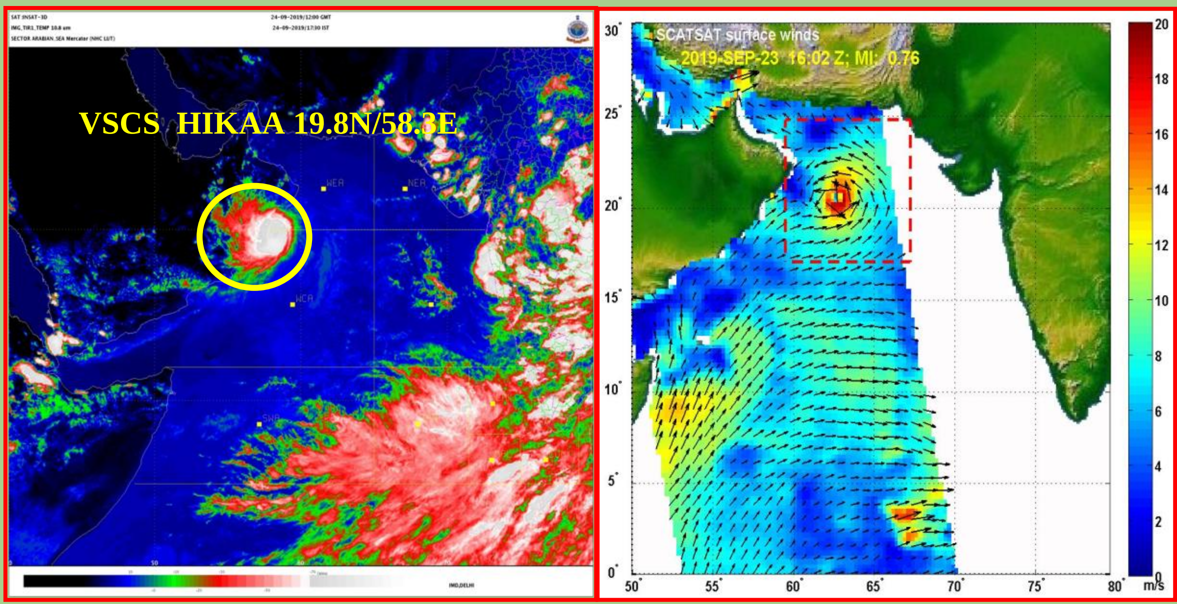
GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
INDIA METEOROLOGICAL DEPARTMENT

Very Severe Cyclonic Storm, 'HIKAA' over the Arabian Sea (22 – 25 September 2019): A Report



INSAT-3D enhanced colored IR imagery of 12 UTC, 24th SEPTEMBER, 2019& Sea surface winds from SCATSAT

Cyclone Warning Division

India Meteorological Department

New Delhi

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Very Severe Cyclonic Storm "HIKAA" over the Arabian Sea (22-25 September 2019)

1. Introduction

- Very Severe Cyclonic Storm (VSCS) "HIKAA" originated from a low pressure area (LPA) which formed over eastcentral Arabian Sea (AS) off north Maharashtra coast in the morning (0300 UTC) of 20th September.
- It lay as a well marked low pressure area (WML) over eastcentral and adjoining northeast AS off south Gujarat coast in the afternoon (0900 UTC) of 21st September.
- Under favourable environmental conditions, it concentrated into a Depression (D) over eastcentral and adjoining northeast AS off Gujarat coast in the morning (0300 UTC) of 22nd September.
- Moving nearly west-northwestwards, it intensified into a deep depression (DD) over northeast and adjoining eastcentral AS off Gujarat coast in the same evening (1200 UTC).
- It moved nearly westwards and intensified into cyclonic storm "HIKAA" in the early morning (0000 UTC) of 23rd over northeast and adjoining eastcentral AS.
- It then moved west-southwestwards and intensified, into a severe cyclonic storm (SCS) in the same afternoon (0900 UTC) over northeast and adjoining northwest & central AS.
- Moving nearly westwards, it further intensified into a VSCS in the early morning (0000 UTC) of 24th September over northwest and adjoining westcentral AS.
- It then moved west-southwestwards and crossed Oman coast near latitude 19.7°N and longitude 57.7°E, close to north of Duqm in the same evening (between 1400 and 1500 UTC of 24th) as a VSCS with maximum sustained surface wind speed of 120-130 kmph gusting to 145 kmph.
- Moving nearly westwards, it further weakened into an SCS over coastal Oman in the same night (1500 UTC of 24th). Continuing to move westwards, it weakened into a cyclonic storm over Oman in the early hours (2100 UTC) of 24th, into a DD over Oman in the morning (0300 UTC), a depression around noon (0600 UTC) over Oman and into a WML over south Oman and adjoining Saudi Arabia in the afternoon (0900 UTC) of 25th September.
- The observed track of VSCS Hikaa is presented in Fig. 1. The best track parameters are presented in Table 1.

2. Salient Features:

The salient features of the system were as follows:

i. It was the second VSCS after "VAYU" developing over AS during 2019 against the normal of 1 per year during 1891-2018.

ii. It was the first VSCS crossing Oman coast in September during 1891-2018. Climatologically, during September out of 11 cyclonic disturbances (depression and above intensity storms) developing over AS, only 2 crossed Oman coast as depression. Tracks of cyclonic disturbances developing over AS in the month of

September and crossing Oman coast during September are presented in **Fig.2 (a-b)**.

iii. It had a straight track with length of 1610 km. It was mainly steered by ridge in middle & upper tropospheric levels to the north of the system centre.

iv. It moved faster as 12 hour average translational speed was about 22.1 kmph against long period average (LPA) during 1990-2013 of 14.3 kmph for VSCS category over north Indian Ocean.

v. It had rapid intensification during 23rd early morning (0000 UTC) to 24th early morning (0000 UTC) over northwest and adjoining westcentral AS, mainly due to decreased vertical wind shear, increased equatorward outflow and increased warm & moist air advection into the core of the system. The wind speed increased by 35 kt (35 kt to 70 kt) during this period.

vi. The peak MSW of the cyclone was 130-140 kmph (75 kt) gusting to 155 kmph during 0600 UTC to 1200 UTC of 23rd September over the westcentral and adjoining northwest AS. The lowest estimated central pressure was 978 hPa during the same period.

vii. HIKAA also exhibited rapid weakening after landfall during 24th evening (1200 UTC) to 25th noon (0600 UTC) with wind speed decreasing from 75 kt to 25 kt.

viii. The system crossed Oman coast near Latitude 19.7 N and longitude 57.7 E close to Duqm between 1400 UTC and 1500 UTC of 24th September, 2019 with maximum sustained wind speed of 120-130 kmph gusting to 145 kmph.

ix. The system maintained the cyclonic storm intensity for almost 12 hours even after landfall till 0300 UTC of 25th.

x. The life period (D to D) of the system was 78 hours (3 days & 6 hours) against long period average (LPA) (1990-2013) of 140 hours (5 days & 20 hrs) for VSCS categories over AS during monsoon season.

xi. The Velocity Flux, Accumulated Cyclone Energy (a measure of damage potential) and Power Dissipation Index (a measure of loss) were 5.05 X10^{2} knots, 3.03 X 10^{4} knots^{2} and 1.91 X10^{6} knots^{3} respectively against long period average during 1990-2013 of 5.28 X10^{2} knots, 8.6 X 10^{4} knots^{2} and 2.8 X10^{6} knots^{3} respectively.

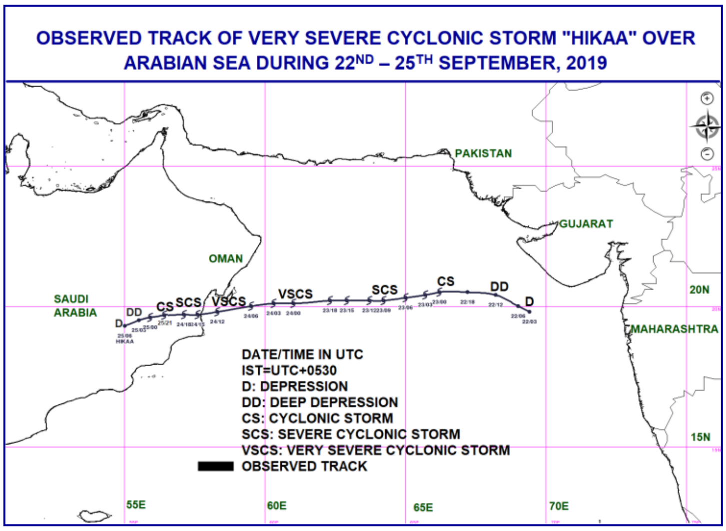


Fig.1 Observed track of VSCS HIKAA (22-25 September, 2019) over Arabian Sea

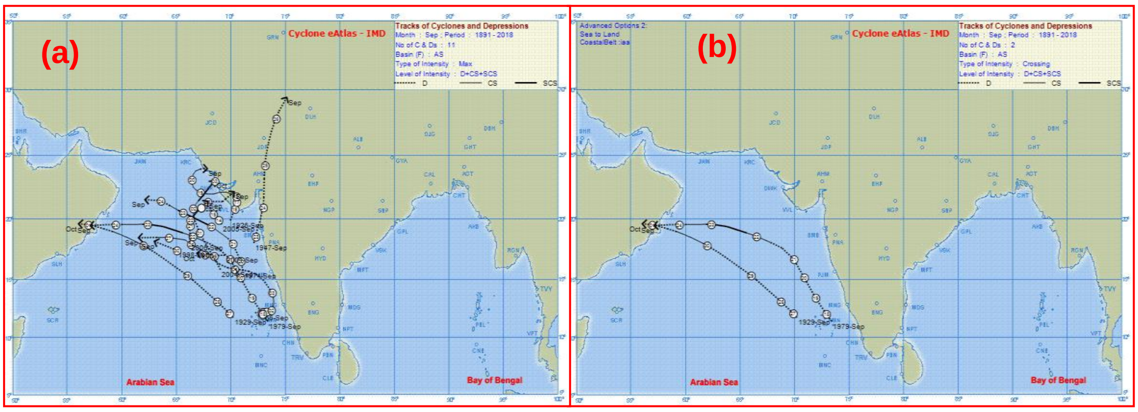


Fig.2: (a) Tracks of severe cyclonic storms forming over the AS and (b) and those crossing Oman coast in the month of September (1891-2018)

Table 1: Best track positions and other parameters of the Very Severe Cyclonic Storm "HIKAA" over the AS during 22nd – 25th September, 2019

Date	Time (UTC)	Centre lat.⁰ N	Centre long. ⁰ E	C.I. NO	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
22/09/2019	0300	19.8	69.4	1.5	1002	25	03	**D**
	0600	20.0	69.0	1.5	1000	25	04	D
	1200	20.4	68.2	2.0	999	30	05	**DD**
	1800	20.5	67.2	2.0	998	30	06	DD
23/09/2019	0000	20.5	66.2	2.5	997	35	07	**CS**
	0300	20.4	65.7	2.5	996	40	08	CS
	0600	20.3	65.0	3.0	994	45	10	CS
	0900	20.2	64.2	3.5	988	55	16	**SCS**
	1200	20.2	63.7	3.5	988	55	16	SCS
	1500	20.2	62.9	3.5	988	55	16	SCS
	1800	20.2	62.3	3.5	986	60	18	SCS
	2100	20.2	61.5	3.5	986	60	18	SCS
24/09/2019	0000	20.1	61.0	4.0	980	70	24	**VSCS**
	0300	20.1	60.3	4.0	980	70	24	VSCS
	0600	20.0	59.5	4.5	978	75	27	VSCS
	0900	19.9	58.9	4.5	978	75	27	VSCS
	1200	19.8	58.3	4.5	978	75	27	VSCS
	Crossed Oman coast near Latitude 19.7 N and longitude 57.7 E between 1400 UTC and 1500 UTC of 24th September, 2019.							
	1500	19.7	57.6	-	986	60	18	**SCS**
	1800	19.7	57.1	-	989	55	15	SCS
	2100	19.6	56.6	-	994	45	10	**CS**
25/09/2019	0000	19.6	55.9	-	997	35	07	CS
	0300	19.5	55.5	-	999	30	05	**DD**
	0600	19.3	55.0	-	1002	25	03	**D**
	0900	Weakened into a well marked low pressure area over south Oman and adjoining Saudi Arabia.						

3. Brief life history

3.1. Genesis:

It developed from an LPA which formed over eastcentral Arabian Sea (AS) off north Maharashtra coast in the morning (0300 UTC) of 20th September. Under favourable environmental conditions, it lay as a WML over eastcentral and adjoining northeast AS off south Gujarat coast in the afternoon (0900 UTC) of 21st September.

3.2. Intensification and movement

At 0300 UTC of 22nd, the Madden Julian Oscillation (MJO) index lay in phase 1 with amplitude more than 1. The sea surface temperature (SST) was 27-28˚C over central and north AS. The tropical cyclone heat potential (TCHP) was less than 50 KJ/cm2 over the system area. However, total precipitable water imageries (TPW) indicated warm air advection into the core of the system (Fig. 3). The low level relative vorticity increased in past 24 hours and was 100 $x10^{-5}sec^{-1}$ around the system centre. It was extending upto 200 hPa level. The lower level convergence was about 10 $x10^{-5}$s-1 around the system center. The upper level divergence was about 20 $x10^{-5}$s-1 to the southeast of the system center. The vertical wind shear was moderate (15-20 kt) over the system area. The system lay to the south of upper tropospheric ridge and was being steered by middle and upper tropospheric easterlies. Under these favourable conditions, a depression formed over eastcentral and adjoining northeast AS off Gujarat coast near latitude 19.8°N and longitude 69.4°E.

At 1200 UTC of 22nd, similar MJO and sea conditions prevailed. TPW imageries indicated warm air advection into the core of the system. The low level relative vorticity increased and was about 120 $x10^{-5}sec^{-1}$ around the system centre extending upto 200 hPa level. The lower level convergence was about 10 $x10^{-5}s^{-1}$ around the system center. The upper level divergence was about 20 $x10^{-5}s^{-1}$ to the south of the system center. The vertical wind shear was moderate (15-20 kt) over the system area. The upper tropospheric ridge ran along 22° N. The increased vorticity, warm air advection and moderate wind shear helped the system to further intensify into a deep depression over northeast and adjoining eastcentral AS near latitude 20.4°N and longitude 68.2°E. The system lay to the south of upper tropospheric ridge and was steered west-northwestwards by the east-southeasterly winds in the middle and upper tropospheric levels.

