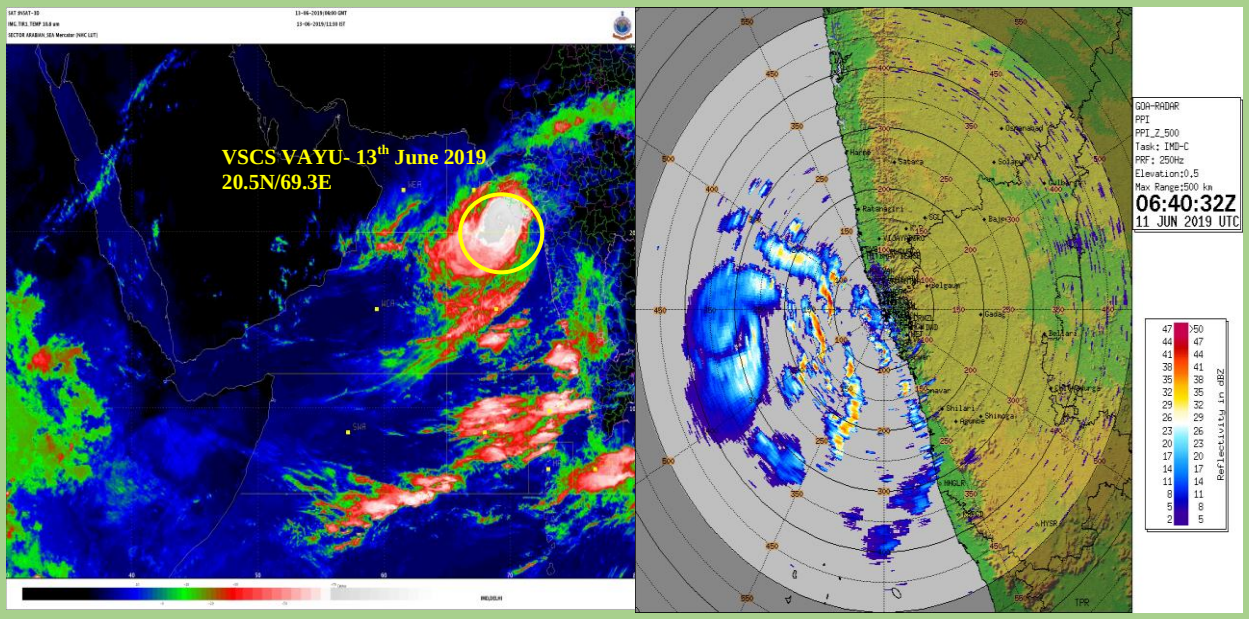
GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
INDIA METEOROLOGICAL DEPARTMENT

Very Severe Cyclonic Storm, 'VAYU' over the Arabian Sea (10 – 17 June 2019): A Report



Typical imagery from INSAT-3D of 13th June 2019 and Doppler Weather Radar, Goa of 11th June, 2019

Cyclone Warning Division

India Meteorological Department

New Delhi

July, 2019

Very Severe Cyclonic Storm "VAYU" over the Arabian Sea (10-17 June 2019)

1. Introduction

Very Severe Cyclonic Storm (VSCS) "VAYU" originated from a low pressure area (LPA) which formed over southeast Arabian Sea and adjoining Lakshadweep & eastcentral Arabian Sea (AS) in the morning (0300 UTC) of 09th June. It lay as a well-marked low pressure area (WML) over the same region in the same evening (1200 UTC). Under favourable environmental conditions, it concentrated into a Depression (D) over eastcentral & adjoining southeast AS in the early morning (0000 UTC) of 10th June. Moving north-northwestwards, it intensified into a deep depression (DD) over the same region by 0600 UTC and further into cyclonic storm (CS) "VAYU" around midnight (1800 UTC) of 10th June, 2019 over eastcentral & adjoining southeast AS. It then moved northwards and intensified into a severe cyclonic storm (SCS) in the evening (1200 UTC) of the 11th June and into very severe cyclonic storm (VSCS) in the same midnight (1800 UTC) over the eastcentral AS. It then moved north-northwestwards till 13th June and then westwards and weakened into an SCS in the early morning (0000 UTC) of 16th June, 2019 over northeast AS. It gradually started re-curving northeastwards from the evening (1200 UTC) of 16th June, and weakened into a CS in the same night (1500 UTC) over northeast AS. Thereafter, it moved east-northeastwards and weakened into a DD in the morning (0300 UTC) of 17th June and into a depression in the same afternoon (0900 UTC) over the over northeast AS. It further moved east-northeastwards and weakened into a well marked low pressure area over northeast AS and adjoining Saurashtra & Kutch in the midnight (1800 UTC) of 18th June. The observed track of VSCS Vayu is presented in **Fig.1.**

2. Salient Features:

The salient features of the system were as follows:

i. The cyclone, VAYU exhibited multiple re-curvatures in its track. It initially moved towards north-northwest and then re-curved towards west and then northeastwards.
ii. Climatologically, it is seen that 4 out of 5 SCS and above intensity storms crossing Gujarat coast in the month of June during 1891-2018 exhibited northeastwards re-curvature.
iii. The track length of the cyclone was 1862 km.
iv. The system skirted south Gujarat coast while moving from eastcentral AS to northeast AS during 13th – 14th June, 2019.
v. It had rapid intensification during 10th evening to 11th June evening, with increase in maximum sustained wind speed (MSW) from 30 knots at 1200 UTC of 10th to 55 knots at 1200 UTC of 11th June.
vi. The peak MSW of the cyclone was 140-150 kmph (80 knots) gusting to 165 kmph during 0600 UTC 0f 12th June to 0000 UTC of 14th June over the eastcentral AS. The lowest estimated central pressure was 970 hPa during the period (Fig.3a).

vii. Though it intensified upto VSCS with wind speed of 80 knots (140-150 kmph), it weakened over the Sea while moving towards north Gujarat coast. It crossed north Gujarat coast as a well marked low pressure area.

viii. The life period (D to D) of the system was 180 hours (7 days & 12 hours) against long period average (LPA) (1990-2013) of 140 hours (5 days & 20 hrs) for VSCS categories over AS during monsoon season.

ix. It moved with 12 hour average translational speed of 10.0 kmph against LPA (1990-2013) of 14.3 kmph for VSCS category over north Indian Ocean (Fig.3b).

x. The Velocity Flux, Accumulated Cyclone Energy (a measure of damage potential) and Power Dissipation Index (a measure of loss) were 16.6 $X10^2$ knots, 11.18 X 10^4 $knots^2$ and 7.82 $X10^6$ $knots^3$ respectively against long period average during 1990-2013 of 2.12 $X10^2$ knots, 1.4 X 10^4 $knots^2$ and 1.0 $X10^6$ $knots^3$ respectively over the Arabian Sea.

xi. The track forecast errors for 24 and 48 hrs lead period were 67.5 and 125.9 km respectively against the average track forecast errors of 86.1 and 132.3km during last five years (2014-18) respectively. The track forecast skill was about 57% and 57% against the long period average (LPA) of 58% and 70% during 2014-18 for 24 and 48 hrs lead period respectively.

xii. The absolute error (AE) of intensity (wind) forecast for 24 and 48 hrs lead period were 6.6 and 11.9 knots against the LPA of 9.6 and 14.1 knots respectively

xiii. The system caused light to moderate rainfall at many places with isolated heavy to very heavy rainfall over Saurashtra & Kutch on 13th & 14th and over Gujarat region on 14th. It also caused light to moderate rainfall at many places with isolated heavy to very heavy falls over Kerala, coastal Karnataka and Konkan & Goa during 10th - 14th June.

xiv. As the cyclone skirted Gujarat coast, the core maximum wind due to the cyclone occurred over the Sea. However, the squally to gale wind speed from 45 kmph to 90 kmph occurred along & off Gujarat coast during 12th to 14thJune.

xv. A total of 61 national bulletins, 91 hourly bulletins and 32,28,156 Nos. of SMS were sent in association with the system.

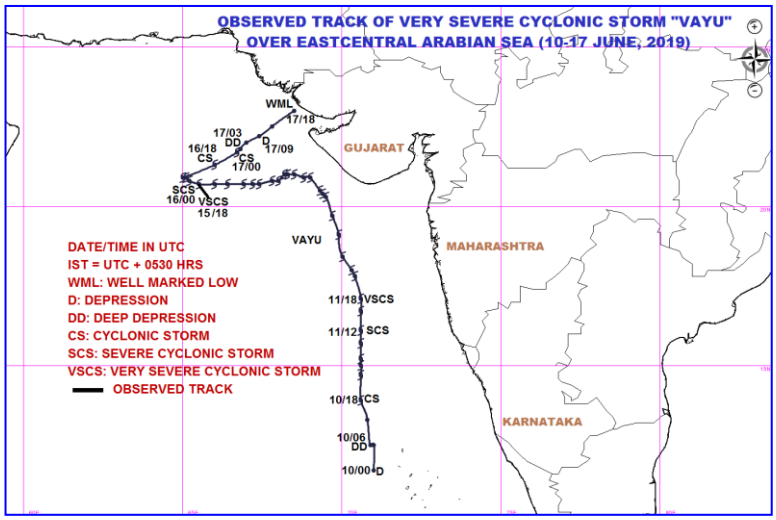


Fig.1 Observed track of VSCS VAYU (10-17 June, 2019) over Arabian Sea

2. Monitoring of VSCS, 'VAYU'

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean and the cyclone was monitored since 6th June about 4 days prior to cyclogenesis. The extended range outlook issued on 6th June, indicated that there is medium probability of cyclogenesis during later part of week 1 (07-13 June) over southeast & adjoining east-central AS and low probability of cyclogenesis during first half of week 2 (14-20 June) over northwest & adjoining west-central AS. Thus the cyclone was monitored & predicted continuously from 6th June onwards by IMD.

The cyclone was monitored with the help of available satellite observations from INSAT 3D and 3DR, polar orbiting satellites, and available ships & buoy observations in the region. The system was also tracked by IMD Doppler Weather Radars at Kochi, Goa, Mumbai and Bhuj as it moved from south to north. Various numerical weather prediction models developed by Ministry of Earth Sciences (MoES) institutions and dynamical-statistical models were utilized to predict the genesis, track, landfall and intensity of the cyclone. A digitized forecasting system of IMD was utilized for analysis and comparison of various model guidance, decision making process and warning product generation.

3. Brief life history

3.1. Genesis

At 0300 UTC of 9th, the sea surface temperature (SST) was 31˚C over central and south AS. The Tropical Cyclone Heat Potential (TCHP) was around 100-110 KJ/cm^2 over the system area. It was less than 60 KJ/cm^2 to the north of 20^{0}N over Arabian Sea. Total Precipitable Water vapour (TPW) imageries indicated warm air advection into the system centre. The Madden Julian Oscillation (MJO) index lay in phase 3 with amplitude more than 1. It was favourable for enhancement of convection & cyclogenesis over AS. The low level relative vorticity was north-south oriented and was around 50-70 x10^{-5}sec^{-1} over southeast AS and was extending upto 200 hPa level in association with the Inter Tropical Convergence Zone (ITCZ) and consequently the southwest monsoon activity over the region. The lower level convergence was about 20 x10^{-5}sec^{-1} over southeast AS. The upper level divergence was about 30x10^{-5}sec^{-1} over southeast AS. The vertical wind shear was moderate (20 kt) over the southeast AS. It was decreasing towards north and towards Oman coast. The upper tropospheric ridge ran along 19^{0}N. Under these favourable conditions, an LPA formed over southeast AS and adjoining Lakshadweep area & eastcentral AS at 0300 UTC of 9th.

At 0000 UTC of 10th, similar Sea conditions prevailed. The MJO index lay in phase 3 with amplitude more than 1. The low level relative vorticity increased in past 24 hours and was around 200 x10^{-5}sec^{-1} to the west of the system centre. Positive vorticity was extending upto 200 hPa level. The lower level convergence increased and was about 30 x10^{-5}sec^{-1} to the west of the system centre. The upper level divergence increased and was about 40 x10^{-5}sec^{-1} to the southwest of the system. The vertical wind shear decreased and was low to moderate (10-20 knots) over the system area. It was decreasing towards north and towards Oman coast. The upper tropospheric ridge ran along 20°N. Under these conditions, the system concentrated into a depression over southeast AS and adjoining Lakshadweep & eastcentral AS at 0000 UTC of 10th June, 2019 near latitude 11.7°N and longitude 71.0°E.

3.2. Intensification

At 0600 UTC of 10th, similar sea conditions and MJO state prevailed. TPW imageries indicated warm air advection into the system centre. The low level relative vorticity was the same around 200 $x10^{-5}sec^{-1}$ to the west of the system centre extending upto 200 hPa level. The lower level convergence increased and was about 50 $x10^{-5}sec^{-1}$ to the southwest of the system centre. The upper level divergence was about 30 $x10^{-5}sec^{-1}$ to the west of the system centre. The vertical wind shear was low to moderate (10-20 knots) over the system area. It was decreasing towards the north. The upper tropospheric ridge ran along 20°N. The system was lying in the outer periphery of the anticyclone over central parts of India. Under these conditions the depression moved northwards and intensified into a DD at 0600 UTC of 10th near 12.5°N/70.9°E over eastcentral and adjoining southeast AS & Lakshadweep area.

At 1800 UTC of 10th, similar Sea and environmental conditions prevailed, the system moved north-northwestwards, intensified into a CS and lay centered near 13.9°N/70.6°E over eastcentral & adjoining southeast AS.

At 1200 UTC of 11th, similar Sea conditions prevailed. MJO lay in phase 3 with amplitude more than 1. The TPW imageries **(Fig. 2)** indicated warm air advection to the system centre. The low level relative vorticity was around $250x10^{-5}sec^{-1}$ around the system centre extending upto 200 hPa level. The lower level convergence increased and was about $40x10^{-5}sec^{-1}$ to the southwest of the system centre. The upper level divergence decreased and was about $20x10^{-5}sec^{-1}$ to the southwest of the system centre. The vertical wind shear was moderate to high (20-25 knots) over the system area. However, it decreased towards north. The upper tropospheric ridge ran along 20°N. The system was lying in the outer periphery of the anticyclone over central parts of India. Under these conditions, the system moved nearly northwards, intensified into an SCS and lay centered near 16.1°N/ 70.6°E over eastcentral AS.

At 1800 UTC of 11th, similar Sea conditions prevailed. MJO lay in phase 3 with amplitude more than 1. The low level relative vorticity was around $250x10^{-5}sec^{-1}$ around the system centre extending upto 200 hPa level. The lower level convergence increased and was about $40x10^{-5}sec^{-1}$ to the southwest of the system centre. The upper level divergence is about $20x10^{-5}sec^{-1}$ to the southwest of the system centre. The vertical wind shear was moderate to high (20-25 knots) over the system area. However, it decreased towards north. The upper tropospheric ridge ran along 20°N. The system lay in the periphery of the anticyclone over central parts of India. Under these conditions, the system moved nearly northwards, intensified into a VSCS and lay centered near 17.5°N/70.6°E over eastcentral AS.

At 0300 UTC of 12th, the MJO lay in phase 3 with amplitude more than 1. Considering the environmental conditions, the SST was 31˚C over central and south AS. However, it was decreasing to 29-30˚C near Gujarat coast. The TCHP was around 70-90 KJ/cm^2 over the system area. TPW imageries indicated warm air advection into the core of the system. The low level relative vorticity was around 250 $x10^{-5}sec^{-1}$ around the system centre extending upto 200 hPa level. The lower level convergence increased and was about 50 $x10^{-5}sec^{-1}$ to the south of the system centre. The upper level divergence also increased and was about 50 $x10^{-5}sec^{-1}$ to the southwest of the system centre. The vertical wind shear was moderate to high (20-25 knots) over the system area. However, it decreased towards north. The upper tropospheric ridge ran along 21°N. The system lay in the outer periphery of the anticyclone over central parts of India. Another anticyclone was lying over Saudi Peninsula. Under these conditions, the westward component of movement gradually increased. The system maintained it's intensity of VSCS, moved

north-northwestwards and lay centered near 18.0°N/ 70.3°E over eastcentral AS. At 0900 UTC, favorable conditions also led to slight intensification of the system.

At 0300 UTC of 13th, the MJO lay in phase 4 with amplitude greater than 1. Similar Sea conditions prevailed. The TPW imageries indicated warm moist air advection into the core of the system. The low level relative vorticity increased and was around 300x10^{-5}sec^{-1} around the system centre extending upto 200 hPa level. The lower level convergence was about 30 x10^{-5}sec^{-1} to the south of the system centre. The upper level divergence was about 30 x10^{-5}sec^{-1} to the southwest of the system centre. The vertical wind shear was low (10-15 knots) over the system area. The upper tropospheric ridge ran along 22°N. The anticyclone over Saudi Arabian Peninsula started influencing the system. It thus moved north-northweswards. The favourable environmental conditions helped the system to maintain it's intensity and it lay as a VSCS near 20.4°N/69.4°E over northeast & adjoining eastcentral AS. The system skirted south Gujarat coast while moving from eastcentral AS to northeast AS during 13th – 14th June, 2019 with gradual increase in westward component of movement. From 1200 UTC of 13th onwards, the system exhibited nearly westwards movement under the influence of anticyclone over Saudi Arabian Peninsula till 0900 UTC of 16th.

At 0300 UTC of 14th, similar conditions w.r.t. MJO, SST and TCHP continued. TPW imageries indicated warm air advection into the core of the system. However, dry air prevailed to the northwest of the system. The low level relative vorticity decreased and was around 250x10^{-5} sec^{-1} to the south of the system centre. It was extending upto 200 hPa level. The lower level convergence decreased significantly and was about 15x10^{-5} sec^{-1} around the system centre. The upper level divergence increased and was about 30x10^{-5} sec^{-1} to the south of the system centre. The vertical wind shear was low (10-15 knots) over the system area. The upper tropospheric ridge ran along 22°N. The system was under the influence of the anticyclone over Saudi Arabian Peninsula. Under these conditions, the system moved west-northwestwards, weakened slightly and lay centered near 21.0°N/68.3°E over northeast & adjoining eastcentral AS.

At 0000 UTC of 16th, the MJO lay in phase 4 with amplitude greater than 1. The SST was around 30-31˚c along Gujarat coast and adjoining northeast AS. It was less (around 28-30˚C) over western parts of northeast AS. The TCHP was around 70-80 KJ/cm^2 over the system area. TPW imageries indicated warm air advection into the system centre. However, dry air intrusion also started into the southwest sector of the system. The low level relative vorticity further decreased and was around 200x10^{-5} sec^{-1} to the south of the system centre. However, it persisted upto 200 hPa level. The lower level convergence was about 40 x10^{-5} sec^{-1} to the southwest of system centre. The upper level divergence was about 30x10^{-5} sec^{-1} to the southwest of the system centre. The vertical wind shear was high (25-30 knots) over the system area. The upper tropospheric ridge ran along 23°N. The system was steered by the anticyclone over Saudi Arabian Peninsula. Under these conditions, the system moved nearly westwards, weakened into an SCS and lay centered near 20.7°N/65.5°E over northeast & adjoining eastcentral AS. Similar conditions prevailed and the system moved nearly westwards till 0900 UTC of 16th.

Under unfavourable conditions like, decreased lower level convergence (20x10^{-5} sec^{-1} to the southwest of system centre), decreased upper level divergence (20 x10^{-5} sec^{-1} to the southwest of the system centre), high vertical wind shear (25-30 knots over the system area) and intrusion of dry air into the southwest sector of the system, it exhibited weakening. Consequently, the vertical extension of the system also decreased. The system came under the influence of lower & mid level westerlies. It then gradually started recurving northeastwards from 1200 UTC of 16th June, and weakened into a CS at 1500 UTC of 16th June over northeast AS.

At 0300 UTC of 17th, the MJO lay in phase 4 with amplitude greater than 1. The SST was around 30-31˚C over northeast AS and along Gujarat coast. The TCHP was around 50-70 KJ/cm^2 over the system area and less than 50 KJ/cm^2 along Gujarat coast. TPW imageries indicated that warm air advection is continuing to the system centre. However, dry air intrusion is taking place in its southwest sector leading to gradual weakening of the system. The low level relative vorticity decreased and was around 150 x10^{-5} sec^{-1} over the system centre. The lower level convergence was about 20 x10^{-5} sec^{-1} over the southwest of the system centre. The upper level divergence decreased and was about 10 x10^{-5} sec^{-1} to the southwest of the system centre. The vertical wind shear decreased and was moderate to high (15-25 knots) over the system area. The upper tropospheric ridge at 200 hPa ran along 26°N. The vertical extension reduced significantly. The system moved east-northeastwards under the influence of lower & mid level westerlies and weakened into a DD near 21.9°N/ 66.8°E over northeast AS & neighbourhood. Similar conditions ensued and the system further weakened into a D near 22.2°N/67.4°E over northeast AS & neighbourhood at 0900 UTC and into a WML over northeast Arabian Sea and adjoining areas of Saurashtra & Kutch at 1800 UTC of 17th June. Continuing to move further east-northeastwards, it crossed north Gujarat coast as a WML subsequently.

The best track parameters of the VSCS Vayu are presented in **Table 1.**

Table 1: Best track positions and other parameters of the Very Severe Cyclonic Storm "VAYU" over the Arabian Sea during 10th June – 17th June, 2019

Date	Time	Lat.	Long	T.No	MS	Estimated Central Pressure (hPa)	Pressure Drop	Grade
10/6/2019	**0000**	11.7	71.0	1.5	25	998	3	**D**
	0300	12.5	71.0	1.5	25	998	3	D
	0600	12.5	70.9	2.0	30	997	4	**DD**
	1200	13.3	70.8	2.0	30	996	5	DD
	1800	13.9	70.6	2.5	35	995	6	**CS**
	2100	14.2	70.6	2.5	35	994	7	CS
11/6/2019	0000	14.7	70.6	2.5	40	993	8	CS
	0300	15.0	70.6	2.5	40	992	9	CS
	0600	15.2	70.6	3.0	45	990	10	CS
	0900	15.7	70.6	3.0	45	988	12	CS
	1200	16.1	70.6	3.5	55	986	15	**SCS**
	1500	16.7	70.6	3.5	60	983	18	SCS
	1800	17.1	70.6	4.0	65	980	21	**VSCS**
	2100	17.5	70.6	4.0	70	977	24	VSCS
12/6/2019	0000	17.8	70.4	4.5	75	975	26	VSCS
	0300	18.0	70.3	4.5	75	973	28	VSCS
	0600	18.4	70.0	4.5	75	971	30	VSCS
	0900	18.8	69.9	4.5	80	970	32	VSCS
	1200	19.1	69.9	4.5	80	970	32	VSCS
	1500	19.5	69.8	4.5	80	970	32	VSCS

	1800	19.7	69.7	4.5	80	970	32	VSCS
	2100	20.0	69.6	4.5	80	970	32	VSCS
13/6/2019	0000	20.3	69.5	4.5	80	970	32	VSCS
	0300	20.4	69.4	4.5	80	970	32	VSCS
	0600	20.5	69.3	4.5	80	970	32	VSCS
	0900	20.7	69.1	4.5	80	970	32	VSCS
	1200	20.9	69.0	4.5	80	970	32	VSCS
	1500	20.9	68.8	4.5	80	970	32	VSCS
	1800	20.9	68.8	4.5	80	970	32	VSCS
	2100	20.9	68.6	4.5	80	970	32	VSCS
14/6/2019	0000	21.0	68.5	4.5	80	970	32	VSCS
	0300	21.0	68.3	4.5	75	973	28	VSCS
	0600	21.0	68.2	4.5	75	973	28	VSCS
	0900	20.9	68.1	4.5	75	973	26	VSCS
	1200	20.8	68.0	4.0	70	976	24	VSCS
	1500	20.8	67.9	4.0	70	976	24	VSCS
	1800	20.8	67.8	4.0	65	978	22	VSCS
	2100	20.8	67.5	4.0	65	978	22	VSCS
15/6/2019	0000	20.7	67.4	4.0	65	978	22	VSCS
	0300	20.7	67.4	4.0	65	979	21	VSCS
	0600	20.7	66.9	4.0	65	979	21	VSCS
	0900	20.7	66.7	4.0	65	980	21	VSCS
	1200	20.7	66.4	4.0	65	980	21	VSCS
	1500	20.7	66.3	4.0	65	980	21	VSCS
	1800	20.7	66.0	4.0	65	981	21	VSCS
	2100	20.7	65.9	4.0	65	981	21	VSCS
16/6/2019	**0000**	20.7	65.5	3.5	60	983	18	**SCS**
	0300	20.8	65.2	3.5	55	985	16	SCS
	0600	20.9	65.1	3.5	55	985	16	SCS
	0900	20.9	65.0	3.5	55	986	15	SCS
	1200	21.0	65.1	3.0	50	988	12	SCS
	1500	21.2	65.5	3.0	45	990	10	**CS**
	1800	21.3	66.0	2.5	40	992	8	CS
	2100	21.5	66.4	2.5	40	993	7	CS
17/6/2019	0000	21.7	66.7	2.5	35	995	6	CS
	0300	21.8	66.8	2.0	30	996	5	**DD**
	0600	22.0	67.0	2.0	30	997	5	DD
	0900	22.2	67.4	1.5	25	998	4	**D**
	1200	22.5	67.8	1.5	20	998	3	D
	1800	Weakened into a **WML** over northeast AS and adjoining areas of Saurashtra & Kutch.						

