storms over SW Asia and Thar Desert which is transported towards the south or easterly direction. Counter clockwise winds due to a severe cyclonic event in the central Bay disperses this dust over the Arabian Sea

(continued)

Table 7.2. (continued)

S. No	Start of event	End of event	Duration of event	Number and name of event		Intensity of event	Remarks
				Days	Popular name in brackets		
84	21-Dec-2002	25-Dec-2002	4	6B		CS	Cyclonic storm east of Sri Lanka disperses fine aerosols over India towards Arabian Sea
85	23-Nov-2002	28-Nov-2002	5	5B		CS	Cyclonic storm in central Bay disperses fine aerosols over India towards Arabian Sea
86	10-Nov-2002	12-Nov-2002	2	4B		SCS	Cyclonic storm in northwestern Bay disperses fine aerosols over India towards Arabian Sea
87	22-Oct-2002	23-Oct-2002	1	3B		D	A local weather disturbance creates a dust storm over western Indo-Gangetic plains and Thar region. Counter-clockwise winds of depression disperses the plume over northeastern Arabian Sea
88	11-May-2002	12-May-2002	1	2B		DD	Two simultaneous cyclones in the western Arabian Sea off Oman and the eastern Bay of Bengal. Since early May is a high dust season due to local convective winds, dust is raised at many locations, but mainly in western Gangetic plains Makaran coast and W Asia. The two cyclones disperse the dust plume over the northern Arabian Sea and Bay of Bengal
89	6-May-2002	10-May-2002	4	1A		CS	Same as above. Even though the cyclone is close to the Oman margin no major dust storm is seen along Oman coast, probably because of coarse sandy material and crust formation along the coast
90	11-Nov-2001	12-Nov-2001	1	6B		D	Counter clockwise winds of cyclone in Arabian Sea on 8th October creates a major dust plume over Makaran and SW Asian region. The dust is dispersed towards the SW direction over western Arabian Sea. After this cyclone dies down, two cyclones in quick succession form over the Bay of Bengal and disperse the remaining dust over Indo-Gangetic plains and NE Arabian Sea. Depression in western Bay disperses fine mode aerosols from India towards eastern Arabian Sea

(continued)

Table 7.2 (continued)

S. No	Start of event	End of event	Duration of event	Number and name of event		Intensity of event	Remarks
				Days	Popular name in brackets		
91	14-Oct-2001	16-Oct-2001	2	5B	CS	Same as above	
92	8-Oct-2001	10-Oct-2001	2	4A	CS	Same as above	
93	24-Sep-2001	27-Sep-2001	3	3A	CS	No major effect of this cyclone seen dust or aerosol transport	
94	12-Jun-2001	13-Jun-2001	1	2B	D	Dust in SW Asia due to local convective winds dispersed down Indo-Gangetic plains by depression in the northern Bay of Bengal	
95	21-May-2001	29-May-2001	8	1A	VSCS	Very severe cyclone in eastern Arabian Sea disperses dust from SW Asia and Thar region towards northern and western Arabian Sea	

Table 7.2. The names and event numbers are according to a classification adopted by the Indian Meteorological Department.

7.2.5 Satellite Data and Images

Satellite images from a number of polar orbiting satellites like Oceansat II, SeaWiifs, MODIS (Terra and Aqua) as well as geostationary satellites like Eumetsat and Kaplana were used for this study. The MODIS (Terra and Aqua) aerosol optical depth (AOD) at 550 nm and Angstrom exponent were obtained from the Giovanni archives. AOD was determined for the northern Arabian Sea for an area located between Lat 18°N–25°N and Longitude 55°E–72.5°E (Fig. 7.2) for