At 0000 UTC of 23rd, similar MJO and sea conditions prevailed. TPW imageries indicated continued warm air advection into the system centre. The low level relative vorticity increased and was about 150 $x10^{-5}sec^{-1}$ around the system centre. The lower level convergence was about 10 $x10^{-5}s^{-1}$ around the system center. The upper level divergence was about 10 $x10^{-5}s^{-1}$ over the system center. The vertical wind shear was moderate (15-20 kt) over the system area. The upper tropospheric ridge ran along 22° N. The increased vorticity, warm air advection and moderate wind shear further aided intensification of the system into a CS over northeast and adjoining eastcentral AS near latitude 20.5°N and longitude 66.2°E. The system lay to the south of upper tropospheric ridge and was steered nearly westwards by middle and upper tropospheric winds.

At 0900 UTC of 23rd, similar MJO and sea conditions prevailed. Also, TPW imageries indicated warm air advection into the system centre. The low level relative vorticity was about 150 $x10^{-5}sec^{-1}$ to the south of system centre. The lower level convergence increased and was about 20 $x10^{-5}s^{-1}$ around the system center. The upper level divergence was about 10 $x10^{-5}s^{-1}$ over the system center. The vertical wind shear was moderate (10-15 kt) over the system area. The upper tropospheric ridge ran along 22° N. Though ocean heat content and MJO were not favourable, the increased vorticity, warm air advection and moderate wind shear helped the system to intensify into an SCS over northeast and adjoining northwest & central AS near latitude 20.2°N and longitude 64.2°E. As the system lay to the south of upper tropospheric ridge and was steered by middle and upper tropospheric winds, the westwards movement continued.

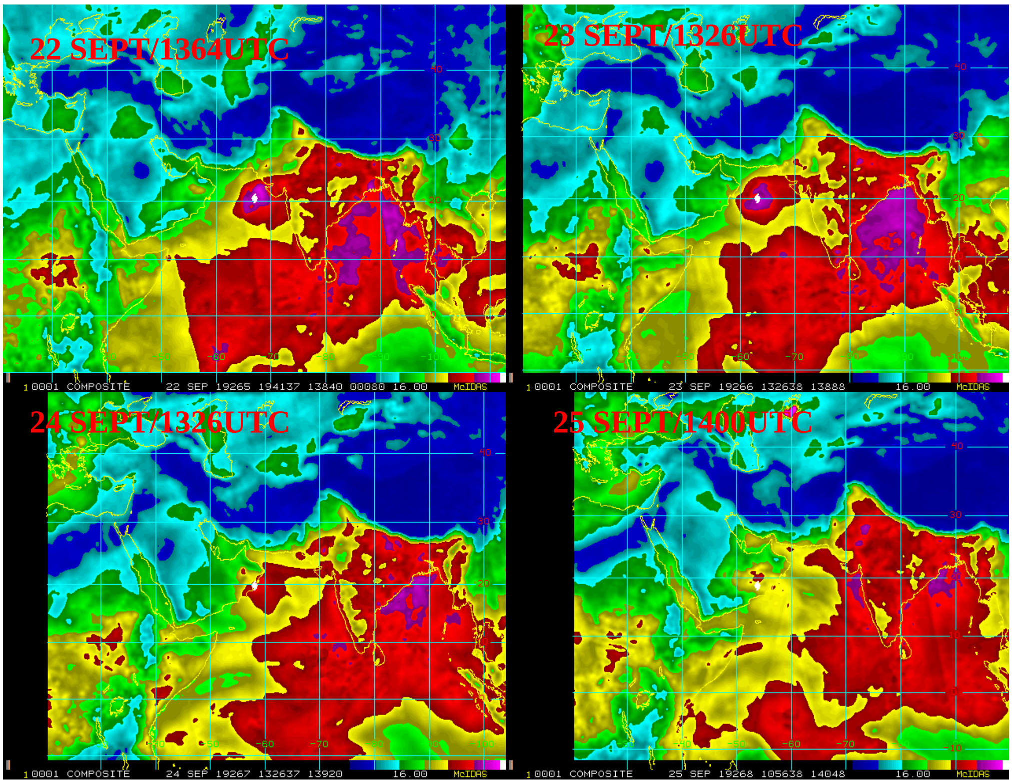


Fig. 3: Total Precipitable Water (TPW) imageries during VSCS HIKAA (22-25 Sept, 2019

At 0000 UTC of 24th, the system entered into an area of decreased vertical wind shear and there was continuous warm air advection into the core of the system. Further equatorward outflow increased significantly. TPW imageries indicated continuous warm air advection into the system centre. The low level relative vorticity increased and was about 170 $x10^{-5}sec^{-1}$ to the south of the system centre. The lower level convergence was about 20 $x10^{-5}$ s^{-1} around the system center. The upper level divergence was about 10 $x10^{-5}$ s^{-1} around the system center. The vertical wind shear was moderate (10-15 kt) over the system area and along the forecast track. The upper tropospheric ridge extended along 24°N. Under these conditions, it moved nearly westwards and intensified into a VSCS over northwest and adjoining westcentral AS near latitude 20.1°N and longitude 61.0°E. Continuing to move westwards, it crossed Oman coast near latitude 19.7°N and longitude 57.7°E between 1400 UTC and 1500 UTC of 24th September, 2019 with maximum sustained wind speed of 120-130 kmph gusting to 145 kmph.

Thereafter, due to land interactions, dry cold air incursion into the core of the system, decreased low level vorticity, lower level convergence and upper level divergence, the system weakened into an SCS over Oman at 1500 UTC of 24th September, 2019 near latitude 19.7°N and longitude 57.6°E close to Duqm and into a CS over Oman at 2100 UTC of 24th over Oman near latitude 19.6°N and longitude 56.6°E about 110 km west of Duqm (41290) and 50 km south-southeast of Haima (41301). Moving further west-southwestwards, it weakened into a DD at 0300 UTC of 25th near latitude 19.5°N and longitude 55.5°E, about 220 km west of Duqm and 110 km west-southwest of Haima, into a depression at 0600 UTC of 25th near latitude 19.3°N and longitude 55.0°E, about 280 km west-southwest of Duqm and 170 km west-southwest of Haima and into a WML over South Oman & adjoining Saudi Arabia at 0900 UTC of 25th September.

3.3. Maximum sustained wind speed and translational speed

The mean wind shear in middle layer around the system centre is presented in **Fig.4 (a)**. The wind shear around the system in the layer 500 to 850 hPa remained low (05-10 knots) throughout the life cycle of Hikaa. The direction of 500-850 hPa mean wind shear was initially west-southwestwards till 23rd/0600 UTC and north-northwestwards thereafter shearing the cloud mass accordingly.

From **Fig. 4 (b-c)**, it is seen that the mean wind speed in the layers 200 to 850 hPa and 500 to 850 hPa direction was nearly westerly. The mean wind speed in the layer 200 to 850 hPa was around 11kt (20 kmph) till 24th/1800 UTC and thereafter it slightly increased. The mean wind speed in the layer 500 to 850 hPa wind speed was slightly higher. The system was thus steered by mean winds in the layer 200 to 850 hPa. The six hourly translational speed of VSCS Hikaa is presented in **Fig.5**. It is seen that the system moved faster than the normal average speed of VSCS category of storms over the north Indian Ocean.

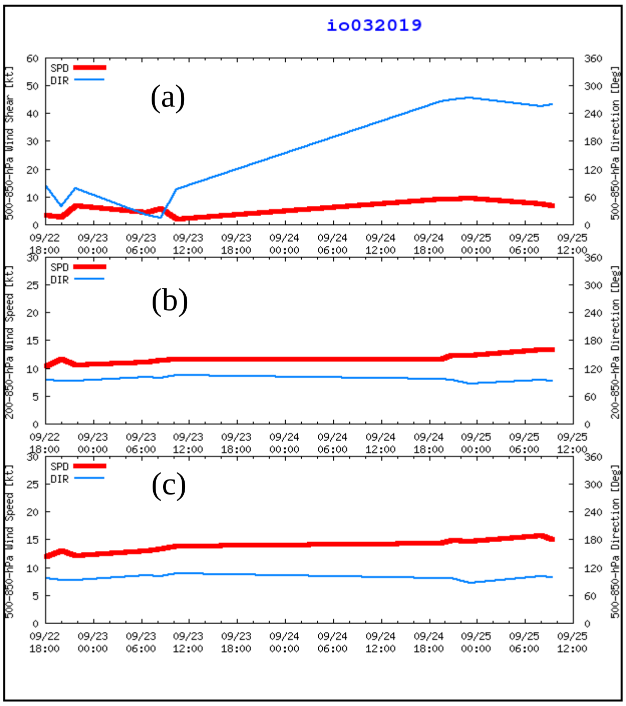


Fig.4: (a) Mean Wind shear in the layer 500 to 850 hPa and (b-c) mean wind speed in the layer 200 to 850 hPa & 500 to 850 hPa around the system VSCS HIKAA (22-25 September, 2019)

The intensity of the system increased gradually till 23rd/0000 UTC. Thereafter, it experienced rapid intensification during 22nd midnight (1800 UTC) to 24th noon (0600 UTC) over northwest and adjoining westcentral AS, mainly due to decreased vertical wind shear, increased equatorward outflow and increased warm & moist air advection into the core of the system. The wind speed increased by 30-35 kt in 24 hours during this period. From 24th/1200 UTC onwards, it gradually weakened till 24th/1800 UTC and thereafter, it weakened rapidly.

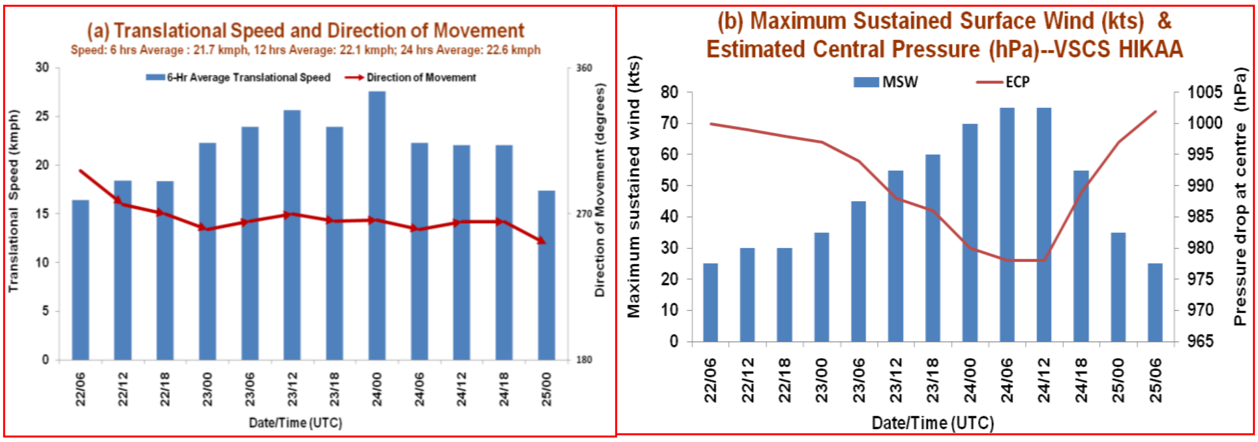


Fig. 5: (a) Translational speed & direction of movement and (b) Maximum sustained surface wind (kt) & Estimated Central Pressure (hPa)

4. Monitoring of VSCS, 'HIKAA'

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean and the cyclone was monitored around 10 days prior to the formation of depression over the AS on 22nd September. First information about possible cyclogenesis over eastcentral AS during first half of week (20-26 September) with moderate probability (34-67%) was indicated in the extended range outlook issued by IMD on 12th September. Thus, the cyclone was monitored & predicted continuously from 12th September onwards by IMD.

The cyclone was monitored mainly with the help of available satellite observations from INSAT 3D and 3DR, polar orbiting satellites and available ships & buoy observations in the region. As the system was moving away from Indian coast, the Doppler weather radars of IMD along the west coast could not be utilised for monitoring the system. Various numerical weather prediction models run 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's guidance, decision making process and warning product generation. Typical satellite imagery and ScatSat based sea surface wind are presented in **Fig. 6**.

At 0300 UTC of 22nd September, the intensity of the system was T1.5. Broken low to medium clouds with embedded intense to very intense convection lay over eastcentral and adjoining northeast AS between latitude 18.0˚N & 22.5 ˚N and longitude 65.0°E & 71.0°E and adjoining Gujarat. Satellite imageries indicated increase in convection and increased organization of clouds around the system centre. Minimum cloud top temperature (CTT) was -90˚C.

At 1200 UTC on 22nd, the intensity of the system was T2.0. Broken low to medium clouds with embedded intense to very intense convection lay over eastcentral and adjoining northeast AS between latitude 18.0 ˚N & 23.0 ˚N and longitude 64.5 ˚E & 69.5 ˚E off Gulf of Kutch & adjoining West Gujarat. Minimum CTT was -91˚C.

At 0900 UTC on 23rd, the convection further organized in curved band pattern. The intensity of the system was T3.5. Broken low to medium clouds with embedded intense to very intense convection lay over north and adjoining central AS between latitude 18.0˚N & 21.5˚N and longitude 59.0˚E & 65.0˚E.

