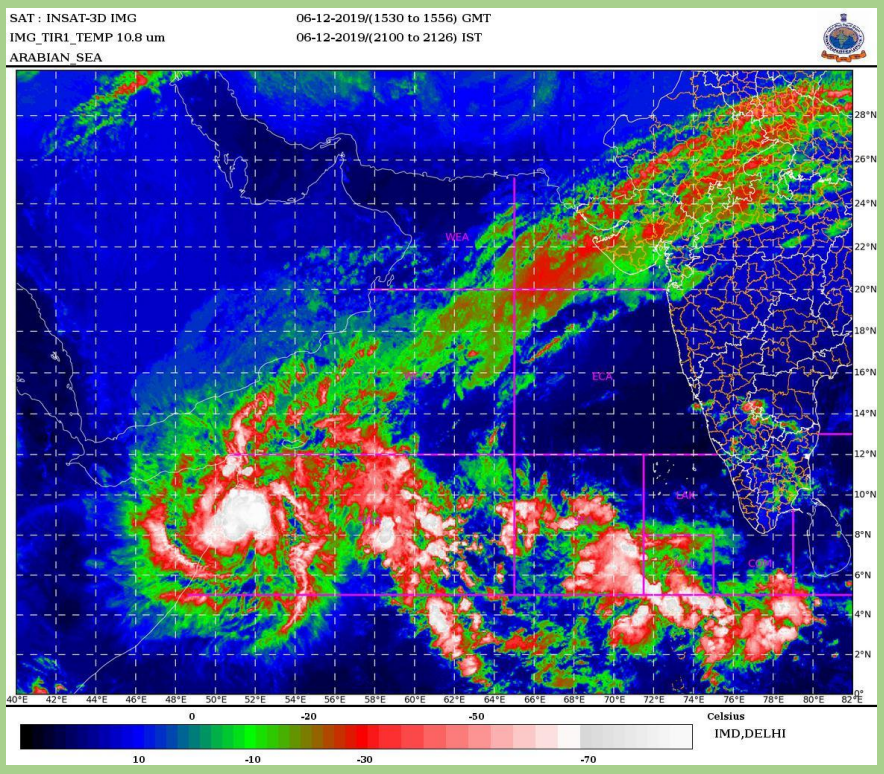
GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
INDIA METEOROLOGICAL DEPARTMENT

Cyclonic Storm 'PAWAN' over the southwest Arabian Sea and adjoining equatorial Indian Ocean (02nd – 07th December 2019): A Report



INSAT-3D enhanced colored IR imagery of 6th December, 2019

Cyclone Warning Division

India Meteorological Department

New Delhi

DECEMBER 2019

Cyclonic Storm 'PAWAN' over the southwest Arabian Sea and adjoining equatorial Indian Ocean (02nd – 07th December 2019)

1. Introduction

The Cyclonic Storm (CS) 'PAWAN' originated as a Low Pressure Area (LPA) over southwest Arabian Sea (AS) and adjoining equatorial Indian Ocean (EIO) in the early morning (0000 UTC) of 30th November, 2019. It lay as a Well Marked Low pressure area (WML) over the same region in the early morning (0000 UTC) of 2nd December. Under favourable environmental conditions, it concentrated into a depression (D) over southwest AS & adjoining EIO in the same is evening (1200 UTC). Moving north-northwestwards, it further intensified into a deep depression (DD) over southwest AS & adjoining EIO in the early morning (0000 UTC) of 3rd December. Continuing to move north-northwestwards, it intensified into the cyclonic storm (CS) "PAWAN" (pronounced as PAVAN) in the early morning (0000 UTC) of 5th December, 2019 over southwest AS. It moved north-northwestwards till noon (0600 UTC) of 5th. Thereafter, it moved nearly westwards till night (1500 UTC) of 5th. After that it exhibited west-southwestward re-curvature. Continuing to move west-southwestwards, it crossed Somalia coast near latitude 7.4°N and longitude 49.6°E during 0200 to 0300 UTC of 07th December 2019 as a CS with maximum sustained wind speed (MSW) of 60-70 kmph gusting to 80 kmph. It exhibited nearly westward re-curvature from midnight (1800 UTC) of 6th. Continuing to move nearly westwards, it weakened into a DD in the morning (0300 UTC) of 07th December, 2019 over coastal Somalia & neighbourhood. It further weakened into a D in the same afternoon (0900 UTC) and into a WML area over north Somalia & adjoining Ethiopia in the same night (1500 UTC of 7th December). Moving further westwards, it lay as a LPA over Ethiopia in the early morning of 8th December and became insignificant thereafter. Observed track of the system during 2nd - 7th December is presented in Fig.1. Best Track parameters associated with the system are presented in Table1.

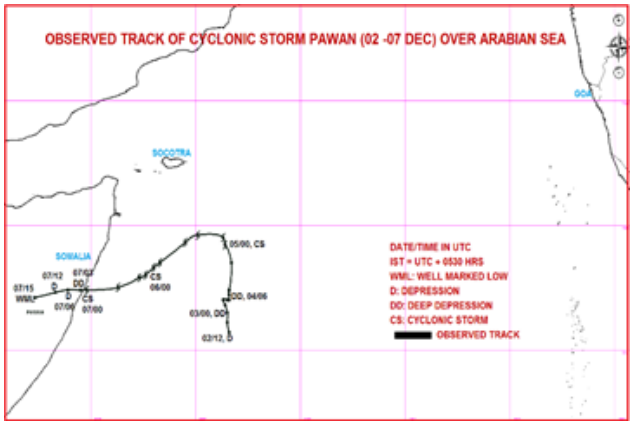


Fig.1 Observed track of CS 'PAWAN' over the Arabian Sea (02nd–07th December, 2019)

The salient features of the system are as follows.

i. It was the fifth CS over the AS during the year 2019 against the normal (1891-2018) of 1 per year.

ii. It had a track length of 1342 km and exhibited multiple re-curvatures (initial north-northwestward movement followed by westward, west-southwestward and westward movement) during it's life period.

iii. Climatologically, a total of 6 CS and above intensity systems developed over AS in the month of December during 1891-2018. Out of these only two intensified into severe cyclonic storms (Fig. 2 a & b).

iv. Also, Pawan is the second CS after Sagar (2018) crossing Somalia coast. Pawan is also the first CS crossing Somalia coast in the month of December.

v. During its life period, a DD developed over southeast AS and adjoining Lakshadweep area (03-05 December). Co-existence of CS Pawan over southwest AS and DD over southeast AS is the second such event after super cyclonic storm Kyarr and extremely severe cyclonic storm Maha co-existed in November, 2019 over AS during 1891-2018. Tracks of these simultaneously occurring systems are presented in Fig. 3 (a& b).

vi. It maintained the cyclonic storm intensity for 51 hours (0000 UTC of 5th to 0300 UTC of 7th). However, the peak MSW of the cyclone was 70-80 kmph (40 knots) gusting to 90 kmph during 1200 to 1500 UTC of 5th December over the southwest AS. The lowest estimated central pressure was 998 hPa during the same period.

vii. The life period (D to D) of the system was 117 hours (04 days & 21 hours) against long period average (LPA) (1990-2013) of 89 hours for CS category over the AS.

viii. It moved with slower speed as 12 hour average translational speed was about 11.8 kmph against LPA (1990-2013) of 15.5 kmph over the AS during post monsoon season.

ix. The Velocity Flux, Accumulated Cyclone Energy (a measure of damage potential) and Power Dissipation Index (a measure of loss) were 3.20x10^2 knots, 1.14X10^4 knots^2 and 0.41X10^6 knots^3 respectively against long period average during 1990-2013 of 1.84 X10^2 knots, 0.8 X 10^4 knots^2 and 0.4 X10^6 knots^3 respectively over the Arabian Sea.