The TPW imageries during 10-18 June, 2019 are presented in **Fig.2**. These imageries indicate continuous warm and moist air advection from the southeast sector into the system, till 14th June. From 15th onwards, dry air incursion from northwest increased and warm moist air around the system centre decreased leading to weakening of the system from 15th onwards.

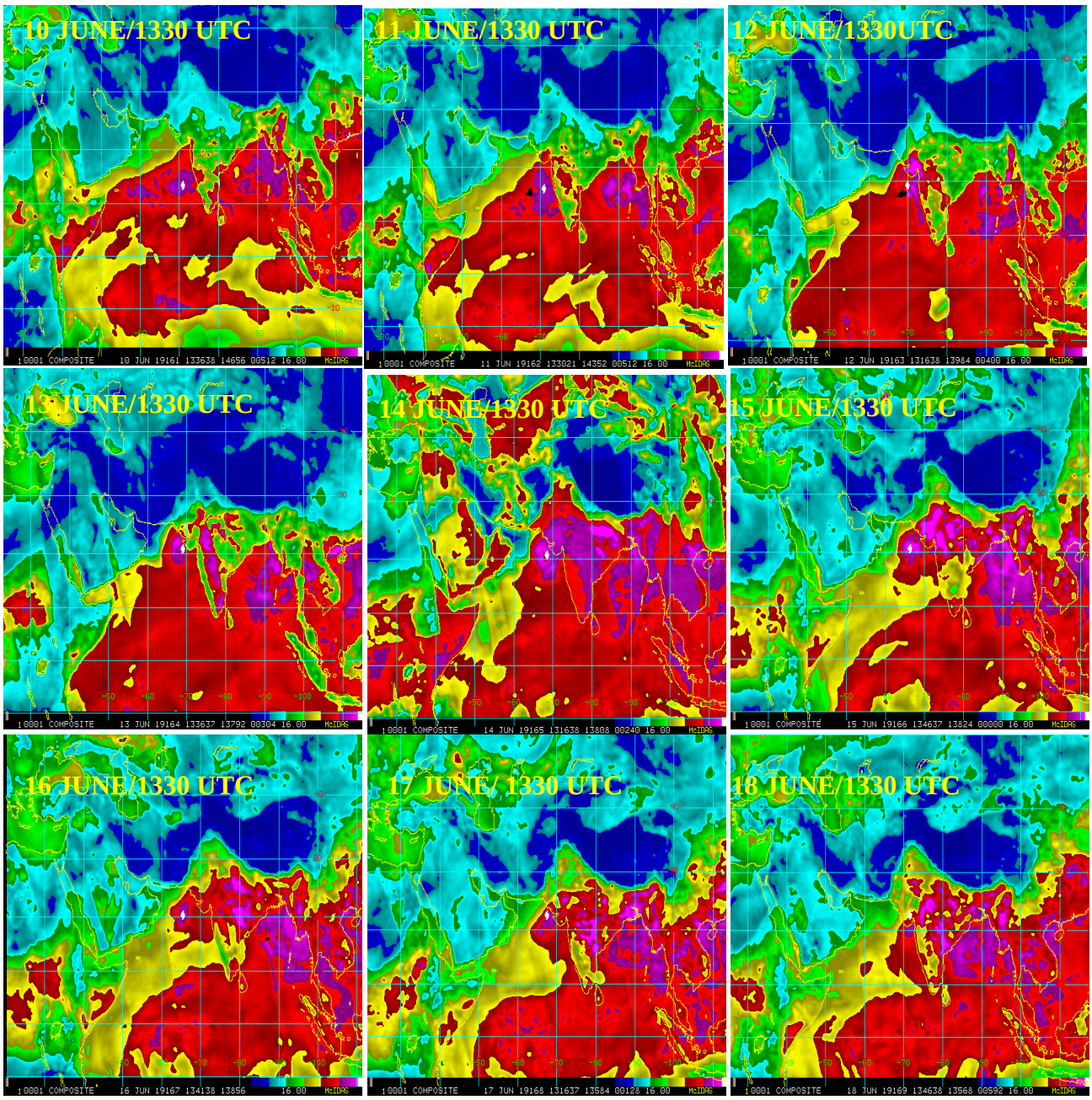


Fig. 2: Total Precipitable Water (TPW) imageries during VSCS VAYU (10-18 June, 2019

The wind speed in middle and deep layer around the system centre is presented in **Fig.3**. The deep layer wind shear around the system between 200 & 850 hPa levels remained moderate (10-20 knots) till 14th June and high (20-30 knots) during 14th to 18th June. The middle layer wind shear around the system between 500 & 850 hPa levels was moderate (10-15 kts) till 1200 UTC of 14th, increased becoming around 20 kts till

1200 UTC of 16th and decreased becoming 10-15 kts thereafter. The deep and middle level wind shear supported intensification during initial stages. From 14th onwards, the increased deep layer shear caused weakening of the system. From 1200 UTC of 16th onwards, the vertical extension of the system decreased significantly and the middle level shear caused weakening of the system.

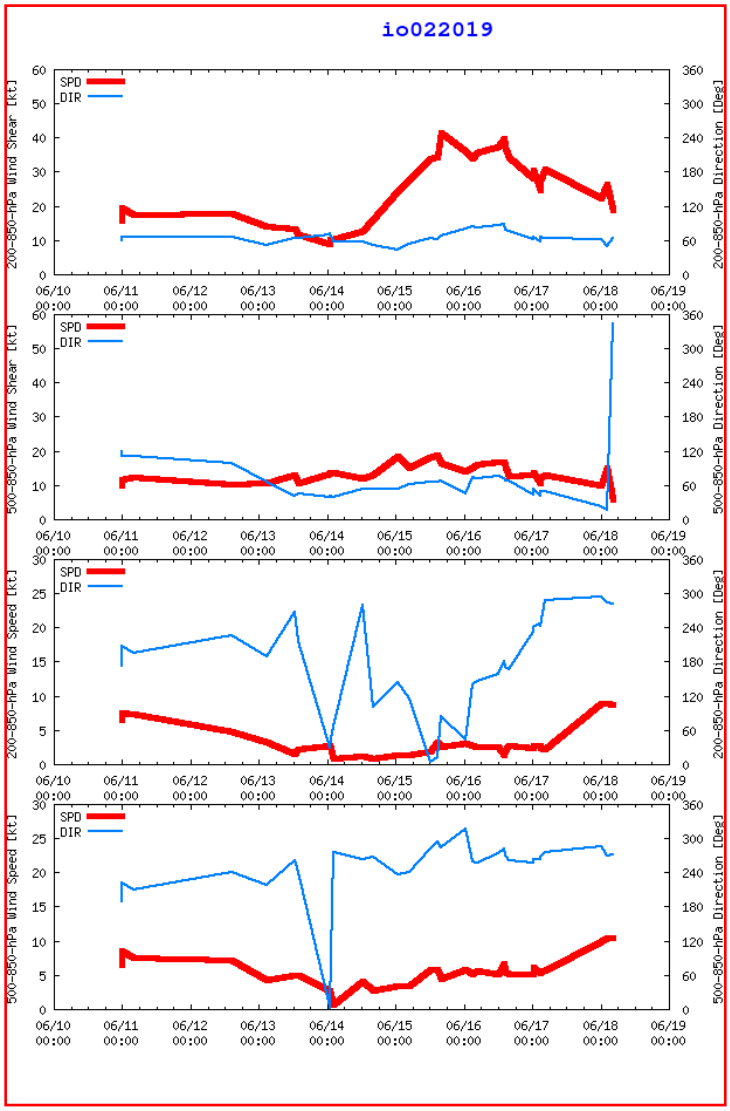


Fig.3 Mean wind shear and wind speed in the deep layer (between 200 & 850 hPa levels) and middle (between 500 & 850 hPa levels) during the life cycle of VSCS VAYU (09-17 June, 2019)

3.3. Movement

The deep-layer (between 200 & 850 hPa levels) mean winds indicate near northward movement till 13th and west-northwestward movement till 16th. As the vertical extension decreased significantly, the middle-layer mean winds accounted for the east-northeastwards movement from 16th onwards. The six hourly movement of VSCS Vayu is presented in **Fig.4a**. The 12 hour average translational speed of the cyclone was about 10.0 kmph and hence the cyclone was moving slower than the normal speed of 14.3 kmph.

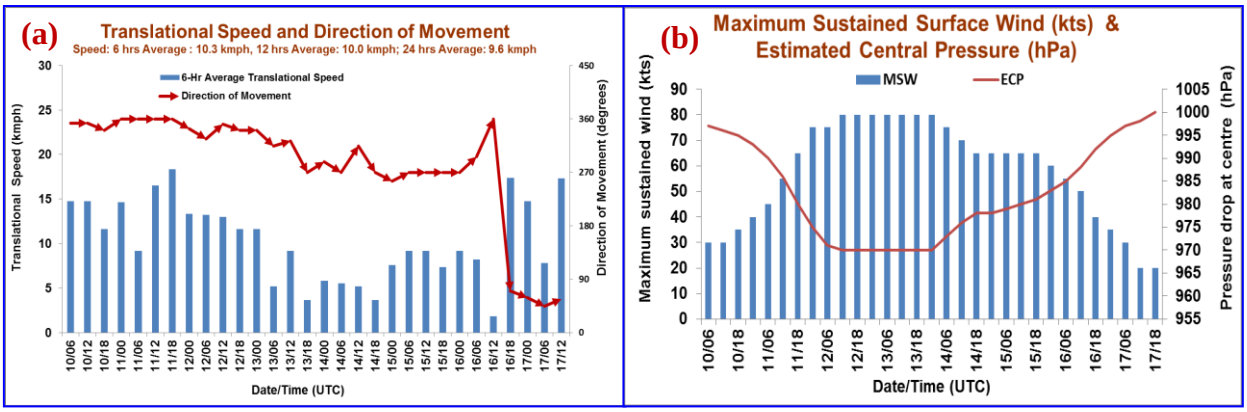


Fig. 4: (a) Translational speed & direction of movement and (b) Maximum sustained surface winds (kts) & Estimated Central Pressure of VSCS Vayu (10-17 June)

3.4. Maximum Sustained Surface Wind speed and estimated central pressure

The lowest estimated central pressure and the maximum sustained wind speed (MSW) are presented in **Fig.4b**. The system intensified gradually reaching peak MSW of 80 kts at 0900 UTC of 12th June. It maintained the peak MSW during 0900 UTC of 12th to 0000 UTC of 14th with the lowest estimated central pressure (ECP) of 970 hPa. Thereafter, it gradually decreased becoming 20 kts at 1200 UTC of 17th.

4. Climatological aspects

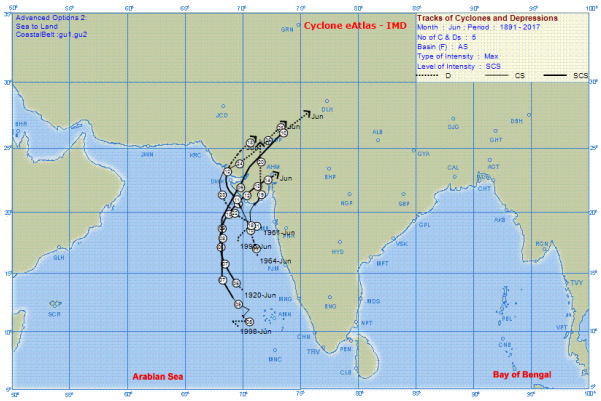


Fig.5: Tracks of severe cyclonic storms and above intensity storms crossing Gujarat coast in the month of June (1891-2018)

Climatologically, it is seen that 4 out of 5 SCS and above intensity storms crossing Gujarat coast in the month of June during 1891-2018 exhibited northeastward re-curvature. Tracks of severe cyclonic storms and above intensity storms crossing Gujarat coast in the month of June during 1891-2018 is presented in **Fig.5**.

5. Features observed through satellite and Radar

Satellite monitoring of the system was mainly done by using half hourly INSAT-3D and 3DR imageries. Satellite imageries of international geostationary satellites Meteosat-

8 & MTSAT and microwave & high resolution images of polar orbiting satellites DMSP, NOAA series, TRMM, Metops were also considered.

Typical INSAT-3D visible/IR imageries, enhanced colored imageries and cloud top brightness temperature imageries are presented in **Fig.6 a-d**. The system showed curved band pattern during genesis and growth stage upto the intensity of CS. Eye was seen during 12th to 14th June. The system was characterized by central dense overcast (CDO) pattern during 15th- 16th and shear pattern on 17th.

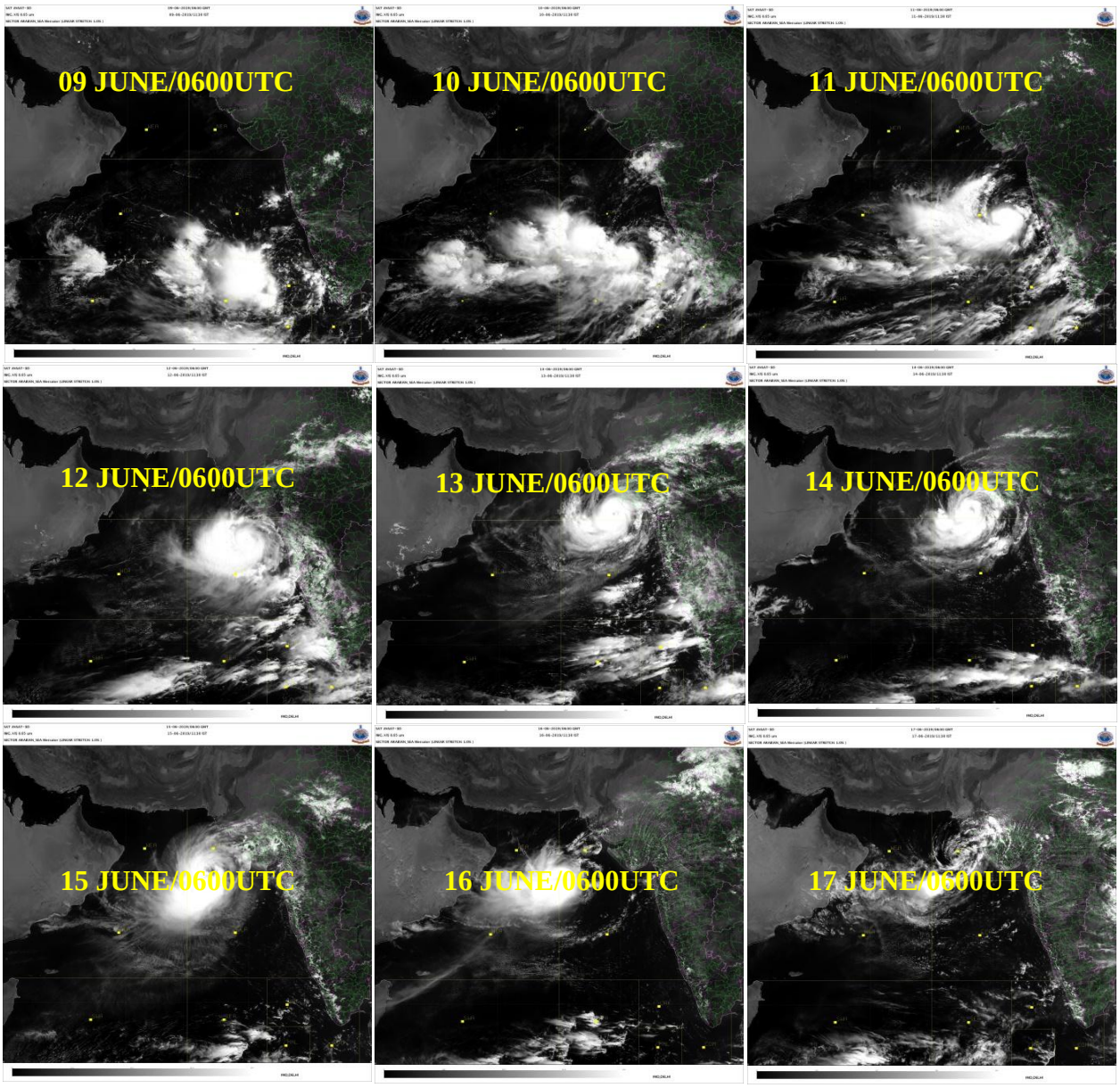


Fig. 6a: INSAT-3D visible imageries during life cycle of VSCS VAYU (09-17 June, 2019)

At 0300 UTC of 7th, scattered, low and medium clouds with embedded intense to very intense convection lay over south adjoining westcentral & extreme western parts of eastcentral AS. At 0300 UTC of 9th, broken low and medium clouds with embedded moderate to intense clouds lay over southeast and adjoining eastcentral AS in association with low level circulation over the area. Scattered low and medium clouds with embedded intense to very intense convection lay over south & adjoining central AS.

At 0300 UTC of 10th June, the intensity of the system was T 1.5. Broken low to medium clouds with embedded intense to very intense convection lay over southeast and adjoining eastcentral AS in association with the system. Satellite imageries indicated increase in convection and increased organisation of clouds around the system centre.

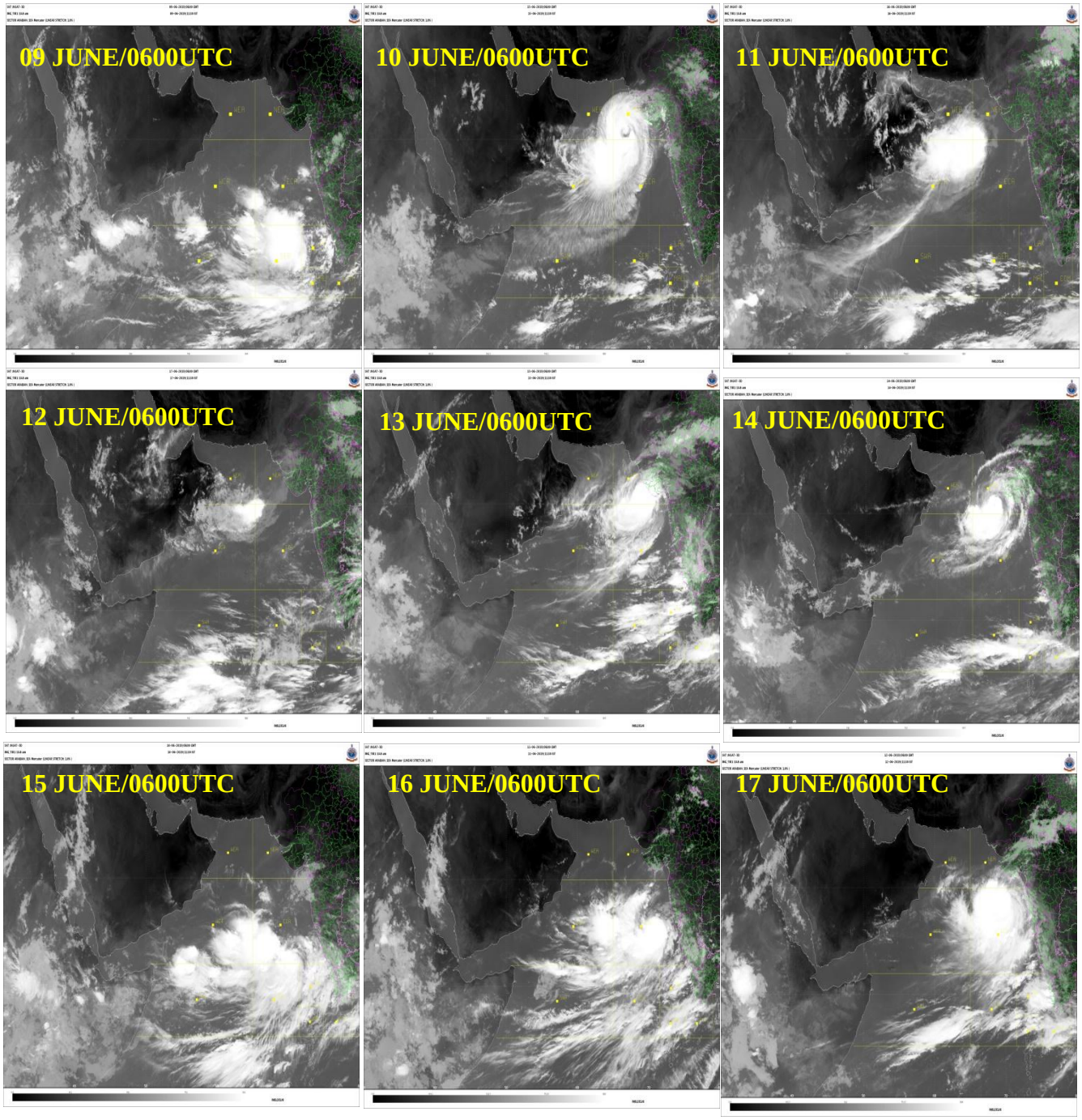


Fig. 6b: INSAT-3D IR imageries during life cycle of VSCS VAYU (09-17 June, 2019)

At 1200 UTC of 10th, the intensity of the system was T 2.0. Broken low to medium clouds with embedded intense to very intense convection lay over southeast and adjoining eastcentral AS. Imagery indicated further organization of cloud mass. Minimum cloud top temperature (CTT) was -93°C. At 1800 UTC of 10th, the intensity of the system was T 2.5. Broken low to medium clouds with embedded intense to very intense convection lay over southeast and adjoining eastcentral AS. There was further increase in convection and organisation of clouds around the system centre. Minimum CTT was -93°C. At 0300

UTC of 11th, the intensity of the system was T2.5. Broken low to medium clouds with embedded intense to very intense convection lay over southeast and adjoining eastcentral AS. Clouds were organized in Curved band pattern. At 1200 UTC of 11th, intensity of the system was T 3.5. Broken low to medium clouds with embedded intense to very intense convection lay over southeast and adjoining eastcentral AS. There was further increase in convection and organisation of clouds around the system centre.

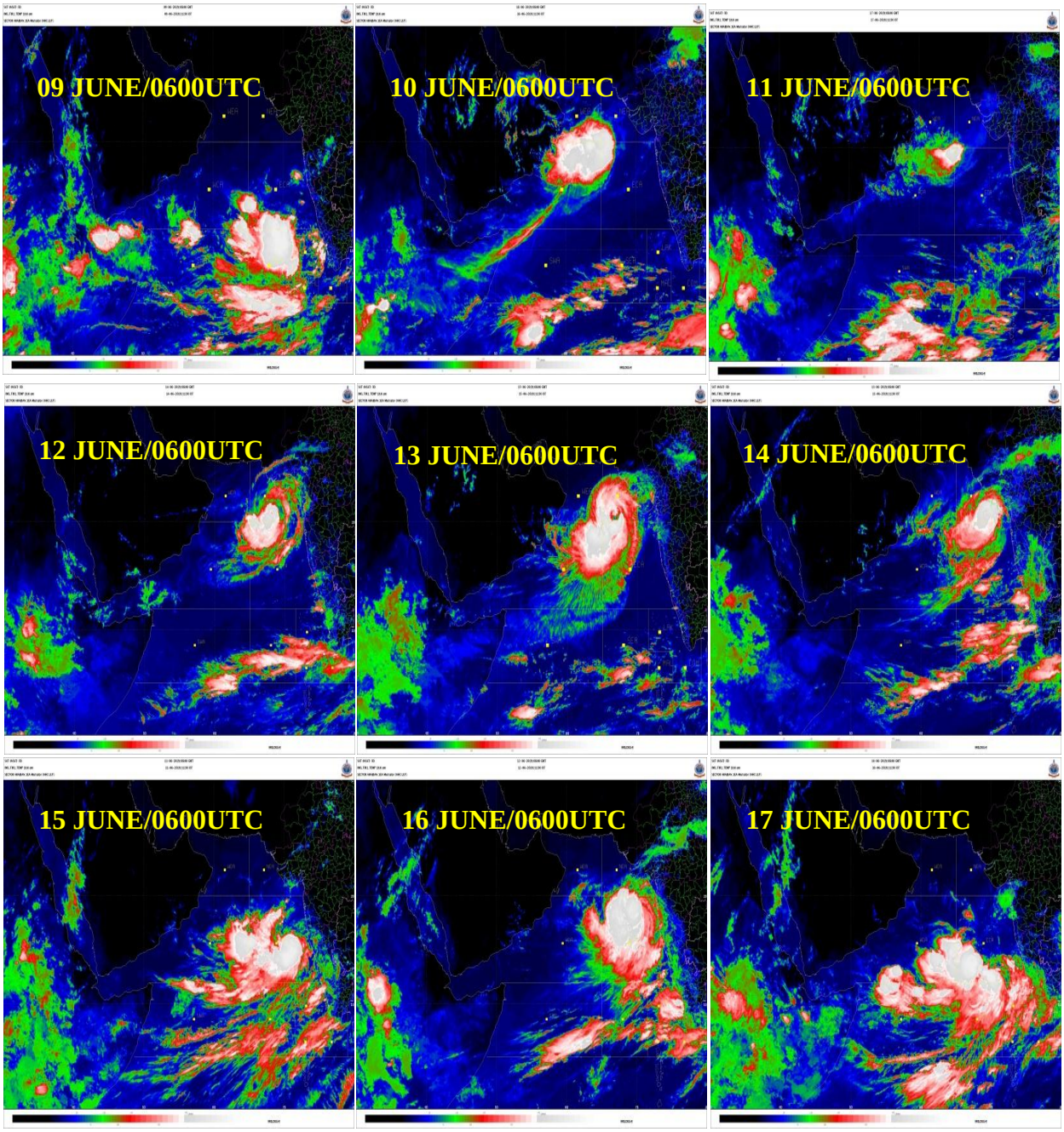


Fig. 6c: INSAT-3D enhanced colored imageries during life cycle of VSCS VAYU (09-17 June, 2019)

At 2100 UTC of 11th, the intensity of the system was T4.0. Broken low to medium clouds with embedded intense to very intense convection lay over southeast and adjoining eastcentral AS. At 0000 UTC of 12th, the intensity of the system was T4.5. Eye pattern was seen in the imagery. Broken low to medium clouds with embedded intense to very intense convection lay over eastcentral AS. At 0300 UTC of 12th, the intensity of the system was T4.5 with an embedded eye pattern. Broken low to medium clouds with embedded intense to very intense convection lay over eastcentral AS between 16.0°N &

19.5°N and 66.0°E & 72.0°E. At 0300 UTC of 13th, the intensity of the system was T4.5. Broken low to medium clouds with embedded intense to very intense convection lay over eastcentral AS between latitude 17°N & 21.5°N and longitude 64.5°E & 71.5°E.