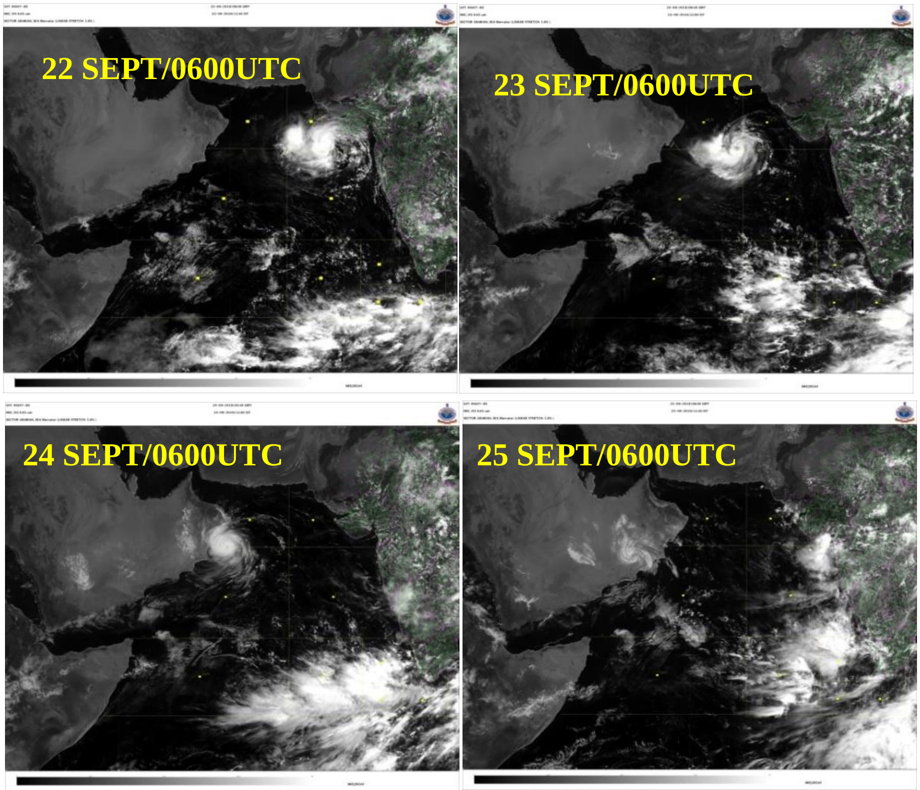


Fig. 6a: INSAT-3D visible imageries during life cycle of VSCS HIKAA (22-25 September, 2019)

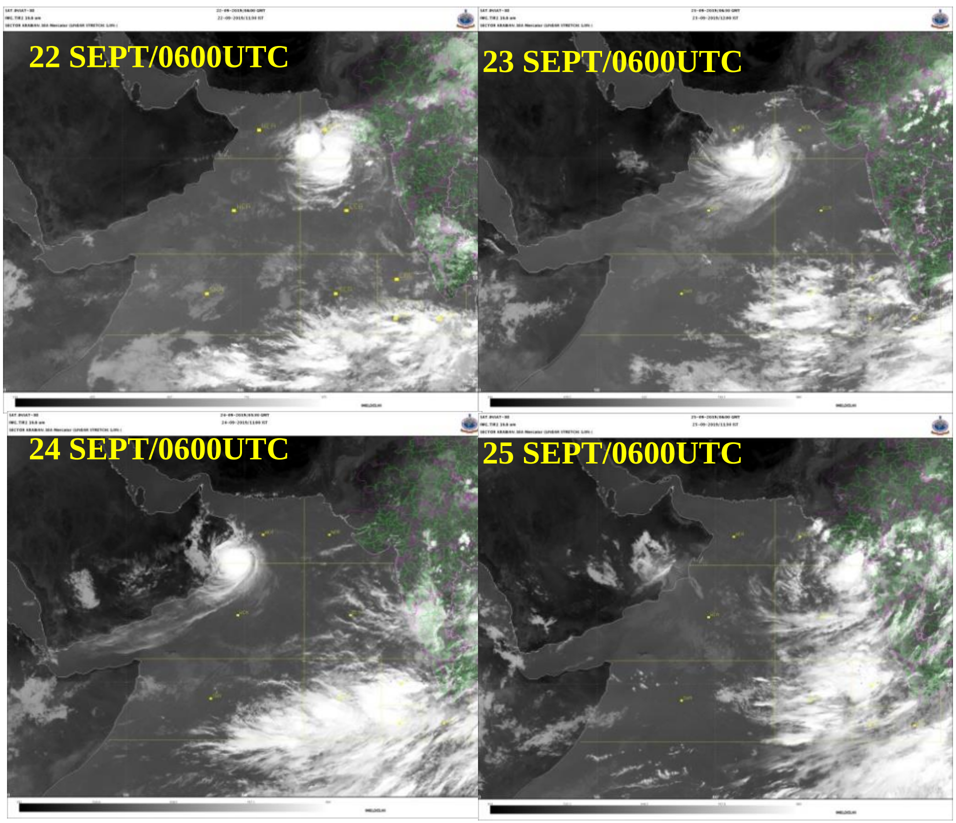


Fig. 6b: INSAT-3D IR imageries during life cycle of VSCS HIKAA (22-25 September, 2019)

At 0000 UTC of 24th, the clouds further organized and the intensity of the system was T4.0. The system showed eye pattern. Broken low to medium clouds with embedded intense to very intense convection lay over westcentral and adjoining northwest AS between latitude 18.5˚N & 21.5˚N and longitude 59.0˚E & 62.0˚E.

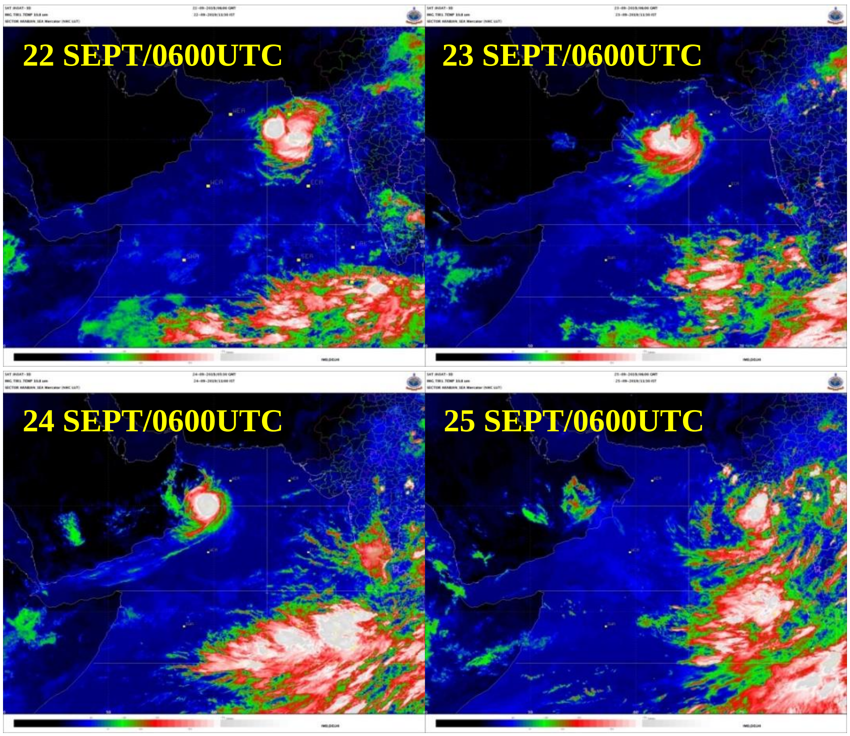


Fig. 6c: INSAT-3D enhanced colored imageries during life cycle of VSCS HIKAA (22-25 September, 2019)

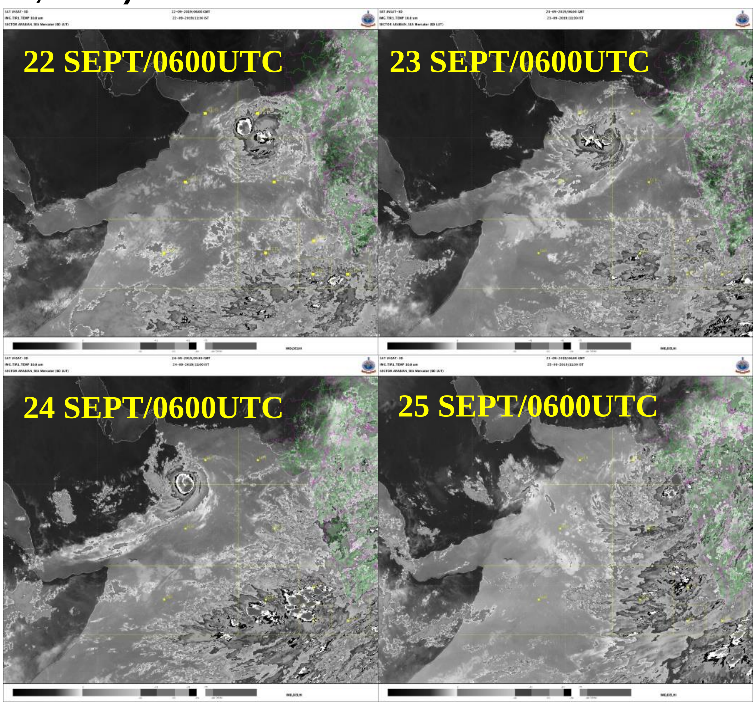


Fig. 6d: INSAT-3D cloud top brightness imageries during life cycle of VSCS HIKAA (22-15 September, 2019

At 0600 UTC of 24th, the intensity of the system was T4.5. The system showed eye pattern with embedded ragged eye. Lowest CTT was -86°C. Broken low to medium clouds with embedded intense to very intense convection lay over westcentral & adjoining northwest AS between latitude 18.5˚N to 21.0˚N and longitude 58.5˚E to 60.5˚E.

At 1500 UTC of 24th, the system was over Oman coast. Due to land interactions and cut off of moisture supply, the system started weakening. The clouds were organized in curved band pattern. Lowest CTT was -80°C. Broken low to medium clouds with embedded intense to very intense convection lay over Oman & adjoining areas of Saudi Arabia and northwest AS between latitude 18.5°N & 21.5°N and longitude 56.5°E & 59.0°E

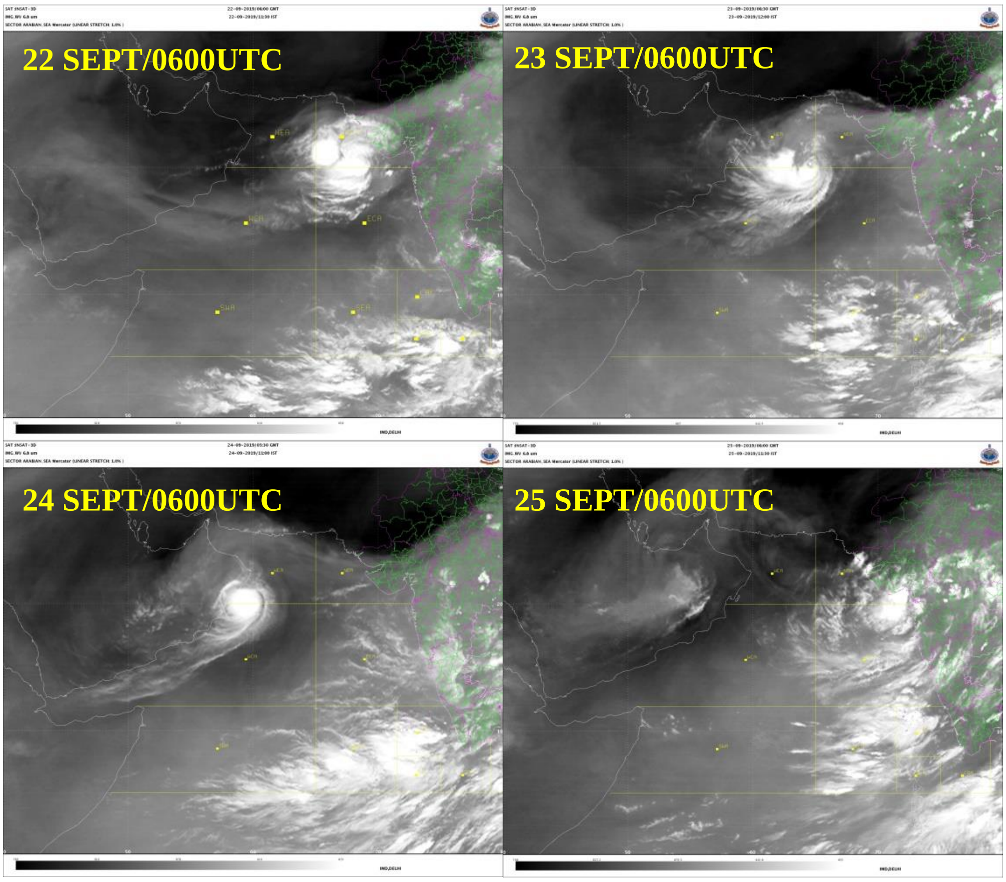


Fig. 6e: INSAT-3D Water Vapor imageries during life cycle of VSCS HIKAA (22-25 September, 2019)

At 2100 UTC of 24th, the depth of convection decreased and the lowest CTT was - 65°C. Broken low to medium clouds with embedded intense to very intense convection lay over Oman & adjoining areas of Saudi Arabia and northwest Arabian Sea between latitude 18.0°N to 21.0°N and longitude 53.0°E to 58.0°E

At 0300 UTC of 25th, the lowest CTT was -46°C. Scattered low & medium clouds with embedded moderate to intense convection lay over Oman & adjoining Saudi Arabia between latitude 18.0˚N & 22.5˚N and longitude 52.0˚E & 57.0˚E.

At 0900 UTC of 25th, the lowest CTT was -40°C. Scattered low & medium clouds with embedded moderate to intense convection lay over Oman & adjoining Saudi Arabia between latitude 18.0˚N & 20.0˚N and longitude 53.0˚E & 56.0˚E.

Typical ASCAT imageries during life cycle of Hikaa are presented in Fig. 6f. The ASCAT pass could not cover the system and circulation centre or intensity could not be well determined with the help of these imageries.