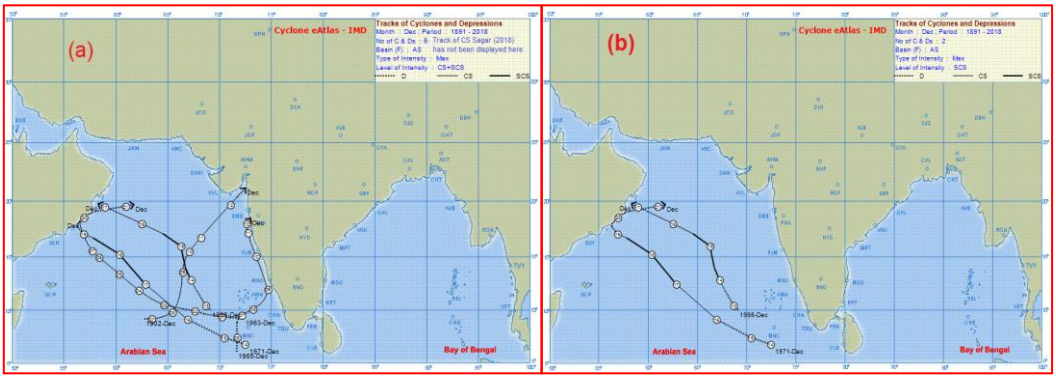


Fig.2: Tracks of (a) cyclonic storms and (b) severe cyclonic storms developing over AS in the month of December during 1891-2018

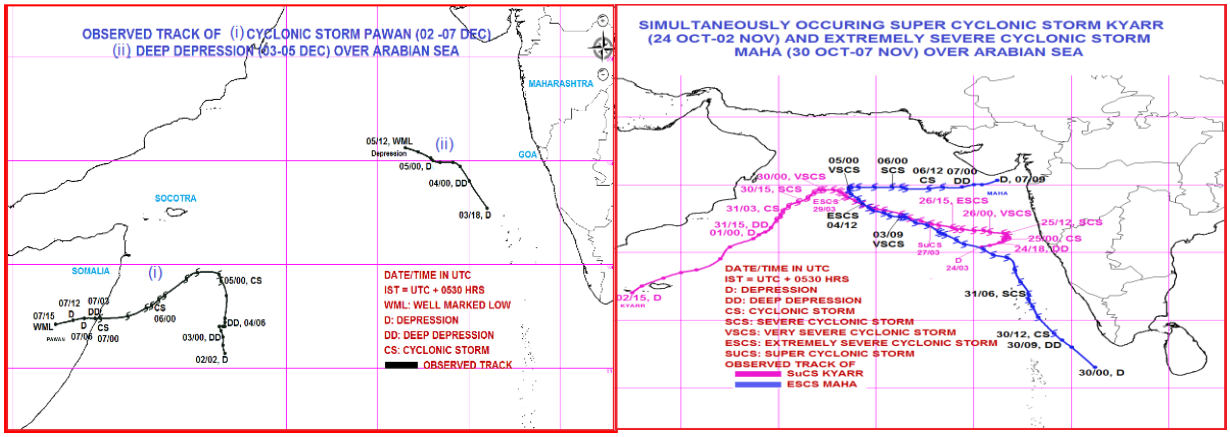


Fig.3: Tracks of simultaneously occurring cyclonic disturbances over AS during 1891-2018 (a) Pawan over southwest AS & DD over southeast AS (Dec., 2019) and (b) Super cyclonic storm Kyarr & ESCS Maha over AS (Oct., 2019)

Table 1: Best track positions and other parameters of the Cyclonic Storm, 'PAWAN' over the Arabian Sea during 2nd – 7th December, 2019

Date	Time (UTC)	Centre lat.^{0} N/ long.^{0} E		C.I. No.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
02/12/2019	1200	5.7	56.6	1.5	1003	25	03	**D**
	1800	6.1	56.5	1.5	1002	25	04	D
03/12/2019	0000	6.5	56.5	2.0	1001	30	05	**DD**
	0300	6.8	56.4	2.0	1000	30	06	DD
	0600	7.0	56.3	2.0	1000	30	06	DD
	1200	7.0	56.5	2.0	1000	30	06	DD
	1800	7.0	56.6	2.0	1000	30	06	DD
04/12/2019	0000	7.2	56.6	2.0	1000	30	06	DD
	0300	7.4	56.6	2.0	1000	30	06	DD
	0600	7.4	56.6	2.0	1000	30	06	DD
	1200	7.4	56.6	2.0	1000	30	06	DD
	1800	8.5	56.7	2.0	1000	30	06	DD
05/12/2019	0000	9.2	56.4	2.5	999	35	07	**CS**
	0300	9.2	56.4	2.5	999	35	07	CS
	0600	9.5	56.3	2.5	999	35	07	CS
	0900	9.5	55.6	2.5	999	35	07	CS
	1200	9.6	55.1	2.5	998	40	08	CS
	1500	9.6	54.9	2.5	999	35	07	CS
	1800	9.3	54.5	2.5	999	35	07	CS
	2100	9.0	54.0	2.5	999	35	07	CS
06/12/2019	0000	8.5	53.3	2.5	999	35	07	CS
	0300	8.3	53.0	2.5	999	35	07	CS

	0600	8.0	52.6	2.5	999	35	07	CS
	0900	7.9	52.6	2.5	999	35	07	CS
	1200	7.9	52.3	2.5	999	35	07	CS
	1500	7.7	51.8	2.5	999	35	07	CS
	1800	7.5	51.3	2.5	999	35	07	CS
	2100	7.5	50.9	2.5	999	35	07	CS
07/12/2019	0000	7.4	49.8	2.5	999	35	07	CS
	Crossed Somalia coast near latitude 7.4°N and longitude 49.6°E during 0200 to 0300 UTC of 7th December							
	0300	7.4	49.5	2.0	1000	30	06	**DD**
	0600	7.4	48.9	2.0	1001	30	05	DD
	0900	7.3	48.3	1.5	1003	25	03	**D**
	1200	**Weakened into a well marked low pressure area over north Somalia and adjoining Ethiopia**.						

2. Brief life history

1. Genesis

A low pressure area (LPA) formed over southwest Arabian Sea (AS) and adjoining equatorial Indian Ocean (EIO) in the early morning (0000 UTC) of 30th November, 2019. It lay as a WML over the same region in the early morning (0000 UTC) of 2nd December. Under favourable environmental conditions, it concentrated into a depression (D) over southwest AS & adjoining EIO in the same is evening (1200 UTC). At 1200 UTC of 2nd December, the MJO lay in phase 1 with amplitude close to 1. Considering the environmental conditions, total precipitable water vapour (TPW) imageries indicate warm air advection to the system centre. The low level relative vorticity was 150 $X10^{-5}S^{-1}$ around the system centre. Positive vorticity was extending upto 200 hPa level. The lower level convergence was about 10-20 $X10^{-5}S^{-1}$ around the system center. The upper level divergence was about 40 $X10^{-5}S^{-1}$ to the southwest of the system center. The vertical wind shear was moderate to high (20-30 knots) over the system area. The upper tropospheric ridge ran along 12° N. Sea surface temperature (SST) over the system area was 28- 29°C. Tropical cyclone heat potential (TCHP) was 40-60KJ/cm^2 over the system area.

3.2. Intensification and movement

At 0000 UTC of 3rd December, the MJO lay in phase 1 with amplitude close to 1. Considering the environmental conditions, TPW imageries indicated warm air advection into the core of system. The low level relative vorticity increased and was 150 $X10^{-5}S^{-1}$ around the system centre. Positive vorticity was extending upto 200 hPa level. The lower level convergence was about 10-20 $X10^{-5}S^{-1}$ around the system center. The upper level divergence was about 40 $X10^{-5}S^{-1}$ to the southwest of the system center. The vertical wind shear was moderate to high (20-30 knots) over the system area. The upper tropospheric ridge ran along 12° N. SST over the system area was 28- 29°C. TCHP was 40-60KJ/CM^2 over the system area. Under these

favourable conditions, the system moved northwestwards and intensified into a deep depression over southwest Arabian Sea & adjoining Equatorial Indian Ocean.

At 0000 UTC of 5th December, the MJO lay in phase 2 with amplitude more than 1. Considering the environmental conditions, TPW imageries indicated warm air advection to the system centre. The low level relative vorticity was about 150X$10^{-5}S^{-1}$ to the west of the system centre and was extending upto 200 hPa level. The lower level convergence was about 20 X$10^{-5}S^{-1}$ around the system area and the upper level divergence was about 30 X$10^{-5}S^{-1}$ to the northeast of the system centre. The vertical wind shear was moderate to high (15-25 knots) over the system. The upper tropospheric ridge ran along 13° N. SST was about 26-27°C and TCHP was 30-40 KJ/CM^2 over the region. The system was lying to the south of the upper tropospheric ridge and was steered by middle and upper tropospheric winds. Under these conditions, the system moved north-northwestwards and intensified into CS 'Pawan' over southwest Arabian Sea.