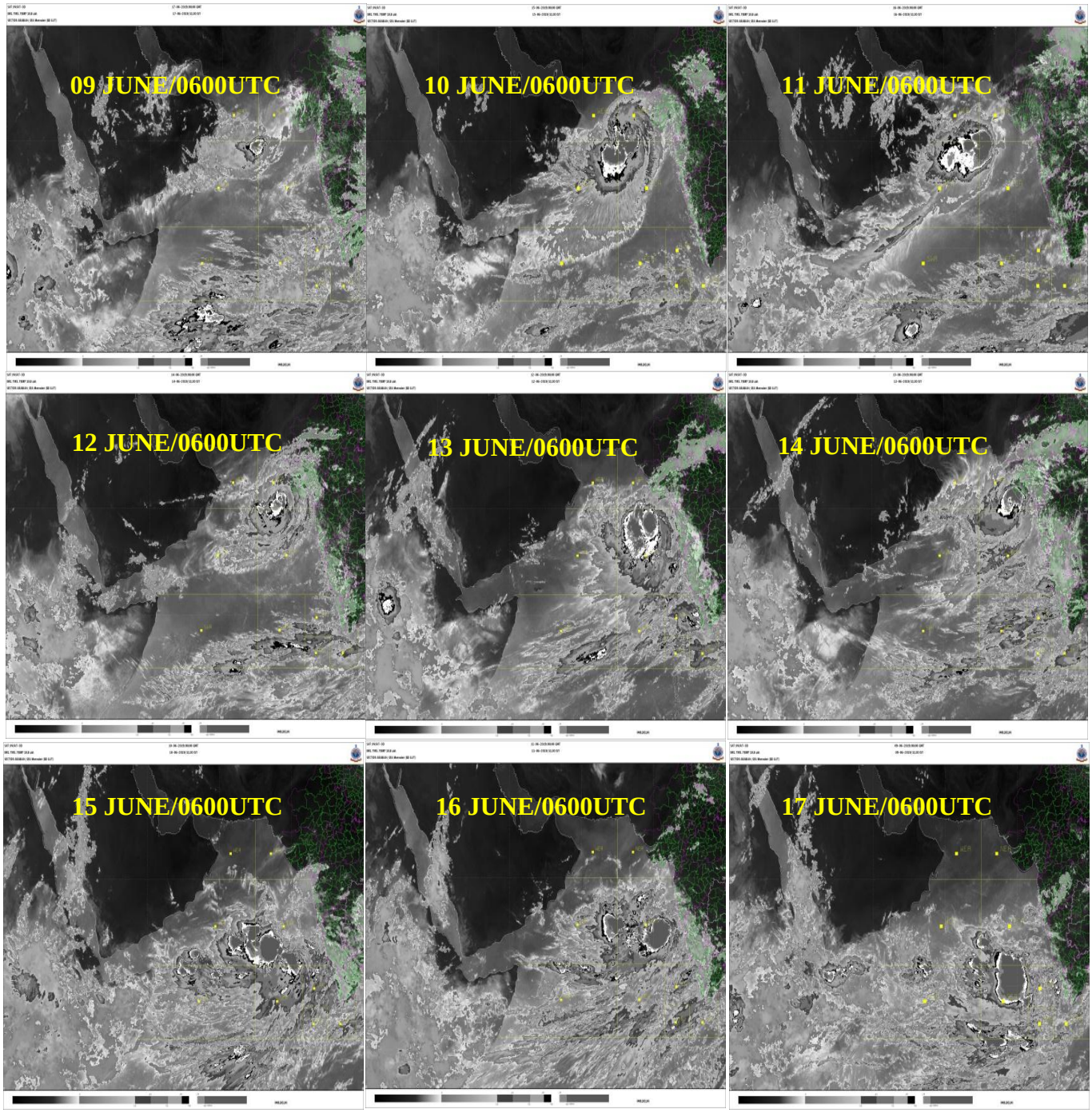


Fig. 6d: INSAT-3D cloud top brightness imageries during the life cycle of VSCS VAYU (09-17 June, 2019)

At 0300 UTC of 14th, the intensity of the system was T4.5. Broken low to medium clouds with embedded intense to very intense convection lay over eastcentral AS between latitude 17.5°N & 23.0°N and longitude 64.0°E to 70.5°E. At 0300 UTC of 15th, the intensity of the system was C.I. 4.5. Broken low to medium clouds with embedded intense to very intense convection lay over northeast and adjoining eastcentral AS between latitude 16.5°N & 23.0°N and longitude 65.0°E & 70.0°E and also over west Gujarat. Minimum Cloud Top Temperature (CTT) was -93°C. At 0000 UTC of 16th, the intensity of the system was T 3.5. Broken low to medium clouds with embedded intense

to very intense convection lay over northeast and adjoining eastcentral AS between latitude 18.0°N & 22.0°N and longitude 61.0°E & 66.0°E and also over west Gujarat. At 1500 UTC of 16th, the intensity of the system was T3.0/C.I. 3.5. Broken low to medium clouds with embedded intense to very intense convection lay over northeast and adjoining northwest & central AS between latitude 17.5°N & 21.5°N and longitude 62.0°E & 65.0°E. Maximum zone of convection lay to the southwest of the system centre. At 0300 UTC of 17th, the intensity of the system was C.I. 2.0. Broken low to medium clouds with embedded intense to very intense convection lay over northeast and adjoining northwest & central AS between latitude 19.0°N & 20.5°N and longitude 64.0°E & 66.5°E. Minimum CTT was -90°C.

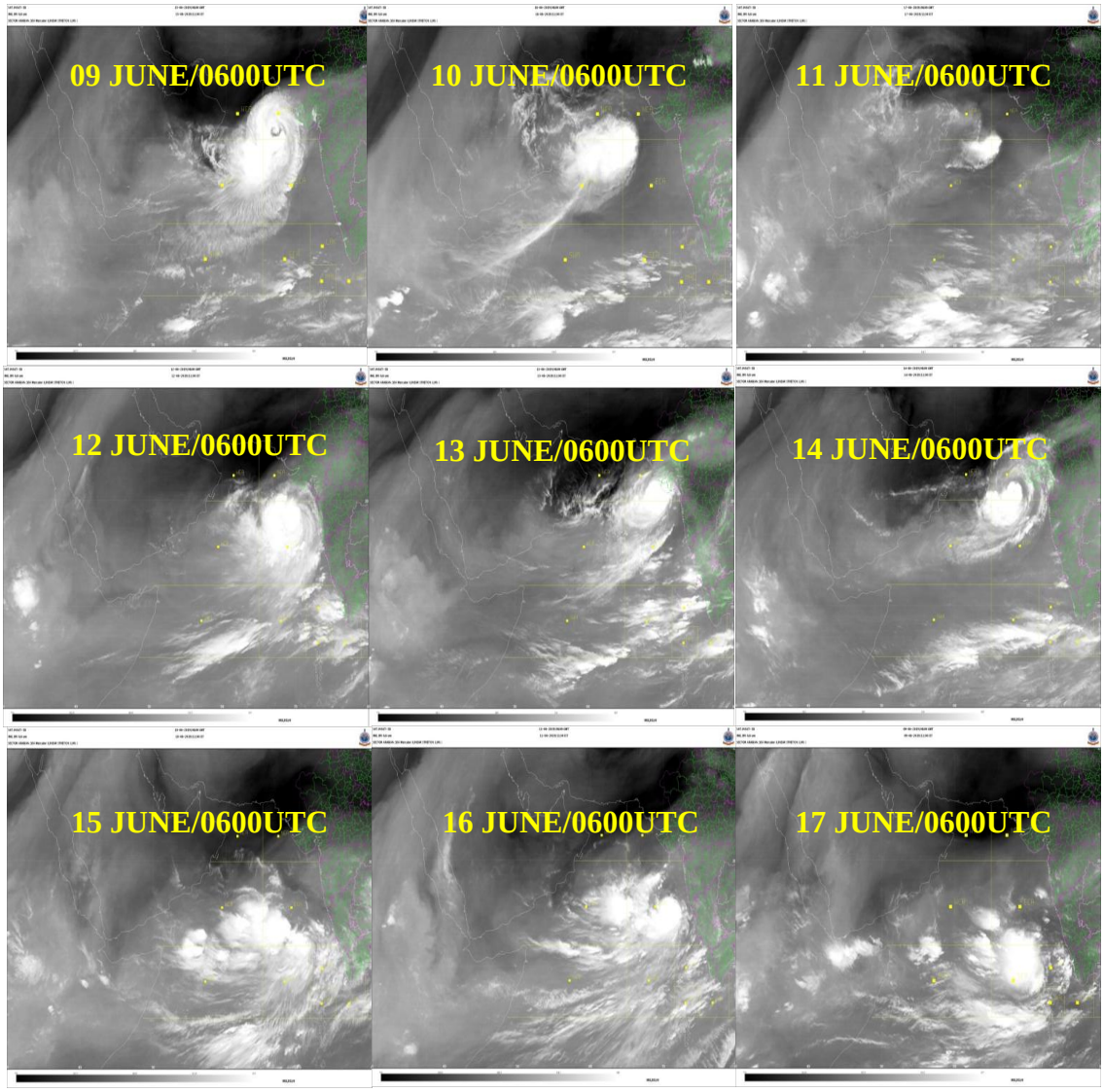


Fig. 6e: INSAT-3D Water Vapor imageries during life cycle of VSCS VAYU (09-17 June, 2019)

Typical imageries from SCATSAT are presented in **Fig. 6f.** The centre could be very correctly determined using SCATSAT imageries. However, intensity was not correctly estimated by SCATSAT winds. At 0300 UTC of 11th, the system was characterized by MSW of 40 kts and at 1500 UTC of 12th, it was having MSW of 80 kts. SCATSAT indicated MSW of 50 kts at 0400 UTC of 11th and 60 kts at 1600 UTC of 12th

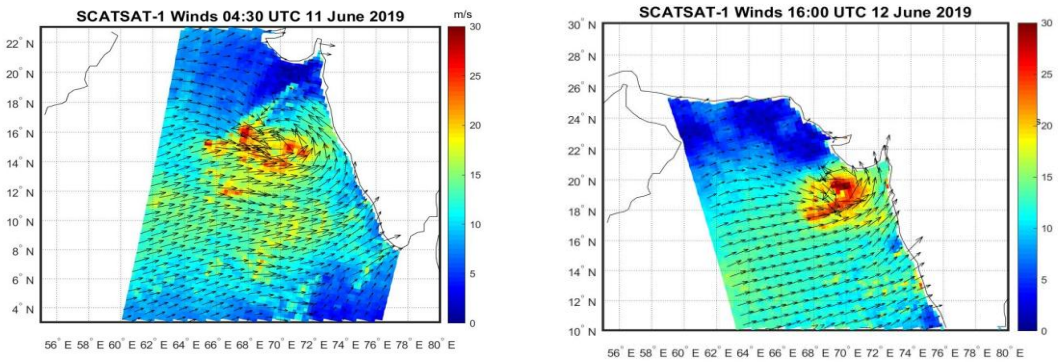
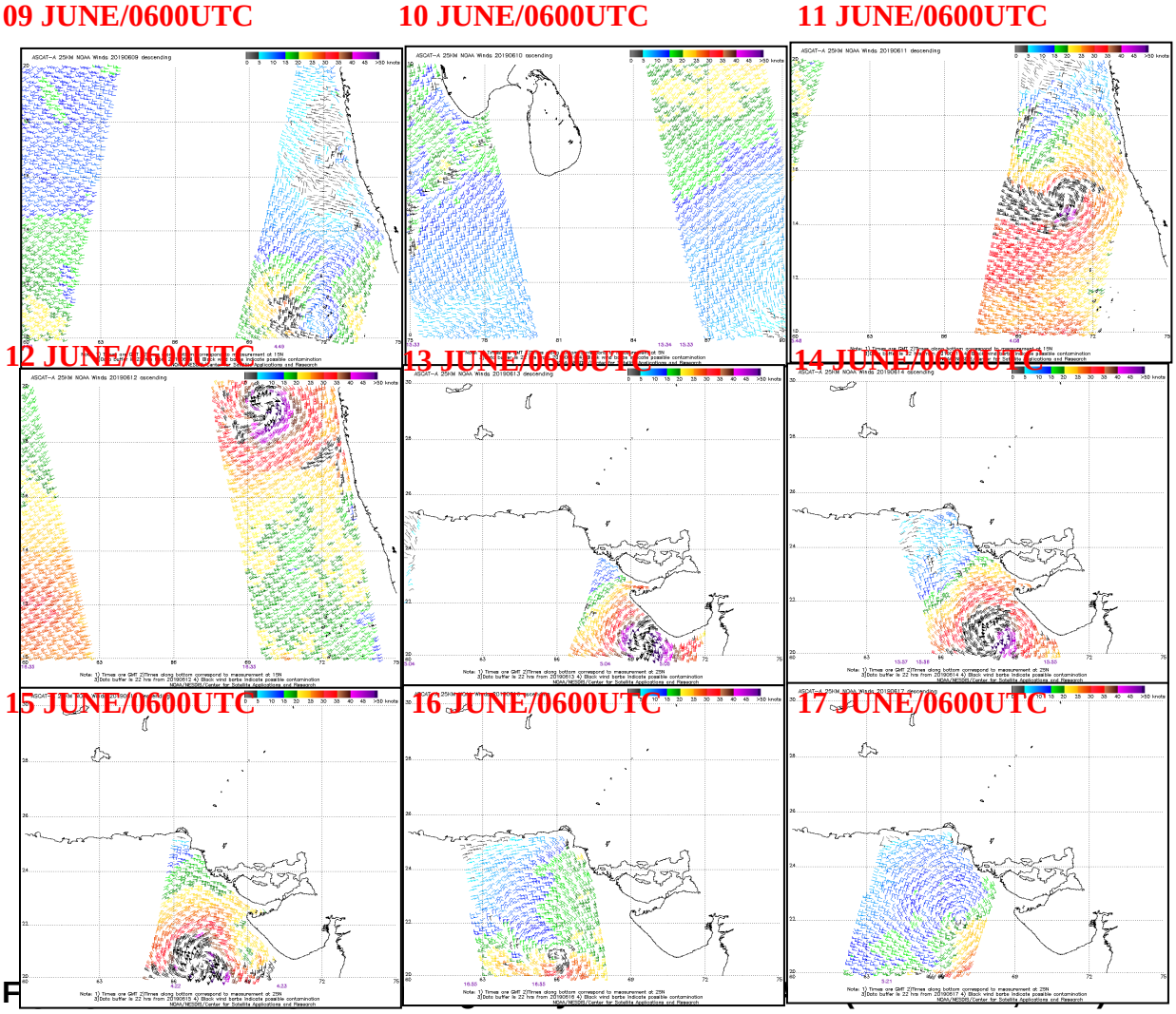


Fig. 6f: SCATSAT imageries during life cycle of VSCS VAYU (11-12 June, 2019)

Typical imageries from ASCAT are presented in Fig. 6g.



F

Typical microwave imageries are presented in **Fig. 6h**.

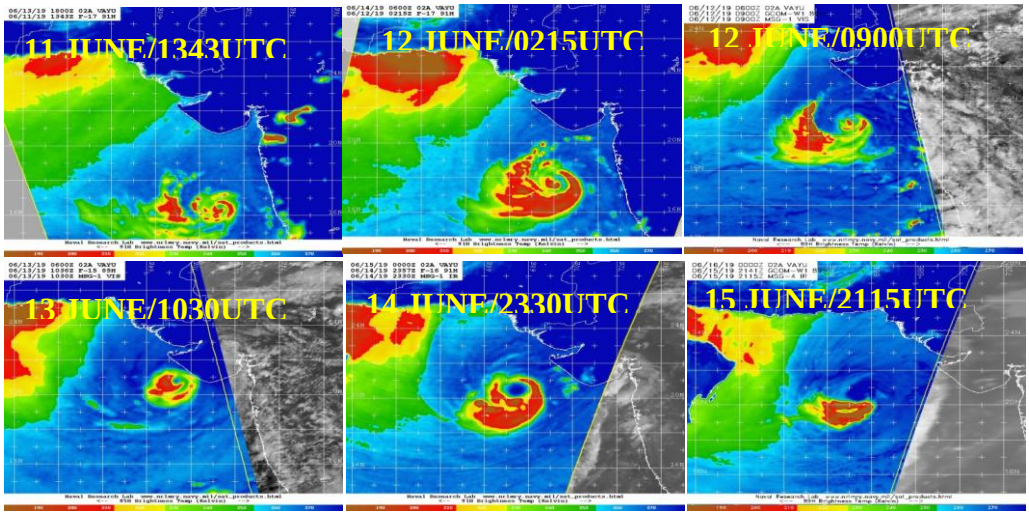


Fig. 6h: Microwave imageries during life cycle of VSCS VAYU (09-15 June, 2019)

5.2. Features observed through Radar

The system was captured by doppler weather radar (DWR) Kochi, DWR Goa, DWR Mumbai and DWR Bhuj during it's movement from southeast to northeast AS. Typical radar imageries from DWR Goa during 11th-12th June are presented in Fig.7 (a), that of Mumbai in Fig. 7 (b) and DWR Bhuj in Fig 7(c).