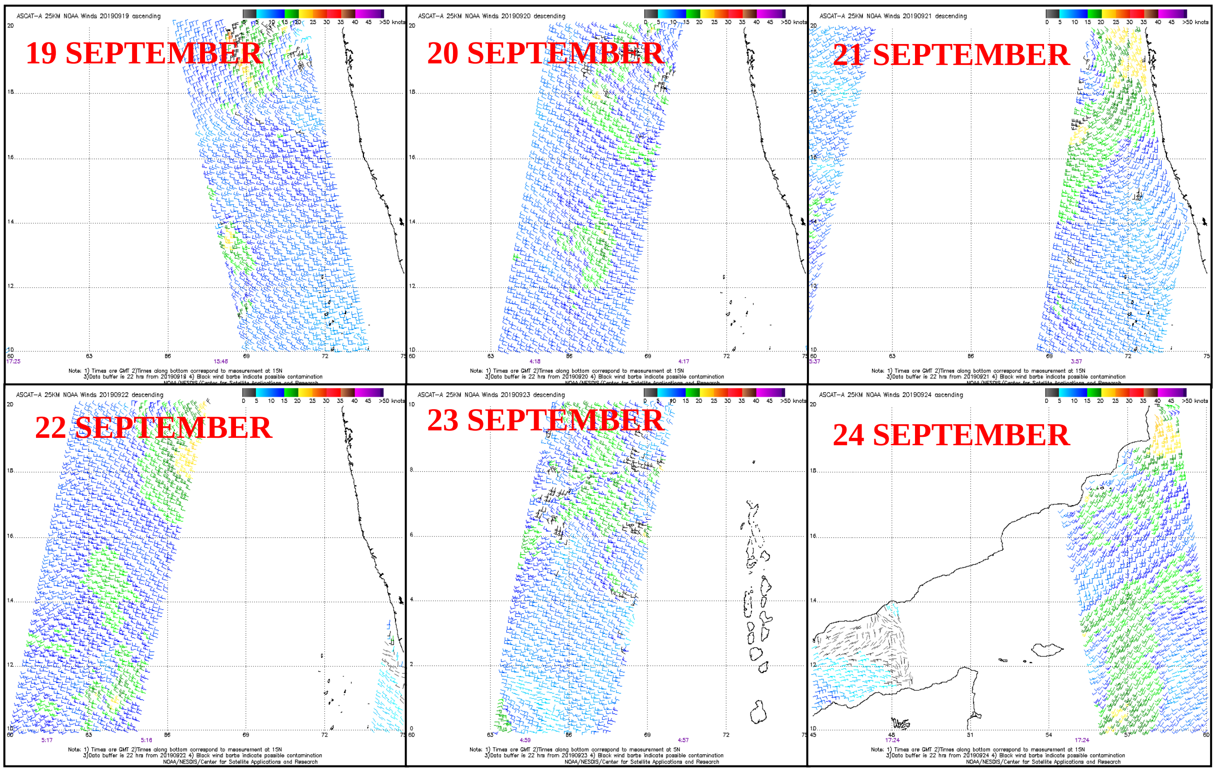


Fig. 6f: ASCAT imageries during life cycle of VSCS HIKAA (22-25 September, 2019

Typical microwave imageries during life cycle of Hikaa are presented in Fig. 6g. Eye was clearly seen on 23rd September.

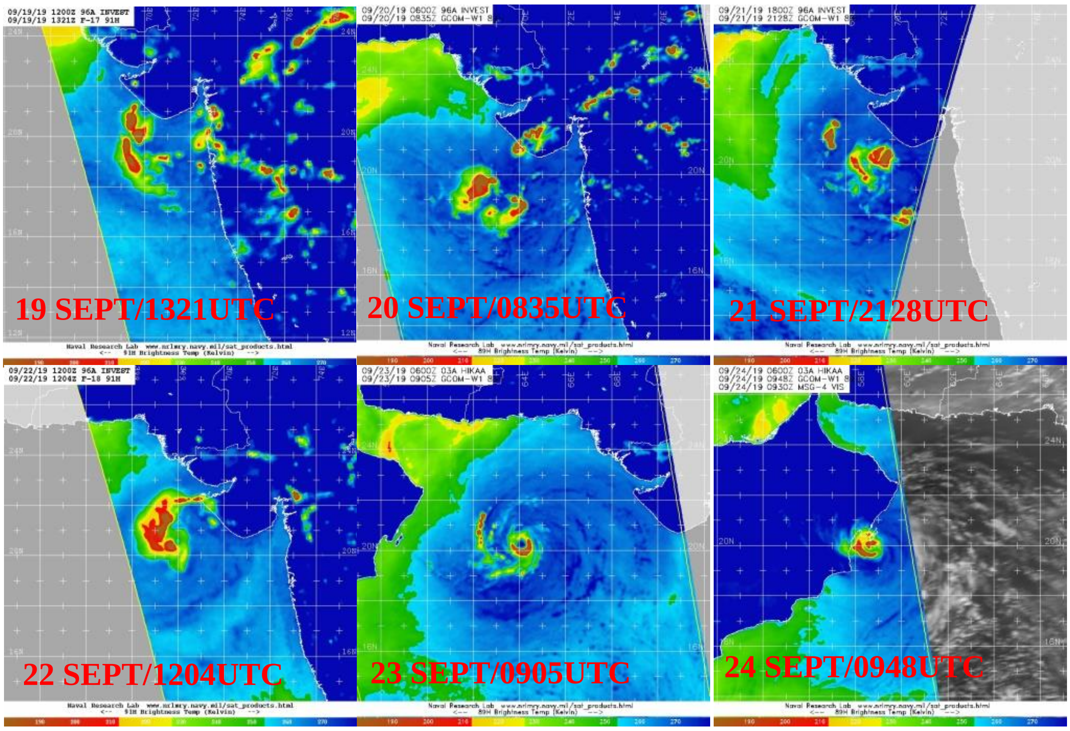


Fig. 6g: Microwave imageries during life cycle of VSCS HIKAA (22-25 September, 2019)

5. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 22nd -25th September are presented in Fig.7. GFS (T1534) analysis based on 0000 UTC of 22nd September, indicates a depression over northeast and adjoining eastcentral AS near 20ºN/70ºE. The circulation extended upto 500 hPa level. Synoptically, the system lay as a depression over eastcentral and adjoining northeast AS near 19.8°N and longitude 69.4°E. The system lay to the south of ridge lying near 22°N. Easterlies were also seen over entire AS upto 20°N suggesting near westward movement of the system away from Indian coast.

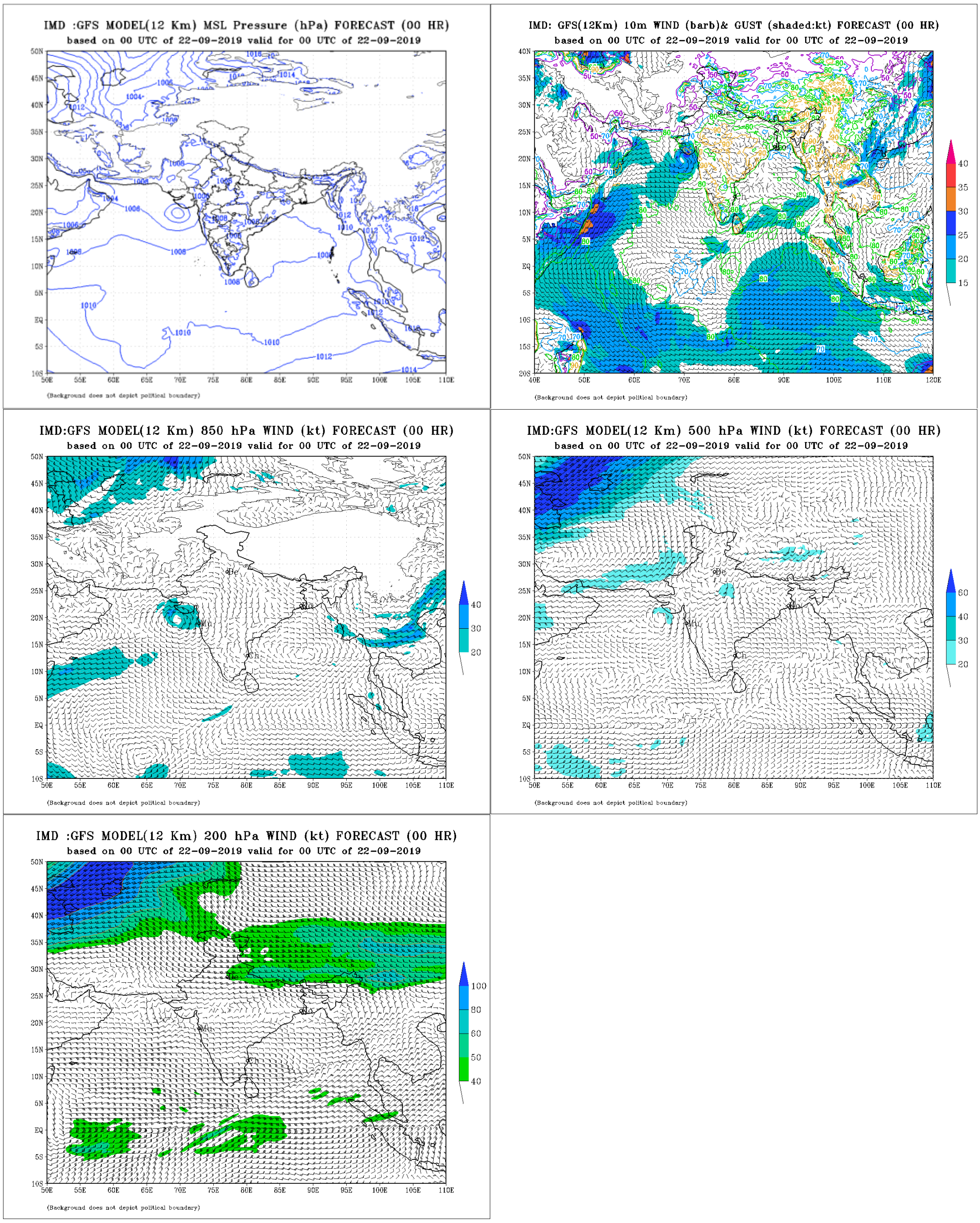


Fig. 7(a): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 22nd September 2019

GFS (T1534) analysis based on 0000 UTC of 23rd September indicated westward movement and intensification of the system into a CS over northeast AS near 20ºN/66.5ºE. The circulation extended upto 500 hPa level. Synoptically, the system lay as a CS over northeast AS near 20.5°N and longitude 66.2°E. The system lay to the south of ridge lying near 22°N. Easterlies were also seen over entire AS upto 20°N suggesting near westward movement of the system away from Indian coast.

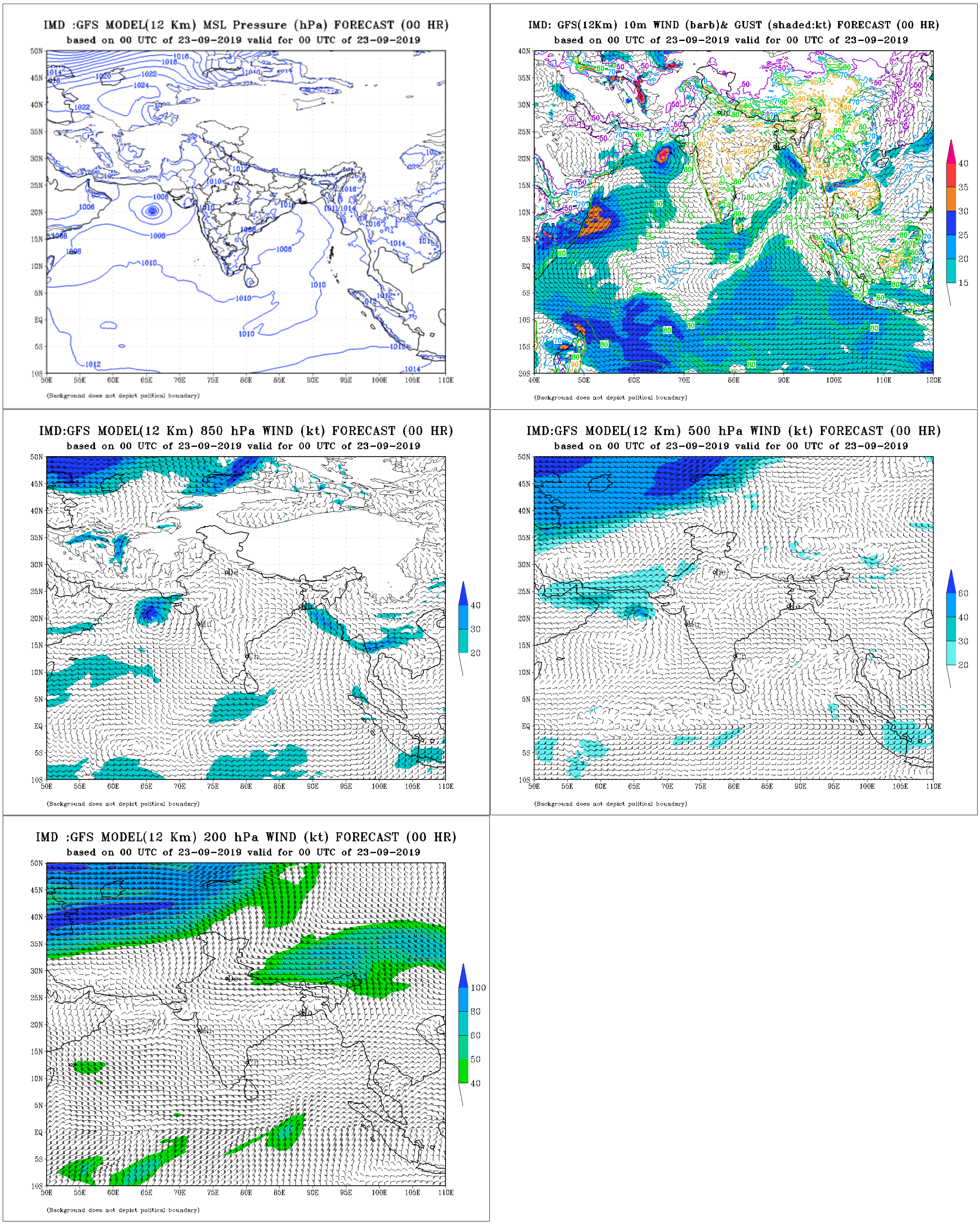


Fig. 7(b): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 23rd September 2019

GFS (T1534) analysis based on 0000 UTC of 24th September, indicated westward movement towards Oman coast and intensification of the system into a SCS/VSCS over northwest AS near 20ºN/62ºE. The circulation extended upto 500 hPa level. Synoptically, the system lay as a VSCS over northeast AS near 20.1°N and longitude 61.0°E. The system lay to the south of ridge lying near 22°N. Easterlies were also seen over entire AS upto 20°N suggesting near westward movement of the system towards Oman coast.