At 0300 UTC of 7th December, similar MJO conditions prevailed. Considering the environmental conditions, the low level relative vorticity was about 150 X$10^{-5}S^{-1}$ to the south of the system centre. The lower level convergence was about 20X$10^{-5}S^{-1}$ to the southwest of the system centre and the upper level divergence was about 20 X$10^{-5}S^{-1}$ to the west of system centre. The vertical wind shear was low (05-10 knots) over the system area. The upper tropospheric ridge ran along 11° N over the system area. The system was steered westwards under the influence of the upper level easterlies to the south of the ridge. Under these conditions, Pawan moved nearly westwards and crossed Somalia coast near latitude 7.4°N and longitude 49.6°E during 0200 to 0300 UTC of 07th December 2019 as a CS with a wind speed of 60-70 kmph gusting to 80 kmph and weakened into a DD over coastal Somalia and neighbourhood near latitude 7.4°N and longitude 49.5°E.

At 0900 UTC of 7th December, similar MJO conditions prevailed. The low level relative vorticity decreased and was about 50 X$10^{-5}S^{-1}$ over the system area. The lower level convergence was about 20 X$10^{-5}S^{-1}$ and the upper level divergence was about 40 X$10^{-5}S^{-1}$ over the system area. The system lay in an area with low to moderate (10-15 knots) vertical wind shear. The upper tropospheric ridge ran roughly along 14° N over the system area. Under these conditions, the system moved nearly westwards and weakened into a depression over north Somalia and neighborhood near latitude 7.3°N and longitude 48.3°E. It further weakened into a WML at 1200 UTC of 07th December over north Somalia & adjoining Ethiopia.

Typical TPW imageries during 3rd-8th December are presented in **Fig.4**. These imageries indicate continuous warm and moist air advection from the southeast sector into the system during 3rd-6th December. From 5th onwards, the warm moist air advection into the core started decreasing.

The mean wind speed and wind shear speed in the layers 850 to 200 hPa and 850 to 500 hPa around the system centre is presented in **Fig.5**. The mean wind shear speed in both the layers has been low to moderate throughout the life cycle of CS Pawan. The mean wind speed in the layer 200 to 850 hPa steered the system initially northwards till 5th/0000 UTC followed by gradual west-southwestward movement. The average mean wind speed was low (5-10 kt) during the entire life cycle as seen in both the layers 850 to 200 hPa and 850 to 500 hPa.

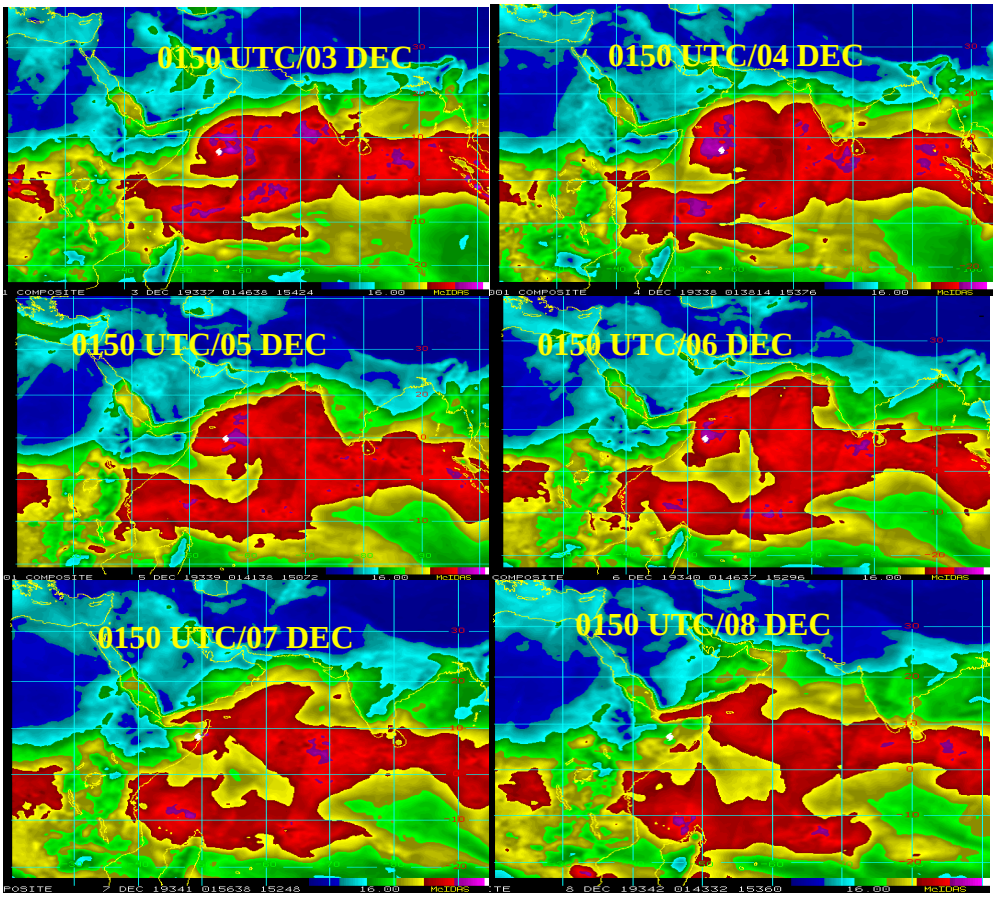


Fig. 4: Total Precipitable Water Imageries during 03-08 December, 2019

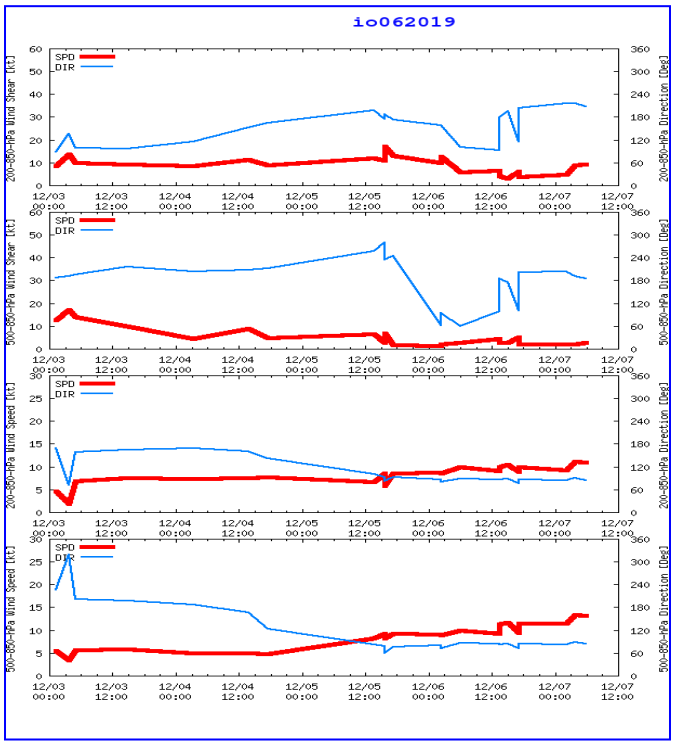


Fig.5 Wind shear and wind speed in the middle and deep layer around the system during 03rd to 07th December 2019.

3.3 Movement

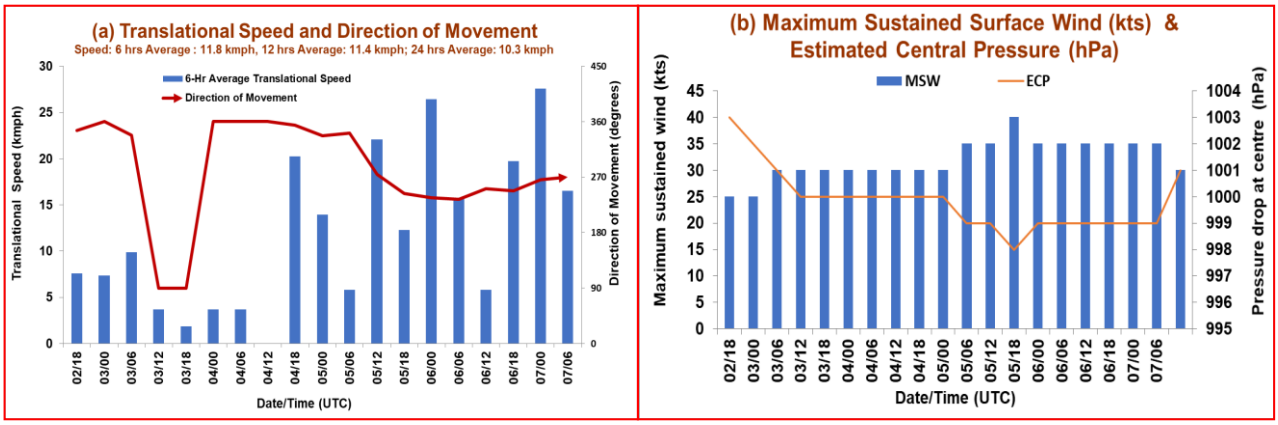


Fig.6 (a) Translational speed & direction of movement and (b) Maximum sustained surface winds (kts) & Estimated Central Pressure (hPa) during life cycle of CS Pawan

From **Fig.5**, it may be noted that the mean deep layer winds between 200 to 850 hPa levels steered the system initially northwards followed by west-southwestwards re-curvature. The six hourly movement of CS Pawan is presented in **Fig.6 (a)**. The six hourly average translational speed of the cyclone was about 11.8 kmph against LPA (1990-2013) of 15.5 kmph over the AS during post monsoon season. Hence Pawan was a slow moving system in nature.

