Chapter 12
Understanding the Development and Progress of Extremely Severe Cyclonic Storm "Fani" Over the Bay of Bengal

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Abstract The Bay of Bengal (BoB) experiences the occurrence of tropical cyclones (TCs) almost throughout the year. However, the extremely severe cyclonic storm (ESCS) Fani has formed in April 2019 has shown uniqueness in terms of its location of origin, direction of track, and landfall location. Therefore, in this study, an attempt has been made to examine the development and progress of ESCS Fani over the BoB. The analyses have shown that a low pressure area has formed near equator (approximately 2.7°N latitude) over the southern BoB on 25 April 2019 and strengthened into depression on 26 April at the same location. This depression has further strengthened into cyclonic, severe cyclonic, very severe cyclonic, and extremely severe cyclonic storm and moved northwestward. Then, it has recurved and moved northeastward and make landfall over Orissa coast. It has been reported among the long-lasting cyclones of BoB as it travelled the distance of about 3030 km. The total accumulated cyclone energy and power dissipation index generated by the ESCS Fani have been found higher than their long-term mean (1972–2017). The analyses of large-scale dynamic and thermodynamic conditions have shown favorable environment for the development of cyclone over the southern BoB. The consistent strong convective activity, high SST (approximately 30 °C), more relative humidity, strong vertical motion, low level cyclonic vorticity, and less vertical wind shear have supported for further intensification of cyclonic system. The cyclone Fani has followed the recurving track which has been chiefly steered by an upper tropospheric level anticyclonic circulation.

Keywords Tropical cyclone · Fani · Development · Environmental conditions · Bay of Bengal

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P. K. Shit et al. (eds.), *Geospatial Technology for Environmental Hazards*, Advances in Geographic Information Science, https://doi.org/10.1007/978-3-030-75197-5_12

12.1 Introduction

Tropical cyclones (TCs) are among the most disastrous events, resulting immense damage to infrastructure and property, and human lives loss at the time of landfall (Peduzzi et al., 2012). Many tropical and subtropical coastal regions are frequently devastated by the occurrence of these TCs (Li & Li, 2013). However, vulnerability and their impact significantly vary from one region to another (Bhardwaj et al., 2020). It is well-known that the development and progress of these TCs is largely controlled by a few thermodynamic and dynamic environmental factors such as high sea surface temperature (SST) (>26.5 °C), reduced vertical wind shear, high low level vorticity, substantial Coriolis force, and high mid-tropospheric relative humidity (Gray, 1968, 1975; Webster et al., 2005). Therefore, these factors have been frequently used as the key predictors for their development and progress (Chan & Liu, 2004; Aiyyer & Thorncroft, 2006).

The Bay of Bengal (BoB) accounts nearly 80 per cent of the total TCs of the North Indian Ocean (IMD, 2011). These TCs cause huge loss of lives in the rim countries, i.e., India, Bangladesh, and Myanmar (Alam & Dominey-Howes, 2015). For example, two extreme cyclones originated in BoB in the years 1970 and 1991 have caused a loss of about 3,00,000 and 1,40,000 human lives, respectively, in Bangladesh (Choudhury, 2001). Likewise, in the year 1999 Orissa super cyclone and in 2008 cyclone Nargis have killed about 10,000 and 1,38,000 people in India and Myanmar, respectively (Chittibabu et al., 2004; Fritz et al., 2009). Bhardwaj and Singh (2020) have shown that majority of TCs in the BoB occurs in two seasons. The post-monsoon season accounts for about 64 per cent, and pre-monsoon season accounts for about 21 per cent of the total annual TCs. However, the conversion rate of cyclonic storms into intense cyclonic storms is greater during pre-monsoon than post-monsoon season in the BoB. Besides, most of pre-monsoon's TCs usually follow the northward tracks or recurved towards northeast and make landfall over Bangladesh and Myanmar coasts. During 1891–2017, 14 TCs have formed in April in the BoB; however, only one TC made landfall over the Indian mainland coast (Sangomla, 2019). Balasubramanian and Chalamalla (2020) have examined the dynamics which led the rapid intensification of Amphan cyclone in the BoB.

Recently, the TCs of BoB have shown an unusual behavior in terms of timings of occurrence and intensification rates. For instance, cyclones Ockhi of 2017 and Titli of 2018 have rapidly intensified just before the landfall. This cyclonic system has formed near the equator (2.7°N latitude). In such lower latitudes, the cyclones' formation is rare. The ESCS Fani of 2019 is second in the past 118 years that has formed in the month of April in BoB and crossed the Indian mainland (Sangomla, 2019). It is the most intense cyclone during satellite era (1965 onwards) which formed during the pre-monsoon season and crossed the Orissa coast. Also, it is the10th most severe TC in Indian subcontinent in the last 52 years. It has affected the large parts of eastern and northeastern Indian states and resulted in about 64 deaths and property loss of about 9000 crores. Moreover, Kumar et al. (2020) have examined the impacts of the Fani cyclone and noticed that it has severely affected the agricultural and built-up area over the eastern India and Bangladesh. Therefore, a detailed study of cyclone Fani is of very much importance. In this study, an attempt has been made to examine the development and progress of ESCS Fani over the BoB. It is believed that the finding pertaining to the formation and intensification of Fani cyclone will be helpful for meteorologists, forecasters, scientific community, and disaster managers to reduce the impacts of future cyclones.