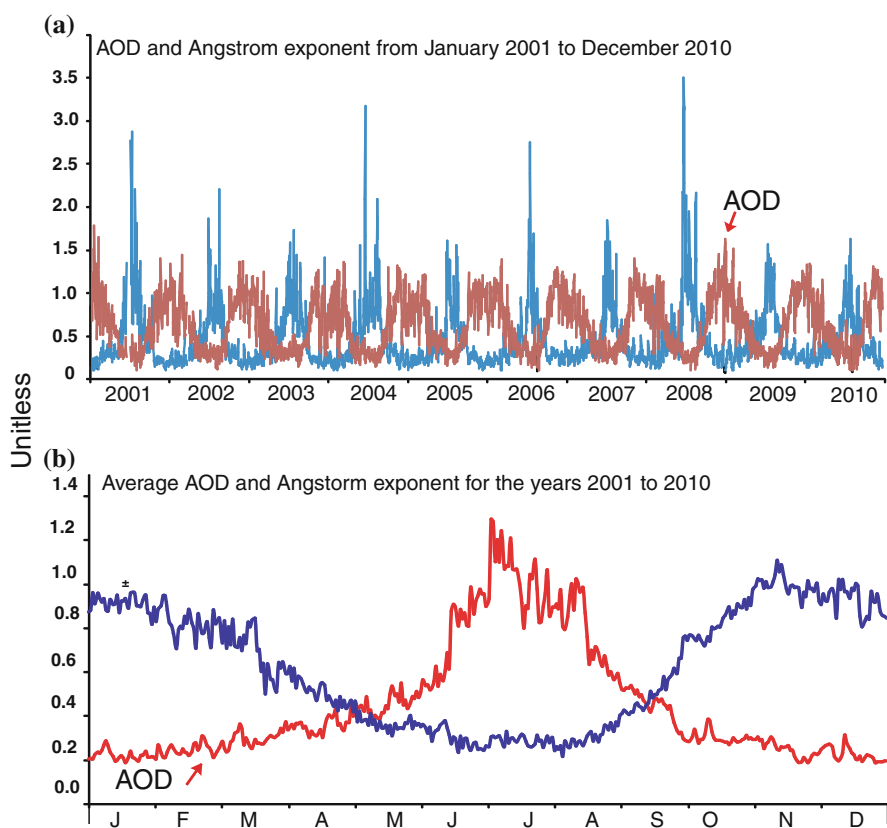


Fig. 7.2 Aerosol optical depth at 550 nm (red line) from MODIS (average of Aqua and Terra) satellites between 1 January 2001 and 31 December 2010 (a) for the northern Arabian Sea (Lat 18–25 and Long 58–72.5). Blue line indicates the Angstrom exponent (α) computed using 550 and 865 nm. The Angstrom exponent provides information on the particle size—larger the exponent, the smaller the particle size. Average AOD and α values (b) for the period 2001–2010

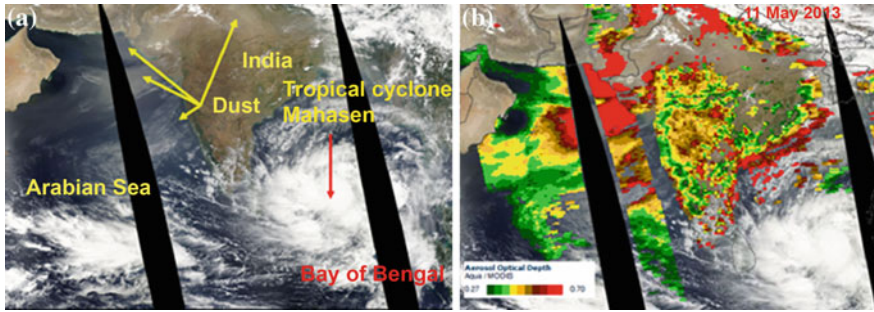


Fig. 7.3 Identification and confirmation of tropical cyclones and dust plumes. Storms, depressions and tropical cyclones were visually identified and then confirmed based on cyclone warnings and tracks published by the Indian Meteorological Department (<http://imd.gov.in>). Dust plumes were initially identified visually in satellite images (a) as they have a *yellowish tinge* in true color images. They were confirmed as dust plumes if the AOD values (b) exceed >0.5 units and have angstrom exponent values (α) less than 0.4. The image shows the effect of cyclonic storm Mahasen in the Bay of Bengal on drawing dust plumes from the Saudi Arabian region over the Indian Peninsula

the period 1 January 2001–31 December 2010. The above area was chosen as it is located close to the dust source regions and has low cloud cover. AOD values over water are more reliable than those over dust source regions as the latter have high reflectivity pattern similar to dust plumes.