3.4. Maximum Sustained Surface Wind speed and estimated central pressure:

The lowest estimated central pressure and the maximum sustained wind speed are presented in **Fig.6 (b)**. The lowest estimated central pressure (ECP) had been 997 hPa at 1200 of 5th December. Similarly, in the wind field it is seen that there was gradual increase in maximum sustained wind speed (MSW) reaching it's peak at 1200 of 5th December.

4. Monitoring of CS, 'PAWAN'

India Meteorological Department (IMD) maintained round the clock watch over the north Indian Ocean and the cyclone was monitored since 28th November when cyclogenesis was predicted in the extended range outlook over southwest AS & adjoining EIO in the later part of week (29.11.2019-05.12.2019) and it's movement towards Somalia. 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. 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 models' guidance, decision making process and warning product generation.

4. Features observed through satellite

Satellite monitoring of the system was mainly done by using half hourly INSAT-3D imageries. Satellite imageries of international geostationary satellites Meteosat-7, microwave & high resolution images of polar orbiting satellites DMSP, NOAA series, TRMM, Metops and SCAT SAT imageries were considered for monitoring the system.

4.1. INSAT-3D features

Typical INSAT-3D visible/IR imageries, enhanced colored imageries and cloud top brightness temperature imageries are presented in **Fig.7 (a-d)**.

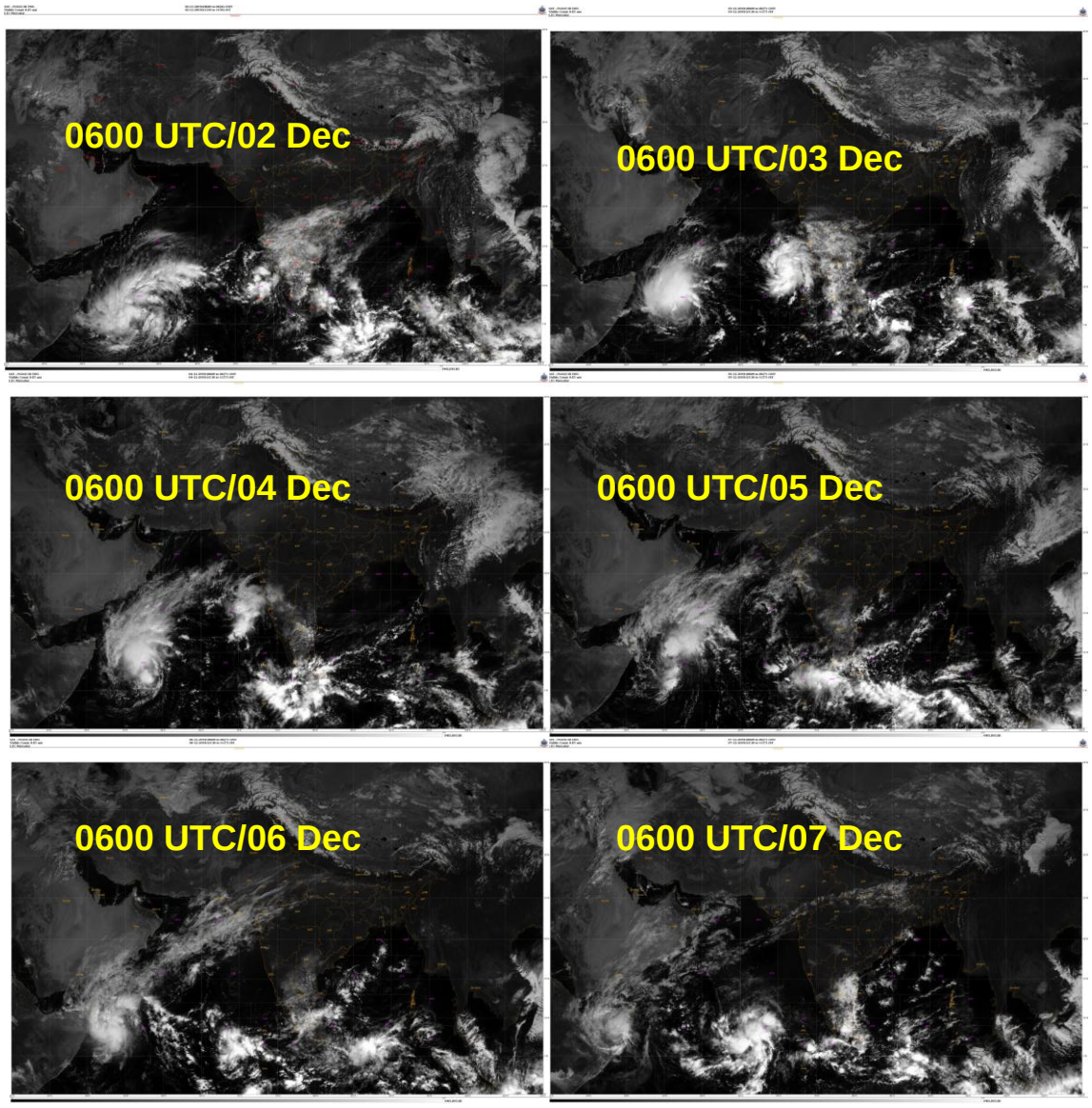


Fig. 7a: INSAT-3D visible imageries during life cycle of CS Pawan (02-07 Dec, 2019)

At 1200 UTC of 2nd December, broken low to medium clouds with embedded intense to very intense convection lay over over southeast Arabian Sea and adjoining Lakshadweep area between Lat 8.5 ^{0}N to 13.0 ^{0}N long 70.5^{0}E to 75.0^{0}E in association with the system.

At 0000 UTC of 3rd, broken low to medium clouds with embedded intense to very intense convection lay over Lakshadweep area and adjoining southeast Arabian Sea between Lat 9.0^{0}N to 13.50^{0}N long 70.0^{0}E to 75.0^{0}E in association with the system over the area. Minimum cloud top temperature is minus 93^{0}C.