12.2 Data and Methods

For North Indian Ocean, Regional Specialized Meteorological Centre (RSMC), New Delhi, provides the TCs' best track data. Therefore, the best track data of RSMC, New Delhi has been used to examine the various characteristics of Fani cyclone (RSMC, 2019a). The TC Fani is chiefly monitored with satellite supported by meteorological buoys, coastal and inland observations, and Doppler Weather Radars. The dataset comprised a detailed information of Fani TC including the latitudinal and longitudinal position, current intensity number, estimated maximum sustained wind (MSW) (kt), estimated central pressure (hPa), estimated pressure drop at the center (hPa), and grade at 3-hourly time (0000, 0300, 0600, 0900, 1200, 1500, 1800, 2100 UTC) (Table 12.1).

Additionally, to examine the development and progress of Fani cyclone, several dynamic and thermodynamic environmental conditions have been examined. The daily SST data has been obtained from Advanced Very High Resolution Radiometer-SST from National Oceanic and Atmospheric Administration. Besides, the data pertaining to relative humidity, outgoing longwave radiation (OLR), precipitable water, vertical velocity (omega), lower (850 hPa) and upper (200 hPa) winds, and vertical wind shear have been acquired from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis (Kalnay et al., 1996). The composite maps of these environmental parameters have been prepared to examine their daily pattern during the cyclone period. The composite maps have been prepared by means of GrADS software. Besides, track of Fani cyclone has been prepared by using the ArcGIS 10.1 software.

12.3 Results and Discussion

A Brief Life History of ESCS Fani

A low-pressure area has formed near equator (approximately 2.7°N latitude) over the southeast BoB in the early morning (0530 IST) on 25 April 2019 (Fig. 12.1). It has deepened over the same region due to favorable environmental conditions and classified as depression on 26 April. Then it has moved northwestward and strengthened into a deep depression on 27 April. It has further intensified into a cyclonic

Table 12.1 Best track positions and other parameters of the ESCS Fani over BoB during 26 April–04 May, 2019

Date	Time (UTC)	Center latitude	Center longitude	Current intensity No.	MSW (kt)	Estimated central pressure (hPa)	Estimated pressure drop at the center (hPa)	Intensity
26-04-19	3	2.7	89.7	1.5	25	998	4	D
	6	3.0	89.4	1.5	25	998	4	D
	12	3.2	89.2	1.5	25	998	4	D
	18	3.7	88.8	1.5	25	998	4	D
27-04-19	0	4.5	88.8	2.0	30	997	5	DD
	3	4.9	88.7	2.0	30	996	6	DD
	6	5.2	88.6	2.5	35	995	7	CS
	9	5.4	88.5	2.5	40	994	8	CS
	12	5.9	88.5	3.0	45	992	10	CS
	15	6.3	88.5	3.0	45	992	10	CS
	18	6.6	88.2	3.0	45	992	10	CS
	21	6.9	87.9	3.0	45	992	10	CS
28-04-19	0	7.3	87.9	3.0	45	992	10	CS
	3	7.3	87.9	3.0	45	992	10	CS
	6	7.4	87.8	3.0	45	992	10	CS
	9	7.7	87.5	3.0	45	992	10	CS
	12	8.2	87.0	3.0	45	992	10	CS
	15	8.3	86.9	3.0	45	992	10	CS
	18	8.4	86.9	3.0	45	992	10	CS
	21	8.5	86.9	3.0	45	992	10	CS
29-04-19	0	8.6	86.9	3.0	45	992	10	CS
	3	8.7	86.9	3.0	45	992	10	CS
	6	9.2	86.9	3.0	45	992	10	CS
	9	9.7	86.8	3.0	45	992	10	CS
	12	10.1	86.7	3.5	55	986	16	SCS
	15	10.4	86.7	3.5	55	986	16	SCS
	18	10.8	86.6	3.5	55	986	16	SCS
	21	11.1	86.5	3.5	60	986	16	SCS
30-04-19	0	11.7	86.5	4.0	65	980	22	VSCS
	3	12.3	86.2	4.5	75	974	28	VSCS
	6	12.6	85.7	4.5	80	970	32	VSCS
	9	13.0	85.3	4.5	85	966	36	VSCS
	12	13.3	84.7	5.0	90	962	40	ESCS
	15	13.4	84.5	5.0	95	957	45	ESCS
	18	13.5	84.4	5.0	95	957	45	ESCS
	21	13.6	84.2	5.0	95	957	45	ESCS
	0	13.9	84.0	5.0	95	957	45	ESCS
	3	14.1	83.9	5.0	95	957	45	ESCS