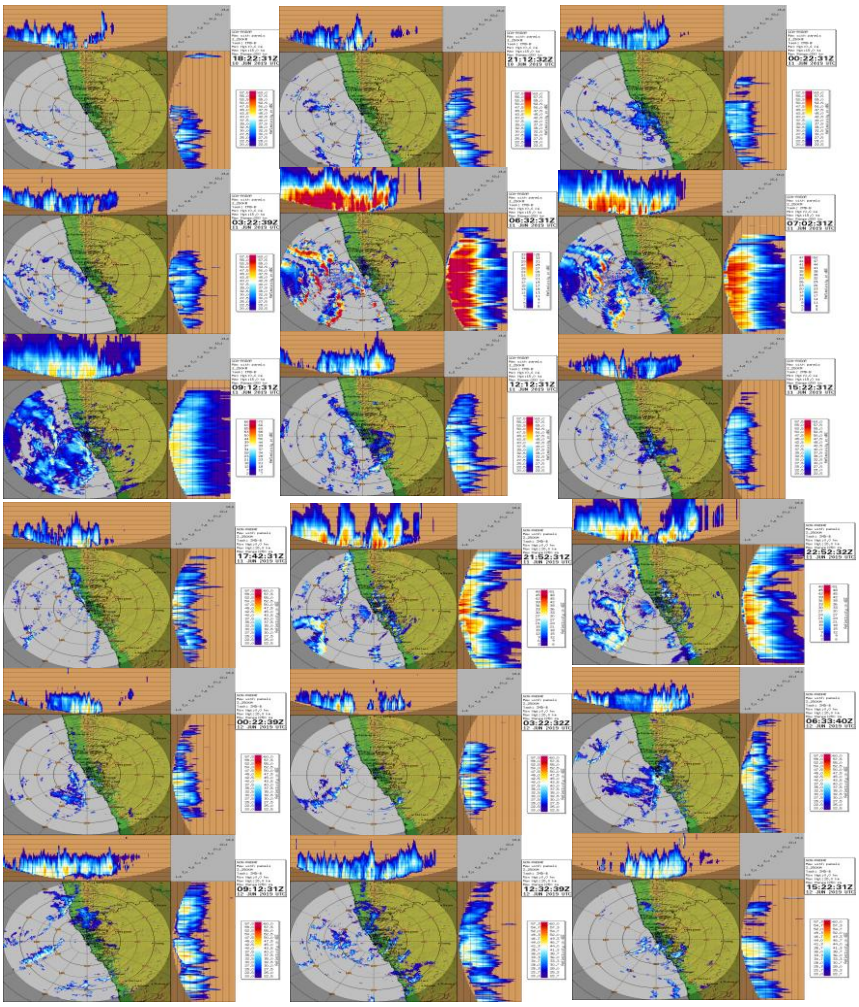


Fig.7(a): Typical Radar imagery from DWR Goa during 11-12 June of VSCS Vayu

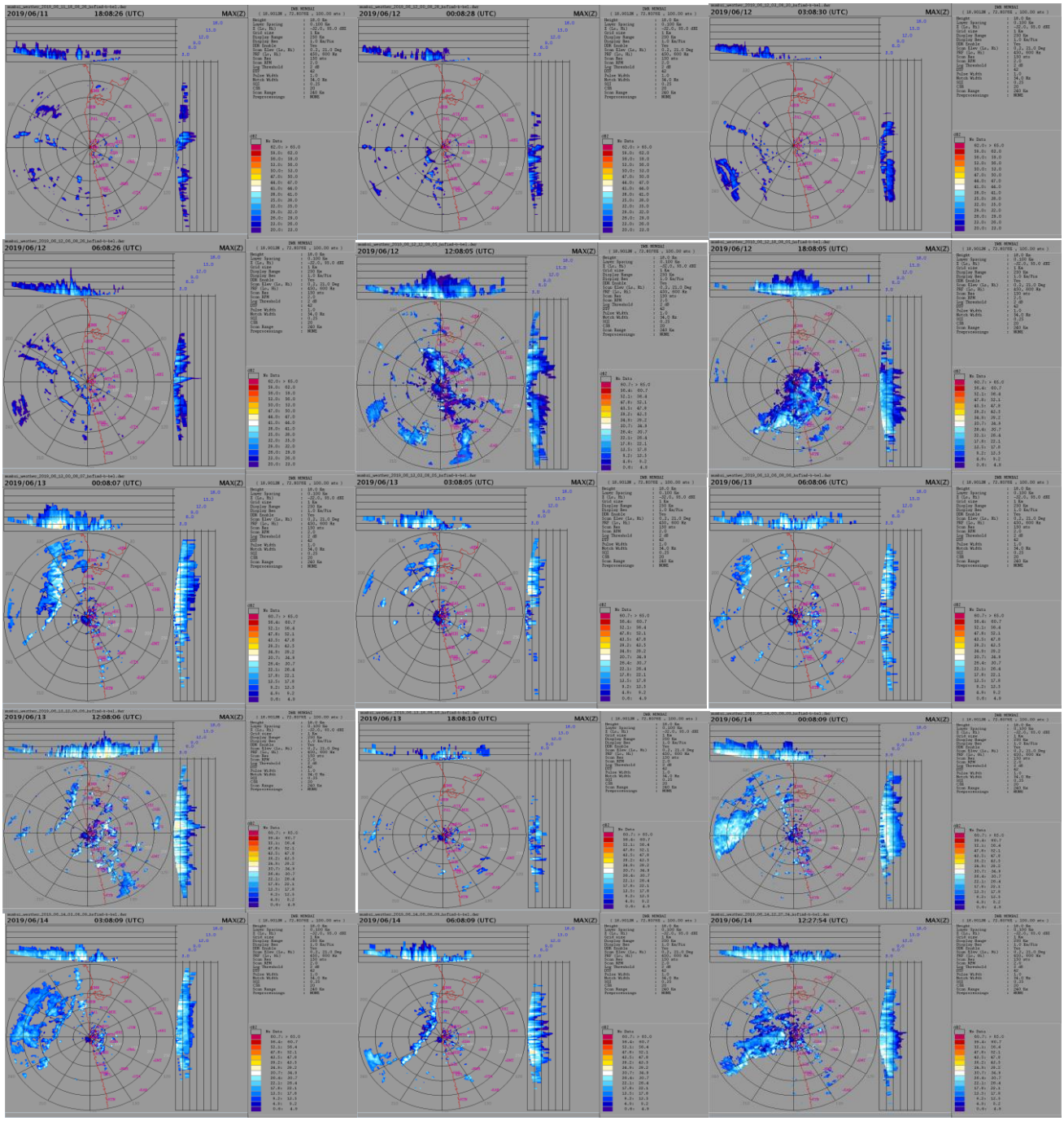


Fig.7(b):Typical Radar imagery from DWR Mumbai during 11-14 June of VSCS Vayu

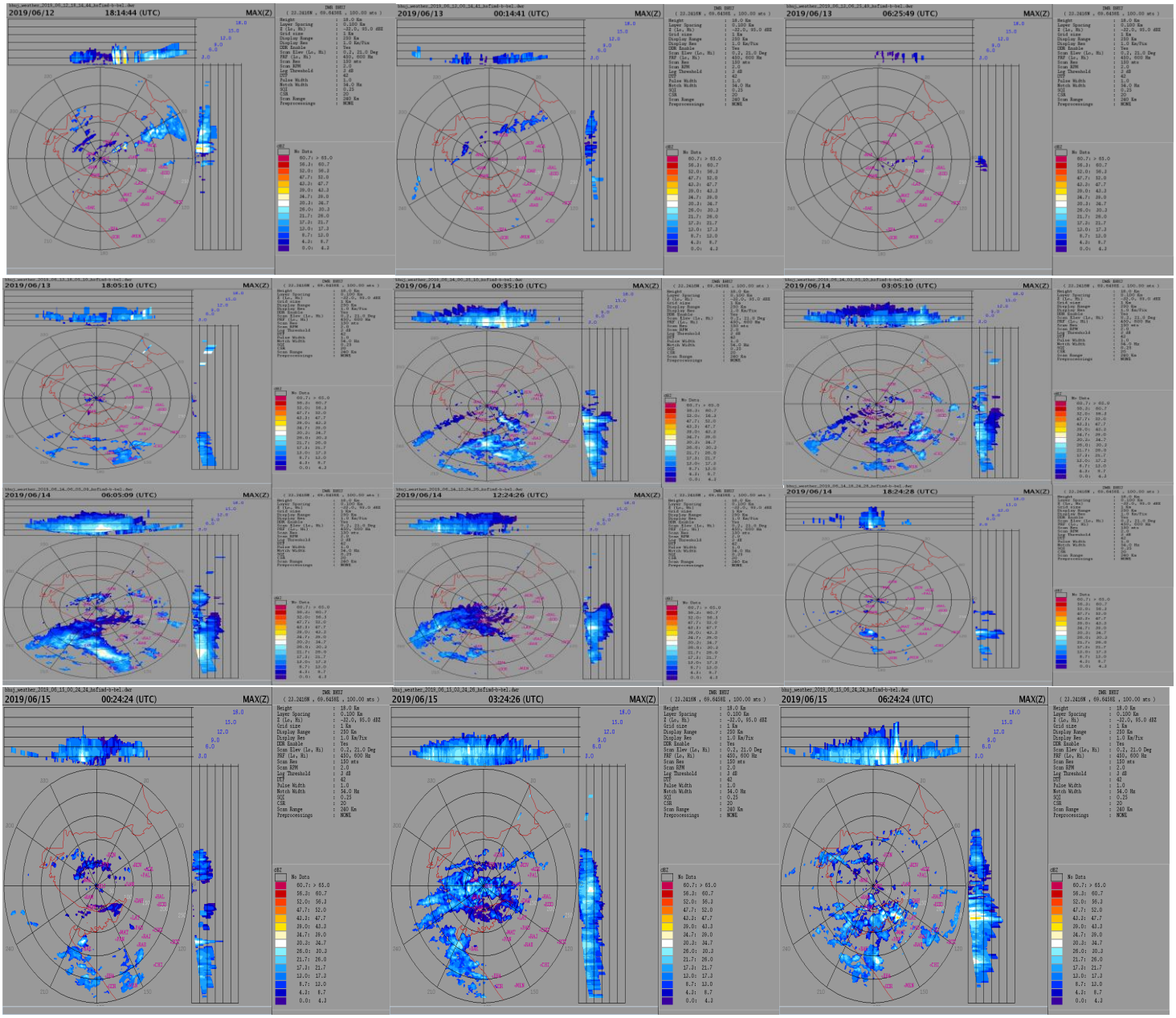


Fig.7(c): Typical Radar imagery from DWR Bhuj during 12-15 June of VSCS Vayu

6. Dynamical features

IMD GFS (T1534) Mean Sea Level Pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 10th-17th June are presented in Fig.8. GFS (T1534) analysis based on 0000 UTC of 10th June, indicates that the model over predicted the intensity of the system on 10th. IMD GFS indicated a cyclonic storm over eastcentral AS. However, the system lay as a depression over D over southeast & adjoining eastcentral AS and Lakshadweep at 0000 UTC of 10th.

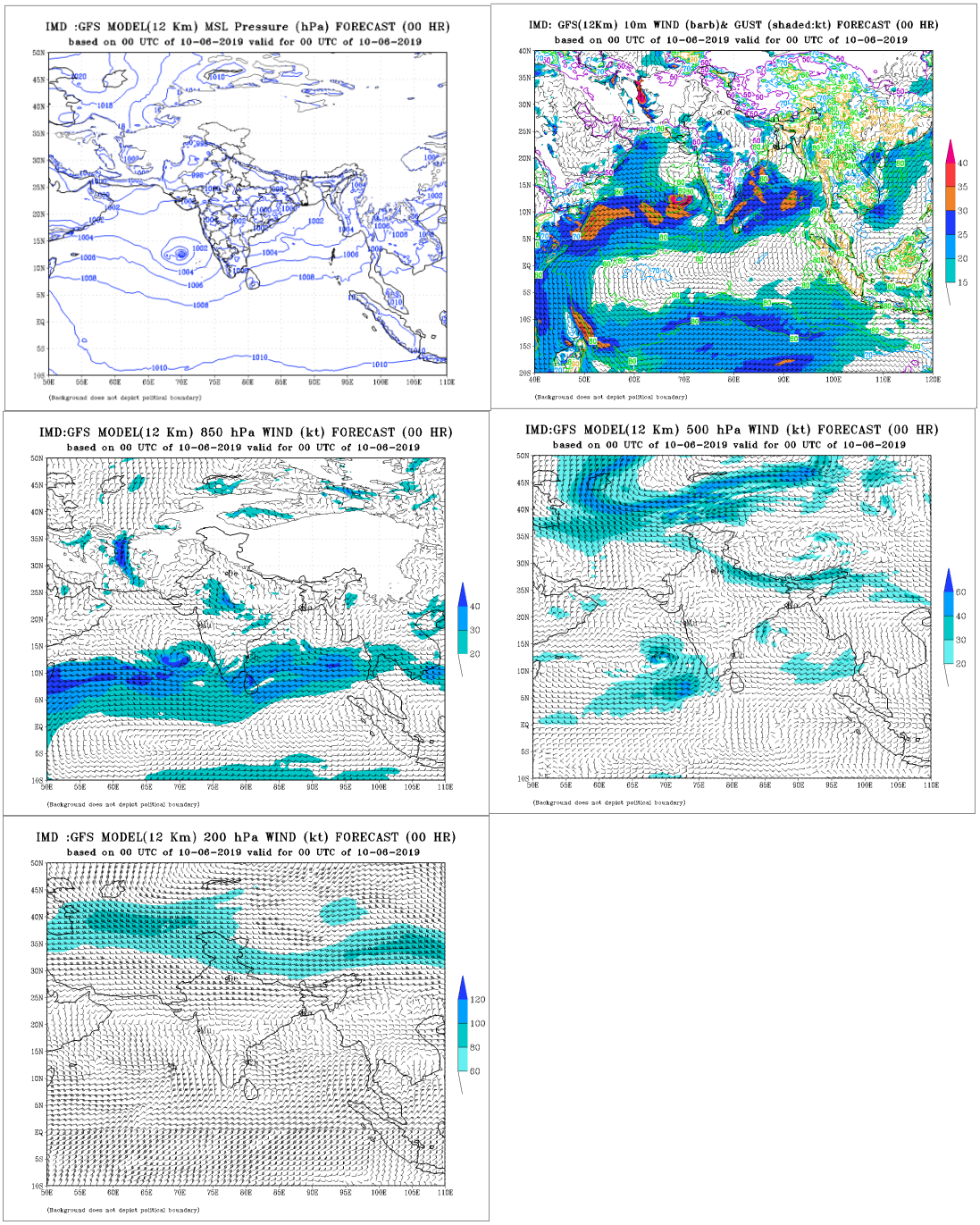


Fig. 8 (a): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 10th June 2019

GFS (T1534) analysis based on 0000 UTC of 11th June indicated a CS/SCS over eastcentral AS. The system lay as a CS over eastcentral AS at 0000 UTC of 11th. It also indicated near northwards movement in past 24 hours correctly. The upper tropospheric ridge was seen near 19^0N in association with anticyclone over central India.

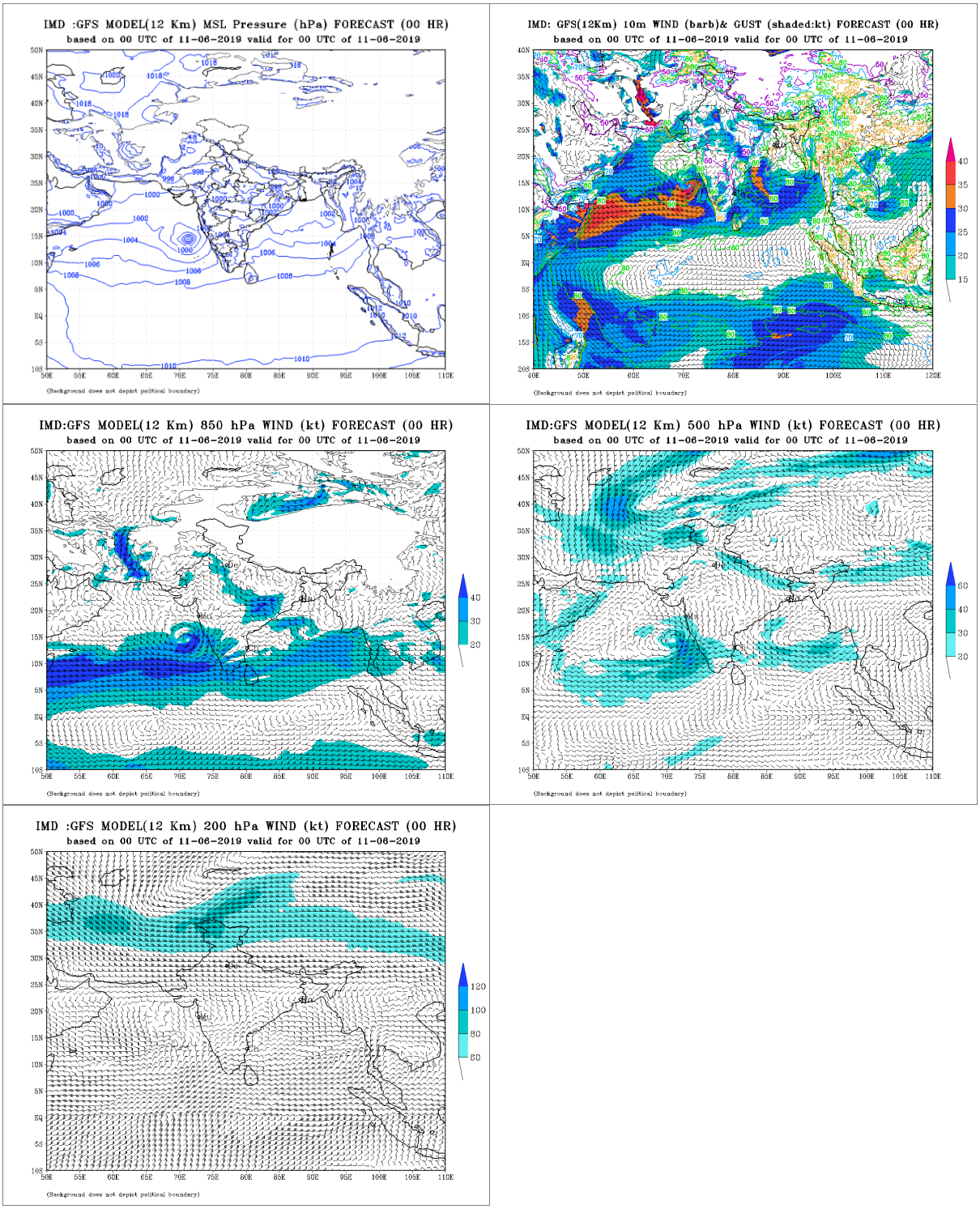


Fig. 8(b): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 11th June 2019

GFS (T1534) analysis based on 0000 UTC of 12th June indicated that the system moved nearly northwards and lay as an SCS/VSCS over eastcentral AS. The upper tropospheric ridge was seen near 20^{0}N in association with anticyclone over central India.

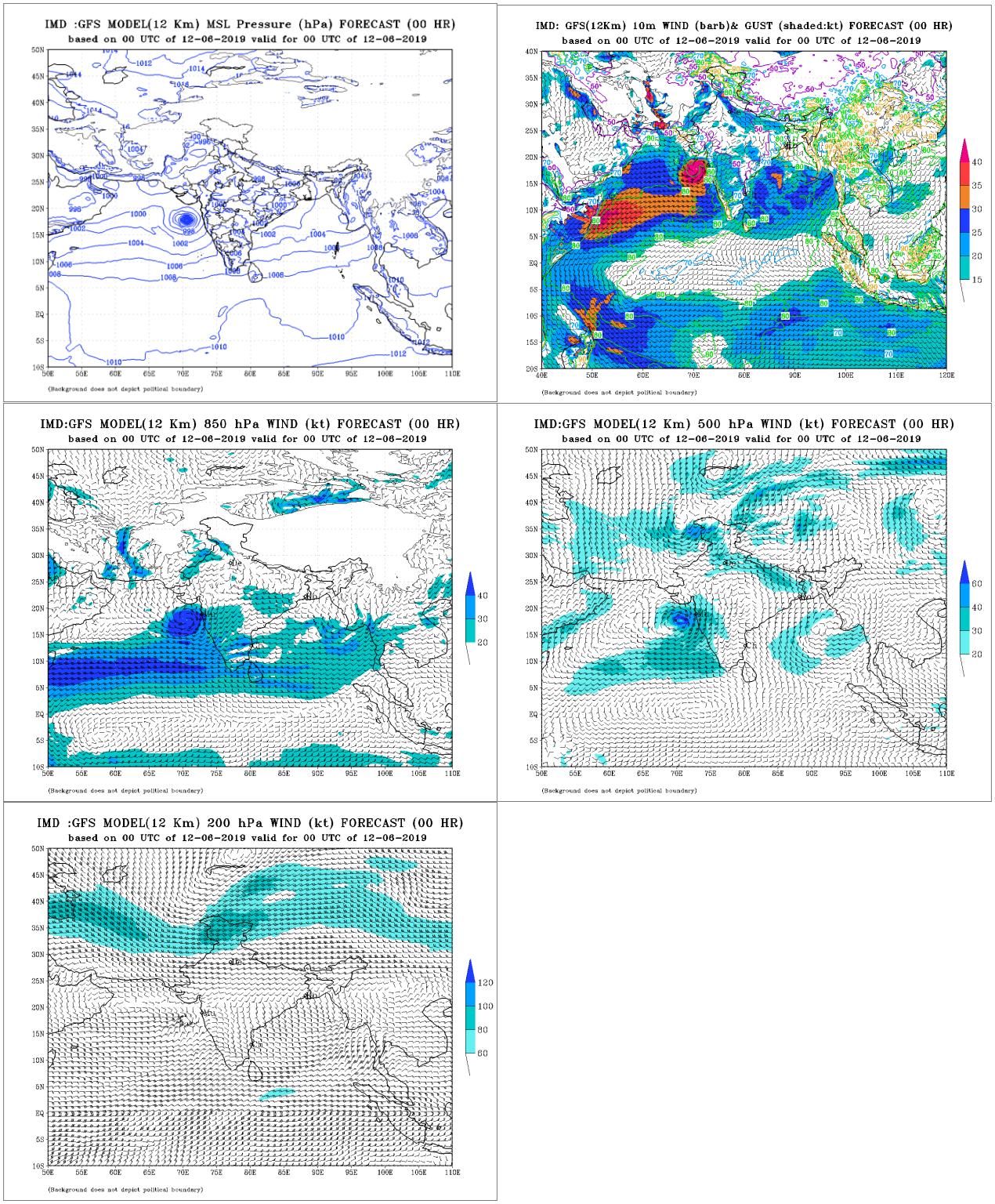


Fig. 8 (c): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 12th June 2019

GFS (T1534) analysis based on 0000 UTC of 13th June indicated that the system moved nearly northwards and lay as a VSCS over northeast AS off Gujarat coast.

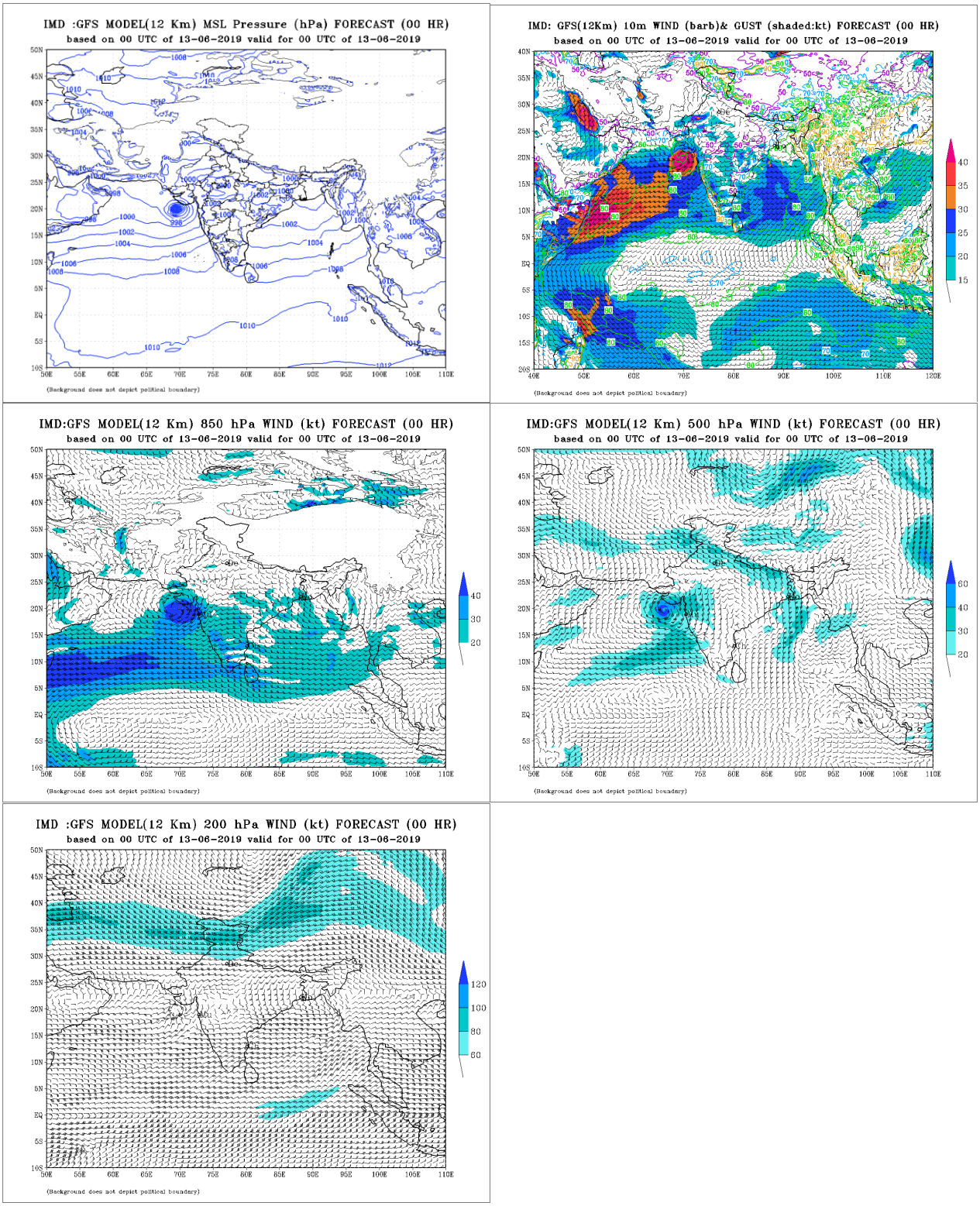


Fig. 8 (d): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 13th June 2019

GFS (T1534) analysis based on 0000 UTC of 14th June indicated that the near westward movement of the system very close to Gujarat coast as a VSCS over northeast AS off Gujarat coast. It also indicated anticyclone over Arabian Peninsula region that steered the system westwards.

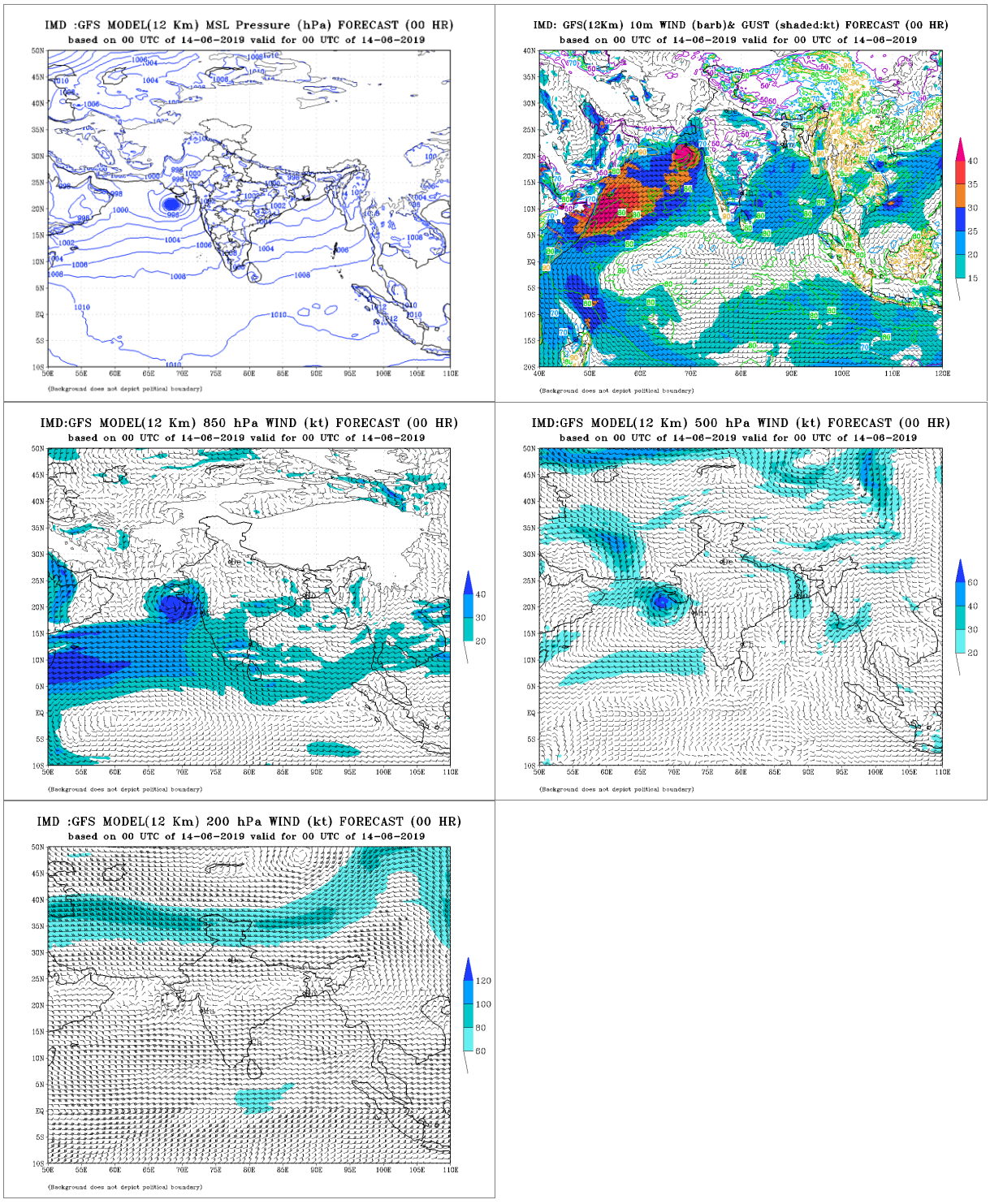


Fig. 8 (e): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 14th June 2019

GFS (T1534) analysis based on 0000 UTC of 15th June indicated that westward movement of the system away from Gujarat coast as a VSCS over northeast AS. It also indicated anticyclone over Arabian Peninsula region that steered the system westwards.