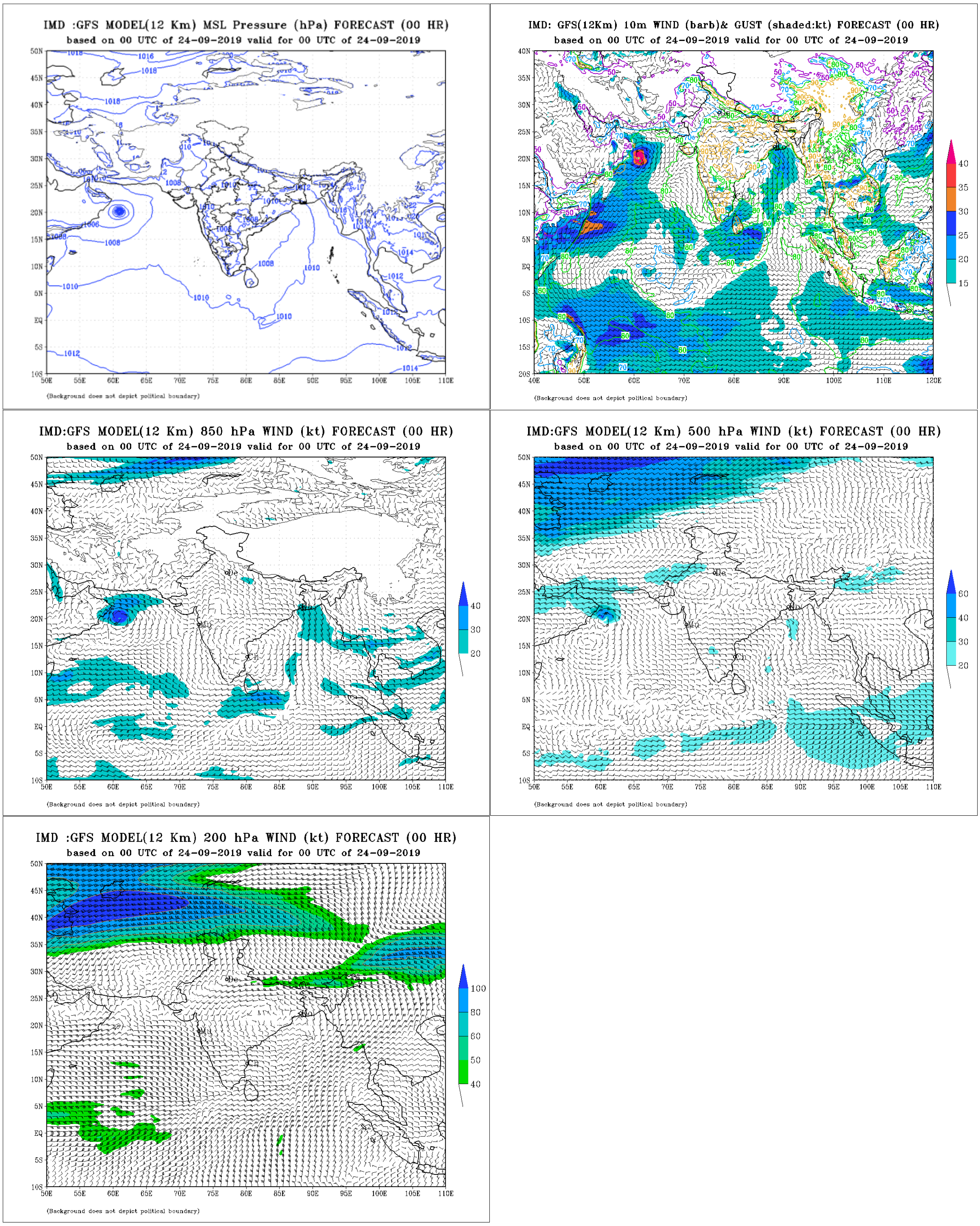


Fig. 7(c): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 24th September 2019

GFS (T1534) analysis based on 0000 UTC of 25th September indicated that the system crossed in the night of 24th and lay over Oman as a DD over northwest AS near 20ºN/55ºE. The circulation extended upto 500 hPa level. Synoptically, the system lay as a CS over Oman near 19.6°N and longitude 55.9°E. It could also capture westward movement of the system.

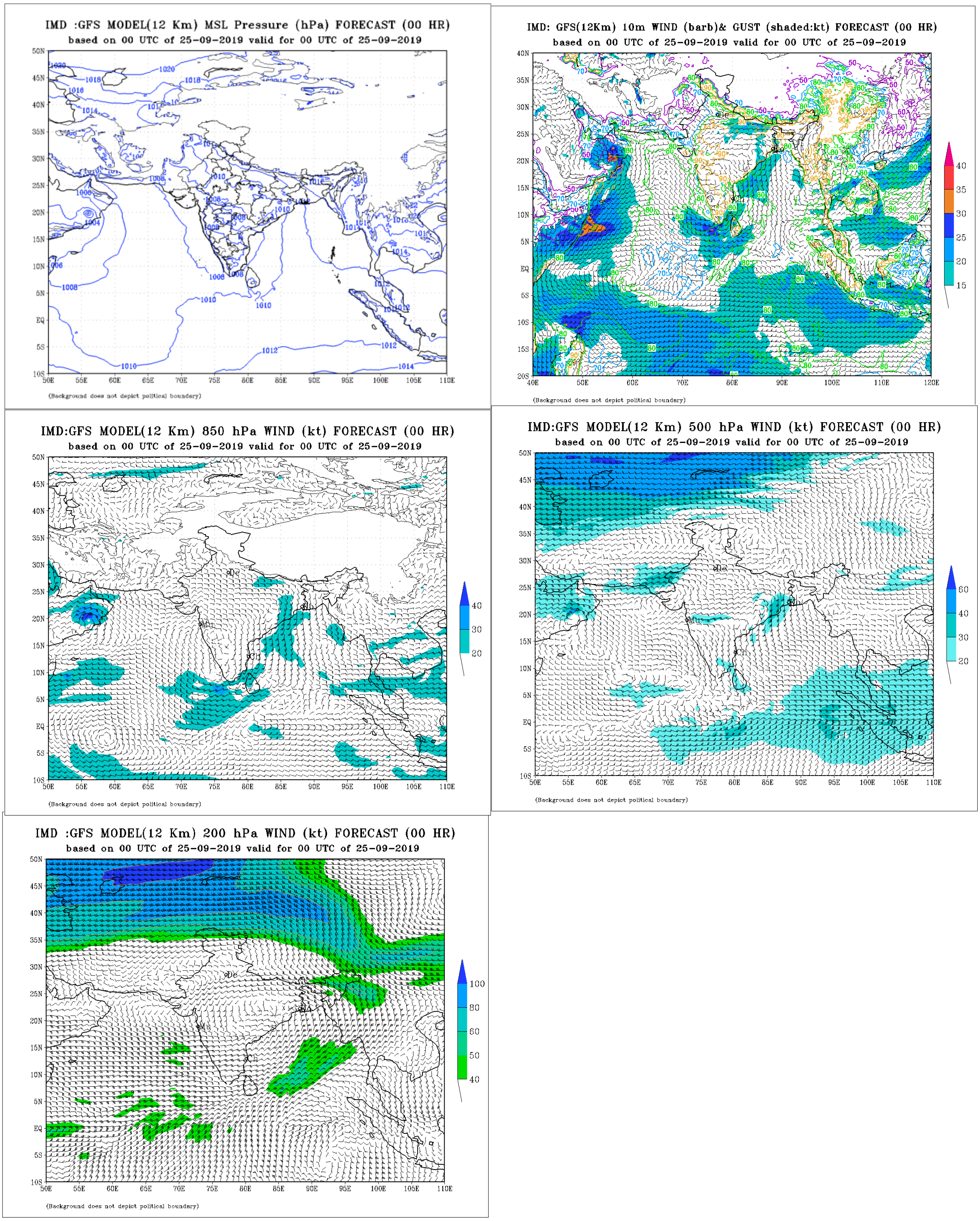


Fig. 7(d): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 25th September, 2019

6. Realized Weather:

Rainfall associated with VSCS HIKAA based on IMD-NCMRWF GPM merged gauge 24 hours cumulative rainfall ending at 0300 UTC of date is depicted in **Fig 8**. It indicates occurrence of heavy to very heavy rainfall over northeast and adjoining eastcentral AS during 20th -22nd September and extremely heavy rainfall on 23rd, heavy rainfall over westcentral AS on 24th and over Oman coast on 25th.

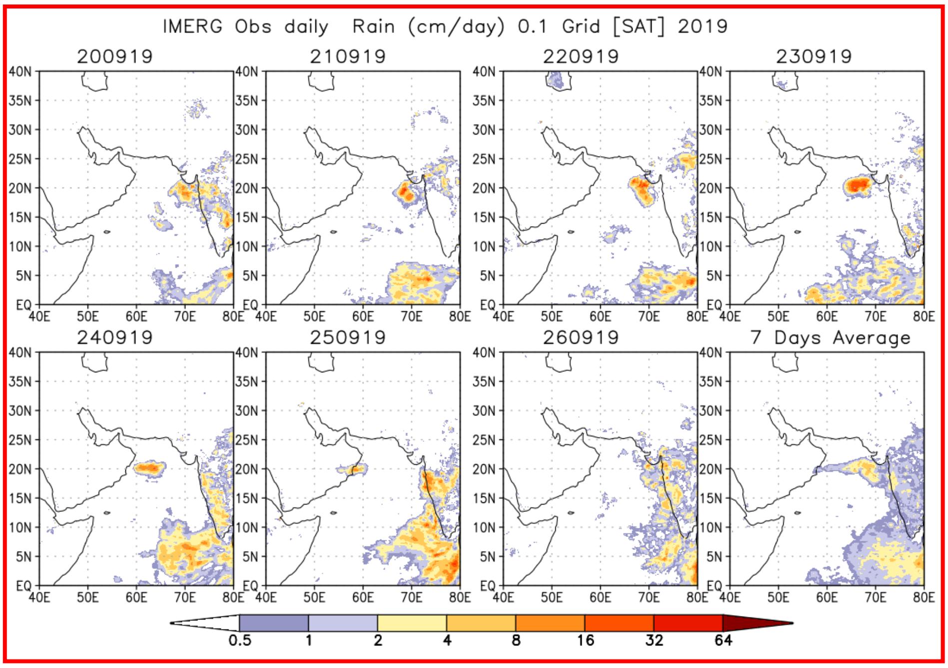


Fig.8: IMD-NCMRWF GPM merged gauge 24 hr cumulative rainfall (cm) ending at 0830 IST of date during 20th – 26th September and 7 days average rainfall (cm/day)

8. Damage due to VSCS HIKAA

Tropical Cyclone Hikaa made landfall in Oman on 24th September, 2019, bringing strong winds, heavy rains and waves of 3 to 4 metres (Source Asia News, 25th September). Six Indian fishermen drowned off Oman Coast (Gulf News, 1st October and The Times of India 30th September). No casualty from Oman mainland was reported.

9. Performance of operational NWP models

IMD operationally runs a regional model, WRF for short-range prediction and one 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.

Global models are also run at NCMRWF. These include GFS and unified model adapted from UK Meteorological Office. 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. The performance of the individual models, MME forecasts, SCIP, GPP, RII for VSCS Hikaa are presented and discussed in this Section.

9.1 Prediction of Cyclogenesis (Genesis Potential Parameter (GPP) for HIKAA

The predicted zone of cyclogenesis based on 0000 UTC during 18th-23rd September is presented in Fig. 9. From 20th September onwards, IMD GPP could capture cyclogenesis over northeast Arabian Sea (about 51 hours prior to formation of depression at 0300 UTC of 22nd September).

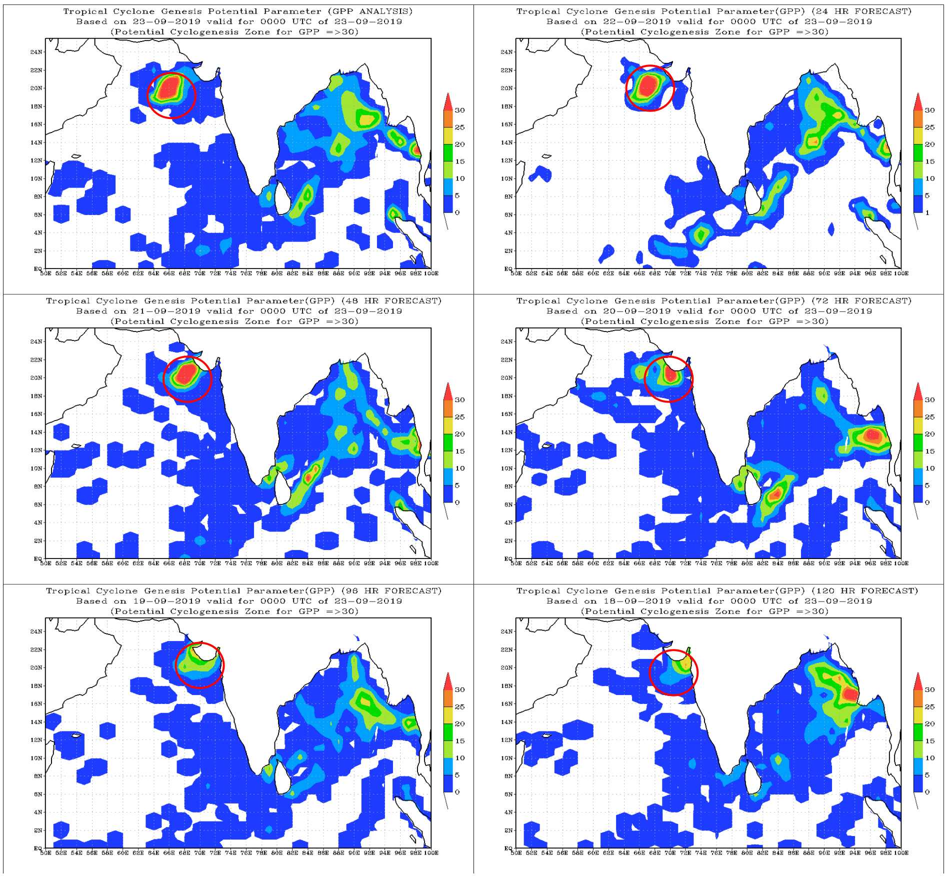


Fig.9 (a-f): Predicted zone of Cyclogenesis based on 0000 UTC from 18th -23rd September 2019

Further all low pressure systems do not intensify into cyclones and it is thus important to identify the potential of intensification of a low pressure system into cyclone at the early stages (T No. 1.0, 1.5, 2.0) of development. For developing system, the threshold value of average GPP is ≥ 8.0 and (ii) for non-developing system, the threshold value of GPP is < 8.0. The area average analysis of GPP is presented in Fig. 10. The area average analysis indicated potential for intensification into CS by 23rd. Actually, the system intensified into a CS at 0000 UTC of 23rd.