(continued)

Table 12.1 (continued)

Date	Time (UTC)	Center latitude	Center longitude	Current intensity No.	MSW (kt)	Estimated central pressure (hPa)	Estimated pressure drop at the center (hPa)	Intensity
01-05-19	6	14.2	83.9	5.0	95	957	45	ESCS
	9	14.5	84.1	5.0	95	955	45	ESCS
	12	14.9	84.1	5.5	100	950	50	ESCS
	15	15.1	84.1	5.5	100	950	50	ESCS
	18	15.2	84.1	5.5	100	950	50	ESCS
	21	15.5	84.2	5.5	100	950	50	ESCS
02-05-19	0	15.9	84.5	5.5	105	945	55	ESCS
	3	16.2	84.6	5.5	105	945	55	ESCS
	6	16.7	84.8	5.5	110	940	60	ESCS
	9	17.1	84.8	6.0	115	932	66	ESCS
	12	17.5	84.8	6.0	115	932	66	ESCS
	15	17.8	84.9	6.0	115	934	66	ESCS
	18	18.2	85.0	6.0	115	934	66	ESCS
	21	18.6	85.2	6.0	115	934	66	ESCS
03-05-19	0	19.1	85.5	6.0	105	945	55	ESCS
	3	19.6	85.7	5.5	100	950	50	ESCS
	6	20.0	85.9	.	85	952	46	VSCS
	9	20.5	86.0	.	75	970	28	VSCS
	12	21.1	86.5	.	70	976	22	VSCS
	15	21.5	86.7	.	60	980	18	SCS
	18	21.9	87.1	.	55	986	16	SCS
	21	22.5	87.9	.	50	990	12	SCS
04-05-19	0	23.1	88.2	.	40	994	8	CS
	3	23.6	88.8	.	30	996	6	DD
	6	24.3	89.3	.	25	998	5	D
	12	25.2	90.7	.	20	1000	4	D

storm named as “Fani” nearby noon on 27 April. Then it has moved towards northwest and further strengthened into severe, very severe, and extremely severe cyclonic storm. It has started to recurve towards north and northeastward from 1 May and reached at its peak (115 kt) on 2 May. It has crossed the Orissa coast as an ESCS with MSW about 110 kt in the morning on 3 May. Then it has moved towards northeast and crossed the West Bengal, Bangladesh, and finally diminished nearby central Assam on 4 May. The total accumulated cyclone energy and power dissipation index generated by the ESCS Fani are approximately 16.7×10^4 kt^2 and 15.1×10^6 kt^3, respectively, which are higher than their long-term mean (1972–2017), i.e., 13.0×10^4 kt^2 and 12.4×10^6 kt^3 (Bhardwaj & Singh, 2020). The 3-hourly detailed information cyclone of Fani has been presented in Table 12.1, and the track and daily development and progress of ESCS Fani have been displayed

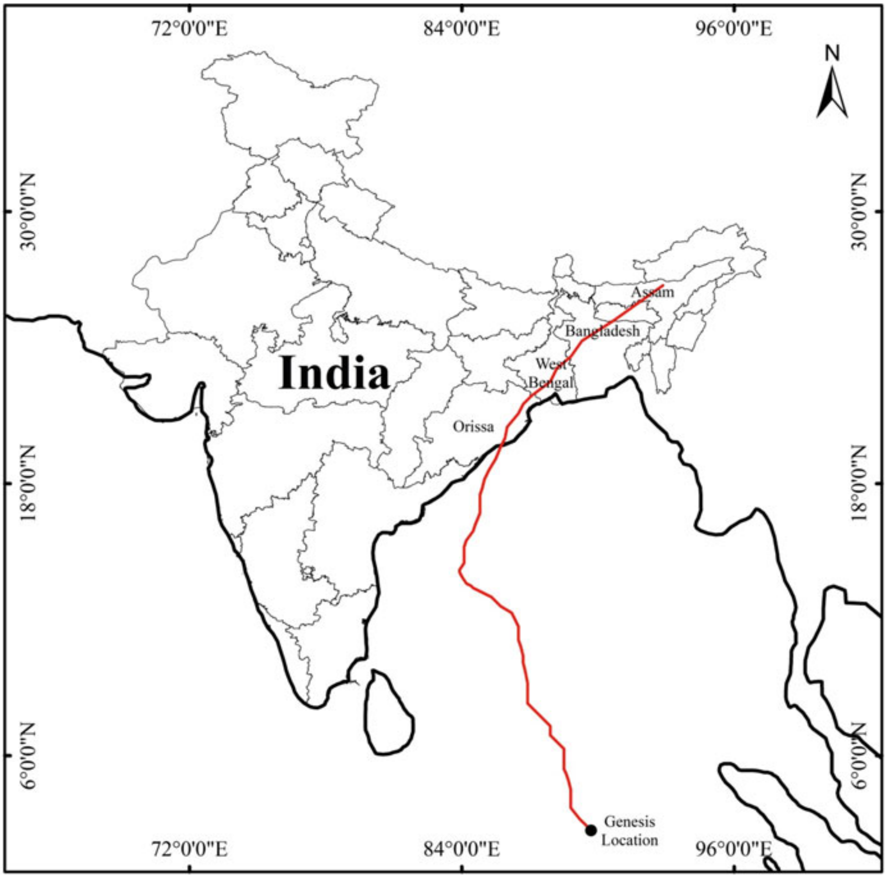

Fig. 12.1 Genesis location and track of ESCS Fani over the Bay of Bengal during April 26 to May 04, 2019