Dust plumes were identified visually in satellite images as they have a *yellowish tinge* in true color images (Figs. 7.3, 7.4, 7.5, 7.6, 7.7 and 7.8). AOD values and Angstrom exponent values for the same images were used from confirmation of

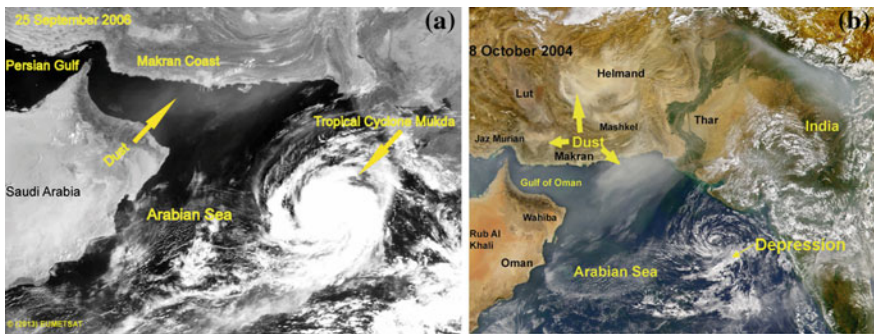


Fig. 7.4 Direct effects of tropical cyclone in the Arabian sea on dust entrainment and transport. Eumetsat image of 25th September 2006 (a), showing tropical cyclone “Mukda” in the north-eastern Arabian Sea and a major dust storm over the SW Asia. The counter clockwise winds transport dust from the Makaran coast towards Oman. Sea-Wifs image of 8 October 2004 (b) showing a minor depression in the NE Arabian Sea with the winds transporting dust from eastern Makaran Coast towards the western Arabian Sea. Fine-mode aerosols from the Indus plains are also being carried towards the western Arabian Sea

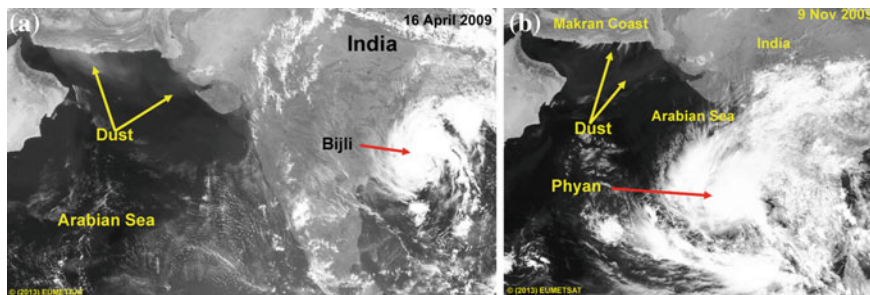


Fig. 7.5 Eumetsat image of 16 April 2009 (a) showing effects of tropical cyclone “Bijli” in the Bay of Bengal on dust transport. Dust plume from a frontal system in the Makaran coast is being transported towards the east due to the presence of a tropical cyclone in the Bay of Bengal. Dust streaks can be seen from Makaran coast in Iran up to peninsular India. Eumetsat image of 9th November 2009 of tropical cyclone “Phyan” in the eastern Arabian Sea (b). Dust from Makaran coast can be seen being transported by counter clockwise cyclonic winds towards western Arabian Sea. A mixture of dust and fine-mode aerosols from the Indus plains is also being transported towards the central Arabian Sea

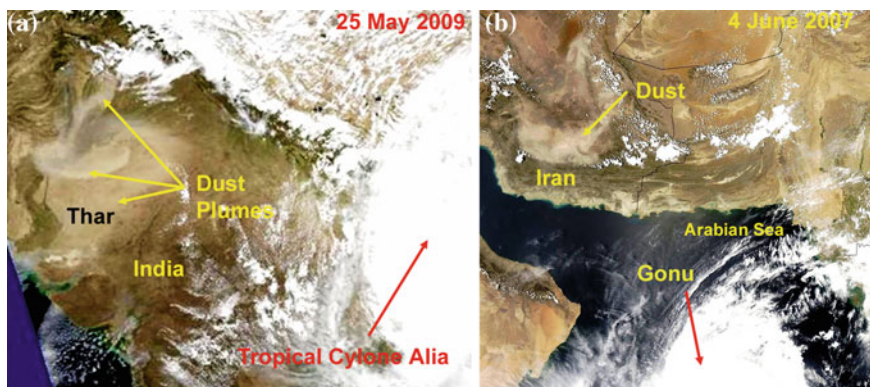


Fig. 7.6 MODIS Aqua image of Tropical cyclone “Aila” 25th May 2009 (a) in the northern Bay of Bengal. Dust from the Thar Desert being transported down the highly populated regions of the Gangetic plains. Eumetsat image of 4th June 2007 (b) showing super-cyclone Gonu in the western Arabian Sea and a large dust events in the Djazz Murian and Lut Basins in south Iran

dust plumes. The plumes were confirmed as dust plumes if the AOD values were over 0.5 (Fig. 7.3b). Distinction between dust and smoke plumes was done by examining the Angstrom coefficient (α) values which are inversely related to the size of the particles. Dust plumes have relatively large particle size and low α values (<0.4) while smoke particles are generally sub-micron size particles having α values much higher than 0.4 (Fig. 7.2).