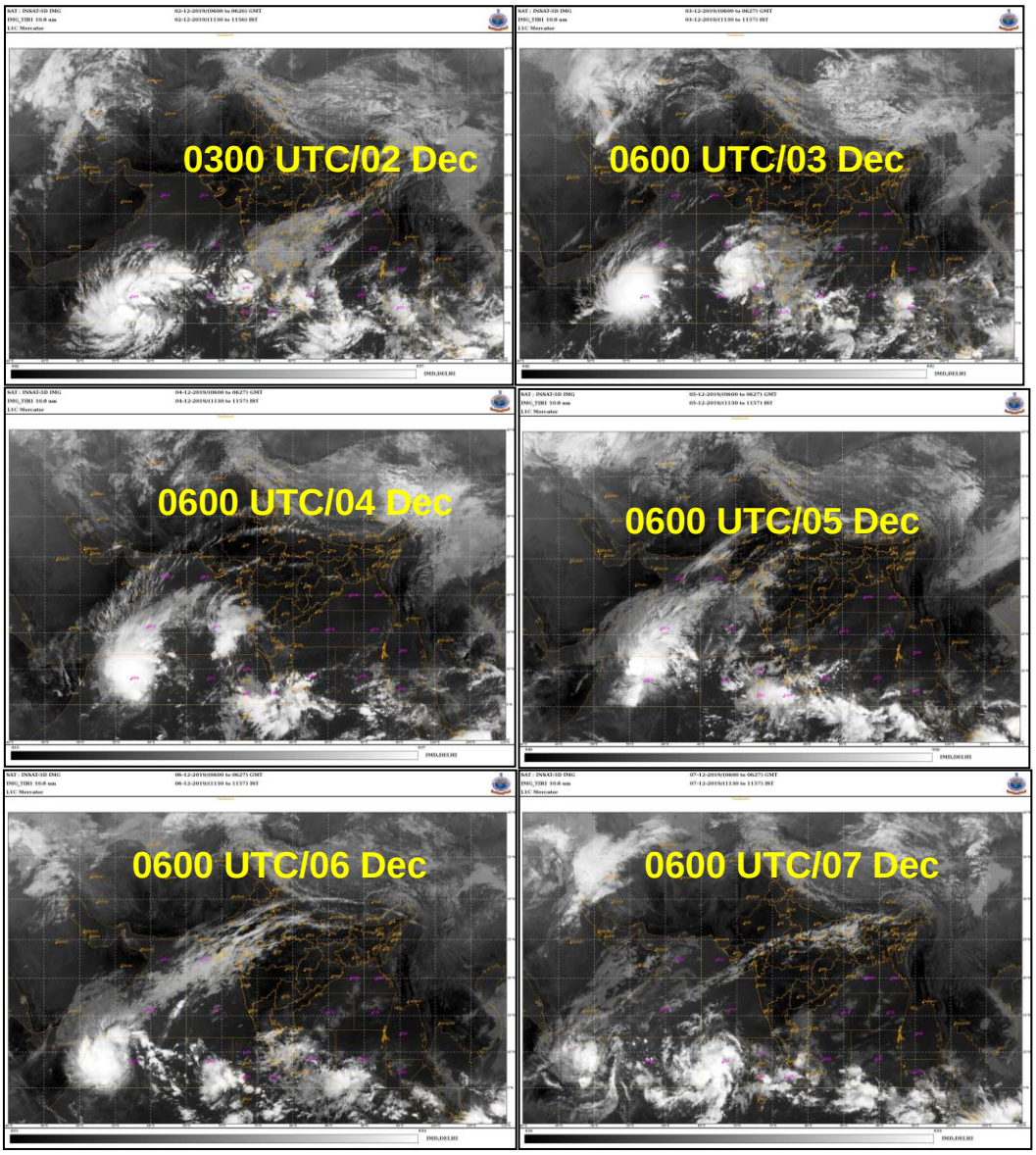


Fig. 7b: INSAT-3D IR imageries during life cycle of CS Pawan (02-07 Dec, 2019)

At 0000 UTC of 4th, the current intensity of the system was T2.0. Associated broken to low/med clouds with embedded intense to very intense convection over south east Arabian Sea adjoining Lakshadweep area between Lat 11.5^{0}N to 16^{0}N long 68.5^{0}E to 72.0^{0}E (minimum CTT minus 92^{0}C)

At 0000 UTC of 5th, the current intensity of the system was T2.0/1.5. Associated broken low to medium clouds with embedded intense to very intense convection lay over east-central Arabian Sea between Lat 10.5^{0}N to 14.0^{0}N & long 68.0^{0}E to 71.0^{0}E. Minimum CTT was minus 58 ^{0}C.

At 0000 UTC of 6th, the current intensity of the system was T2.5. Associated broken low to medium clouds with embedded intense to very intense convection lay over southwest Arabian Sea between Lat 5.5^{0}N to 12.0^{0}N and long 51.5^{0}E to 56.0^{0}E. Minimum cloud top temperature was minus 93 ^{0}C.

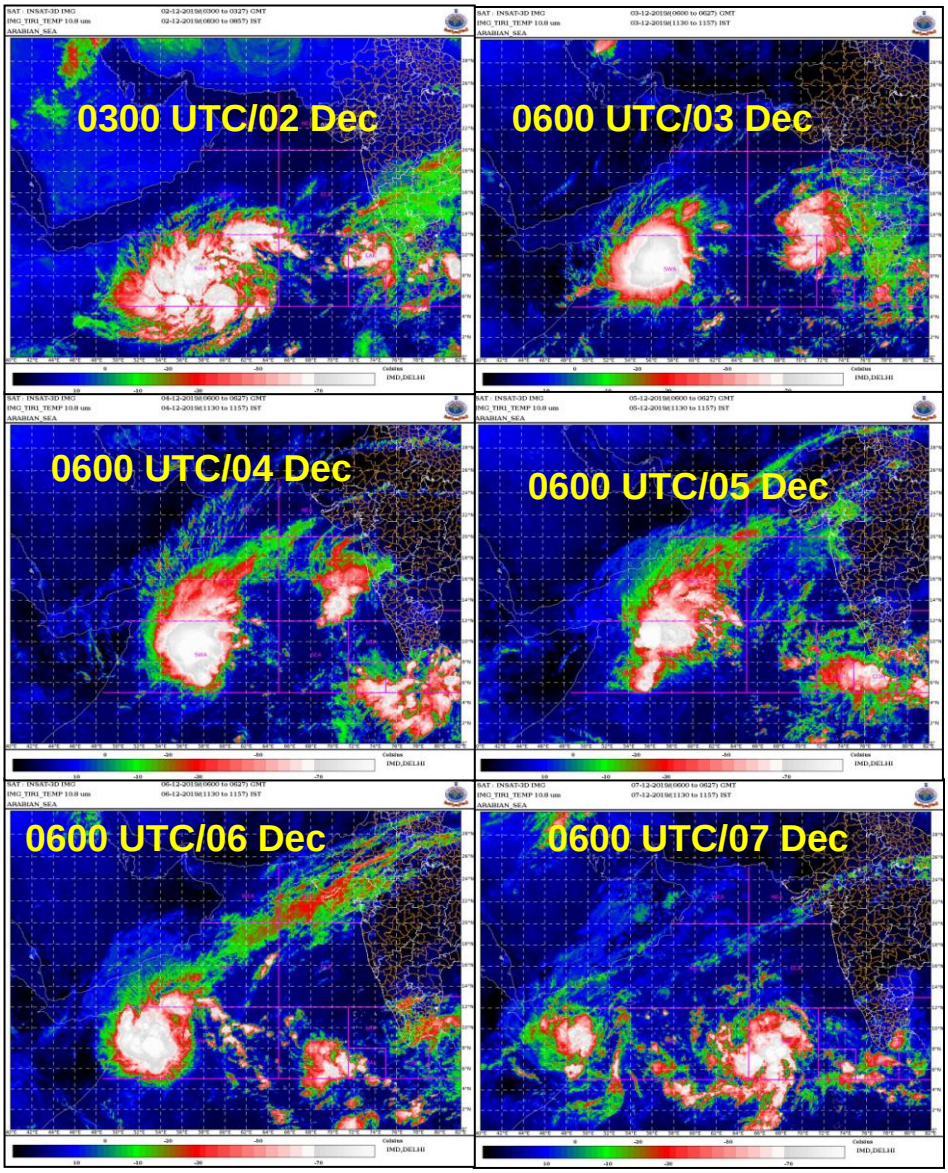


Fig. 7c: INSAT-3D enhanced colored imageries during life cycle of CS Pawan (02-07 Dec, 2019)

At 0000 UTC of 7th, the current intensity of the system was T2.5. associated broken low to medium clouds with embedded intense to very intense convection lay over southwest Arabian Sea and adjoining coastal Somalia between Lat 7.0^{0}N to 10.0^{0}N and long 49.5^{0}E to 52.0^{0}E. minimum cloud top temperature was minus 93 ^{0}C.

At 0300 UTC of 7th, broken low to medium clouds with embedded intense to very intense convection lay over north Somalia and adjoining southwest Arabian Sea and adjoining coastal Somalia between Lat 6.5^{0}N to 11.0^{0}N and long 47.0^{0}E to 51.0^{0}E in association with the system over north Somalia coast and neighborhood. Minimum cloud top temperature was minus 93 ^{0}C. Microwave imagery showed intense convective cloud mass over north and north-east sector of the system.

At 0600 UTC of 7th, broken low to medium clouds with embedded intense to very intense convection lay over southeast Arabian Sea and adjoining equatorial Indian ocean between Lat 4.0^{0}N to 10.0^{0}N and long 62.5^{0}E to 69.0^{0}E in association with the system. Minimum cloud top temperature was minus 93 ^{0}C.