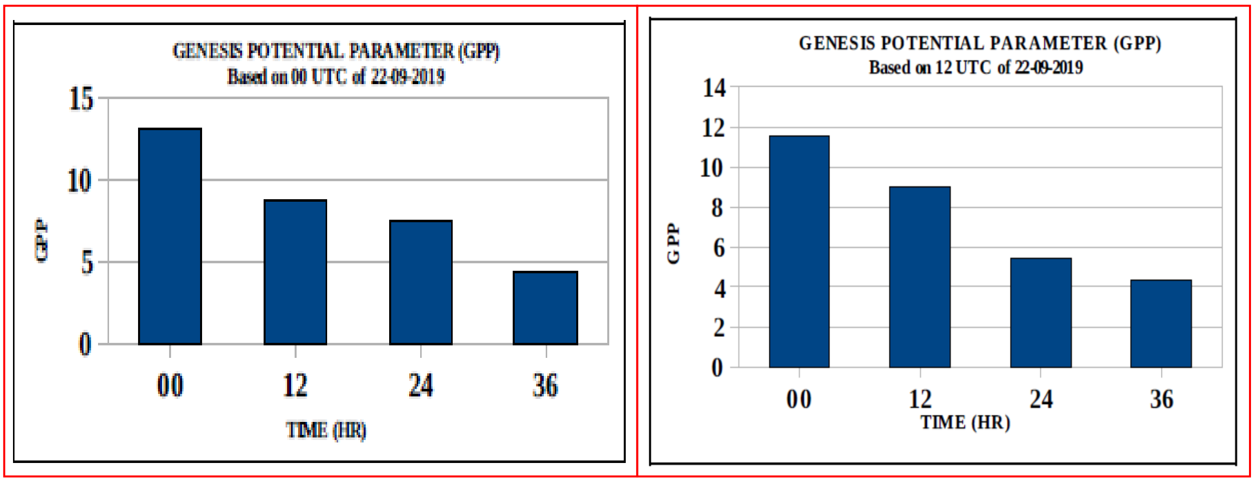


Fig.10: Area average analysis and forecasts of GPP based on 0000 and 1200 UTC of 22nd September

9.2 Track prediction by NWP models

Track prediction by various NWP models is presented in **Fig.11**. Based on initial conditions of 0000 UTC of 22nd September, most of the models indicated westward movement towards Oman coast. However, NCEP GFS indicated weakening over eastcentral and adjoining westcentral AS. WRF VAR was indicating southwestward movement and weakening over westcentral AS. ECMWF, IMD GFS and MME were indicating weakening over northwest AS off Oman coast. However, models like UKMO, JMA and HWRF were indicating landfall over Oman near 20ºN/58ºE with landfall between 1500 & 1800 UTC of 24th.

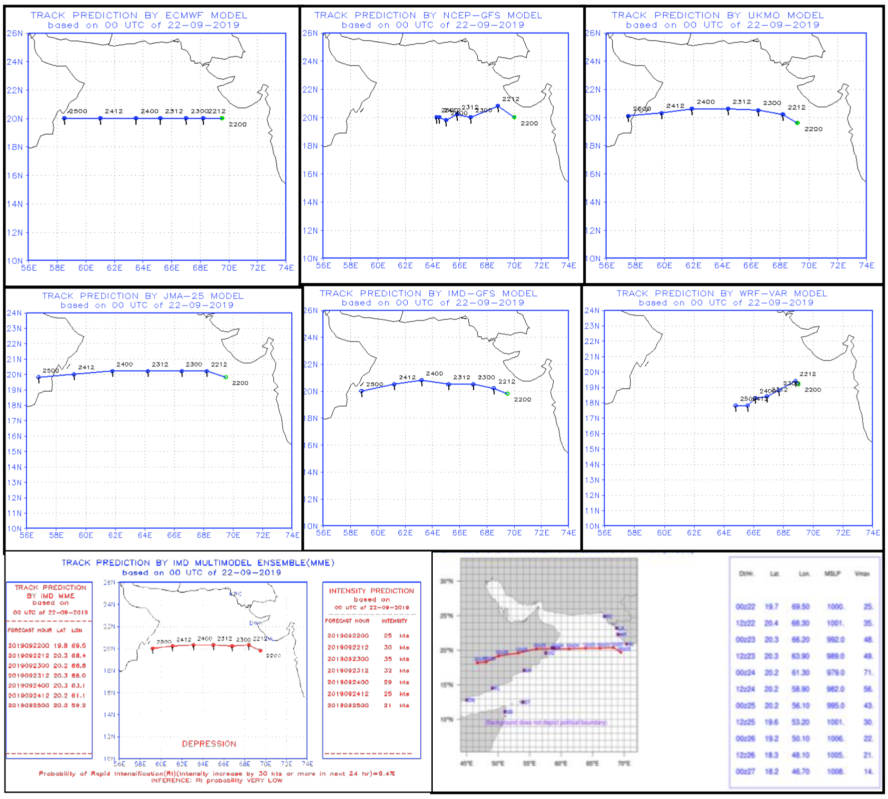
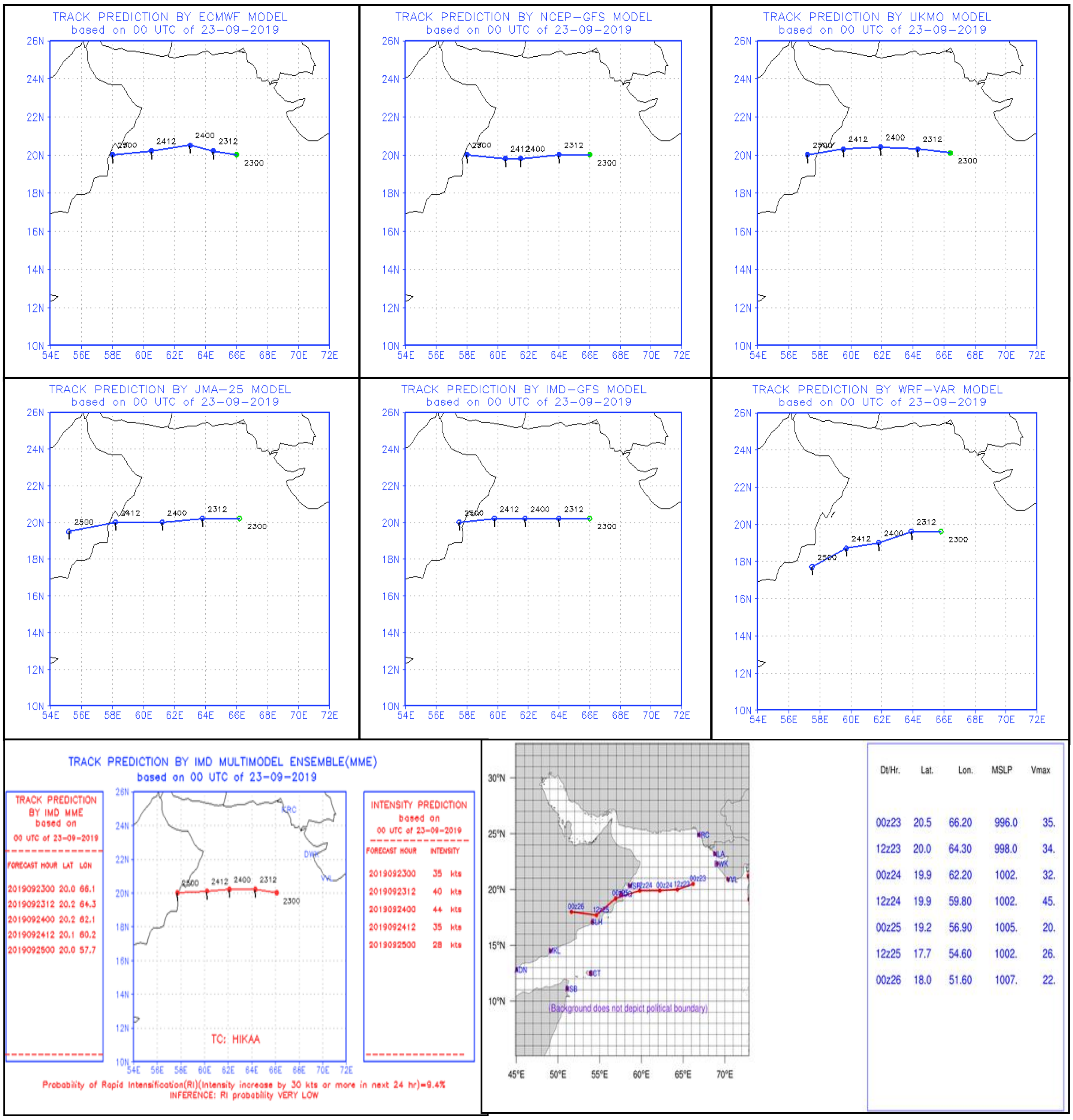


Fig. 11 (a): NWP model track forecast based on 0000 UTC of 22nd September, 2019

Based on initial conditions of 0000 UTC of 23rd September, most of the models indicated westward movement towards Oman coast. However, NCEP GFS, ECMWF and MME were indicating weakening just near Oman coast. WRF VAR was indicating west-southwestwards movement and weakening over westcentral AS near Yemen coast. However, models like UKMO, JMA and HWRF were indicating landfall over Oman near 20ºN/58ºE with landfall between 1500 & 1800 UTC of 24th.



Dt/Hr.	Lat.	Lon.	MSLP	Vmax
00z23	20.5	66.20	996.0	35.
12z23	20.0	64.30	998.0	34.
00z24	19.9	62.20	1002.	32.
12z24	19.9	59.80	1002.	45.
00z25	19.2	56.90	1005.	20.
12z25	17.7	54.60	1002.	26.
00z26	18.0	51.60	1007.	22.

Fig. 11 (b): NWP model track forecast based on 0000 UTC of 23rd September, 2019

Based on initial conditions of 0000 UTC of 24th September, most of the models indicated westward movement towards Oman coast. However, including NCEP GFS, ECMWF, UKMO, JMA, IMD GFS, WRF VAR indicated weakening over the Sea over westcentral AS. However, HWRF and MME indicated landfall over Oman near 20ºN/58ºE with landfall near 1500 UTC of 24th.

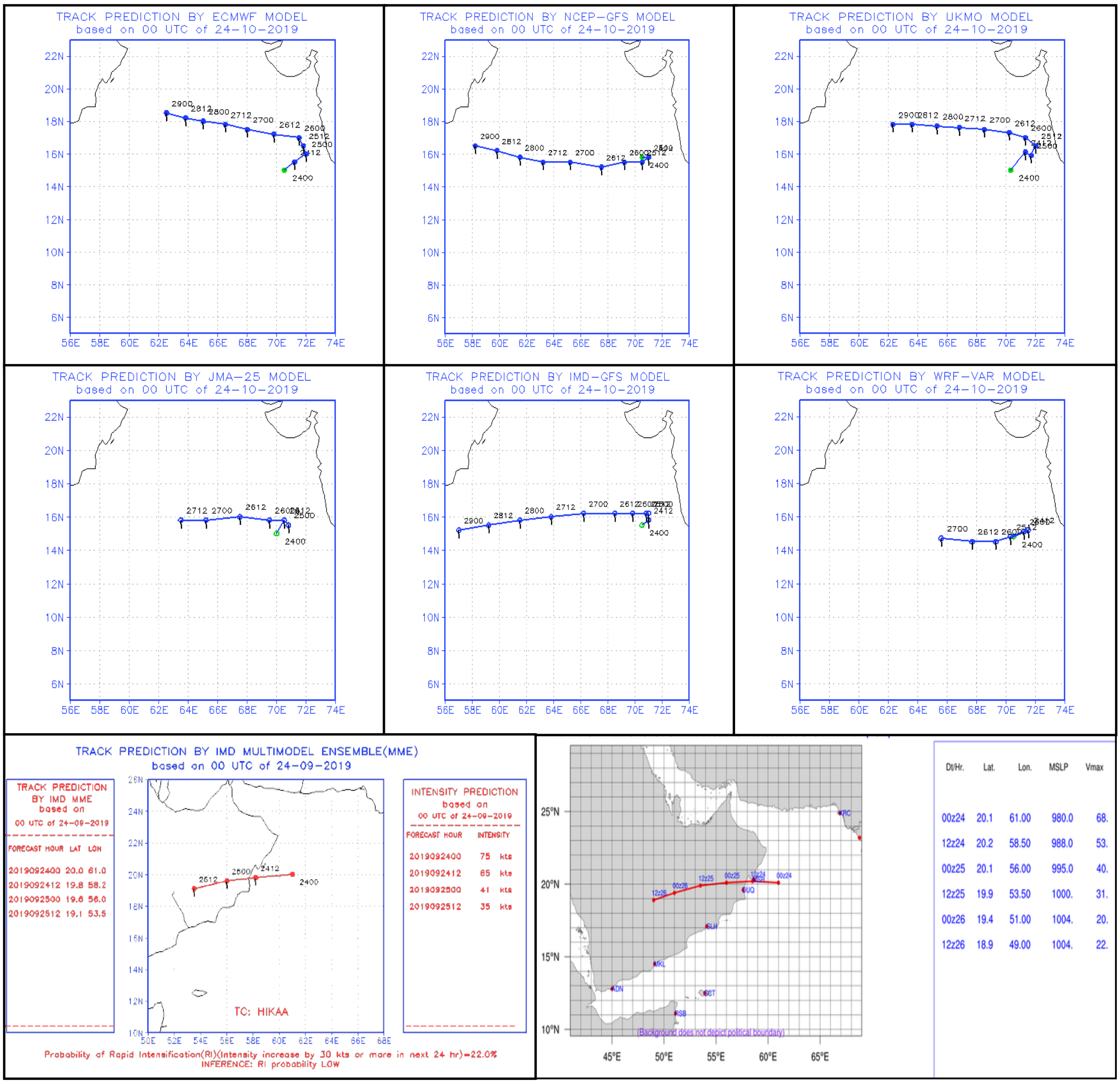


Fig. 11 (c): NWP model track forecast based on 0000 UTC of 24th September, 2019

Comparing different models IMD HWRF could correctly pick up the movement, intensification and landfall characteristics of VSCS Hikaa.