in Figs. 12.1 and 12.2. It is among the long-lasting cyclones of BoB as it travelled the distance of about 3030 km. Hence, all these facts suggest the need for a detailed analysis of the large-scale environmental conditions linked with the development and progress of ESCS Fani. These have been discussed in the subsequent section:

Large-Scale Environmental Conditions

Outgoing Longwave Radiation (OLR)

OLR is a proxy indicator of convective clouds. Strong convective activity over a region supports the formation of TCs. The higher OLR values indicate less convective activity and vice-versa. Figure 12.3 demonstrates the daily mean OLR pattern

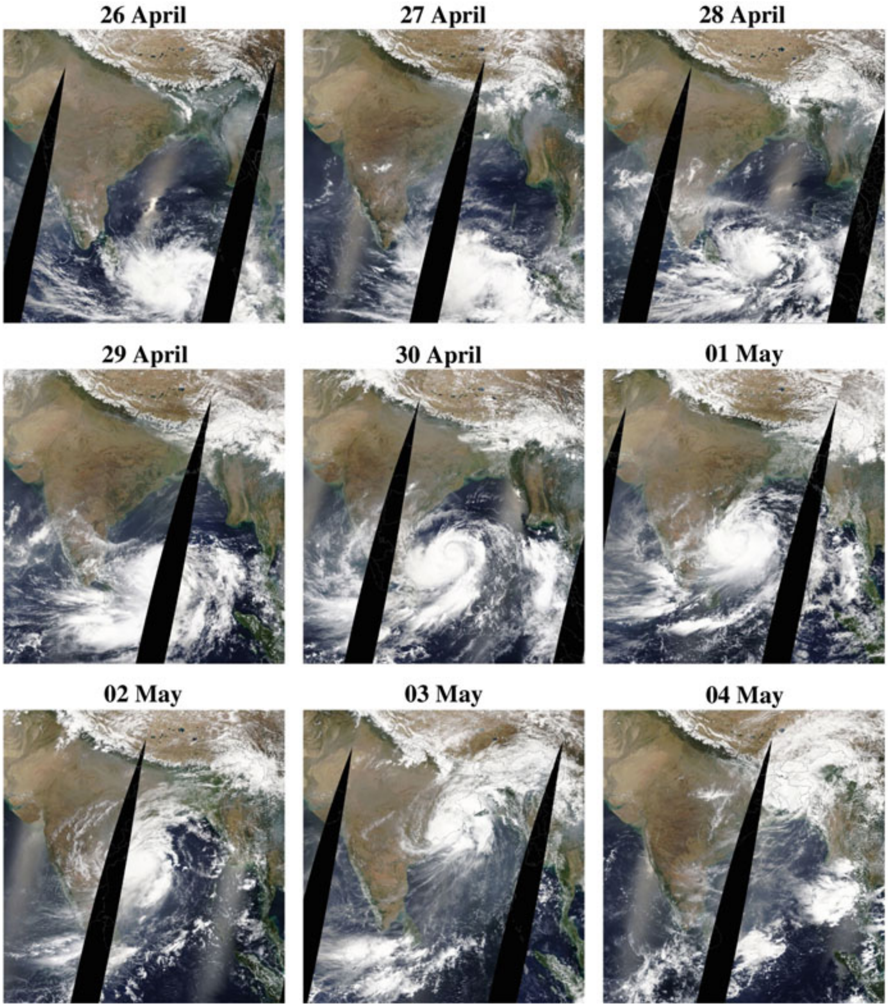

Fig. 12.2 Progress of ESCS Fani over the Bay of Bengal during April 26 to May 04, 2019.Images are of moderate-resolution imaging spectroradiometer (MODIS) Terra sensor

during April 26 to May 04, 2019.The figure clearly shows that the convective activity is higher in the region where the Fani has initially developed as low pressure area. The convectively active phase of Madden-Julian Oscillation (MJO) with amplitude greater than 1 has also located continuously over the Bay of Bengal which provided the favorable conditions for the enhancement of convection and strengthening of Fani (Bhardwaj et al., 2019a; RSMC, 2019b). Then this region of strong convective activity has moved towards Orissa coast. However, the convective activity has weakened near the coast and reduced significantly after the landfall of ESCS Fani.