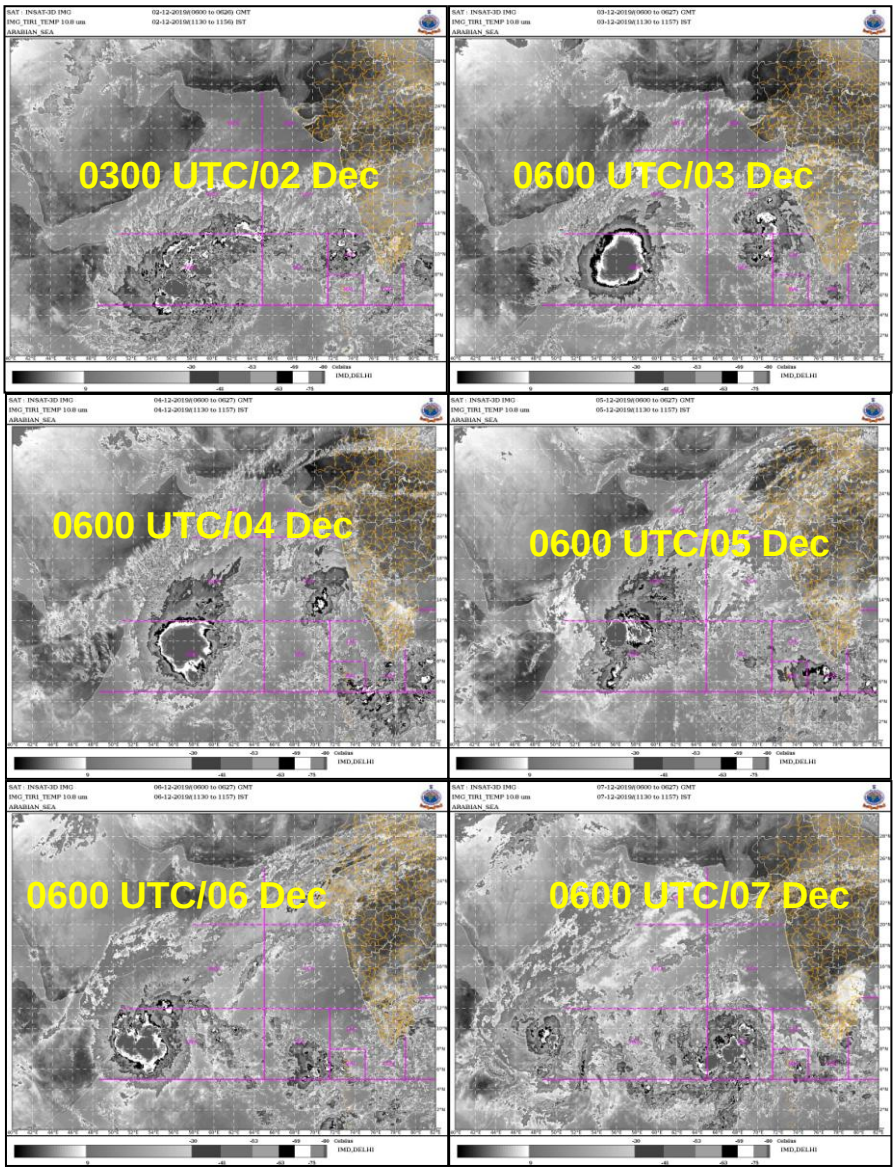


Fig. 7d: INSAT-3D cloud top brightness imageries during life cycle of CS Pawan (02-07 Dec, 2019)

Microwave imageries from polar orbiting satellites F-15, F-16, F-18, GCOM W1, GPM 89, NOAA-19 were utilised for determining the centre and area of intense convection. Typical microwave imageries during the life cycle of CS Pawan are presented in **Fig. 7(e).**

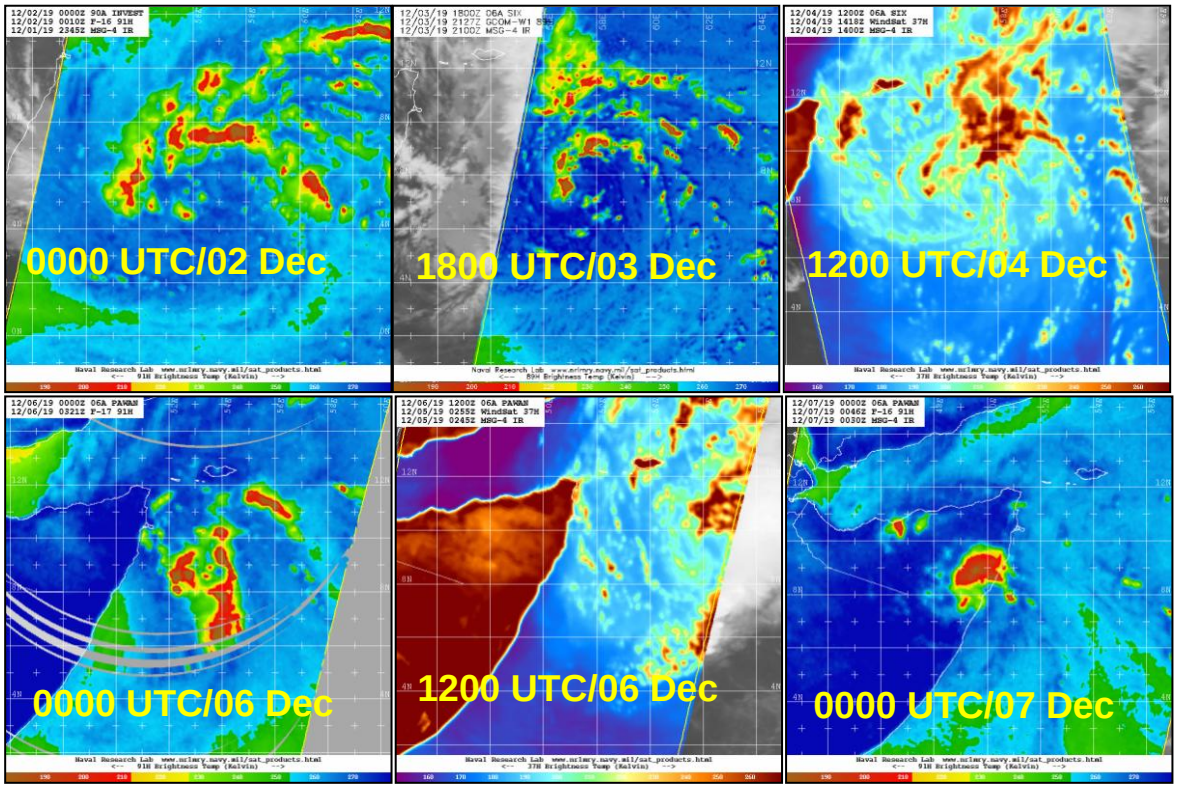


Fig. 7e: Microwave imageries during life cycle of CS Pawan (02-07 Dec, 2019)

Typical imageries from polar satellite, SCATSAT are presented in Fig. 7(f). SCATSAT passes are available twice a day at http://mosdac.gov.in/scorpio/SCATSAT_Data. The SCAT SAT imageries correctly picked up the centre and intensity of Pawan. Matching Index was also>0.6 on 4th and 5th December, indicating the potential of intensification into a CS.

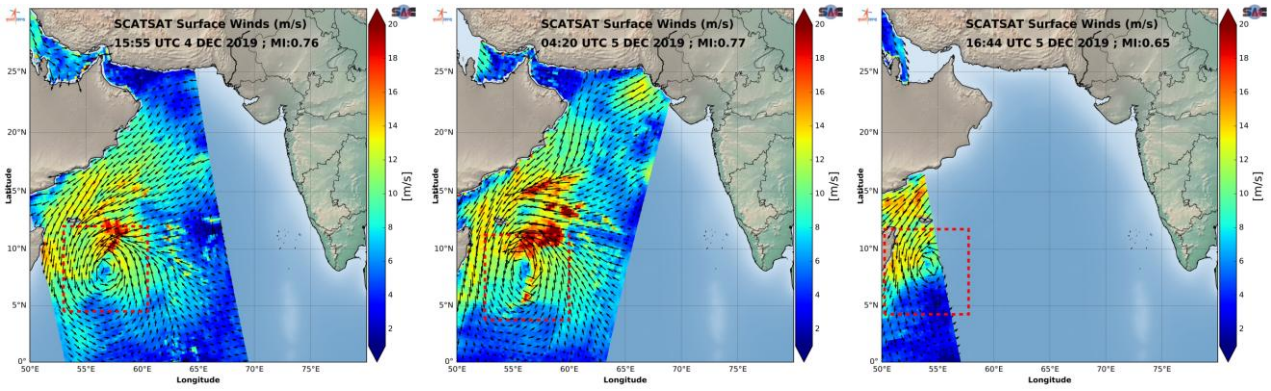


Fig. 7(f): SCAT SAT imageries during life cycle of CS Pawan

When the system was over the Sea, imageries from ASCAT were also utilized for determination of centre, intensity and wind distribution around the centre of the system. Typical ASCAT imageries from Metop-B are presented in Fig. 7(g).