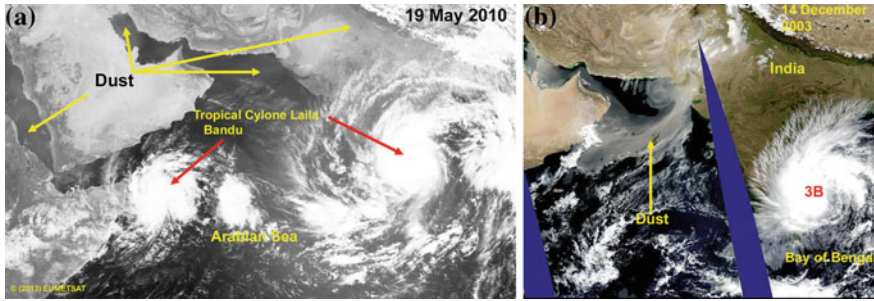


Fig. 7.7 Eumetsat image of 19th May 2010 (a) showing two cyclones in the northern Indian Ocean. Tropical cyclone Bandu is the western Arabian Sea and tropical cyclone Laila in the Bay of Bengal. High dust can be seen in the Red Sea, northern Persian Gulf and northern Arabian Sea. MODIS Aqua Image of 14 December 2003 (b). Tropical cyclone 3B in the central Bay of Bengal in Dec 2003. A cold front created a large dust storm in the Persian gulf region. A thick dust plume can be seen being transported towards the low pressure region of the SE Arabian Sea

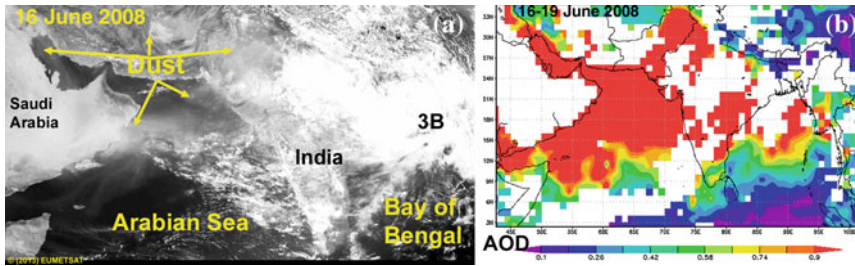


Fig. 7.8 Eumetsat image of 16th June 2008 (a) showing cyclone 3B in the northern Bay of Bengal pulling dust from the Saudi Arabia over the Arabian Sea, India and up to the eastern Bay of Bengal. Confirmation of long-range dust plumes is from MODIS (Aqua), average AOD values (unit less) for the period 16th–19th June 2008 (b). AOD values above 0.7 over the sea indicate major dust events. High dust can be seen over the Persian Gulf, Red Sea, Arabian Sea and northern Bay of Bengal up to the Andaman Sea

7.3 Results

7.3.1 Storms and Tropical Cyclone Between 2001 and 2010

Ninety five cyclone events (tropical cyclones, storms and depressions) were recorded in the northern Indian Ocean between January 2001 and December 2010 (Table 7.2). The effect of each cyclone on aerosols were studied from a number of satellite images. A brief description of the effects of each storm on aerosol transport is given in Table 7.2. While tropical cyclones in the northern Indian Ocean can occur any time between April and January the maximum number of strong events are noticed during May and between October and December.

The Bay of Bengal recorded more cyclones and storms (69 events) compared to the Arabian Sea (26 events). Of the ninety five events, fifty five were during the post-monsoon period. However, of the nine very severe cyclonic storms (VSCS), seven were during the pre-monsoon period and only two during the post-monsoon period. During 2001–2010 there were no cyclone events during February and March. Of the fifteen pre-SW Monsoon (April–May) cyclones thirteen occurred during the month of May. The SW monsoon period (June–September) witnessed thirty nine events; most of them were minor depressions in the northern part of the Bay of Bengal and Arabian Sea. The post-SW monsoon period (October–January) witnessed forty one cyclones.