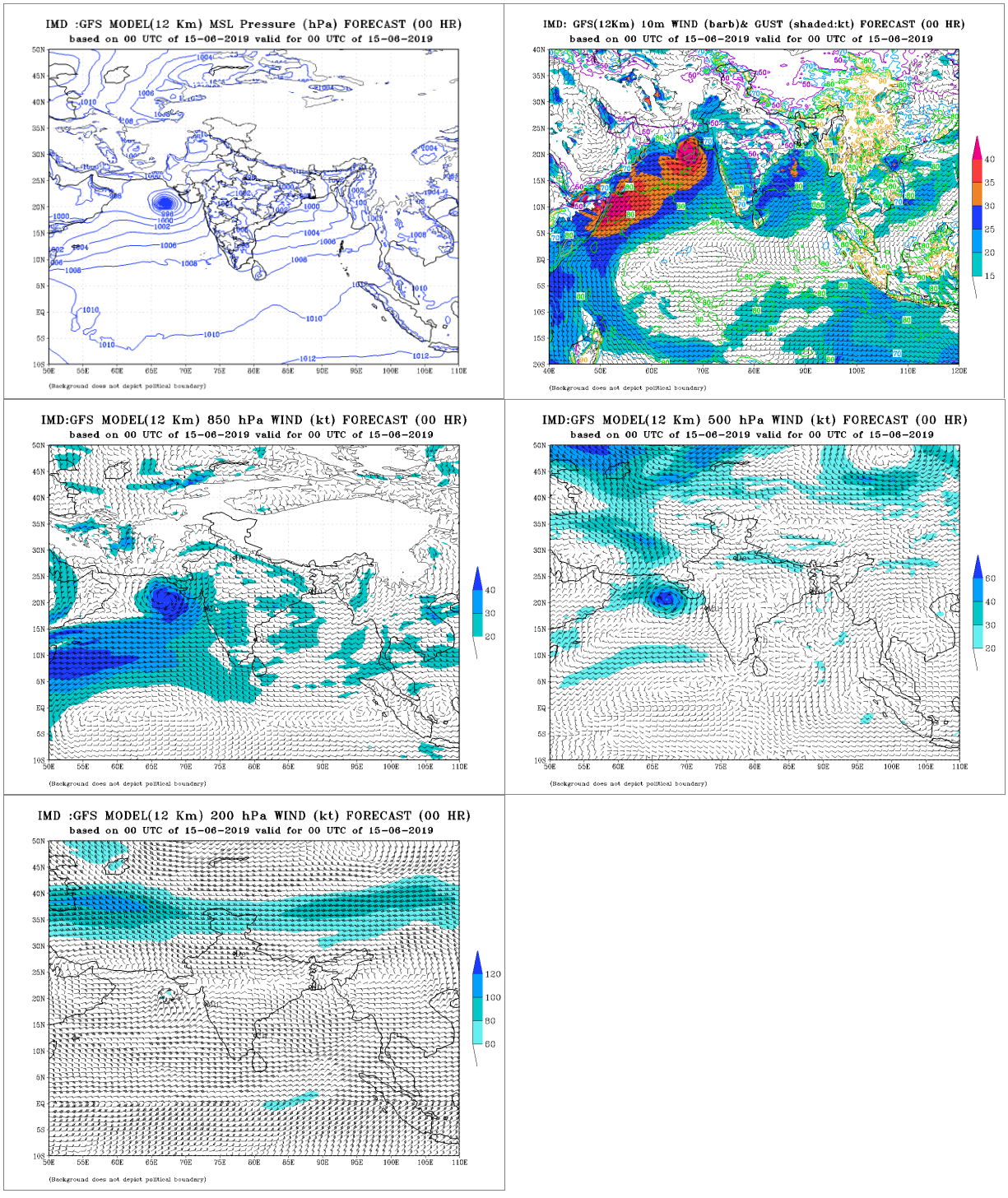


Fig. 8 (f): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 15th June 2019

GFS (T1534) analysis based on 0000 UTC of 16th June indicated that westward movement of the system away from Gujarat coast as a VSCS over northeast AS. It also indicated anticyclone over Arabian Peninsula region that steered the system westwards.

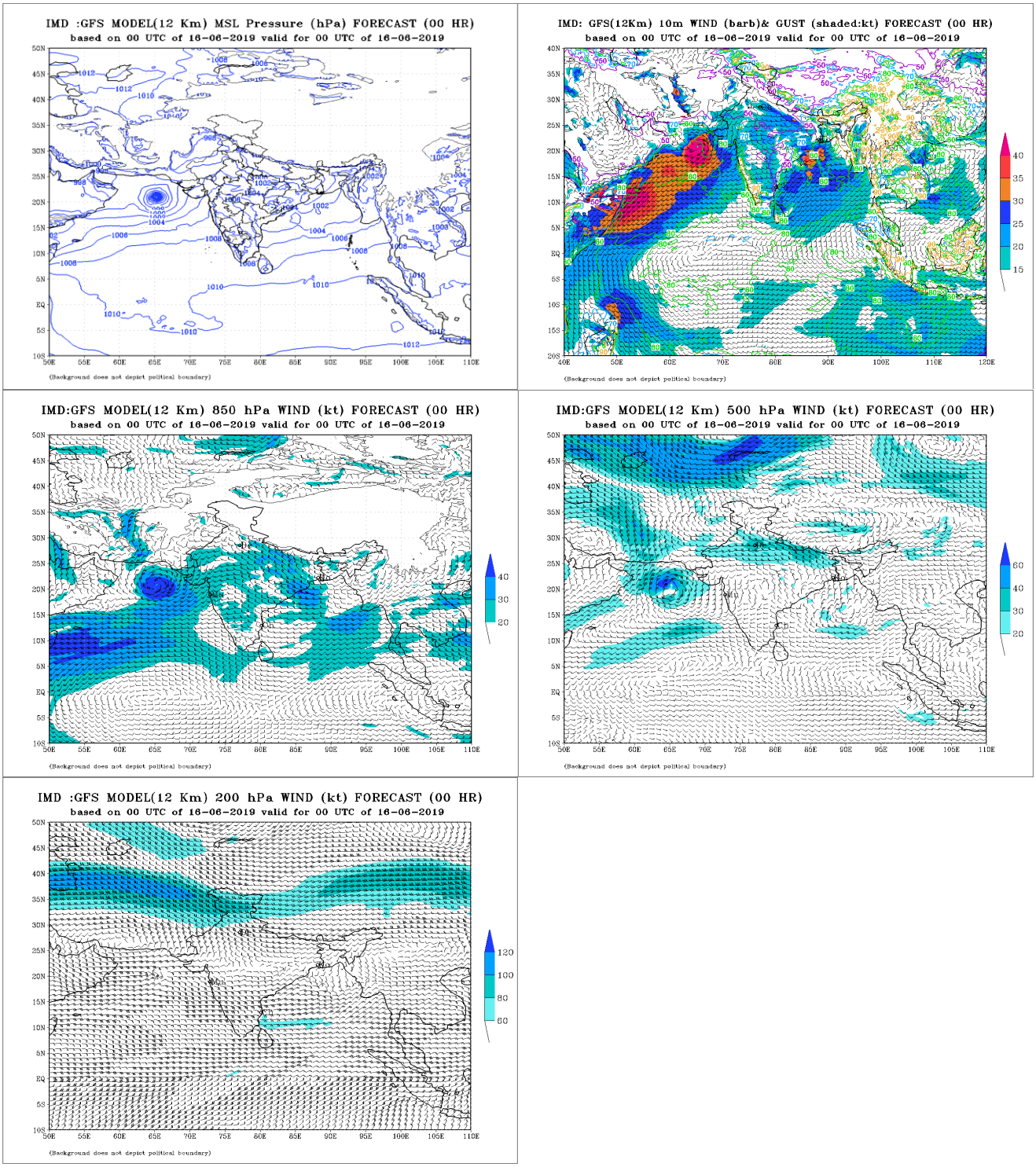


Fig. 8 (g): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 16th June 2019

GFS (T1534) analysis based on 0000 UTC of 17th June indicated northeastward movement of the system towards Gujarat coast as a CS over northeast AS. It also indicated westerlies steering the system towards east.

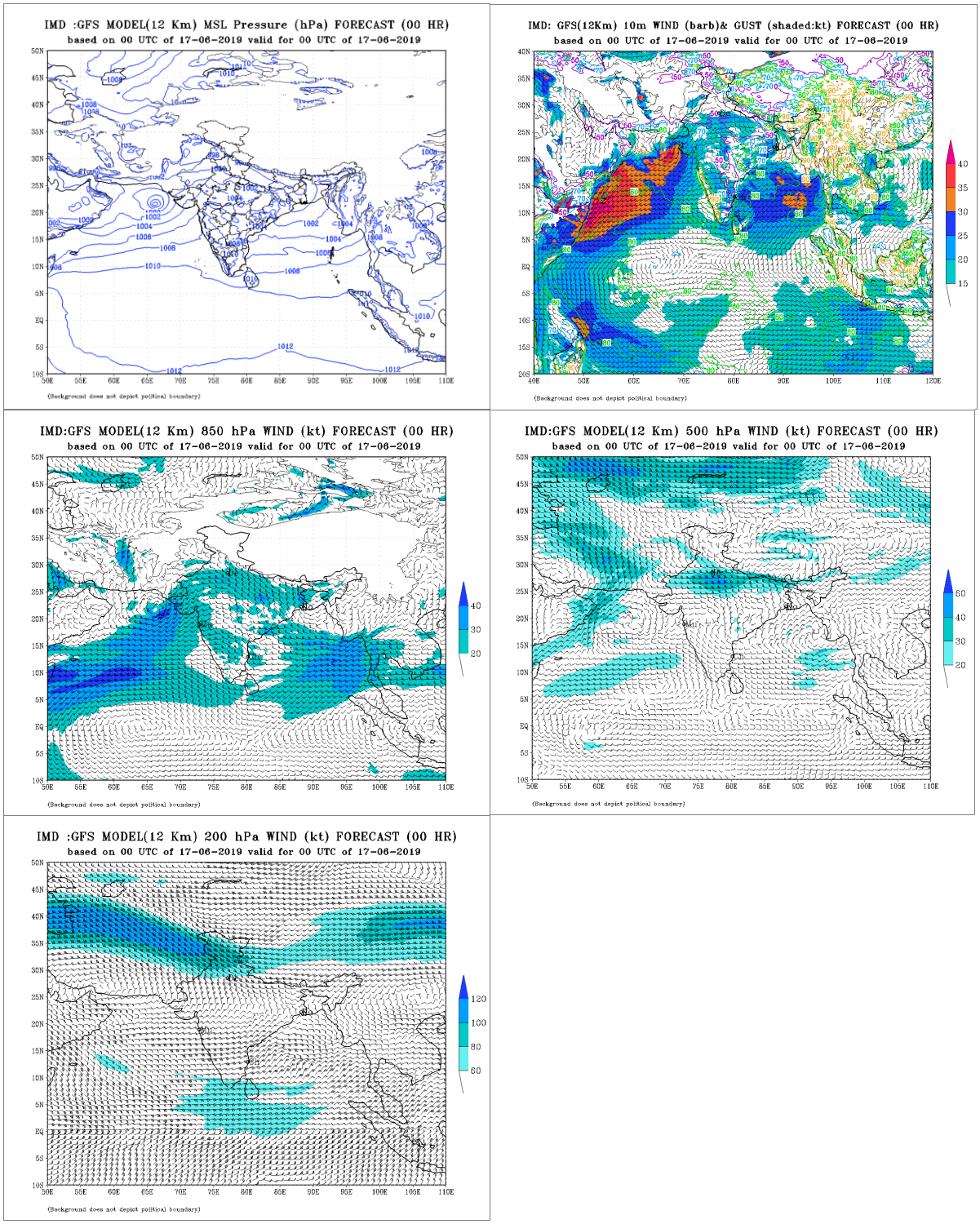


Fig. 8 (h): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 17th June 2019

Thus, IMD GFS captured the movement and intensity of the system correctly.

7. Realised Weather:

7.1. Realised Rainfall

Rainfall associated with VSCS VAYU based on IMD-NCMRWF GPM merged gauge 24 hours cumulative rainfall ending at 0300 UTC of date is depicted in **Fig 9**.

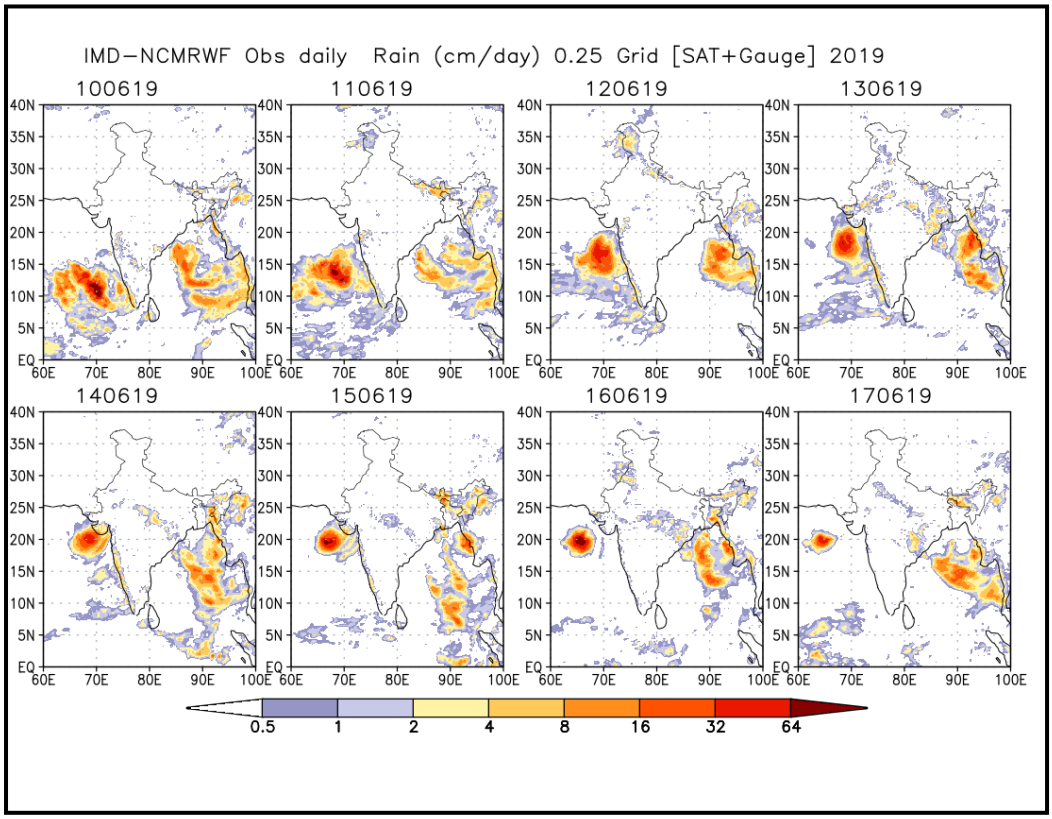


Fig.9: IMD-NCMRWF merged satellite and rain gauge observed rainfall (cm/day) during 10-17 June in association with VSCS VAYU.

Light to moderate rainfall at many places with isolated heavy to very heavy rainfall occurred over Saurashtra & Kutch on 13th & 14th and over Gujarat region on 14th. It also caused light to moderate rainfall at many places with isolated heavy to very falls over Kerala, coastal Karnataka and Konkan & Goa during 10th -14th June.

Realised 24 hrs accumulated rainfall (≥7cm) ending at 0300 UTC of date during the life cycle of the system is presented below:

10th June

Kerala & Mahe:

Piravam – 14, Nedumangad – 12, Cherthala & Alappuzha – 11 each, Mancompu, Vaikom & Kodungallur – 10 each, Kottayam , Kochi & Ernakulam South – 9 each, Chalakudi – 8 and Peermade, Kayamkulam, Chengannur & Aluva – 7 each

11th June

Kerala:

Vyttiri – 10, Taliparamba – 8 and Quilandi & Vadakara – 7 each

12th June

Coastal Karnataka:

Kumta – 14 and Gokarna - 11

Kerala:

Vadakara – 10 and Enamakkal - 9

13th June

Konkan & Goa:

Tala – 9, Margao & Harnai – 8 each and Shriwardhan & Murud – 7 each

Coastal Karnataka:

Udupi – 17, Kota – 13, Mulki, Manki, Gersoppa & Kollur – 12 each, Mangaluru – 11, Karkala – 10, Kadra – 9, Shirali & Kumta – 8 each, Mudubidre, Manchikere & Honavar - 7 each

S. I. Karnataka:

Kottigehara – 8

14th June

Saurashtra & Kutch:

Talala – 16, Sutrapada – 15, Vanthali – 9, Bhavnagar – 8, Mendarda, Mangrol & Malia – 7 each

Konkan & Goa:

Valpoi – 10, Vaibhavwadi, Ponda, Kudal, Kankavli & Dodamarg – 8 each and Margao - 7

Madhya Maharashtra:

Gaganbawada – 13, Mahabaleshwar & Gargoti / Bhudargad – 8 each and Velhe - 7

Coastal Karnataka:

Kollur – 13, Siddapura – 11, Kundapur, Ankola, Mani & Karwar- 9 each, Kadra – 8, Shirali, Panambur, Bhatkal, Gokarna, Uppinangadi, Manki & Mudubidre – 7 each

S. I. Karnataka:

Virajpet & Kottigehara – 7 each

15th June

Gujarat Region:

Mangrol - 9

Saurashtra & Kutch:

Sutrapada – 12, Talala – 10, Veraval – 9 and Kodinar - 8

Konkan & Goa:

Mhasla - 8

Coastal Karnataka:

Kollur - 10

S. I. Karnataka:

Kottigehara - 8

7.1 Realised Wind

As the cyclone skirted Gujarat coast, the core maximum wind due to the cyclone occurred over the Sea. However, the squally to gale wind speed from 45 kmph to 90 kmph occurred along & off Gujarat coast during 12th to 14th. On 12th June, Bhavnagar reported estimated maximum sustained surface winds (MSW) of 46 kmph during 1400 – 1800 UTC (1930-2330 hrs IST). On 13th June, Porbandar reported MSW of 84 kmph at 0800 UTC (1330 hrs IST), Veraval reported 60 kmph of MSW at 0900 & 1000 UTC (1430 & 1530 hrs IST) and Diu reported MSW of 41 kmph at 0900 UTC (1430 hrs IST). On 14th June, Veraval reported MSW of 63 kmph and Diu reported 37 kmph of MSW at around 1830 UTC (0103 hrs IST).

7.2 Realised storm surge:

No storm surge was reported from any part of the Gujarat coast as cyclone dissipated over the Sea and did not make landfall.

8. Damage due to VSCS VAYU

No significant damage has been reported due to this storm.

9. Performance of operational NWP models

IMD operationally runs regional models, WRF for short-range prediction and Global model T1534 for medium range prediction (10 days). The WRF-VAR model is run at the horizontal resolution of 9 km and 3 km with 38 Eta levels in the vertical and the integration is carried up to 72 hours over three domains covering the area between lat. 25^0S to 45^0 N long 40^0 E to 120^0 E. Initial and boundary conditions are obtained from the IMD Global Forecast System (IMD-GFS) at the resolution of 12 km. The boundary conditions are updated at every six hours interval. In addition, IMD also runs cyclone specific Hurricane Weather Research & Forecast Model (HWRF) with horizontal resolution of 18 km for parent domain and 6 km & 2 km for intermediate and innermost nested domains following the center of cyclonic storm. The model is running with 61 vertical levels with parent domain, intermediate and innermost domain covering area of 80^ox80^o, 24^ox24^o and 7^ox7^o respectively. Global models are also run at NCMRWF. These include GFS and unified model adapted from UK Meteorological Office. The Ministry of Earth Sciences (MoES) has commissioned two very high resolution (12 km grid scale) state-of-the-art global Ensemble Prediction Systems (EPS) for generating operational 10-days probabilistic forecasts of weather. The EPS involves the generation of multiple forecasts using slightly varying initial conditions. The forecast products from these two prediction systems are available at the following links (http://nwp.imd.gov.in/gefspro.php) and (http://www.ncmrwf.gov.in/product_main.php). The frameworks of the new EPSs are among the best weather prediction systems in the world at present. Very few forecasting centres in the world use this high resolution for short-medium range probabilistic weather forecasts. In addition to the above NWP models, IMD also run operationally dynamical statistical models. The dynamical statistical models have been developed for (a) Cyclone Genesis Potential Parameter (GPP), (b) Multi-Model Ensemble (MME) technique for cyclone track prediction, (c) Cyclone intensity prediction, (d) Rapid intensification and (e) Predicting decay in intensity after the landfall. Genesis potential parameter (GPP) is used for predicting potential of cyclogenesis (T3.0) and forecast for potential cyclogenesis zone. The multi-model ensemble (MME) for predicting the track (at 12h interval up to 120h) of tropical cyclones for the Indian Seas is developed applying multiple linear regression technique using the member models IMD-GFS, IMD-WRF, GFS (NCEP), ECMWF and JMA. The SCIP model is used for 12 hourly intensity predictions up to 72-h and a rapid intensification index (RII) is developed and implemented for the probability forecast of rapid intensification (RI). Decay model is used for prediction of intensity after landfall. IMD also makes use of NWP products prepared by some other operational NWP Centres like, ECMWF (European Centre for Medium Range Weather

Forecasting), GFS (NCEP), UKMO (UKMet), JMA (Japan Meteorological Agency). Ensemble prediction system (EPS) has been implemented at the NWP Division of the IMD HQ for operational forecasting of cyclones. In this report performance of the individual models, MME forecasts, SCIP, GPP, RII and Decay model for cyclone VAYU are presented and discussed.

9.1 Prediction of Cyclogenesis [Genesis Potential Parameter (GPP)] for VAYU

The predicted zone of cyclogenesis for 1200 UTC of 10th based on 1200 UTC of 5th-10th is presented Fig.10. The model could predict cyclogenesis zone over southeast and adjoining eastcentral AS correctly about 120 hrs in advance. However, at the same time it was also indicating a false potential zone of cyclogenesis over eastcentral Bay of Bengal.

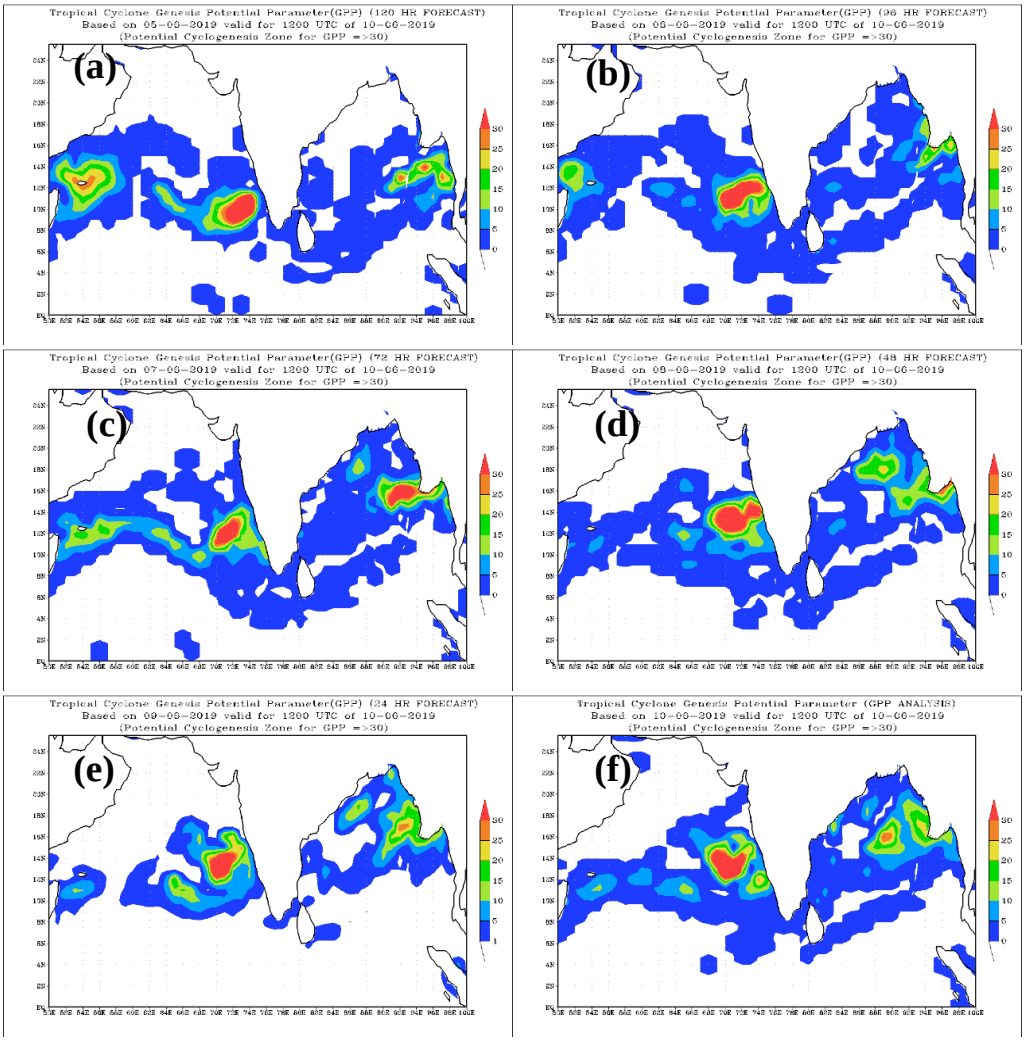


Fig.10 (a-f): Predicted zone of cyclogenesis based on 1200 UTC from 05-10 June 2019 for 1200 UTC of 10th June

Since all low pressure systems do not intensify into cyclones, it is important to identify the potential of intensification (into cyclone) of a low pressure system at the early stages (T No. 1.0, 1.5, 2.0) of development. Conditions for (i) Developed system: Threshold value of average GPP ≥ 8.0 and (ii) Non-developed system: Threshold value of GPP < 8.0. The area average analysis and forecast of GPP based on 1200 UTC of 9th and 0000 & 1200 UTC of 10th is presented in **Fig.11**. The analysis based on 1200 UTC of

9th indicated CS & above intensity for next 120 hrs with gradual increasing tendency and gradual weakening tendency from 1200 UTC of 13th. System actually started weakening from 0000 UTC of 14th, but maintained CS & above intensity. The analysis based on 0000 UTC of 10th indicated gradual intensification till 1200 UTC of 11th (next 36 hours) slight weakening in subsequent 12 hrs (0000 UTC of 12th) and intensification in next 12 hours (1200 UTC of 12th). The analysis based on 1200 UTC of 10th, indicated intensification till 1200 UTC of 11th and slight weakening during next 24 hrs. However, actually the system continued to intensify till 0000 UTC of 14th and weakened thereafter.