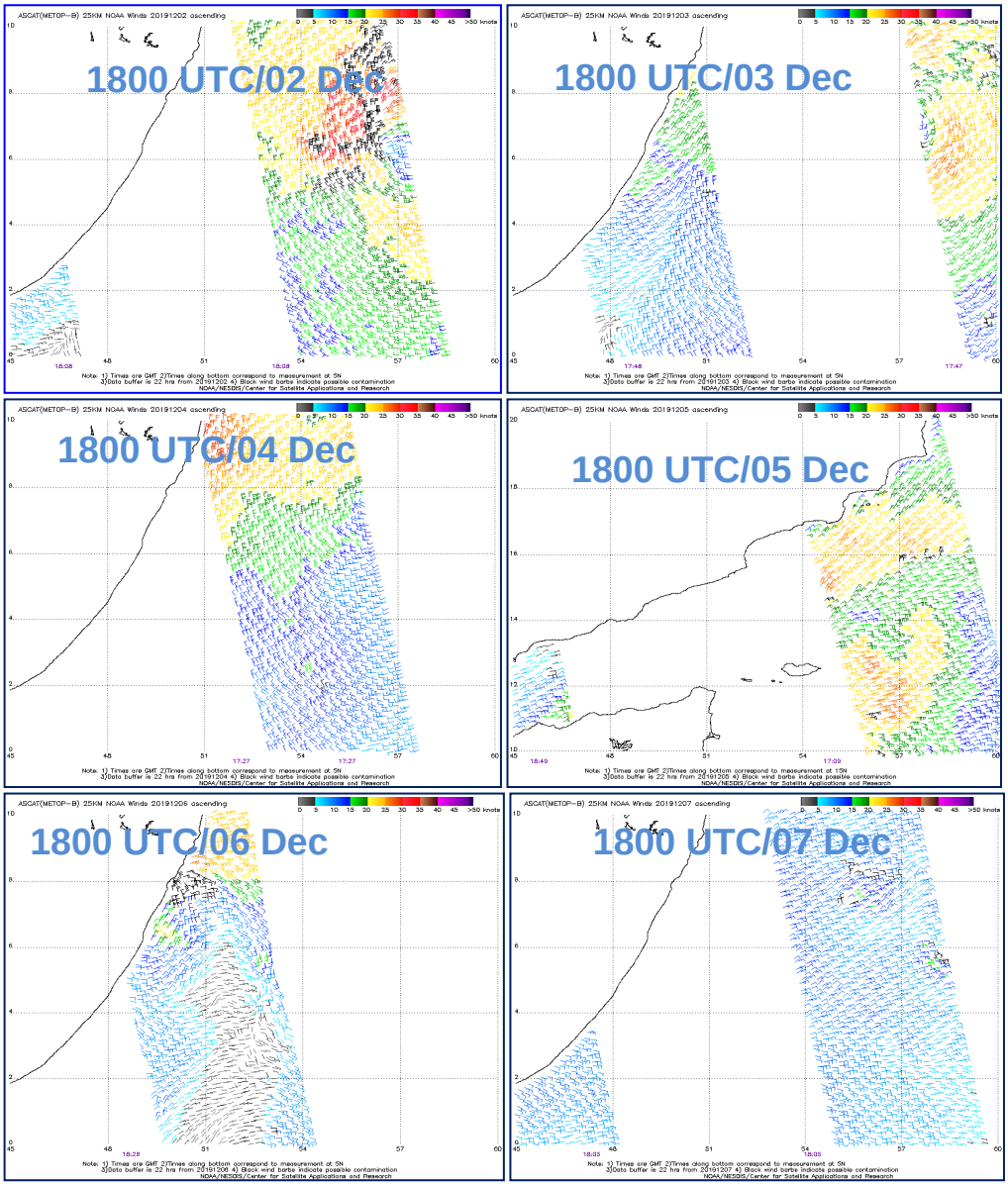


Fig. 7(g): ASCAT (Met-Op B) imageries during life cycle of CS Pawan (02-07 Dec, 2019)

5. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 2nd to 6th December are presented in Fig.8. The analysis field of IMD GFS (T1534) at 0000 UTC 2nd, simulated a depression over southwest AS. The circulation was extending upto 500 hPa level. Synoptically, the system lay as a WML over southwest and adjoining EIO.

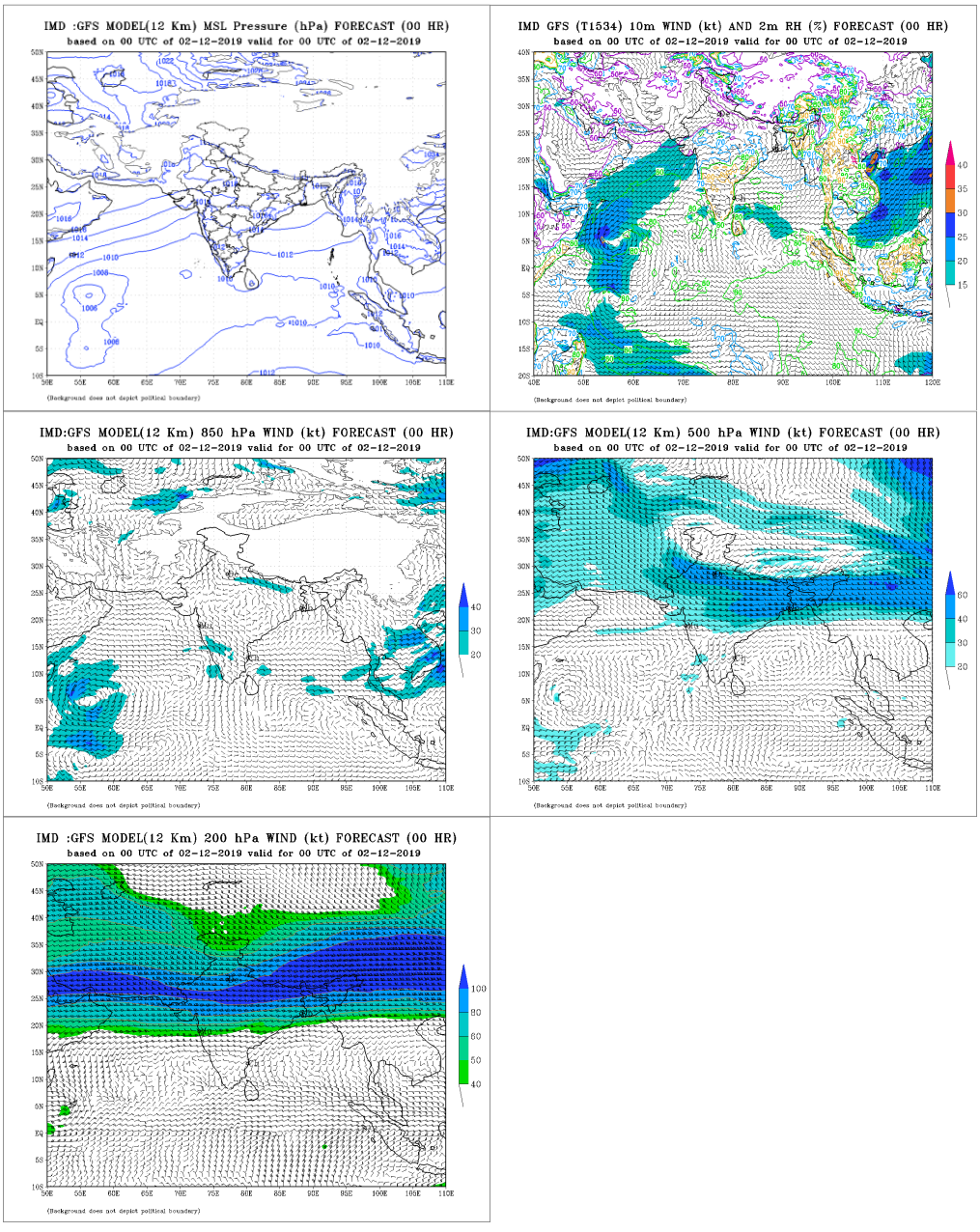


Fig. 8 (a): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 2nd December

The analysis field of IMD GFS (T1534) at 0000 UTC of 3rd, indicated a CS over southwest AS. The circulation was extending upto 500 hPa level. Synoptically, the system lay as a DD over southwest AS.