During April–May the entire South Asia and Middle-East region has low soil moisture levels with local convective winds creating a number of dust events. The summer Shamal winds start by mid-May. All the fifteen tropical cyclones during the pre-monsoon months had a major effect on dust transport by directly raising dust events or altering the transport pathways (Table 7.2). Notable among them were the Arabian Sea Cyclones like Phet (2010, Fig. 7.7a), Bandu (2010, Fig. 7.7a), 1A (2004), 1A (2001) which were the cause of major dust events. Cyclone 1A (2004) and 3A (2004) recurved towards the NE Arabian Sea and caused major dust events in the Thar and Afghanistan regions (Table 7.2). The very severe cyclonic storms in the Bay of Bengal, Aila, (2009, Fig. 7.6a) Bijli (2009, Fig. 7.5a) Nargis (2008), Mala (2006), 2B (2004), 1B (2003), 2B (2002) were observed to cause major dust storms in the Thar Desert and Indo-Gangetic plains and disperse the dust plumes eastward towards the Bay of Bengal.

Almost all cyclone events in the Arabian Sea and Bay of Bengal had significant effect on transport pathways of dust raised by the Shamal Winds. Though most storms during the SW monsoon period are minor depressions, strong cyclonic storms can occur in beginning of June and end of September. Satellite images show that strong to severe cyclones during the SW monsoon period such as Gonu (2007, Fig. 7.5b), Yemyin (2007), Pyaar (2005) 3A (2001) had severe impact on dust entrainment and transport over the entire region.

Between October and January, dust events are less numerous because of gentler winds and enhanced soil moisture levels. Occurrence of tropical cyclones however, is at a maximum during this period. The frontal systems passing over the region north of the Arabian Sea create dust events which are dispersed by the prevailing weak NE trade winds. Whenever passage of the frontal system coincides with a tropical cyclone a major deviation in dust transport pathway occurs. Out of forty one cyclones between October and January, ten cyclonic storm events coincided with dust storms caused by passage of frontal events (Table 7.2). In most cases the Arabian Sea cyclones transported the dust towards the Arabian Peninsula as the principal dust sources are to the north of the cyclone where the winds blow towards the west or south-west. The northern Bay of Bengal cyclones on the other hand dispersed the aerosols and dust mostly in the eastward direction as the winds south of the tropical cyclone blow mainly in the SE or eastward direction. Post-SW monsoon cyclones also had major effect on fine-mode anthropogenic aerosols. Since fine-mode aerosols levels are high between October

and March almost all post-monsoon tropical cyclones play a major role in dispersing them. Out of the forty one cyclones, thirty five had a significant effect on anthropogenic aerosol dispersion from the Indian subcontinent to over the adjacent Arabian Sea and Bay of Bengal (Table 7.2).

7.3.2 Aerosol Optical Depth and Angstrom Exponent Variations

MODIS satellite Aerosol optical depth (AOD) values (average of Terra and Aqua) from the northern Arabian Sea between 1st January 2001 and 31 December 2010 are shown in Fig. 7.2. AOD values are generally high (>0.5) between May and September and comparatively low (<0.5) between October and April. High AOD values indicate high particle concentration in the atmospheric column. The Angstrom exponent (α) is inversely related to the average size of the particles; larger the particles, smaller the α values. α values less than 0.4 units are found during the summer monsoons indicating particles dominated by coarse mineral-dust particles. During October–April large α values indicate dominance of sub-micron size particles derived mostly from burning of fossil fuels and biomass (Gautam et al. 2009; George et al. 2008; Prasad and Singh 2007). Combining the AOD and α values we can generalize that coarse mode mineral-dust particles dominate during May–September and fine mode particles dominate between October and April. The large dust inputs between end of May and September is due to the persistent summer Shamal Winds. During the low dust period (October–April) occasional high AOD values (>0.7) are seen due to short-term dust events due to winter Shamals associated with passage of cold fronts or as will be discussed below, due to tropical cyclones.