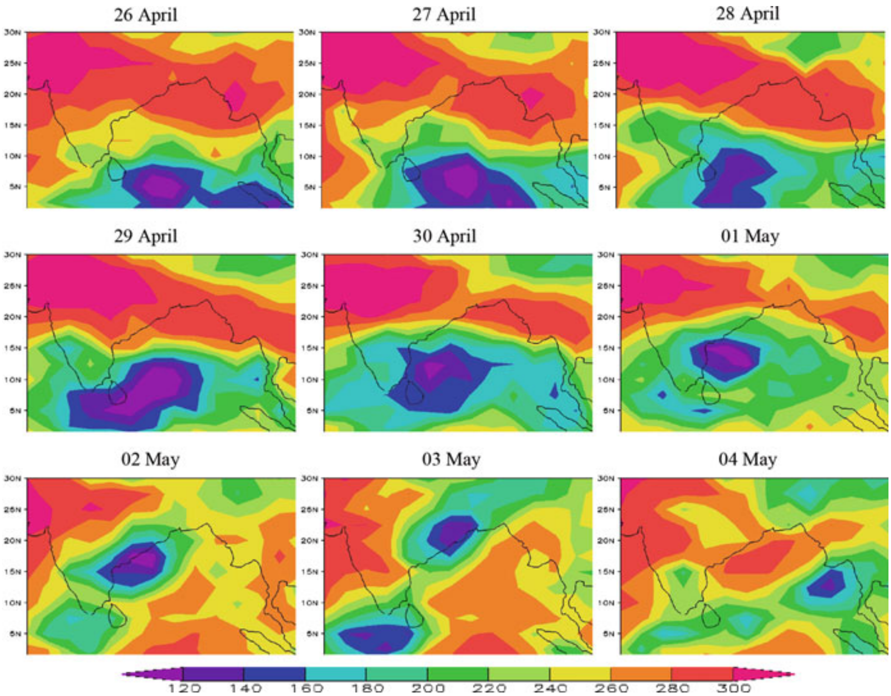

Fig. 12.3 Composites of OLR (Wm^{-2}) during the lifetime of ESCS Fani during 26 April to 04 May, 2019

Sea Surface Temperature (SST)

SST is the most important factor which controls the development and strengthening of TCs (Sebastian & Behera, 2015). Figure 12.4 displays the daily SST pattern over the BoB during April 26–May 04, 2019. The figure clearly exhibits that SST is near about 30 °C over the large parts of BoB during the cyclone period, which is very high than the minimum required SST (>26.5 °C) for the formation of a cyclone (Gray, 1968). The consistent high SST is suitable for the formation and strengthening of cyclone Fani over the BoB. Also, a cooling of SST can be seen over the central parts of the BoB from the 1 May, as the Fani has intensified further. This cooling of SST is mainly ascribed to the evaporation produced by the strong winds and blockage of solar radiations due to presence of large-scale convective clouds associated with Fani (Bhardwaj et al., 2019b). Similarly, a rapid reduction in SST can be seen towards the coastal areas of Orissa where Fani reached at its peak.

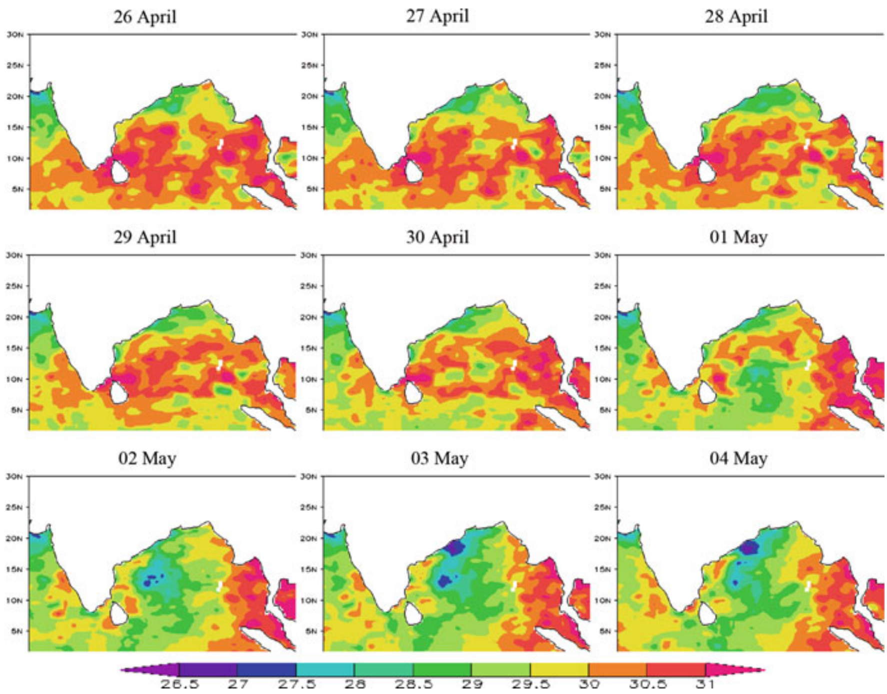

Fig. 12.4 As in Fig. 12.3, but for SST (°C)

Relative Humidity

The sufficient amount of relative humidity (at least 40%) at mid-tropospheric level is required for the intensification of TCs (Gray, 1968). Figure 12.5 exhibits that relative humidity is approximately 80 per cent at mid-tropospheric level where the Fani has developed as depression on 26 April in the southern BoB. Then, this region of high humidity has migrated towards north with the movement of cyclone over the BoB. The presence of higher relative humidity at mid-tropospheric level has released high latent heat which energized and intensified the system. However, after the landfall of the Fani, the relative humidity has decreased rapidly.