The average track forecast errors by different models is presented in Table 2. The track forecast errors by MME were the least for 12 & 24 hrs lead period and for HWRF were the least for all lead periods from 36hrs to 72 hrs.

Track prediction by various Ensemble Prediction Systems (EPS) is presented in Fig. 12. Based on 0000 UTC of 23rd, the MSC ensemble members indicated 40-60% strike probability over Oman coast while NCEP members indicated >80% strike probability (Fig. 12 a). Based on 0000 UTC of 24th September, both NCEP and ECMWF ensemble members indicated >80% strike probability over Oman coast.

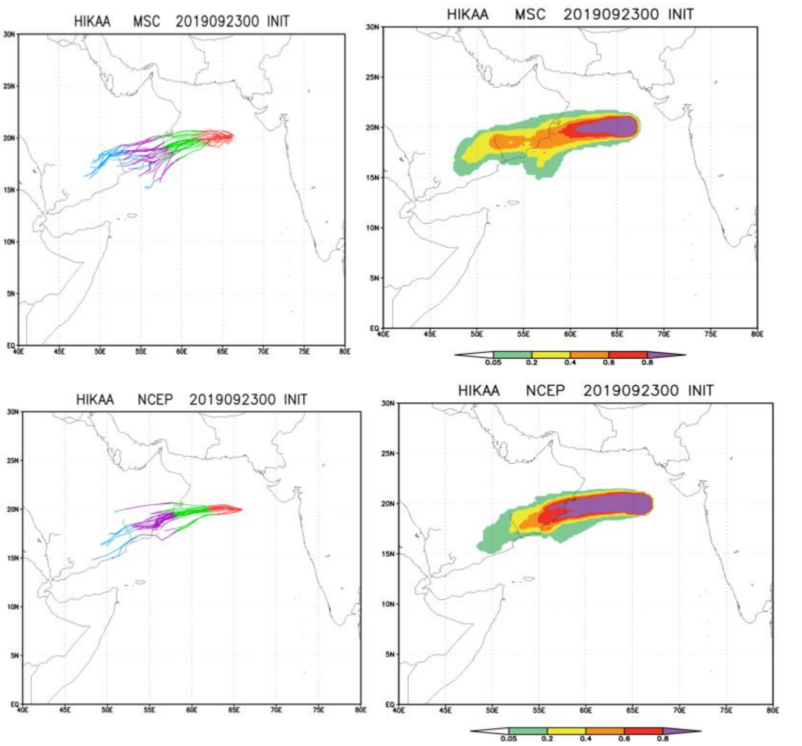


Fig. 12(a): EPS forecast based on 0000 UTC of 23rd September

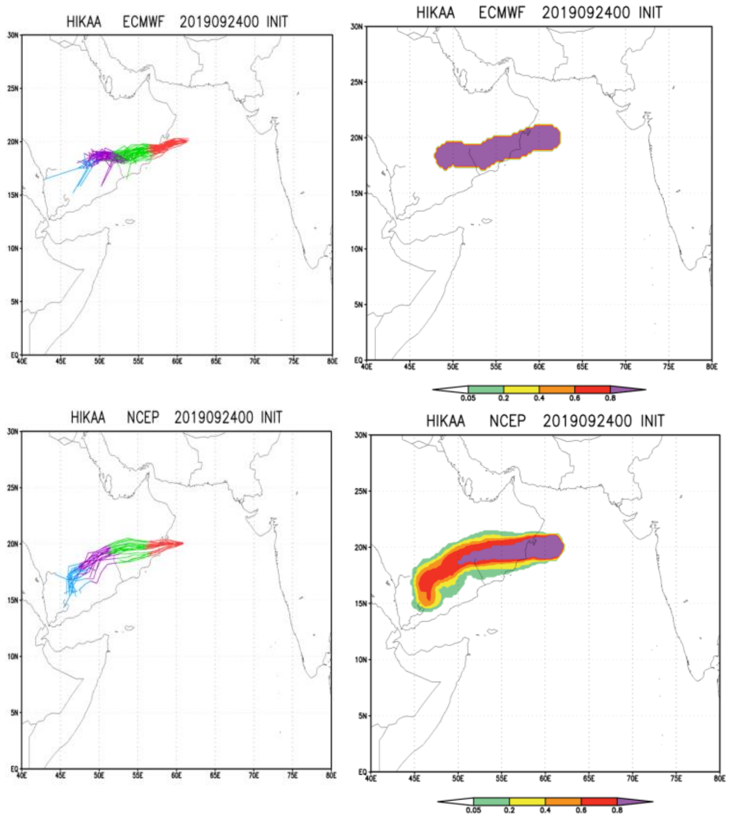


Fig. 12(b): EPS forecast based on 0000 UTC of 24th September

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
IMD-MME	32(5)	71(5)	125(4)	198(3)	237(2)	348(1)
ECMWF	59(5)	114(5)	149(4)	211(3)	203(2)	275(1)
NCEP-GFS	64(5)	80(5)	173(4)	309(3)	460(2)	879(1)
UKMO	34(5)	57(5)	89(4)	126(3)	162(2)	176(1)
JMA	28(5)	44(5)	63(4)	105(3)	110(2)	97(1)
IMD-GFS	35(5)	72(5)	135(4)	198(3)	266(2)	306(1)
WRF-VAR	94(5)	155(5)	231(4)	377(3)	586(2)	958(1)
HWRF	48(12)	90(10)	98(8)	126(6)	98(4)	52(2)

9.3 Intensity forecast errors by various NWP Models

Intensity forecast by IMD's Statistical Cyclone Intensity Prediction (SCIP) Model and intensity forecast errors by IMD SCIP are presented in Fig.13. Form Fig. 13 (a), it is seen that IMD-SCIP picked up intensity correctly for 12-24 hrs lead period. Beyond that, it all along underestimated the intensity of the system.

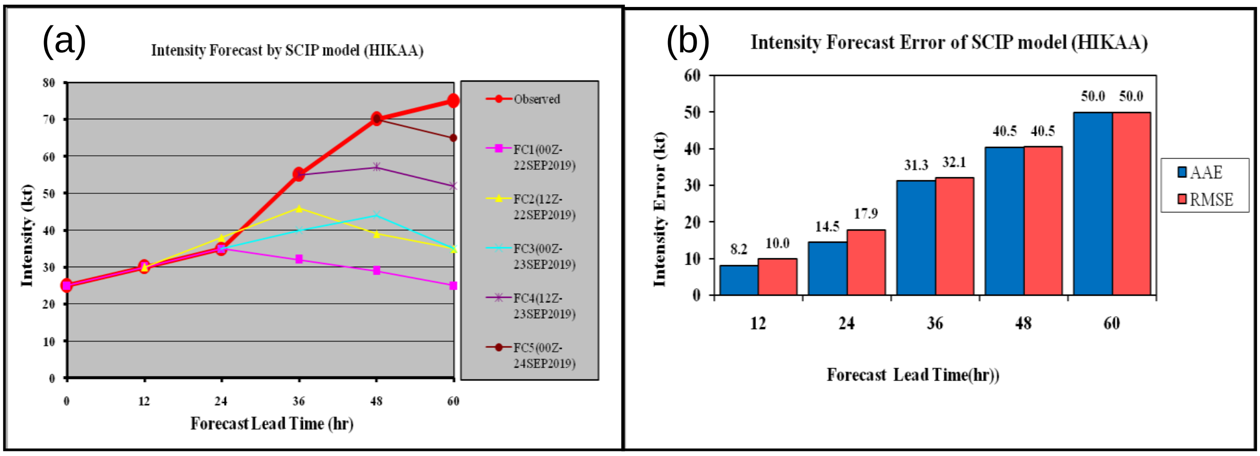


Fig. 13: (a) Intensity forecast by SCIP and (b) Intensity Forecast Error by SCIP model

The intensity forecast errors of IMD-SCIP model and HWRF model are shown in Table **3.** The intensity forecast errors by MME were the least for 12 & 24 hrs lead period and for HWRF were the least for all lead periods from 36hrs to 72 hrs.

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
IMD-SCIP (AAE)	8.2(5)	14.5(4)	31.3(3)	40.5(2)	50.0(1)	
IMD-SCIP (RMSE)	10.0	17.9	32.1	40.5	50.0	
IMD-HWRF (AAE)	16.2(12)	21.2(10)	21.0(8)	23.8(6)	15.5(4)	8.0(2)
IMD-HWRF (RMSE)	18.3(12)	24.4(10)	22.8(8)	25.2(6)	16.1(4)	8.0(2)

10. Operational Forecast Performance

10.1. Genesis Forecast

- First information about possible cyclogenesis over eastcentral AS during first half of week (20-26 Sep) with moderate probability (34-67%) was indicated in the extended range outlook issued by IMD on 12th September (about 10 days prior to formation of depression over eastcentral AS on 22nd morning (0300 UTC).
- First information about formation of LPA over eastcentral AS & adjoining areas around 20th was given in Tropical Weather Outlook issued on 18th September (about 48 hours prior to formation of LPA in the morning (0300 UTC) of 20th). It was also predicted that it would move west-northwestwards and concentrate into a depression around 22nd (about 96 hours prior to formation of depression over eastcentral AS on 22nd morning (0300 UTC)).

10.2 Track, Intensity and Landfall Forecast

- In the first bulletin issued at 1115 hours IST (around 0600 UTC) of 22nd, it was indicated that the system would move towards Oman coast and cross Oman near 20^0N in the night (around 2200 UTC of 24th). The system actually crossed Oman coast near 19.7°N/ longitude 57.7°E in the late evening (around 1430 UTC) of 24th. Further intensification of the system was also predicted in this bulletin.
- In the bulletin issued at 2030 hours IST (1500 UTC) of 23rd, it was predicted that the system would move nearly westwards and cross Oman coast between latitude 19°N and 20°N close to Duqm during early hours of 25th September 2019 as a Cyclonic Storm with a wind speed of 70-80 kmph gusting to 90 kmph.
- The warning was further upgraded and in the bulletin issued at 1615 IST (around 1030 UTC) of 24th that the system would cross Oman coast between latitude 19.5°N and 20°N close to Duqm around 2030 Hours IST of 24th September 2019 as a Severe Cyclonic Storm with a wind speed of 110-120 kmph gusting to 135 kmph.
- Typical observed and forecast track along with cone of uncertainty and wind distribution is presented in **Fig. 14**.

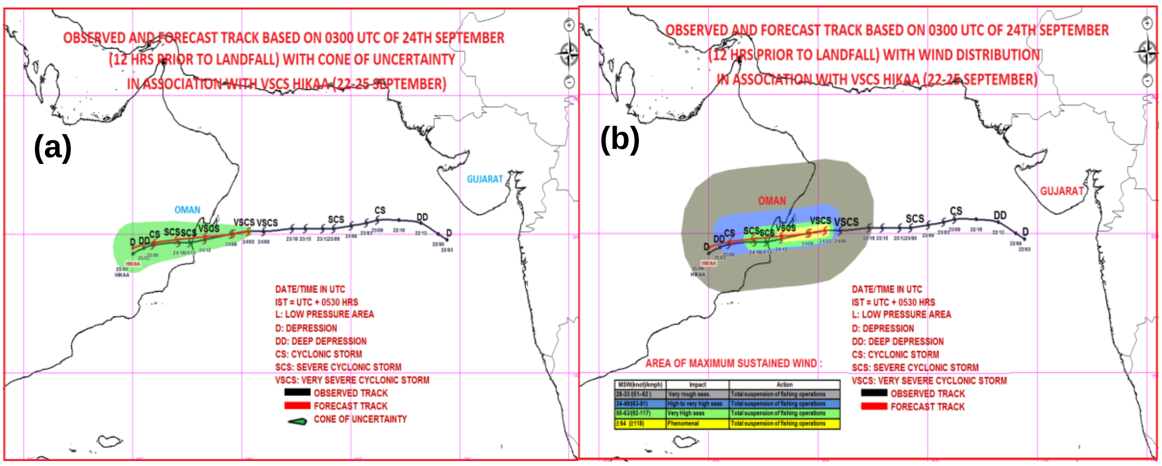


Fig.14: Observed and forecast track of VSCS HIKAA alongwith (a) cone of uncertainty and (b) wind distribution indicating accuracy in landfall, track and intensity predictions near Oman.

- Observed and forecast tracks based on 0000 and 1200 UTC observations during 22nd-25th September indicating accuracy in track and landfall point is presented in **Fig. 15**.
- Thus the genesis, track, landfall and intensity of the system were well predicted by IMD. Adverse weather like heavy rainfall, strong wind and storm surge associated with the system were also well predicted by IMD. Since first bulletin, state of sea and warnings for fishermen in deep seas of central and northern parts of Arabian Sea and along & off Gujarat, Maharashtra coasts were issued both in textual and graphical form. storm surge guidance was also issued for Oman coast.