7.4 Discussion

7.4.1 Direct Effect of Cyclonic Events Which Migrate Close to Dust Source Areas

The wind speeds associated with different categories of tropical cyclonic events in the northern Indian Ocean range from 8.8 m s^{-1} to over 61 m s^{-1} (Table 7.2). The threshold velocity for initiation of dust events are in the range of $5\text{--}20 \text{ m s}^{-1}$ which means that most cyclonic storms impinging on dust source regions should be able to initiate dust storms. Severe and very severe cyclonic storms in the Arabian Sea, if close to dust source areas, should be able to initiate major dust events over large areas. Between 2001 and 2010 fifteen tropical cyclones and storms Phet (2010) Bandu (2010), O3B (2008), O5A Gonu 2007; Mukda 2007;

Agni O4A, 10th Oct, O3A (2004) O2A (2003) O1A (2002); TS3, TS2, TS1 (2001) made landfall or passed close to dust source areas. Satellite images show that strong anti-clockwise winds associated with these cyclones are able to entrain dust and transport it mostly in a SW direction (Fig. 7.4a, b). However, there is no direct relation between intensity of the tropical cyclone and amount of dust raised, because other factors like soil moisture, crust formation etc. can raise the threshold for dust entrainment. Large dust plumes were observed when the cyclonic storms move towards the north or northwestern Arabian Sea because of proximity to dust source areas along the Makaran Coast and the endhoreic basins north of the coast. The Makaran coast and the endhoreic basins of Helmand (Seistan), Jaz Murian and Mashkel are dust prone because of the presence of fine dry loose soils derived from uplifted recent marine sediment and dry lake beds. Moreover, these sediments do not have much large pebbles or boulders to form desert pavements which can inhibit dust storms. The northern coast of the Persian Gulf (Iran) do not have large-scale dust events because of the presence of numerous salt domes in the region which contribute to salt-crust formation. The main dust sources in the Rub Al Khali desert or Mesopotamia are located far away from the Arabian Sea and are less responsive due to drop in wind speed because of greater friction over land. Dust events in the above regions are seen only during very severe cyclonic storms. The southern Oman or Yemen coast highland regions receive high rainfall during the summer monsoon and do not have major dust source areas. However, cyclones moving close to the Gulf of Aden are observed to raise large dust plumes along both sides of the Red Sea coast (Fig. 7.7a) and especially off the Tokar Delta.

7.4.2 Indirect Effects by Tropical Cyclones Located Further Away from Dust Source Regions

Tropical cyclone located further away from the source region can affect dust entrainment by intensification of the pressure gradient leading to greater wind speeds over dust source regions (Badrinath et al. 2009, 2010). Also, if dust raised by Shamal or local winds are present then the transport direction of the dust plumes can be significantly altered. Tropical cyclones during the SW monsoon period, though rare, have a major effect on the dust transport as significant amount of dust is present in the western and northern Arabian Sea due to the summer Shamal Winds. A example of this is tropical cyclone 2A located in the central Arabian Sea on 6th June 2008. From satellite images, dust plumes from Oman and Saudi Arabian Peninsula could be traced up to the western Arabian Sea but not eastward of the cyclone. Ten days later a tropical cyclone (3B 16–18 June 2008) struck the northern Bay of Bengal (Fig. 7.8). Huge dust plumes could be traced from the Middle-East right across the Arabian Sea, Peninsular India and up to the eastern Bay of Bengal (Fig. 7.8b). The highest AOD values recorded in the Arabian Sea during the 10 year study period was during this period (Fig. 7.2).

The most important effect of tropical cyclones on dust transport is deflection of dust plumes away from their normal pathways. Mineral dust is normally transported by the relatively steady trade winds. As the dust plumes come under the influence of cyclonic winds its transport direction is sharply altered because of the counter clockwise winds. In case of the Arabian Sea cyclones, the dust sources lie towards the north or east of the cyclone hence the plumes are generally deflected in a southwesterly direction. The Bay of Bengal cyclones lie much further eastwards of dust sources and it is observed that the dust plumes are generally deflected towards the east or southeasterly direction. An illustration of this is tropical cyclone Bijli (Fig. 7.5a) which formed in the central Bay of Bengal and migrated northward towards the Bangladesh coast between 14 and 17 April 2009. Dust plumes from the Makaran coast of Iran can be seen being pulled in a southeasterly direction towards India. A similar case is a large tropical cyclone Aila in May 2009 (Fig. 7.6a) where east flowing winds south of the cyclone transported dust from the Thar Desert down the Gangetic plains towards the Bay of Bengal. Another example of the effect of tropical cyclone on deflection of dust plumes is tropical cyclone Phyan (9–11 Nov 2009) in the north-western Arabian Sea (Fig. 7.5b). Dust from Makaran is blown by the counter-clockwise winds in a southwesterly direction towards the Arabian Coast.