Vertical Velocity (Omega)

Figure 12.6 shows the spatial pattern of vertical velocity over the BoB during April 26 to May 04, 2019, at mid-tropospheric level. A negative omega indicates upward motion and vice-versa. Small negative omega values indicate slightly weak vertical motion over the areas where cyclone has initially developed as depression on 26 April over the southern BoB. After that, a strong vertical motion has taken place over the central to northern BoB on 29–30 April. On 30 April, again small

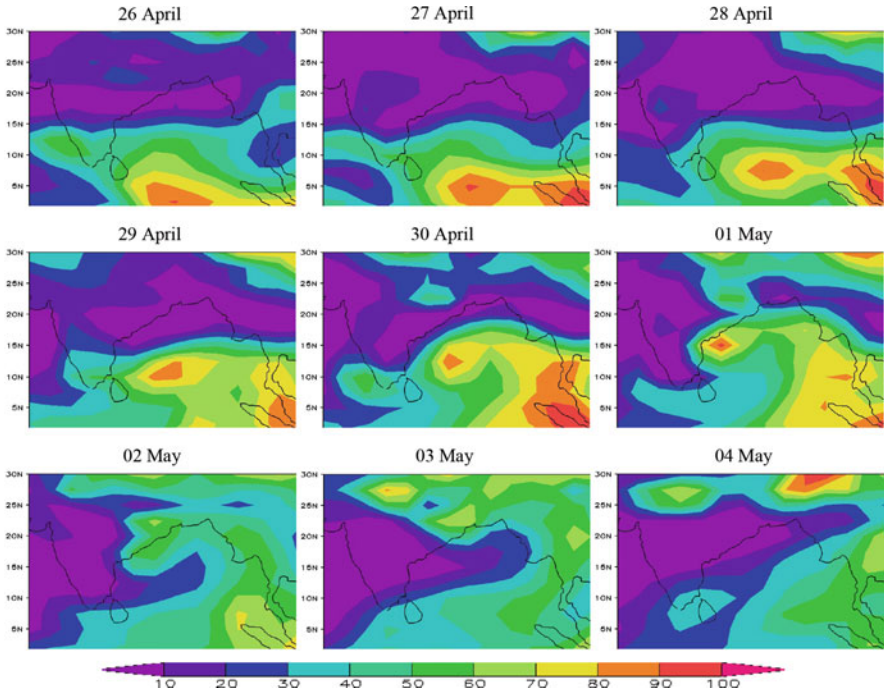

Fig. 12.5 As in Fig. 12.3, but for relative humidity (%)

negative omega values indicate the fast surface motion of cyclone towards Orissa coasts. After 30 April, again strong vertical motion has occurred over the Orissa coast and continued after the landfall. The presence of strong vertical motion over warm oceanic water has transported the moisture to mid-tropospheric level and helped in intensification of cyclone.

Low Level Winds (850 hPa)

Figure 12.7 shows the pattern of low-level winds during April 26 to May 04, 2019, over the BoB. The figure clearly shows that a low level cyclonic circulation is present over the southern BoB on 26 April, which assisted in formation of cyclone. On 27–28 April, the cyclonic circulation has moved towards the central BoB. Later, this cyclonic circulation has intensified with movement towards Orissa coast between April 29 and May 02. On 3 May, the cyclonic circulation has mostly crossed the Orissa coast. The strong winds can be seen around the eye of cyclonic circulation, whereas winds are weak within eye and nearby region. The cyclonic circulation has weakened rapidly on 04 May after the landfall on 3 May.