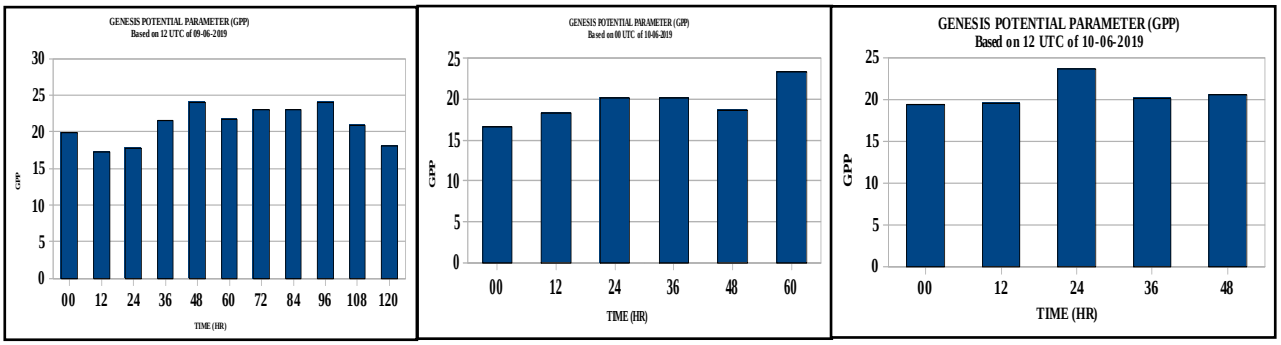


Fig.11: Area average analysis and forecasts of GPP based on (i) 1200 UTC of 09.06.2019, (ii) 0000 UTC of 10.06.2019 and (iii) 1200 UTC of 10.06.2019

9.2 Track prediction by NWP models

Track prediction by various NWP models including ECMWF, NCEP GFS, IMD GFS, WRF-VAR, UKMO, JMA-25, MME and IMD HWRF based on 0000 UTC during 10th-17th June is presented in **Fig.12**. Initially various models predicted landfall over Gujarat. However, from 0000 UTC of 12th onwards, models indicated that the system would skirt Gujarat coast and move westwards. Considering individual models forecast, ECMWF predicted landfall till 0000 UTC of 11th. Thereafter it indicated westwards movement indicating the system to skirt Gujarat coast based on initial conditions of 1200 UTC of 11th, 0000 & 1200 UTC of 12th. UKMO predicted landfall over Gujarat coast based on initial conditions of 1200 UTC of 10th, again predicted landfall based on 0000 UTC of 11th and skirting of Gujarat coast based on 1200 UTC of 11th and 0000 & 1200 UTC of 12th. Thus, the UKMO was inconsistent in prediction of the track till 0000 UTC of 11th and became consistent indicating the TC to skirt Gujarat coast and move westward based on 1200 UTC of 11th onwards.

Considering NCEP GFS, it was consistently predicting the TC to skirt Gujarat Coast and move westwards based on 0000 UTC of 10th to 1200 UTC of 11th. Thereafter, as the TC was moving closer to coast it predicted landfall based on 0000 UTC of 12th. It again switched over to the earlier forecast of skirting the coast based on 1200 UTC of 12th. Thus, as the TC was moving closer to the coast, the NCEP GFS model guidance became inconsistent. Considering IMD-GFS, it also predicted like NCEP GFS and hence was not consistent as the TC was moving towards the Gujarat Coast.

Considering JMA, it predicted the system to skirt Gujarat coast based on 0000 and 1200 UTC of 10th, 11th and 12th. JMA though predicted consistently no landfall over the Gujarat coast, its track forecast was available only upto 84 hours and the initial position of the track was shifted to the south of the best track position by about 2° latitude. Similar was the case with WRF-VAR which provides forecast upto 72 hours only. Comparing all these individual models, all models indicated the track to skirt the Gujarat coast based on initial condition of 1200 UTC of 12th. By 0000 UTC of 12th, all models except GFS based models like IMD GFS, NCEP GFS and HWRF indicated the TC to skirt the Gujarat coast.

Considering MME forecast, it was continuously indicating landfall over Gujarat coast based on initial conditions of 0000 UTC of 10th to 1200 UTC of 11th. From 0000 UTC of 12th, MME being supported by majority of individual constituent member models indicated that Vayu will skirt the Gujarat coast. Thus, the numerical guidance had moderate confidence (60% of the total models indicating skirting of the coast) based on 0000 UTC of 12th and high confidence (100% of all the models indicating skirting of the coast) based on initial condition of 1200 UTC of 12th. As the individual model outputs along with the MME guidance are available to the forecasters after about 06 hours of initial conditions, the skirting of the coast could have been predicted by the forecasters with moderate confidence in the forecast issued based on 0600 UTC of 12th and with high confidence based on 1800 UTC of 12th. Considering the high impact of the TC in case of landfall, IMD issued skirting of the coast only when there was high confidence in the model guidance i.e. based on 1800 UTC of 12th.

At 0000 UTC of 10th, ECMWF, NCEP-GFS, UKMO, MME and HWRF predicted landfall over Gujarat. All models were indicating near northwards movement. MME was indicating the system to cross the coast around 1800 UTC of 12th. The statistical cyclone intensity prediction (SCIP) model predicted intensity as SCS (68 kts) at the time of landfall and HWRF was indicating it to cross as ESCS (90 kts).

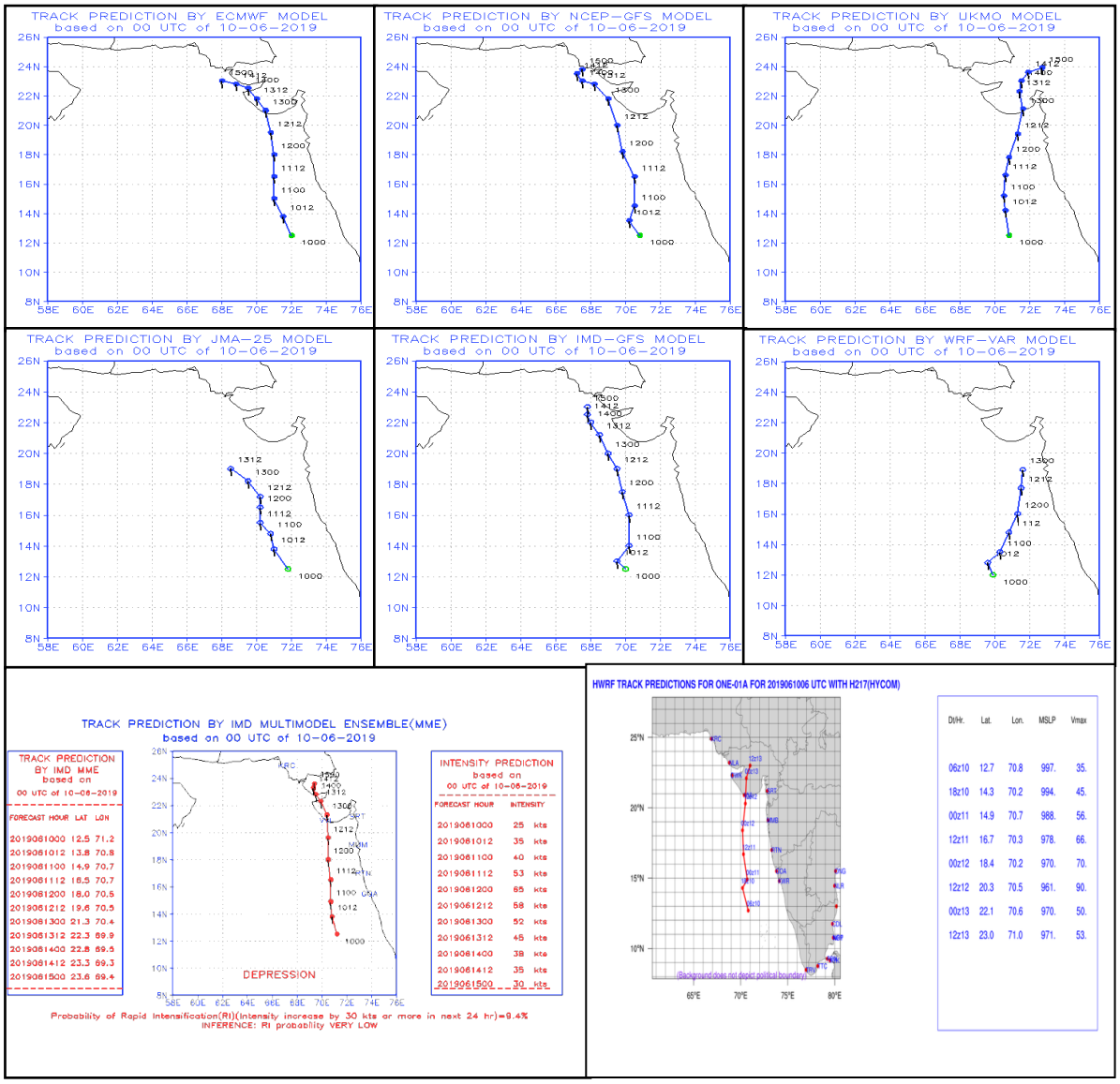


Fig. 12 (a): NWP models track forecast based on 0000 UTC of 10.06.2019

At 0000 UTC of 11th, ECMWF, UKMO, MME and HWRF predicted landfall over Gujarat. However, NCEP GFS, IMD GFS and WRF-VAR indicated that the system would skirt Gujarat coast. All models were indicating initial northwards movement. JMA-25 indicated initial northwards movement followed by westwards movement much away from Gujarat coast. MME was indicating the system to cross as SCS (60 kts) and HWRF was indicating it to cross as ESCS (90 kts).

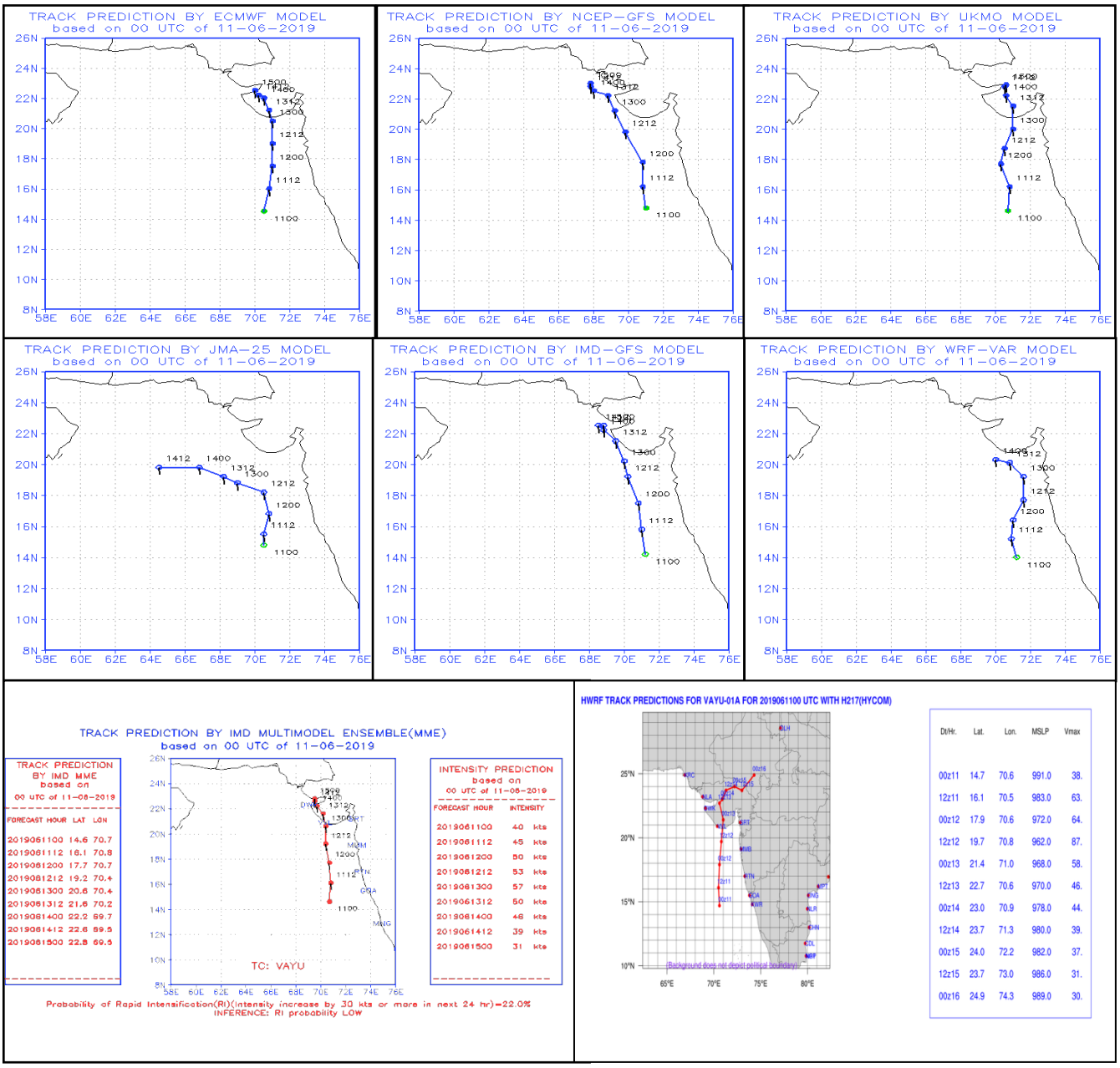


Fig. 12 (b): NWP model track forecast based on 0000 UTC of 11.06.2019

At 0000 UTC of 12th, there was large divergence among various models. ECMWF predicted initial northward movement followed by westward and northeastward movement thereafter. NCEP-GFS, IMD-GFS and HWRF indicated landfall over Gujarat. UKMO, JMA, WRF VAR and MME were indicating that system would skirt Gujarat coast and move westwards. MME was indicating the system to skirt the coast on 13th. The statistical cyclone intensity prediction (SCIP) model predicted intensity as VSCS (86 kts) at the time of skirting the coast and HWRF indicated it to cross Gujarat coast with MSW of 68 kts.

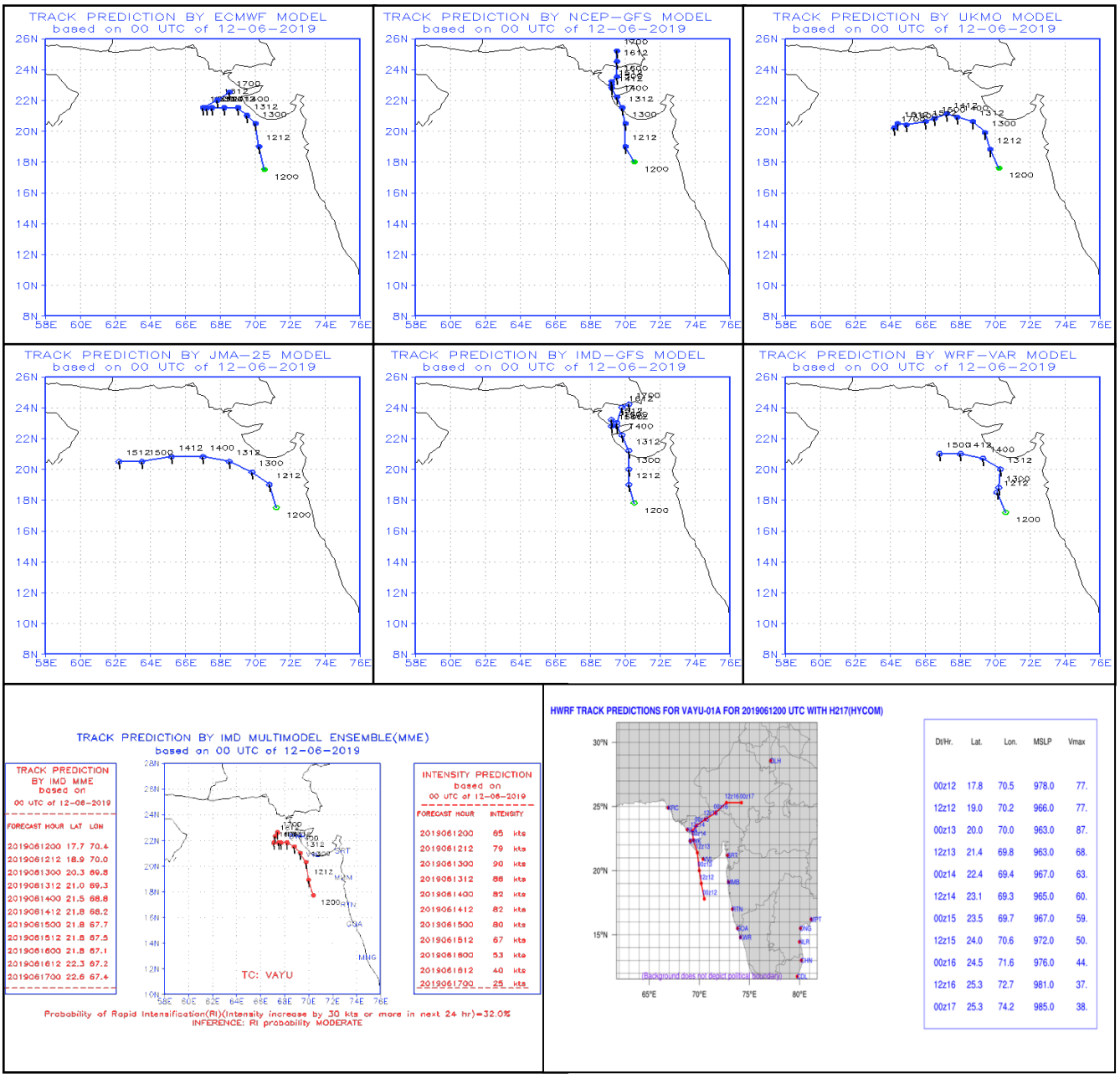


Fig. 12 (c): NWP model track forecast based on 0000 UTC of 12.06.2019

At 0000 UTC of 13th, most of the models indicated the system to skirt the coast. ECMWF, NCEP-GFS, MME and HWRF also indicated east-northeastwards re-curvature while other models indicated westward movement.

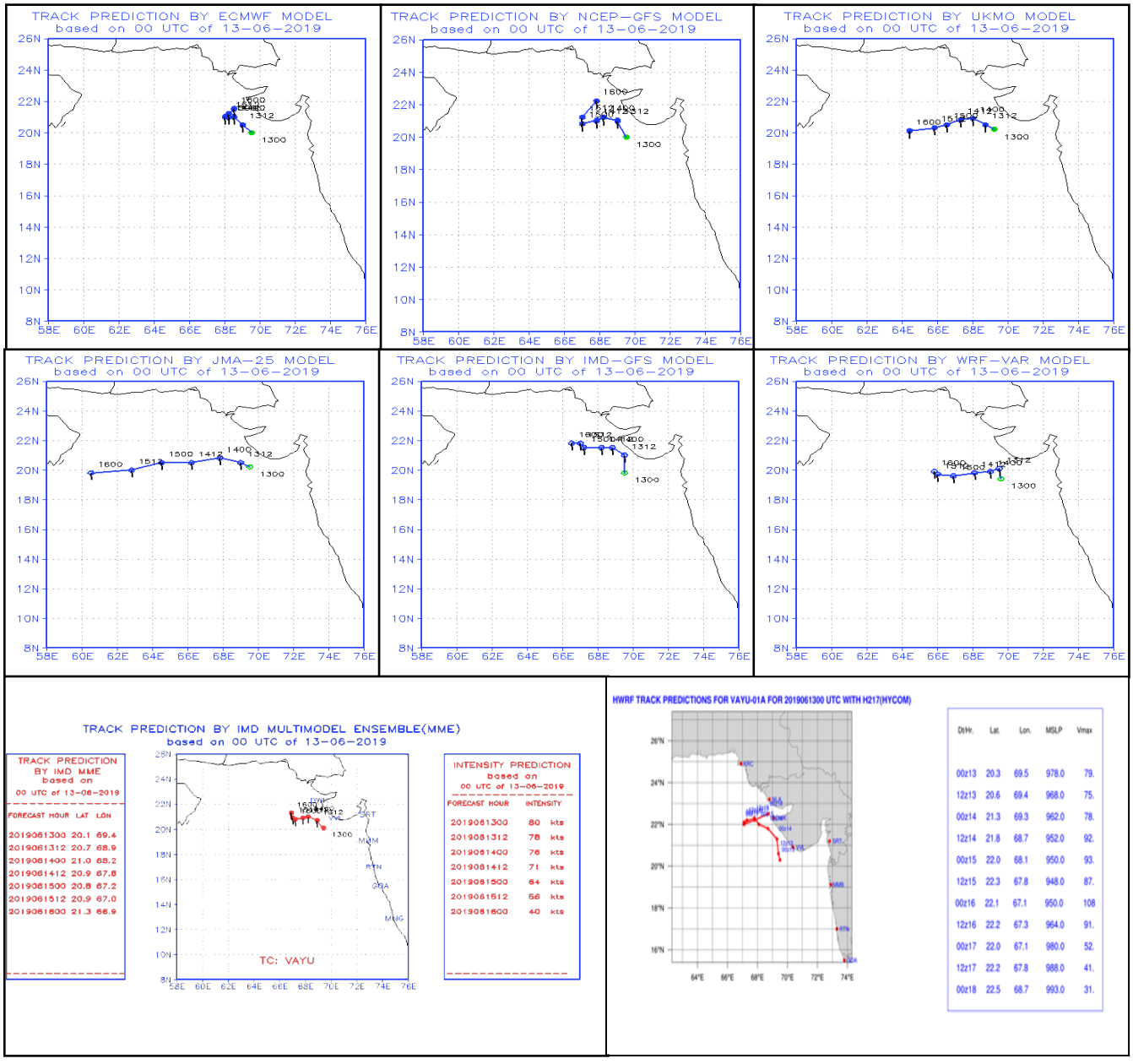


Fig. 12 (d): NWP model track forecast based on 0000 UTC of 13.06.2019

At 0000 UTC of 14th, except JMA and WRF-VAR all models indicated east-northeastwards re-curvature except JMA, which indicated westward movement.