After the retreat of the SW monsoon in September, wind speeds are generally low and no dust storms are expected in the Thar Desert region between October and December. However, major cyclones in the Bay of Bengal or north-eastern Arabian Sea during the post SW monsoon period have led to major dust storms in the region. For example, tropical cyclone Sidr in October 2007 created a major dust storm over the Thar Desert and the plume was traceable for more than a 1,000 km up to the northern Bay of Bengal (Badrinath et al. 2009). Another example is the tropical cyclone Agni (28 Nov–2 Dec 2004) in the western Arabian Sea which caused a major dust storm and plume to be blown from the Indus-Thar region into the northern Arabian Sea (Table 7.2).

Tropical cyclones also have a major effect on deflection of dust plumes created by the winter Shamal dust events. The dust raised by these north-westerly winds transport dust from the Mesopotamian region towards the Persian Gulf. The winter frontal systems also affect the endorheic basins of SW Asia (Iran, Afghanistan, and Baluchistan) and the Makaran coast. The dust from these regions is normally transported by the prevailing northeasterly trade winds towards Saudi Arabia and North Africa. Winter Shamals are short lived events occurring between October and April and lasting between 3 and 5 days. The post SW-Monsoon tropical cyclones in the northern Indian Ocean last for 2–8 days and the probability of these two events coinciding are high between September and December. If these events coincide then the dust transport pathway can be significantly deviate from its normal path. In December 2003 a massive dust plume generated in Iran and Saudi Arabian Peninsula was affected by the tropical cyclone 3B in the central Bay of Bengal (Fig. 7.7b). The dust plume could be traced up to the southeastern Arabian Sea. Another example of combination of events is the 10th October 2004 event where a cold front caused a major dust storm in the Afghanistan, Thar, and

Makaran region. A minor cyclonic depression in the northern Arabian Sea deflected the plumes towards the north-western Arabian Sea (Fig. 7.4b).

7.4.3 Tropical Cyclones and Dispersal of Anthropogenic Aerosols

During October to end of March, the Indian subcontinent has high aerosol levels dominated by fine mode particles from mostly low temperature biomass burning, especially over the highly populated Indo-Gangetic plains (Ramanathan et al. 2001b). High fine-mode aerosols levels can persist near source regions for long periods as prevailing wind speeds are low. Enhanced wind circulation during tropical cyclones can disperse these fine-mode particles to long distances. Tropical cyclones have a major effect on dispersing these fine-mode particles as they are the major cause of high wind-speed events during winter. Even minor storms can help in dispersion of the fine mode particles because, unlike dust, no energy is required for entraining them. The Himalayan mountain chain with a height of over 4.5 km forms a formidable barrier and prevents dispersal of fine mode particles from south Asia to the north. However the fine mode aerosols are easily dispersed towards the south and adjoining Arabian Sea and Bay of Bengal. Satellite images show plumes of grey aerosol clouds trailing out into the Arabian Sea and Bay of Bengal during tropical cyclone events (Fig. 7.6). These plumes can be traced even south of the equator and westwards to the Middle-East. The fine-mode particle plumes can be easily identified by their ash grey color and high angstrom exponent (α) values.

Post SW monsoon cyclones disperse fine-mode and mineral dust particles (Fig. 7.4b) from different sources. The two size-classes of particles can collide leading to formation of complex aggregates. Fine mode particles have more sulphate ions which when dissolved in water form acidic waters which can enhance the solubility and release of trace-nutrients from mineral dust particles (Ooki and Uematsu 2005). Dispersal of dust and fine-mode particles by tropical cyclones over the oceans can therefore contribute significantly to increase in ocean productivity and capacity of oceans to absorb atmospheric carbon dioxide.

7.5 Summary

Study of ninety five cyclonic storms between 2001 and 2010 show that they have a major effect on dust entrainment and transport. Tropical cyclones which move close to dust source regions in the north and northwestern Arabian Sea raise dust but transport them mainly westwards towards the western Arabian Sea and Arabian Peninsula. Tropical cyclones located further away in the SE Arabian Sea and Bay of Bengal alter the transport pathway of dust and transport them towards the

Indian Peninsula. Severe tropical cyclones in the northern Bay of Bengal aid advection of dust plumes from southwest Asia and Thar Desert over highly populated regions of the Indo-Gangetic plains. Tropical cyclones also disperse fine-mode aerosols over South Asia leading to formation of complex aerosol-dust mixtures.

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