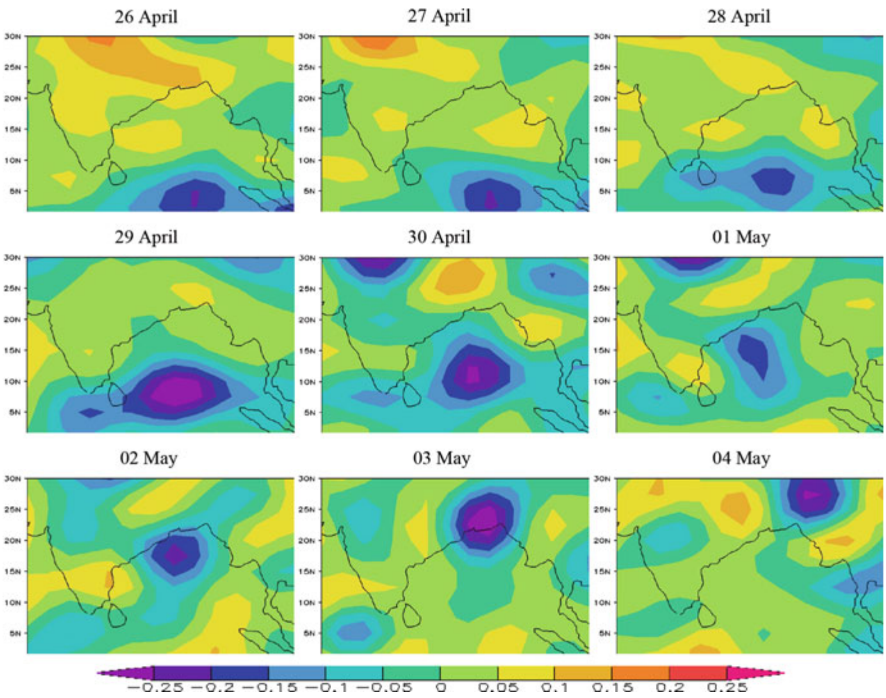

Fig. 12.6 As in Fig. 12.3, but for vertical velocity (Omega; Pa/s)

Upper Level Winds (200 hPa)

It is well-known that upper level winds control the track direction of cyclones. Figure 12.8 displays the pattern of upper level winds during April 26 to May 04, 2019, over the BoB. On 26 and 27 April, strong easterly (westerly) winds can be seen in the upper troposphere over the southern (northern) BoB when the cyclone Fani is in initial stage. An anticyclonic circulation lies over South Thailand and adjoining South Andaman Sea in the middle and upper tropospheric levels (RSMC, 2019b). This anticyclonic circulation has steered the system northwestward. Then, this anticyclonic system has embedded with strong upper level westerly winds and steered the cyclone northeastward. After landfall, due to the impact of upper level westerly winds, the cyclonic system has moved rapidly with an average speed of 24.0 km/h.

Vertical Wind Shear (200–850 hPa)

Vertical wind shear is a vital factor which controls the TCs. The less amount of vertical wind shear is favorable for the development and strengthening of TCs and vice-versa. Figure 12.9 demonstrates the pattern of vertical wind shear during April

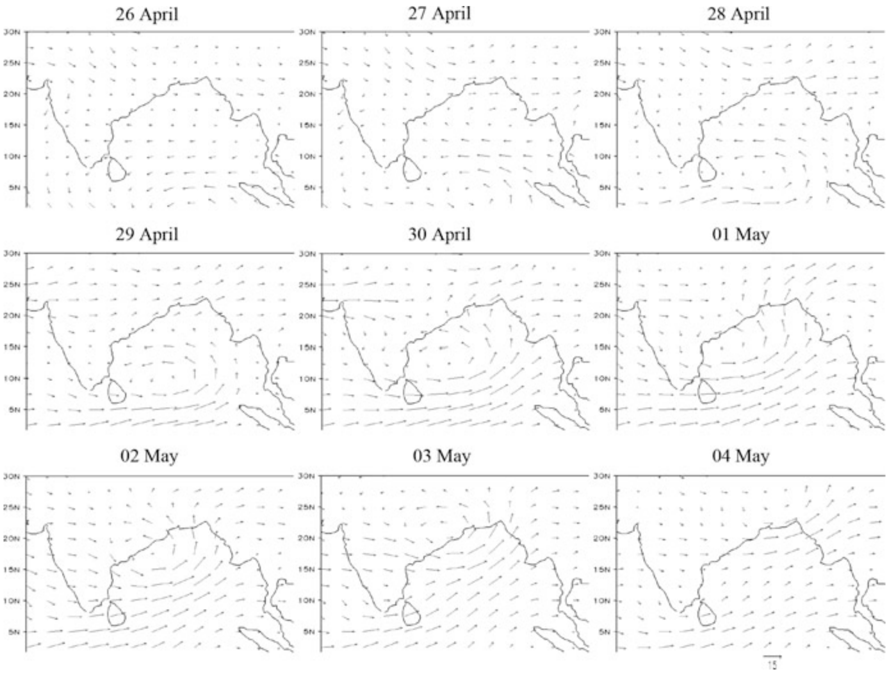

Fig. 12.7 As in Fig. 12.3, but for low level winds (850 hPa; ms^{-1})