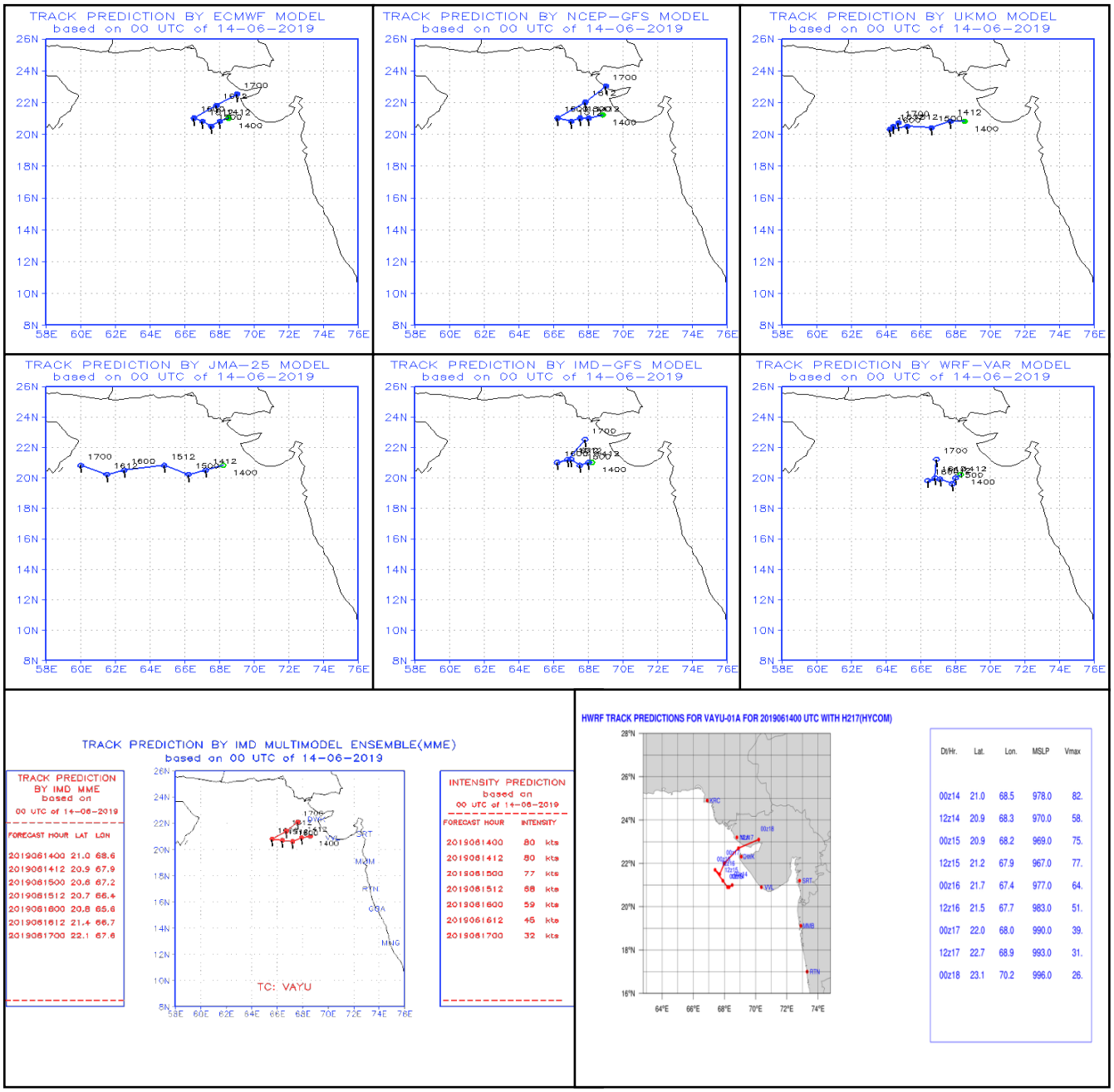


Fig. 12 (e): NWP model track forecast based on 0000 UTC of 14.06.2019

At 0000 UTC of 15th, all models except HWRF were indicating east-northeastward re-curvature with weakening over sea. HWRF indicated the system to cross as DD.

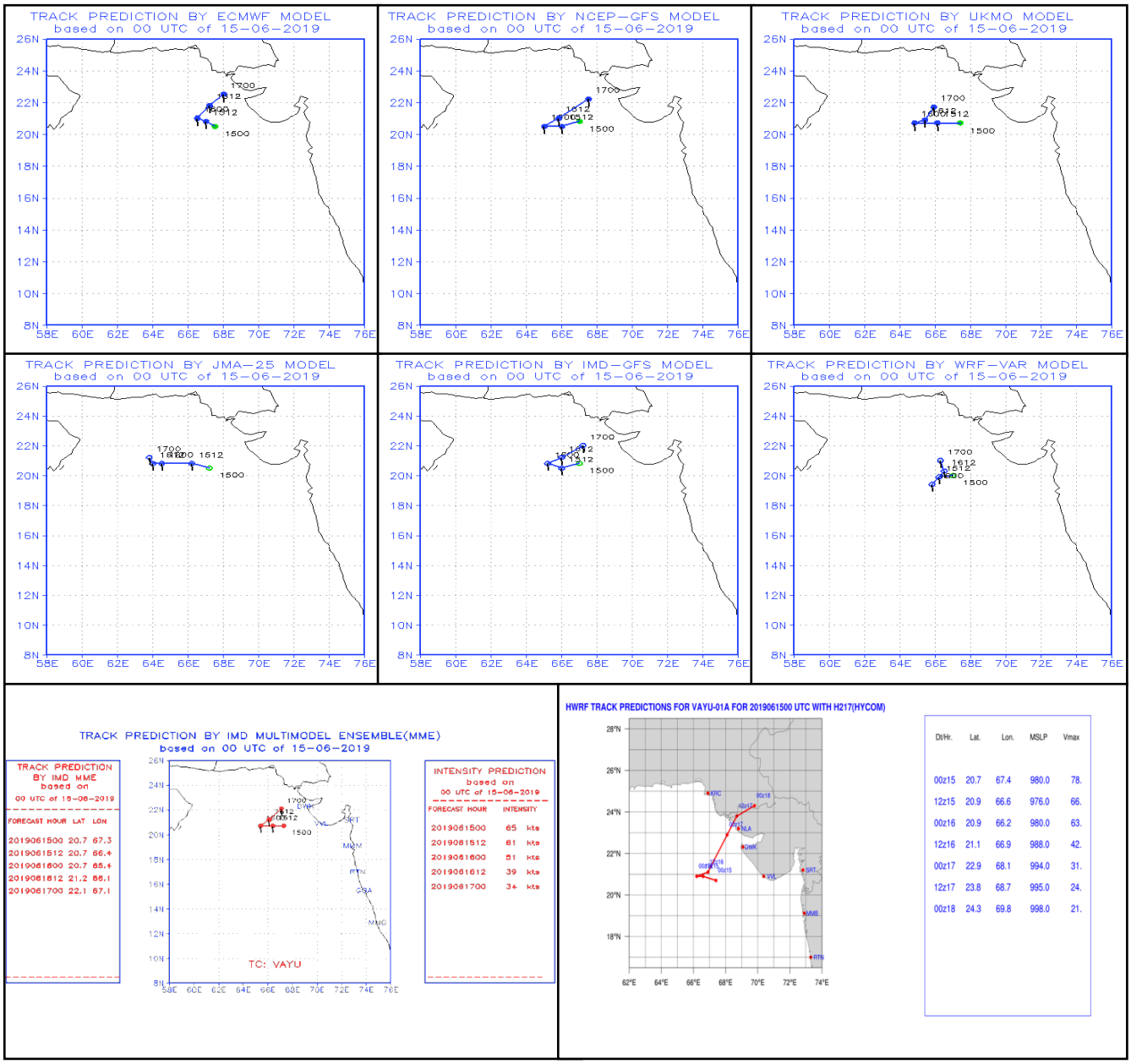


Fig. 12 (f): NWP model track forecast based on 0000 UTC of 15.06.2019

At 0000 UTC of 17th, ECMWF, NCEP-GFS and HWRF indicated that system would cross near north Gujarat coast. HWRF indicated the system to cross as DD.

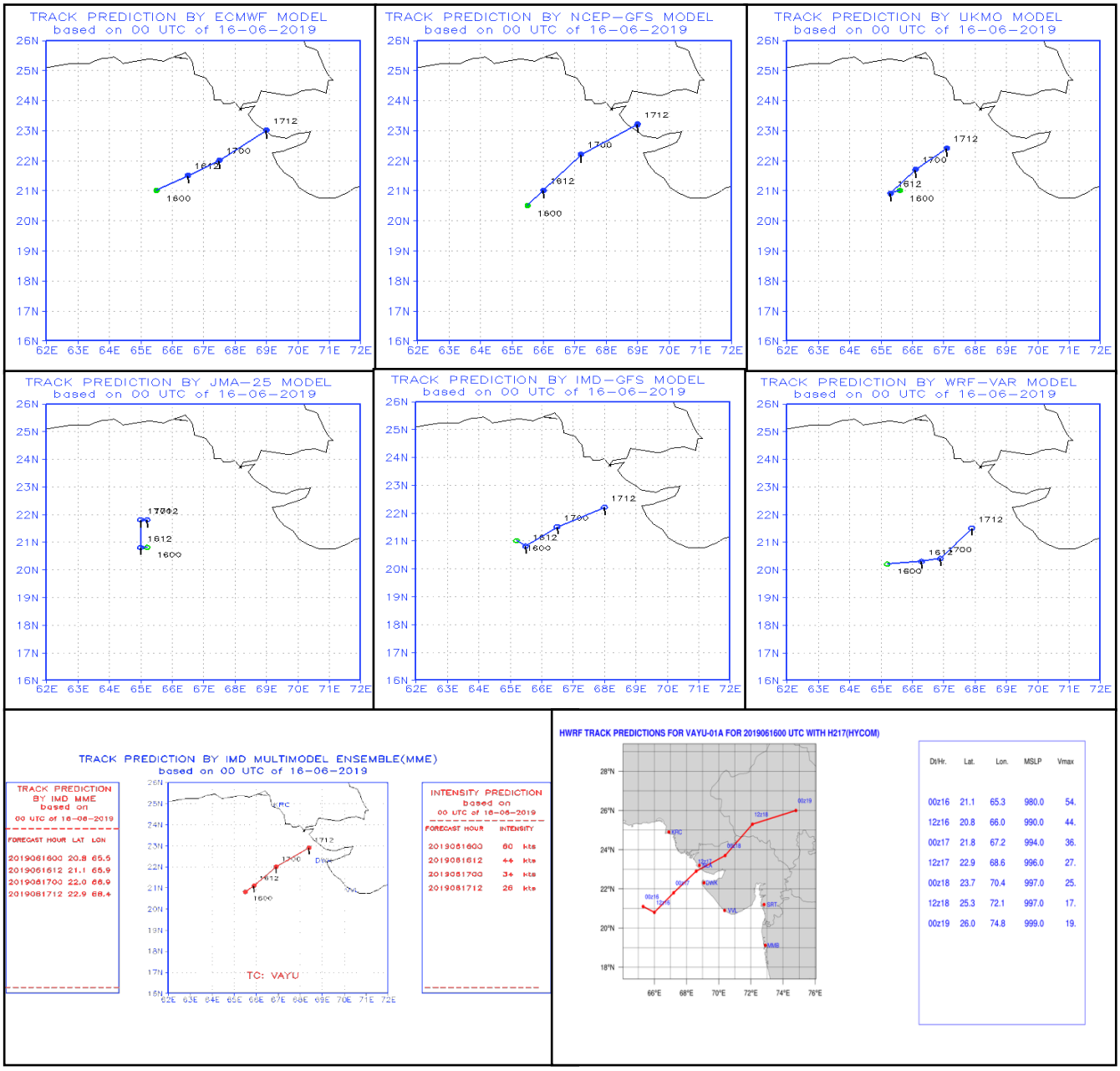


Fig. 12 (g): NWP model track forecast based on 0000 UTC of 16.06.2019

Table-2. Average track forecast errors (Direct Position Error (DPE)) in km (Number of forecasts verified is given in the parentheses)

Lead time →	12H	24H	36H	48H	60H	72H	84H	96H	108 H	120 H
IMD-MME	31(14)	33(13)	45(13)	60(12)	104(10)	144(10)	189(6)	219(5)	271(4)	288(3)
ECMWF	57(14)	63(13)	94(13)	117(12)	159(10)	194(10)	155(6)	182(5)	224(4)	263(3)

NCEP-GFS	36(14)	47(13)	66(13)	98(13)	147(10)	223(10)	240(6)	286(5)	359(4)	415(3)
UKMO	48(14)	60(13)	92(13)	119(13)	155(10)	204(10)	253(6)	312(5)	416(4)	479(2)
JMA-25	63(14)	94(13)	142(13)	220(13)	308(10)	423(10)	382(6)	-	-	-
IMD-GFS	58(14)	56(13)	80(13)	93(13)	129(10)	142(10)	164(6)	250(5)	271(4)	343(3)
WRF-VAR	104(14)	124(13)	142(13)	181(13)	189(10)	193(10)	-	-	-	-
NCUM-G	46 (15)	67 (15)	92 (16)	110(16)	125(15)	148(14)	200(13)	242(11)	315(10)	394 (9)
NEPS-G	59 (15)	74 (16)	89 (16)	100(16)	89 (15)	113(14)	136(13)	200(12)	271(11)	341(10)
NCUM-R	56 (15)	76 (15)	95 (16)	109(16)	148(15)	228(14)	329(13)			
HWRF	46(29)	70(26)	107(24)	156(22)	198(20)	242(18)	320(17)	445(13)	552(11)	732(8)

For all lead periods, the DPE was the least for MME upto 60 hrs lead period and NEPS G for longer lead period from 72 to 120 hours. The DPE was less compared to other models for IMD-GFS, NCEP GFS and ECMWF also for all lead periods.

9.3 Intensity forecast errors by various NWP Models

The intensity forecasts of IMD-SCIP model and HWRF model are shown in Table **3.** IMD-SCIP underestimated the intensity of the system based on initial conditions of 0000 & 1200 UTC of 10th and 11th for all lead periods. Based on initial conditions from 0000 UTC of 12th onwards, SCIP model over-estimated the intensity of the system.

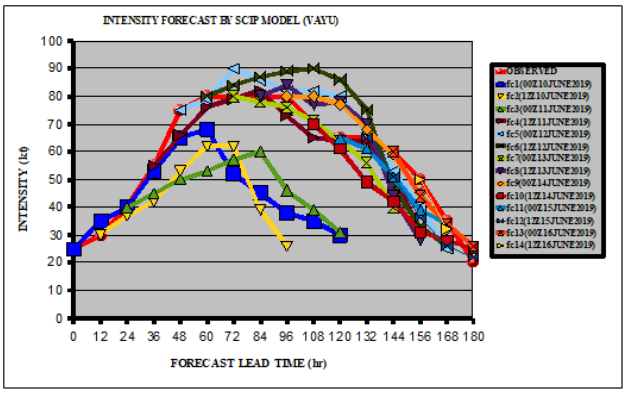


Fig. 13: Intensity prediction by IMD-SCIP Model

Table 3: Average absolute errors (AAE) and Root Mean Square (RMSE) errors in knots of SCIP model (Number of forecasts verified is given in the parentheses)

Lead time →	**12H**	**24H**	**36H**	**48H**	**60H**	**72H**	**84H**	**96H**	**108H**	**120H**
IMD-SCIP (AAE)	5.3 (14)	9.4 (13)	9.8 (13)	8.7 (12)	12.7 (10)	18.3 (10)	22.7 (6)	20.2 (5)	15.8 (4)	20.8 (4)
IMD-SCIP (RMSE)	6.0	11.4	12.6	12.1	13.8	22.1	29.7	25.5	19.3	22.6
HWRF (AAE)	8.4 (29)	6.6 (26)	9.8 (24)	13.1 (22)	16.7 (20)	24.1 (18)	25.9 (17)	27.1 (13)	27.3 (11)	25.3(8)
HWRF (RMSE)	10.0 (29)	7.9 (26)	11.7 (24)	16.1 (22)	19.7 (20)	27.8 (18)	29.3 (17)	30.9 (13)	32.3 (11)	26.9 (8)

10. Operational Forecast Performance

10.1. Genesis Forecast

- The extended range outlook issued on 6th June, indicated that there is medium probability of cyclogenesis during later part of week 1 (07-13 June) over southeast & adjoining eastcentral AS and low probability of cyclogenesis during first half of week 2 (14-20 June) over northwest & adjoining westcentral AS.
- In the Tropical Weather Outlook issued on 7th June at 0600 UTC (1130 hrs IST), it was mentioned that a low pressure area is very likely to form over southeast & adjoining areas of AS around 9th June. It was also mentioned that, it would move north-northwestwards and intensify gradually.
- In the first informatory message issued at 0800 UTC (1330 hrs IST) of 9th June on formation of low pressure area over Lakshadweep and adjoining eastcentral AS, it was mentioned that the system would intensify into a depression during next 48 hrs and further into a cyclonic storm in subsequent 24 hrs.
- The genesis (formation of Depression) occurred in the morning of 10th and cyclonic storm formed in the midnight of 10th.

10.2. Track and Intensity Forecast

- First bulletin issued at 0700 UTC (1230 hrs IST) of 10th June indicated north-northwestwards movement of the system towards Gujarat coast.
- The bulletin issued at 1000 UTC (0330) hrs IST of 13th indicated that the system would not cross Gujarat coast but would skirt Gujarat coast affecting coastal districts of south Gujarat coast . On 13th June, Porbandar reported MSW of 84 kmph at 1330 hrs IST, Veraval reported 60 kmph of MSW at 1430 & 1530 hrs IST and Diu reported MSW of 41 kmph at 1430 hrs IST. On 14th June, Veraval reported MSW of 63 kmph and Diu reported 37 kmph of MSW at 0103 hrs IST.
- Typical observed and forecast tracks based on 1200 UTC (1730 hrs IST) of 11th June and 0600 UTC (1130 hrs IST) of 14th June (before and after re-curvature) is presented in **Fig.14.** Northeastward re-curvature from 1730 hrs IST of 16th was predicted in the bulletin issued at 1500 hrs IST of 14th June (about 60 hours in advance).

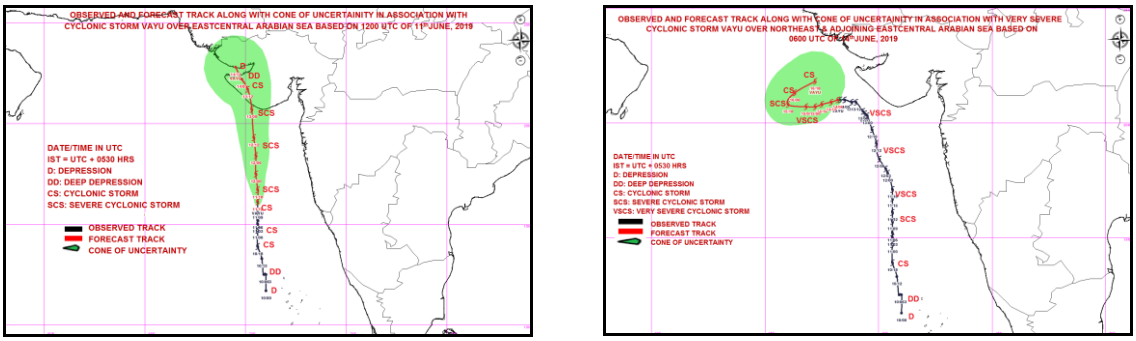


Fig.14: **Observed and forecast tracks based on 1200 UTC of 11th June and 0600 UTC of 14th June (before and after re-curvature, respectively)**

10.3. Track Forecast Errors:

- The track forecast errors for 24, 48 and 72 hrs lead period were 67.5, 125.9, and 264.9 km respectively against the average track forecast errors of 86.1, 132.3, and 177.7 km during last five years (2014-18) respectively (**Fig.15)**.
- The track forecast skill was about 57%, 57%, and 39% against the long period average (LPA) of 58%, 70%, and 74% during 2014-18 for 24, 48 and 72 hrs lead period respectively (**Fig.15)**.

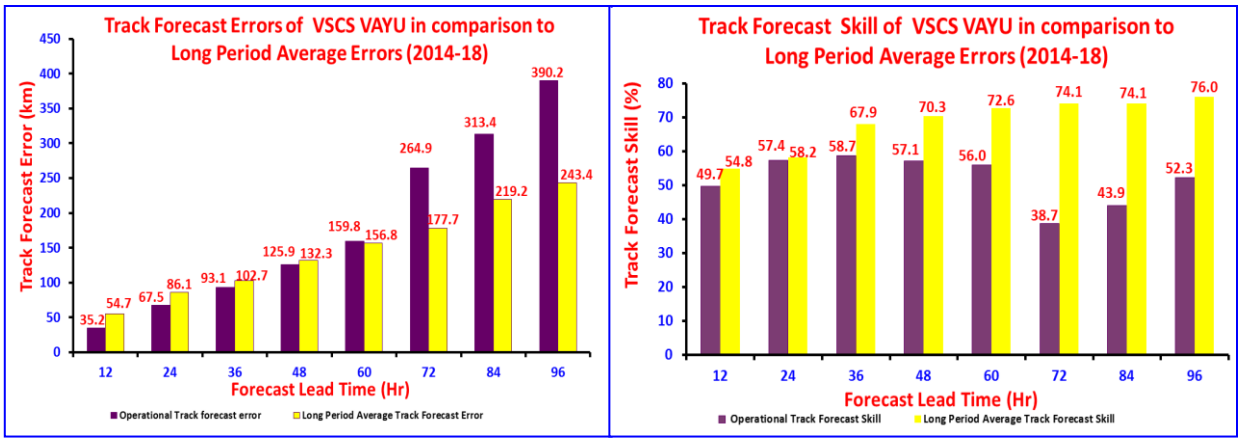


Fig. 15: Track forecast Errors and skill of VSCS VAYU as compared to long period average (2014-18)

Table 4: Operational track forecast error (km) and skill (%) in association with VSCS Vayu

Lead Period	No. of observations	Operational Track forecast error	Operational Track Forecast Skill	Long Period Average Track Forecast Error during 2014-18	Long Period Average Track Forecast Skill during 2014-18
12	28	35.2	49.7	54.7	54.8
24	26	67.5	57.4	86.1	58.2
36	24	93.1	58.7	102.7	67.9
48	22	125.9	57.1	132.3	70.3
60	20	159.8	56.0	156.8	72.6
72	10	264.9	38.7	177.7	74.1
84	4	313.4	43.9	219.2	74.1
96	1	390.2	52.3	243.4	76.0

10.4. Intensity Forecast Errors:

- The absolute error (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 6.6, 11.9 and 33.7 knots against the LPA of 9.6, 14.1, and 14.3 knots respectively **(Fig. 16).**

- The root mean square error (RMSE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 12.5, 15.0 and 37.9 knots against the LPA of 12.5, 19.0, and 19.0 knots respectively **(Fig. 16).**
- The intensity forecast skill based on AE for 24, 48 and 72 hrs lead period were 48%, 54% and 41% respectively **(Fig. 17).**
- The intensity forecast skill based on RMSE for 24, 48 and 72 hrs lead period were 44%, 55% and 48% respectively **(Fig. 17).**

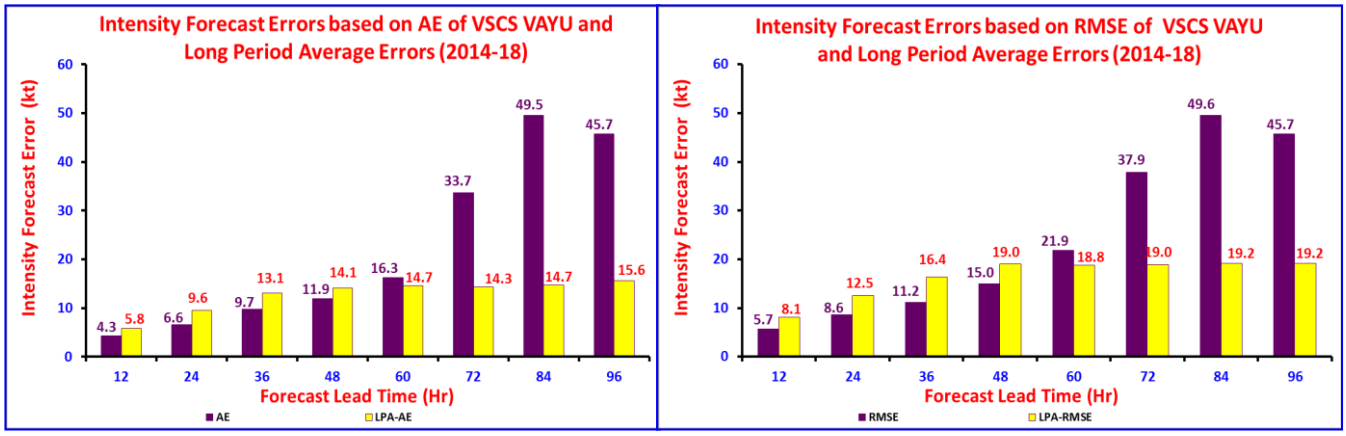


Fig. 16: Absolute errors (AE) and Root Mean Square errors (RMSE) in intensity forecast (winds in knots) of VSCS VAYU as compared to long period average (2014-18)

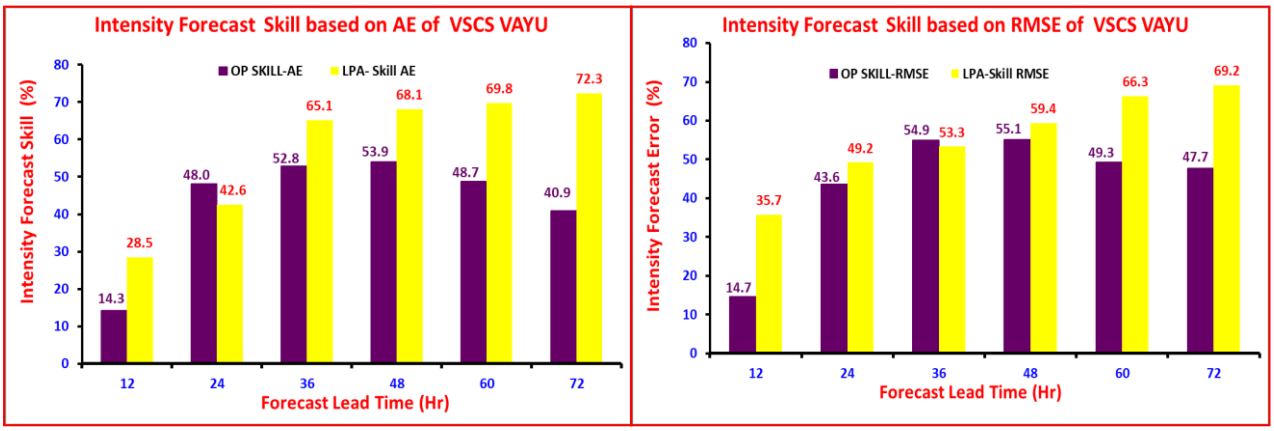


Fig. 17: Skill in intensity forecast based on Absolute errors (AE) and Root Mean Square errors (RMSE) (%) of VSCS VAYU as compared to long period average (2014-18)

Table 5: Operational Intensity forecast errors based on AE and RMSE in kts and corresponding skill (%)

Lead Period (hrs)	No. of observations	OP-AE (kts)	OP-RMSE (kts)	OP SKILL-AE (%)	OP SKILL-RMSE (%)	LPA-AE (kts)	LPA-RMSE (kts)	LPA-Skill AE (%)	LPA-Skill RMSE (%)
12	28	4.3	5.7	14.3	14.7	5.8	8.1	28.5	35.7
24	26	6.6	8.6	48.0	43.6	9.6	12.5	42.6	49.2
36	24	9.7	11.2	52.8	54.9	13.1	16.4	65.1	53.3
48	22	11.9	15.0	53.9	55.1	14.1	19.0	68.1	59.4
60	20	16.3	21.9	48.7	49.3	14.7	18.8	69.8	66.3
72	10	33.7	37.9	40.9	47.7	14.3	19.0	72.3	69.2

OP-Operational, LPA – Long Period Average, AE-Absolute error

11. Warning Services

Bulletins issued by Cyclone Warning Division, New Delhi

- **Track, intensity and landfall forecast:** IMD continuously monitored, predicted and issued bulletins containing track, intensity and landfall forecast for +06, +12, +18, +24, +36 and +48… +120 hrs lead period till the system weakened into a low pressure area. The above forecasts were issued from the stage of depression onwards along with the cone of uncertainty in the track forecast five times a day and every three hours during the cyclone period. The hourly updates were also provided when the system was skirting Gujarat coast during 13th-14th June and after northeastward re-curvature of the system during 16th-18th June.
- **Cyclone structure forecast for shipping and coastal hazard management** The radius of maximum wind and radii of MSW ≥28 knots and ≥34 knots wind in four quadrants of cyclone was issued every six hourly giving forecast for +06, +12, +18, +24, +36 ,+96 & +120 hrs lead period.
- **Four stage Warning:**
  - **Pre Cyclone Watch:** Pre Cyclone watch for Gujarat coast was issued at 0700 UTC (1230 hrs IST) of 10th June (3 days in advance of commencement of adverse weather) when the system was a depression over eastcentral AS and adjoining areas.
  - **Cyclone Alert:** Cyclone Alert for Gujarat coast was issued at 2100 hrs IST of 10th June (Two and a half days in advance of commencement of adverse weather) when the system was a deep depression over eastcentral AS and adjoining areas.
  - **Cyclone Warning:** Cyclone Warning for Gujarat coast was issued at 1730 hrs IST of 11th June (One and a half days in advance of commencement of adverse weather) when the system was a cyclonic storm over eastcentral Arabian Sea.
  - **De-warning message:** As it was expected that the cyclone would skirt the Gujarat coast, de-warning was issued for Gujarat & Diu coast in the bulletin issued at 0330 hrs IST of 13th June. However, it was mentioned that the system will move north-northwestwards along Saurashtra coast affecting

coastal districts of Amreli, Gir Somnath, Diu, Junagarh, Porbandar, Rajkot, Jamnagar, Devbhoomi Dwarka and Kutch. Comparing the realized weather as discussed in Section ii), the predicted adverse weather as mentioned in de-warning message was realized.