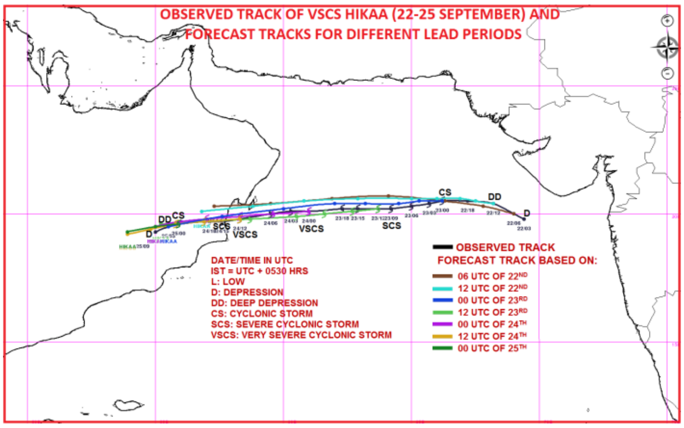


Fig. 15: Typical observed and forecast tracks based on 0000 & 1200 UTC during 22nd to 25th September indicating accuracy in landfall and track

10.3. Landfall Forecast Errors:

- The landfall point forecast errors for 24, 48 and 60 hrs lead period were 20, 32, and 62 km respectively against long period average errors of 47, 70 and 89 km during 2014-18 respectively **(Fig. 16a).**
- The landfall time forecast errors for 24, 48 and 60 hrs lead period were 4, 11, and 7 hours respectively against long period average errors of 3, 5 and 4 hours during 2014-18 respectively **(Fig. 16b).**

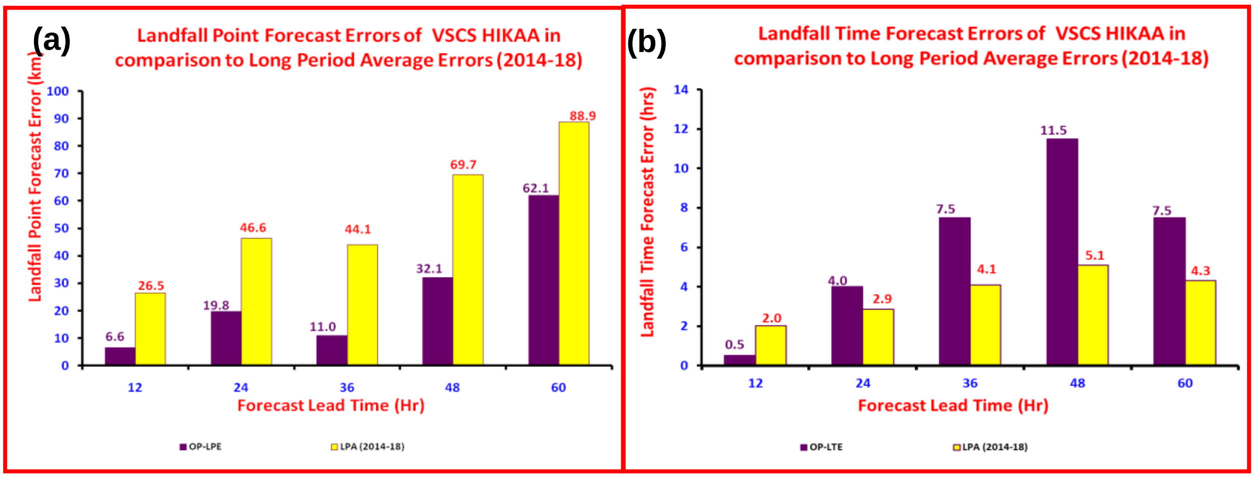


Fig. 16: (a) Landfall point and (b) Landfall time forecast Errors of VSCS HIKAA as compared to long period average (2014-18)

10.4. Track Forecast Errors:

- The track forecast errors for 12, 24 and 48 hrs lead period were 44, 56, and 195 km respectively against the average track forecast errors of 55, 86, and 132 km during last five years (2014-18) respectively (**Fig.17a)**.
- The track forecast skill was about 60%, 73%, and 51% against the long period average (LPA) of 55%, 58%, and 70% during 2014-18 for 12, 24 and 48 hrs lead period respectively (**Fig.17b)**.

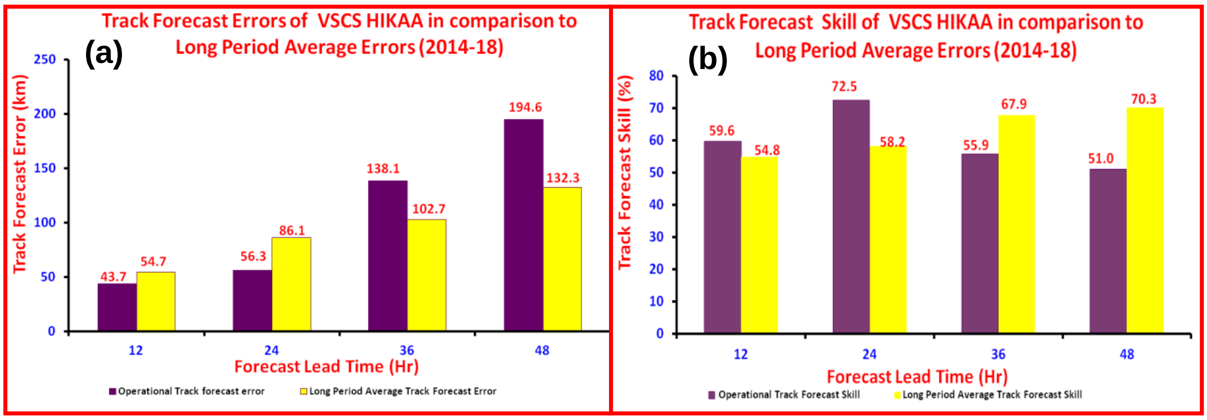


Fig. 17: Track forecast (a) Errors and (b) skill of VSCS HIKAA as compared to long period average (2014-18)

10.5. Intensity Forecast Errors:

- The absolute error (AE) of intensity (wind) forecast for 12, 24 and 48 hrs lead period were 10, 19 and 6 knots against the LPA of 6, 10 and 14 knots respectively **(Fig. 18a).**
- The root mean square error (RMSE) of intensity (wind) forecast for 12, 24 and 48 hrs lead period were 12, 24 and 6 knots against the LPA of 8, 13 and 19 knots respectively **(Fig. 18b).**

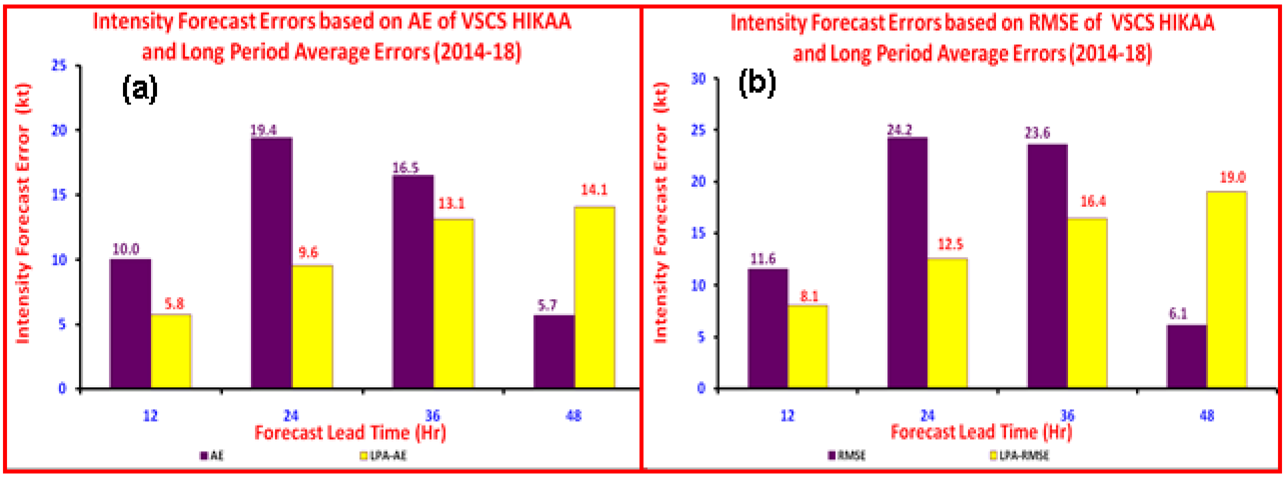


Fig. 18: (a) Absolute errors (AE) and (b) Root Mean Square errors (RMSE) in intensity forecast (winds in knots) in association with VSCS HIKAA as compared to long period average (2014-18)

- The skill in intensity forecast based on AE for 12, 24 and 48 hrs lead period was 33, 48 and 89 % against the LPA of 29, 43 and 68 % respectively **(Fig. 19).**

The skill in intensity forecast based on RMSE for 12, 24 and 48 hrs lead period was 46, 48 and 90 % against the LPA of 36, 49 and 59 % respectively **(Fig. 19).**

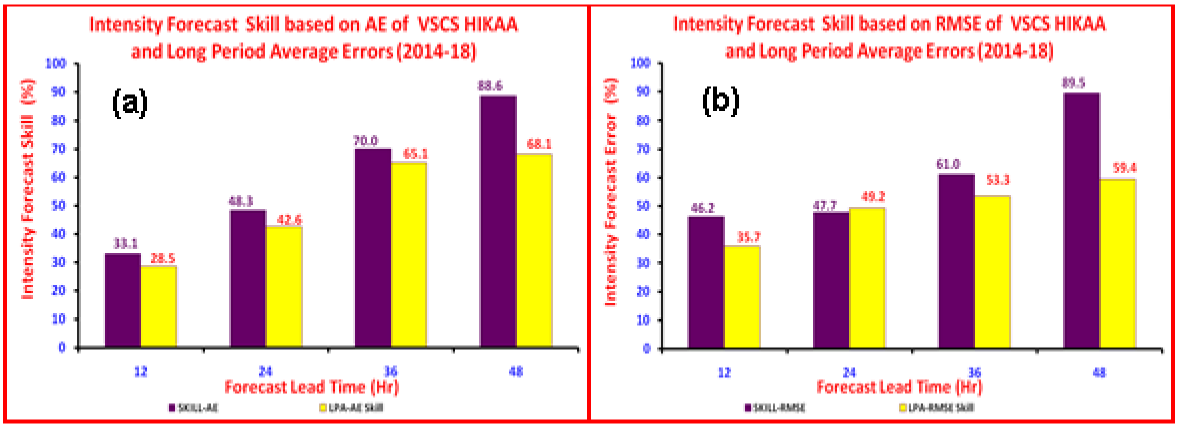


Fig. 19: Skill in intensity forecast (%) based on (a) Absolute errors (AE) and (b) Root Mean Square errors (RMSE) in association with VSCS HIKAA as compared to long period average (2014-18)

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 to Oman on the day of landfall till the system crossed Oman coast. Typical graphical product is presented in **Fig. 14a**.
- **Cyclone structure forecast for shipping and coastal hazard management** The radius of maximum wind and radii of MSW ≥28 knots, ≥34 knots, ≥50 knots and ≥64 knots wind in four quadrants of cyclone was issued every six hourly giving forecast for +06, +12, +18, +24, …. +120 hrs lead period. Typical graphical product is presented in **Fig. 14b**.
- **Adverse weather warning bulletins:** The tropical cyclone forecasts alongwith 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 Kerala, Karnataka, Maharashtra, Goa, Gujarat, Lakshadweep, Daman & Diu and Dadra Nagar Haveli. The storm surge warnings were also issued to Oman. Typical storm surge guidance product is presented in **Fig.20**. 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 gale/squally wind & storm surge were also presented in graphics 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) were uploaded on Face book and Twitter regularly during the life period of the system. Bulletins were also issued to state level disaster managers through whatsapp. The tropical cyclone advisories were also sent to Oman Meteorological Department through whatsapp.
- **Press release and press briefing:** Press and electronic media were given daily updates since inception of system 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, 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 central and north Arabian Sea and the states of Gujarat, Maharashtra & Goa, Karnataka, Kerala and Lakshadweep.
- **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 prognosis and diagnosis of the systems were described in the RSMC bulletins.
- **Hourly Bulletin:** Hourly updates on the location, distance from recognised station, intensity and landfall commenced from 0700 UTC of 24th till 1600 UTC on the day of landfall.

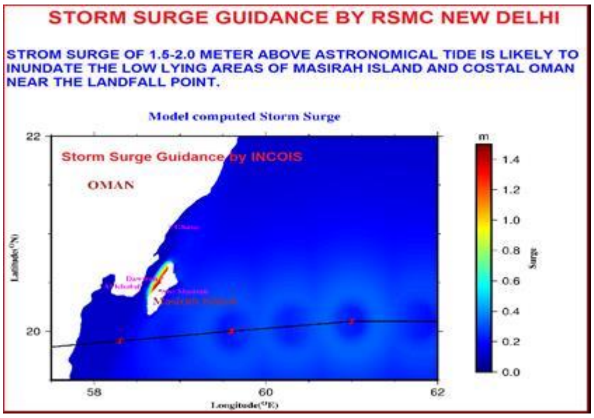


Fig. 20: Typical storm surge guidance in association with VSCS Hikaa

Bulletins issued by RSMC New Delhi, IMD are presented in Table 4.
Table 4: Bulletins issued by RSMC New Delhi

S.N	Bulletin	No. of Bulletins	Issued to
1	National Bulletin	24	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-Kerala, Karnataka, Goa, Gujarat and Maharashtra, Administrator- Lakshadweep Islands, Union Territory of Daman and Diu, Union Territory of Dadar and Nagar Haveli.
2	RSMC Bulletin	24	1. IMD's website 2. WMO/ESCAP member countries and WMO through GTS and E-mail.
3	GMDSS Bulletins	07	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 (Text & Graphics)	08	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	09	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	Daily	SMS to disaster managers at national level and concerned states (every time when there was change in intensity) To general public to users registered with RSMC website from the states of Kerala, Karnataka, Goa, Gujarat and Maharashtra and National level disaster managers. Through INCOIS on Ocean State Forecast

12. Appreciation earned for monitoring and forecasting of VSCS HIKAA from Oman Meteorological Department:

Director General of Meteorology, Public Authority for Civil Aviation, Oman appreciated India Meteorological Department for cyclone warnings and hourly updates provided to Oman Meteorological Department during cyclone HIKAA.

13. Acknowledgement:

India Meteorological Department (IMD) and RSMC New Delhi duly acknowledge contribution from WMO and Oman Meteorological Department in dissemination of bulletins and warnings associated with VSCS Hikaa.

IMD and RSMC New Delhi also acknowledge the contribution from all the stake holders and disaster management agencies who contributed to the successful monitoring, prediction and early warning service of VSCS HIKAA. We acknowledge the contribution of all sister organisations of Ministry of Earth Sciences including National Centre for Medium Range Weather Forecasting Centre (NCMRWF), Indian National Centre for Ocean Information Services (INCOIS), National Institute of Ocean Technology (NIOT), Indian Institute of Tropical Meteorology (IITM) Pune, research institutes including IIT Bhubaneswar, IIT Delhi and Space Application Centre, Indian Space Research Organisation (SAC-ISRO) for their valuable support. The support from various Divisions/Sections of IMD including Area Cyclone Warning Centre (ACWC) Chennai, Mumbai, Cyclone Warning Centre (CWC) Thiruvananthapuram, Ahmedabad, Meteorological Centre (MC) Goa, and coastal observatories along the west coast of India. The contribution from Numerical Weather Prediction Division, Satellite and Radar Division, Surface & Upper air instruments Divisions, New Delhi and Information System and Services Division at IMD is also duly acknowledged.