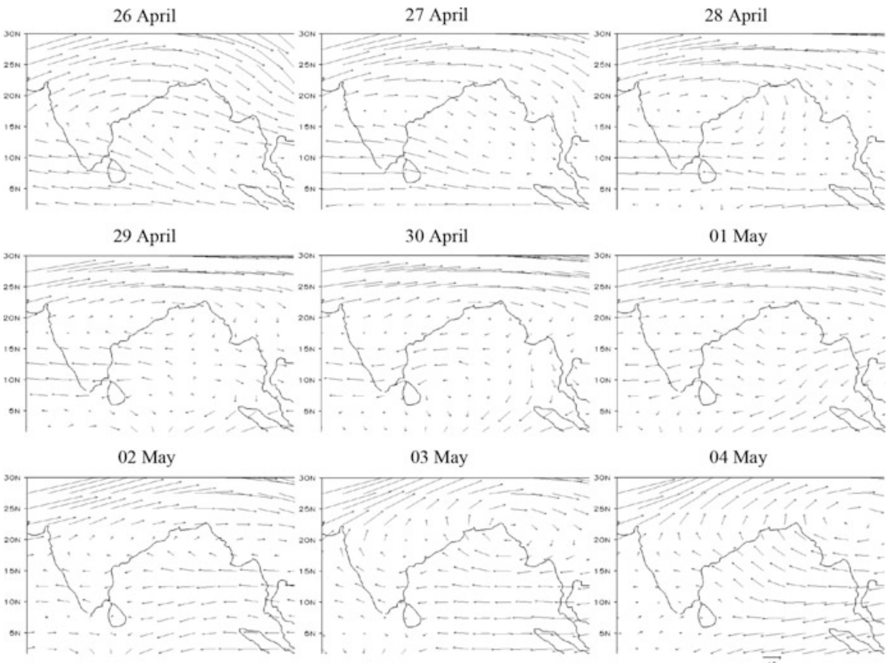

Fig. 12.8 As in Fig. 12.3, but for upper level winds (200 hPa; ms^{-1})

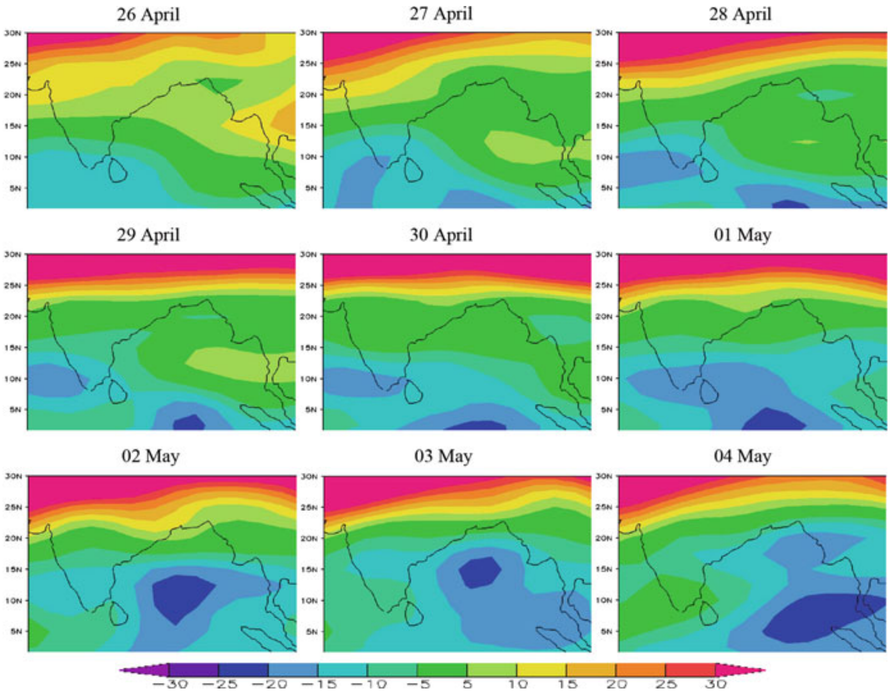

Fig. 12.9 As in Fig. 12.3, but for vertical wind shear (200–850 U; ms^{-1})

26 to May 04, 2019, over the BoB. The vertical wind shear is less on 26 April when initial low pressure system has developed as depression over the southern BoB. Later, the region of less vertical wind shear has spread over all the parts of BoB during the cyclone period. This less vertical wind shear has continuously provided the favorable condition for the intensification of cyclone Fani over the BoB.

12.4 Conclusions

The major conclusions of this study are as follows:

- The cyclone Fani of April 2019 is among the most intense cyclones which formed over the southern BoB and crossed the Indian mainland.
- It is distinctive in terms of its location of origin, direction of track, and landfall location.
- It is the most intense cyclone during the satellite era (1965 onwards), which has formed during the pre-monsoon season and crossed the Orissa state of Indian mainland.

- Various environmental conditions are favorable for the formation of initial low pressure system near the equator.
- For example, SST has been found approximately 30 °C over the large parts of BoB, which is sufficient for development of cyclonic system.
- Strong convective activities along with the active MJO have taken place during the storm period.
- Relative humidity is very high at mid-tropospheric level, which has released the latent heat and energized the system. Strong vertical motion has transported the moisture up to mid-tropospheric level.
- Presence of cyclonic vorticity at lower level and less vertical wind shear has helped in strengthening of system during the entire life period.
- It is believed that this comprehensive analysis of large-scale environmental conditions during the period of ESCS Fani will be helpful to understand the development and progress of future extreme TCs.
- Further, comparative studies may be conducted on the recent extreme cyclones of the BoB for their better understanding.

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