- **Adverse weather warning bulletins:** Adverse weather warning bulletins: The tropical cyclone forecasts along with expected adverse weather like heavy rain, gale wind and storm surge was issued with every three hourly update to central, state and district level disaster management agencies including MHA NDRF, NDMA for all concerned states along the west coast of India including Lakshadweep, Kerala, Karnataka, Goa, Maharashtra, Gujarat and Daman & Diu. The bulletins also contained the suggested action for disaster managers and general public in particular for fishermen. These bulletins were also issued to Defense including Indian Navy & Indian Air Force.
- **Warning graphics:** The graphical display of the observed and forecast track with cone of uncertainty and the wind forecast for different quadrants were disseminated by email and uploaded in the RSMC, New Delhi website (http://rsmcnewdelhi.imd.gov.in/) regularly. The adverse weather warnings related to heavy rain, gale/squally wind & storm surge were also presented in graphics along with colour codes in the website.
- **Warning and advisory through social media:** Daily updates (every six hourly or whenever there was any significant change in intensity/track/landfall) and hourly updates when the system was moving towards the Gujarat coast during 13th-14th and 16th-18th June were uploaded on face book and Twitter regularly during the life period of the system.
- **Press release and press briefing:** Press and electronic media were given daily updates since the development of low pressure area on 9th June through press release, e-mail, website and SMS.
- **Warning and advisory for marine community:** The three/six hourly Global Maritime Distress Safety System (GMDSS) bulletins were issued by the Marine Weather Services division at New Delhi and bulletins for maritime interest were issued by Area cyclone warning centres of IMD at Chennai, Mumbai and Cyclone Warning Centres at Thiruvananthapuram and Ahmedabad to ports, fishermen, coastal and high Sea shipping community.
- **Fishermen Warning:** Regular warnings for fishermen for deep Sea of eastern and central parts of Arabian Sea and the states of Kerala, Karnataka, Goa, Maharashtra and Gujarat were issued since 9th June.
- **Advisory for international Civil Aviation:** The Tropical Cyclone Advisory Centre (TCAC) bulletin for International Civil Aviation were issued every six hourly to all meteorological watch offices in Asia Pacific region for issue of significant meteorological information (SIGMET). It was also sent to Aviation Disaster Risk Reduction (ADRR) centre of WMO at Hong Kong.
- **Diagnostic and prognostic features of cyclone:** The prognostics and diagnostics of the systems were described in the RSMC bulletins.

- **Hourly Bulletin:** Hourly updates on the location, distance from recognised station, intensity and realised weather were given during 13th-14th and 16th-18th June.

Statistics of bulletins issued by RSMC New Delhi in association with the VSCS Vayu are given in **Table 6.**

Table 6 (a): Bulletins issued by RSMC New Delhi

S.N	Bulletin type	No. of Bulletins	Issued to
1	National Bulletin	61	1. IMD's website, RSMC New Delhi website 2. FAX and e-mail to Control Room Ministry of Home Affairs & National Disaster Management Authority, Cabinet Secretariat, Minister of Science & Technology, Headquarter Integrated Defense Staff, Director General Doordarshan, All India Radio, National Disaster Response Force, Chief Secretary & Administrator, Government of Lakshadweep, Kerala, Karnataka, Goa, Maharashtra, Gujarat and Daman & Diu.
2	RSMC Bulletin	58	1. IMD's website 2. WMO/ESCAP member countries through GTS and E-mail.
3	GMDSS Bulletins	39	1. IMD website, RSMC New Delhi website 2. Transmitted through WMO Information System (WIS) to Joint WMO/IOC Technical Commission for Ocean and Marine Meteorology (JCOMM)
4	Tropical Cyclone Advisory Centre Bulletin	29	1. Met Watch offices in Asia Pacific regions and middle east through GTS to issue Significant Meteorological information for International Civil Aviation 2. WMO's Aviation Disaster Risk Reduction (ADRR), Hong Kong through ftp 3. RSMC website
5	Tropical Cyclone Vital Statistics	28	Modelling group of IMD, National Centre for Medium Range Weather Forecasting Centre (NCMRWF), Indian National Centre for Ocean Information Services (INCOIS), Indian Institute of Technology (IIT) Delhi, IIT Bhubaneswar etc.
6	Warnings through SMS	32,28,156	SMS to disaster managers at national level and concerned states (every time when there was change in track, intensity and landfall characteristics and hourly when system was moving towards Gujarat coast) (i) 2,16,523 SMS to General Public by IMD Headquarters (ii) 3933 SMS to disaster managers by IMD Headquarters (iii) 12,18,178 to fishermen by INCOIS (iv) 17,67,494 SMS to farmers by Kisaan Portal
7	Warnings through Social Media	Daily	Cyclone Warnings were uploaded on Social networking sites (Facebook (67), Twitter (75) and Whats App) since inception to weakening of system (every time when there was change in track, intensity and landfall characteristics and hourly when the system was approaching Gujarat coast).
8	Press	10	Disaster Managers, Media persons by email and uploaded on

	Release		website
9	Press Briefings	Daily	Regular briefing daily
10	Hourly Updates	91	Hourly bulletins by email, website, social media [26 (during 13th & 14th June) & 65 (during 15th to 17th June)]

Table 6 (b): Statistics of bulletins issued by ACWC Mumbai and CWC Ahmedabad, Meteorological Centre, Goa & Bangaluru

S.No.	Type of Bulletin	No. of Bulletins issued			
		ACWC Mumbai	CWC Ahmedabad	MC Goa	MC Bangalore
1.	Sea Area Bulletin	35	Nil	NIL	Nil
2.	Coastal Weather Bulletins	16	16	NIL	Nil
3.	Fishermen Warnings issued	38	28	36	45 (as received from by MC Thiruvananthapuram/ ACWC Chennai
4.	Port Warnings	40	24	17	Nil
5.	Heavy Rainfall warning	8	07	5	20
6.	Gale Wind Warning	NIL	24 along with port warning	NIL	Nil
7.	Storm Surge Warning	NIL	16 along with port warning	NIL	Nil
8.	Information & Warning issued to State Government and other Agencies	16	32	37	Nil
9.	SMS	17721	3010	1267	30
10.	Radar Bulletins	-	-	21	-

12. Adverse weather forecast verification

The verification of adverse weather like heavy rainfall, gale wind and storm surge forecast issued by IMD are presented in Tables **7-9**. It is found that all the three types of adverse weather were predicted accurately and well in advance, though the multiple re-curvatures and weakening characteristics displayed by the system led to some over warnings as well.

Table 7: Verification of heavy rainfall forecast

Date/Base Time of observation (0300 UTC)	24 hr Heavy rainfall warning ending at 0830 hrs IST of next day	Realised 24-hour heavy rainfall ending at 0300 UTC of date
09/06/2019	Heavy to very heavy falls at isolated places over Kerala and heavy rainfall at isolated places over Lakshadweep, coastal & south interior Karnataka	**10th June** **Kerala:** Piravam – 14, Nedumangad – 12, Cherthala & Alappuzha – 11 each, Mancompu, Vaikom
10/06/2019	Heavy to very heavy falls at isolated places over Lakshadweep area and coastal	

	Karnataka, Heavy rainfall at isolated places over Kerala, south interior Karnataka and Goa	& Kodungallur – 10 each, Kottayam , Kochi & Ernakulam South – 9 each, Chalakudi – 8 and Peermade, Kayamkulam, Chengannur & Aluva – 7 each **11th June** **Kerala:** Vyttiri – 10, Taliparamba – 8 and Quilandi & Vadakara – 7 each **13th June** **Konkan & Goa:** Tala – 9, Margao & Harnai – 8 each and Shriwardhan & Murud – 7 each **14th June** **Saurashtra & Kutch:** Talala – 16, Sutrapada – 15, Vanthali – 9, Bhavnagar – 8, Mendarda, Mangrol & Malia – 7 each **Konkan & Goa:** Valpoi – 10, Vaibhavwadi, Ponda, Kudal, Kankavli & Dodamarg – 8 each and Margao - 7 **Madhya Maharashtra:** Gaganbawada – 13, Mahabaleshwar & Gargoti / Bhudargad – 8 each and Velhe - 7 **15th June** **Gujarat Region:** Mangrol - 9 **Saurashtra & Kutch:** Sutrapada – 12, Talala – 10, Veraval – 9 and Kodinar - 8
11/06/2019	Heavy rainfall at isolated places over Konkan & Goa	
12/06/2019	Heavy to very heavy falls at isolated places over Konkan & Goa, Heavy rainfall at isolated places over south Gujarat region, Saurashtra & Kutch	
13/06/2019 0300 UTC	Heavy to very heavy rainfall at a few places with extremely heavy falls at isolated places over coastal districts of Saurashtra, heavy rainfall at isolated places over Saurashtra & Kutch	
14/06/2019 0300 UTC	Heavy rainfall at isolated places over Saurashtra & Kutch	
15/06/2019 0300 UTC	Nil for 15th & 16th. Predicted isolated heavy falls over coastal districts of Saurashtra & Kutch for 17th & 18th & for Gujarat and south Rajasthan on 18th.	
16/06/2019 0300 UTC	Nil for 16th. Predicted isolated heavy falls over Saurashtra & Kutch for 17th, heavy to very heavy falls on 18th, also heavy to very heavy falls over north Gujarat region and isolated heavy falls over south Rajasthan on 18th.	
17/06/2019 0300 UTC	Heavy falls at isolated places over Saurashtra & Kutch on 17th & 18th, over south Rajasthan on 17th, heavy to very heavy falls at isolated places over north Gujarat region and south Rajasthan on 18th.	

Table 8: Verification of Squally / Gale wind forecast

Date/ Time of observation (0300 UTC)	Gale/ Squally wind Forecast for north Andhra Pradesh, Odisha and West Bengal	Realised wind speed
09/06/2019	○ Strong wind speed reaching 35-45 kmph gusting to 55 kmph very likely to prevail over southeast and adjoining Lakshadweep & eastcentral Arabian Sea, Kerala & Karnataka Coasts on 09th June, 2019 and very likely to become 40-50 kmph gusting to 60 kmph on 10th June 2019. Sea Conditions	As the cyclone skirted Gujarat coast, the

	are very likely to be rough over the above areas. Fishermen are advised not to venture into above sea areas during the same period. ○ Wind speed is very likely to increase gradually and become squally wind speed reaching 55-65 kmph gusting to 75 kmph over eastcentral & adjoining southeast Arabian Sea on 11th June 2019. It is very likely to be 40-50 kmph gusting to 60 kmph over Lakshadweep area, Kerala, Karnataka & south Maharashtra Coasts on the same day. Sea Conditions is likely to be rough over the above areas. Fishermen are advised not to venture into above sea areas during the same period. ○ Wind speed is very likely to increase further becoming gale wind speed reaching **70-80 kmph gusting to 90 kmph** over eastcentral & adjoining northeast Arabian Sea on 12th June 2019 and become **90-100 kmph gusting to 110 kmph** over north Arabian Sea on 13th June 2019. It is very likely to be 45-55 kmph gusting to 65 kmph over Gujarat & Maharashtra Coasts on 12th and 55-65 kmph gusting to 75 kmph over entire Gujarat and north Maharashtra Coasts on 13th June, 2019.	core maximum wind due to the cyclone occurred over the Sea. However, the squally to gale wind speed from 45 kmph to 90 kmph occurred along & off Gujarat coast during 12th to 14th. On 12th June, Bhavnagar reported estimated maximum sustained surface winds (MSW) of 46 kmph during 1400 – 1800 UTC . On 13th June, Porbandar reported MSW of 84 kmph at 0800 UTC , Veraval reported 60 kmph of MSW at 0900 & 1000 UTC and Diu reported MSW of 41 kmph at 0900 UTC On 14th June, Veraval
10/06/2019	○ **10th June:** Squally wind speed reaching 50-60 kmph gusting to 70 kmph very likely to prevail over Eastcentral and adjoining Southeast Arabian Sea & Lakshadweep area. The strong wind speed reaching 35-45 kmph gusting to 55 kmph very likely to prevail over Kerala & Karnataka Coasts. ○ **11th June:** Wind speed is very likely to increase gradually and become gale wind speed reaching 65-75 kmph gusting to 85 kmph over eastcentral & adjoining southeast Arabian Sea. It is very likely to be 40-50 kmph gusting to 60 kmph over Lakshadweep area, Kerala, Karnataka & south Maharashtra Coasts. ○ **12th June:** Wind speed is very likely to increase further becoming gale wind speed reaching **90-100 kmph gusting to 115 kmph** over eastcentral & adjoining northeast Arabian Sea. It is very likely to be 50-60 kmph gusting to 70 kmph over South Gujarat & Maharashtra Coasts. ○ **13th June:** Wind speed is very likely to increase further becomes **110-120 kmph gusting to 135 kmph** over north Arabian Sea. It is very likely to be 65-75 kmph gusting to 75 kmph over Gujarat coast; and 50-60 kmph gusting to 70 kmph over north Maharashtra Coasts & northern parts of eastcentral Arabian Sea.	
11/06/2019 0300 UTC	○ **11th June:** Gale Wind speed reaching 70-80 kmph gusting to 90 kmph over Eastcentral Arabian Sea and 50-60 kmph gusting to 70 kmph along & off North Maharashtra coast by 11th evening. It is very likely to be 40-50 kmph gusting to 60 kmph over Lakshadweep area, Kerala, Karnataka & south	

	Maharashtra Coasts. ○ **12th June:** Wind speed is very likely to increase further becoming gale wind speed reaching **110-120 kmph gusting to 135 kmph** over eastcentral & adjoining northeast Arabian Sea by 12th night. It is very likely to be 60-70 kmph gusting to 80 kmph over Gujarat Coast from 12th morning and become gale wind speed reaching **110-120 kmph gusting to 135 kmph** by 12th night. It is very likely to be 50-60 kmph gusting to 70 kmph over Maharashtra Coast. ○ **13th June:** Gale wind speed of the order of **110-120 kmph gusting to 135 kmph** very likely over north Arabian Sea & Gujarat coast in morning hours and decrease gradually thereafter. It is very likely to be 50-60 kmph gusting to 70 kmph over north Maharashtra Coasts & northern parts of eastcentral Arabian Sea.	reported MSW of 63 kmph and Diu reported 37 kmph of MSW at around 1830 UTC
12/06/2019 0300 UTC	○ **12th June:** Gale wind speed reaching **140-150 kmph gusting to 165 kmph** prevails over eastcentral & adjoining northeast Arabian Sea and become **145-155 kmph gusting to 170 kmph** by 12th night. It is very likely to be 60-70 kmph gusting to 80 kmph over Gujarat Coast from 12th morning and become gale wind speed reaching **145-155 kmph gusting to 170 kmph** by 12th night. It is very likely to be 50-60 kmph gusting to 70 kmph over Maharashtra Coast. ○ **13th June:** Gale wind speed of the order of **145-155 kmph gusting to 170 kmph** very likely over north Arabian Sea & Gujarat coast in morning hours and decrease gradually thereafter. It is very likely to be 50-60 kmph gusting to 70 kmph over north Maharashtra Coasts & northern parts of eastcentral Arabian Sea.	
13/06/2019 0300 UTC	○ **13th June:** Gale wind speed of the order of **135-145 kmph gusting to 160 kmph** very likely over north Arabian Sea & Gujarat coast. It is very likely to be 50-60 kmph gusting to 70 kmph over north Maharashtra Coasts & northern parts of eastcentral Arabian Sea. ○ **14th June:** Gale wind speed of the order of **120-130 kmph gusting to 145 kmph** very likely over north Arabian Sea & Gujarat coast in morning hours and decrease gradually thereafter. It is very likely to be 40-50 kmph gusting to 60 kmph over northern parts of eastcentral Arabian Sea. ○ **15th June:** Gale wind speed of the order of **100-110 kmph gusting to 125 kmph** very likely over north Arabian Sea & Gujarat coast till evening and decrease gradually thereafter.	
14/06/2019 0300 UTC	○ The system is moving nearly west-northwestwards affecting Porbandar & Devbhoomi Dwarka with wind speed 50-60 kmph gusting to 70 kmph and Gir Somnath & Junagarh with wind speed 30-40 kmph gusting to 50 kmph. The wind speed over these districts is very likely to decrease gradually, as the system is moving away from the coast.	

	○ **14th June:** Gale wind speed of the order of **120-130 kmph gusting to 145 kmph** very likely over north Arabian Sea. Gale wind speed of the order of **60-70 kmph gusting to 80 kmph** very likely over Gujarat coast during next 12 hours and decrease gradually thereafter. It is very likely to be 40-50 kmph gusting to 60 kmph over northern parts of eastcentral Arabian Sea. ○ **15th June:** Gale wind speed of the order of **100-110 kmph gusting to 125 kmph** very likely over north Arabian Sea. Squally wind speed of the order of **50-60 kmph gusting to 70 kmph** very likely over Gujarat coast. ○ **16th June:** Gale wind speed of the order of **80-90 kmph gusting to 100 kmph** very likely over north Arabian Sea. Squally wind speed of the order of **45-55 kmph gusting to 65 kmph** very likely over Gujarat coast.	
15/06/2019 0300 UTC	○ **15th June:** Gale wind speed of the order of **120-130 kmph gusting to 145 kmph** very likely over northeast Arabian Sea and adjoining areas of northwest and central Arabian Sea. Squally wind speed of the order of **45-55 kmph gusting to 65 kmph** very likely along & off Gujarat coast. ○ **16th June:** Gale wind speed of the order of **100-110 kmph gusting to 125 kmph** very likely over northeast Arabian Sea and adjoining areas of northwest and central Arabian Sea. Strong wind speed of the order of **40-50 kmph gusting to 60 kmph** very likely along & off Gujarat coast. ○ **17th June:** Squally wind speed of the order of **55-65 kmph gusting to 75 kmph** very likely over northeast Arabian Sea and adjoining east central Arabian Sea. Strong wind speed of the order of **40-50 kmph gusting to 60 kmph** very likely along & off Gujarat coast.	
16/06/2019 0300 UTC	○ **16th June:** Gale wind speed of the order of **105-115 kmph gusting to 130 kmph** very likely over northeast Arabian Sea and adjoining areas of northwest and central Arabian Sea and decrease gradually thereafter. Strong wind speed of the order of **40-50 kmph gusting to 60 kmph** very likely along & off Gujarat coast. ○ **17th June:** Gale wind speed of the order of **70-80 kmph gusting to 90 kmph** very likely over northeast Arabian Sea and adjoining east central Arabian Sea in morning hours and decrease gradually thereafter. Strong wind speed of the order of **40-50 kmph gusting to 60 kmph** very likely along & off Gujarat coast from the morning and gradually become squally winds speed reaching **50-60 kmph gusting to 70 kmph** towards evening.	
17/06/2019 0300 UTC	○ Squally wind speed of the order of **50-60 kmph gusting to 70 kmph** is prevailing over northeast Arabian Sea and adjoining central Arabian Sea and it is very likely to decrease gradually becoming **40-50 kmph gusting to 60 kmph by the night of 17th June, 2019.** Squally wind speed of the order of **40-50**	

	kmph gusting to 60 kmph very likely to commence along & off Gujarat coast from the evening of 17th.	

Table 9: Verification of Storm surge forecast

Date/ Time(UTC)	Storm Surge Forecast	Recorded storm surge
11/06/2019 0300 UTC	Storm surge of height of about 1.0- 1.5 m above the astronomical tides likely to inundate the low lying coastal areas of Kutch, Devbhoomi Dwarka, Porbandar, Junagarh, Diu, Gir Somnath, Amreli and Bhavnagar districts at the time of landfall.	No significant storm surge was reported as the system skirted the coast and later on weakened over the Sea
12/06/2019 0300 UTC	Storm surge of height of about 1.5-2.0 m above the astronomical tides likely to inundate the low lying coastal areas of Kutch, Devbhoomi, Dwarka, Porbandar, Junagarh, Diu, Gir Somnath, Amreli and Bhavnagar districts at the time of landfall.	
13/06/2019 0300 UTC	Storm surge of height about 0.6m to 1.3 m above the astronomical tides likely to inundate the low lying coastal areas in the districts Gir Somnath, Diu, Junagarh, Porbandar and Devbhoomi Dwarka from the afternoon of 13th June 2019.	
14/06/2019 0300 UTC	No warning	

13. Summary

Very Severe Cyclonic Storm (VSCS) "VAYU" originated from an LPA which formed over southeast Arabian Sea and adjoining Lakshadweep & eastcentral Arabian Sea (AS) on 09th June. Under favourable environmental conditions, it concentrated into a D over southeast & adjoining eastcentral AS and Lakshadweep on 10th June, into CS "VAYU" at 1800 UTC of 10th June, 2019 and into a VSCS by 1800 UTC of 11th June over the eastcentral AS. Thereafter, it started weakening from 16th June onwards and weakened into a WML over northeast AS and adjoining Saurashtra & Kutch on 17th June. The track forecast errors for 24, 48 and 72 hrs lead period were 67.5, 125.9, and 264.9 km respectively against the average track forecast errors of 86.1, 132.3, and 177.7 km during last five years (2014-18) respectively. The absolute error (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 6.6, 11.9 and 33.7 knots against the LPA of 9.6, 14.1, and 14.3 knots respectively. The system caused light to moderate rainfall at many places with isolated heavy to very heavy rainfall over Saurashtra & Kutch on 13th & 14th and over Gujarat region on 14th. It also caused light to moderate rainfall at many places with isolated heavy to very falls over Kerala, coastal Karnataka and Konkan & Goa during 10th -14th June. As the cyclone skirted Gujarat coast, the core maximum wind

due to the cyclone occurred over the Sea. However, squally to gale wind speed from 45 kmph to 90 kmph occurred along & off Gujarat coast during 12th to 14th. IMD issued a total of 61 National, 58 International, 91 Hourly Bulletins and 32,28,156 SMS to disaster managers, general public including farmers & fishermen.

13. Acknowledgement:

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