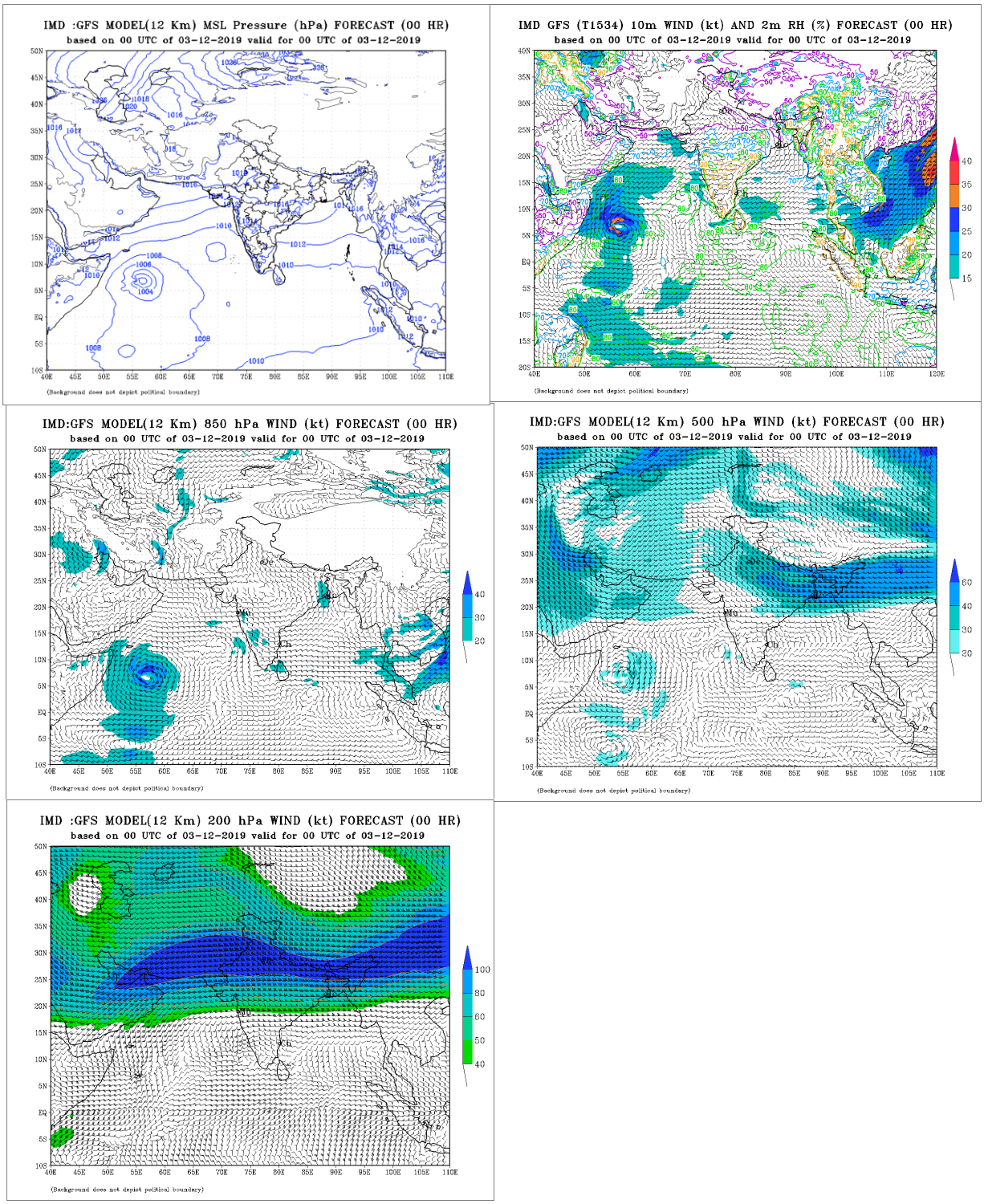


Fig. 8 (b): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 3rd December

The analysis field of IMD GFS (T1534) at 0000 UTC of 4th, indicated further intensification of system over southwest AS. The circulation was extending upto 500 hPa level. Synoptically, the system lay as a DD over southwest AS.

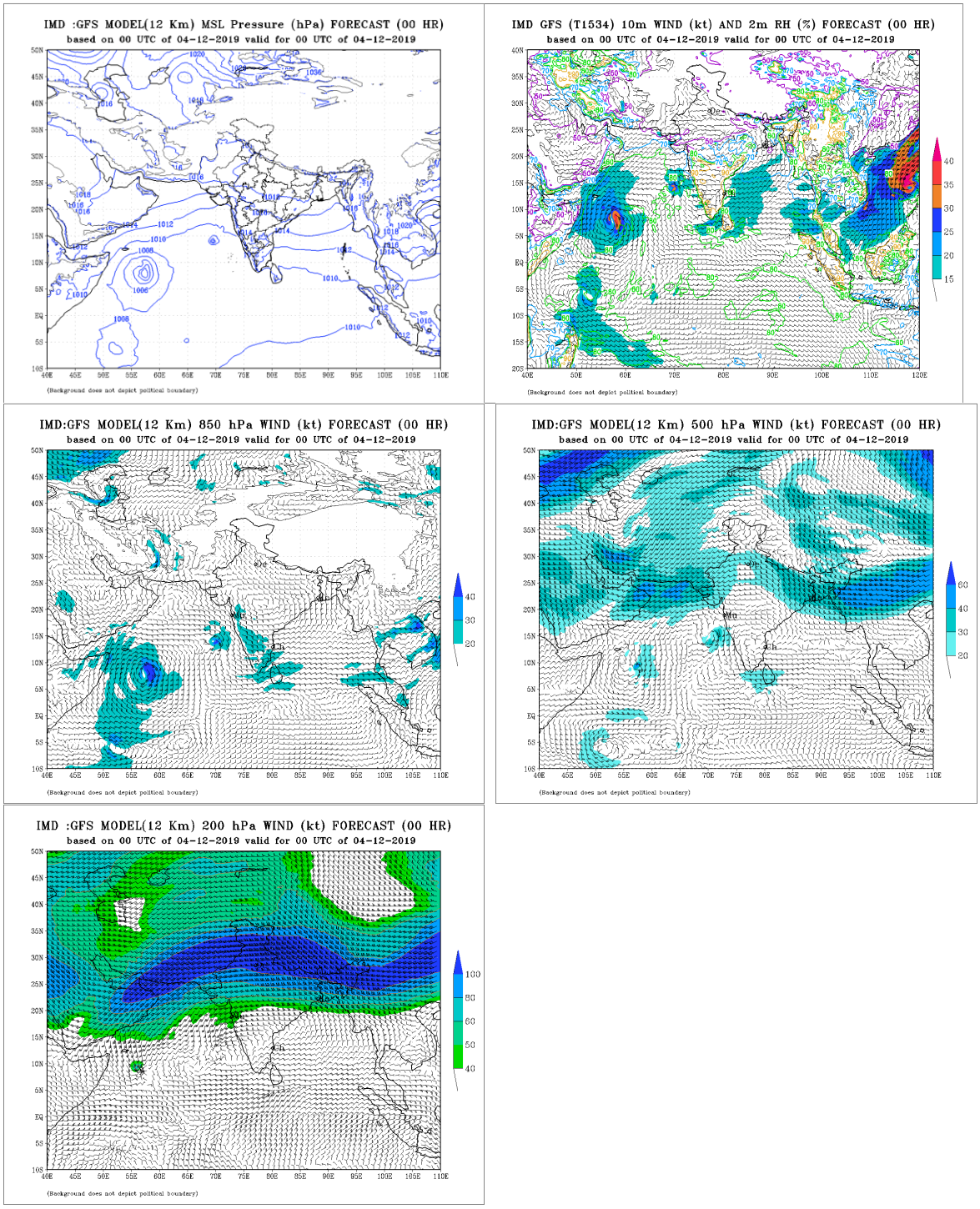


Fig. 8 (c): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 4th December

The analysis field of IMD GFS (T1534) at 0000 UTC of 5th, indicated slight weakening of system over southwest AS. The circulation was extending upto 500 hPa level. Synoptically, the system lay as a CS over southwest AS.

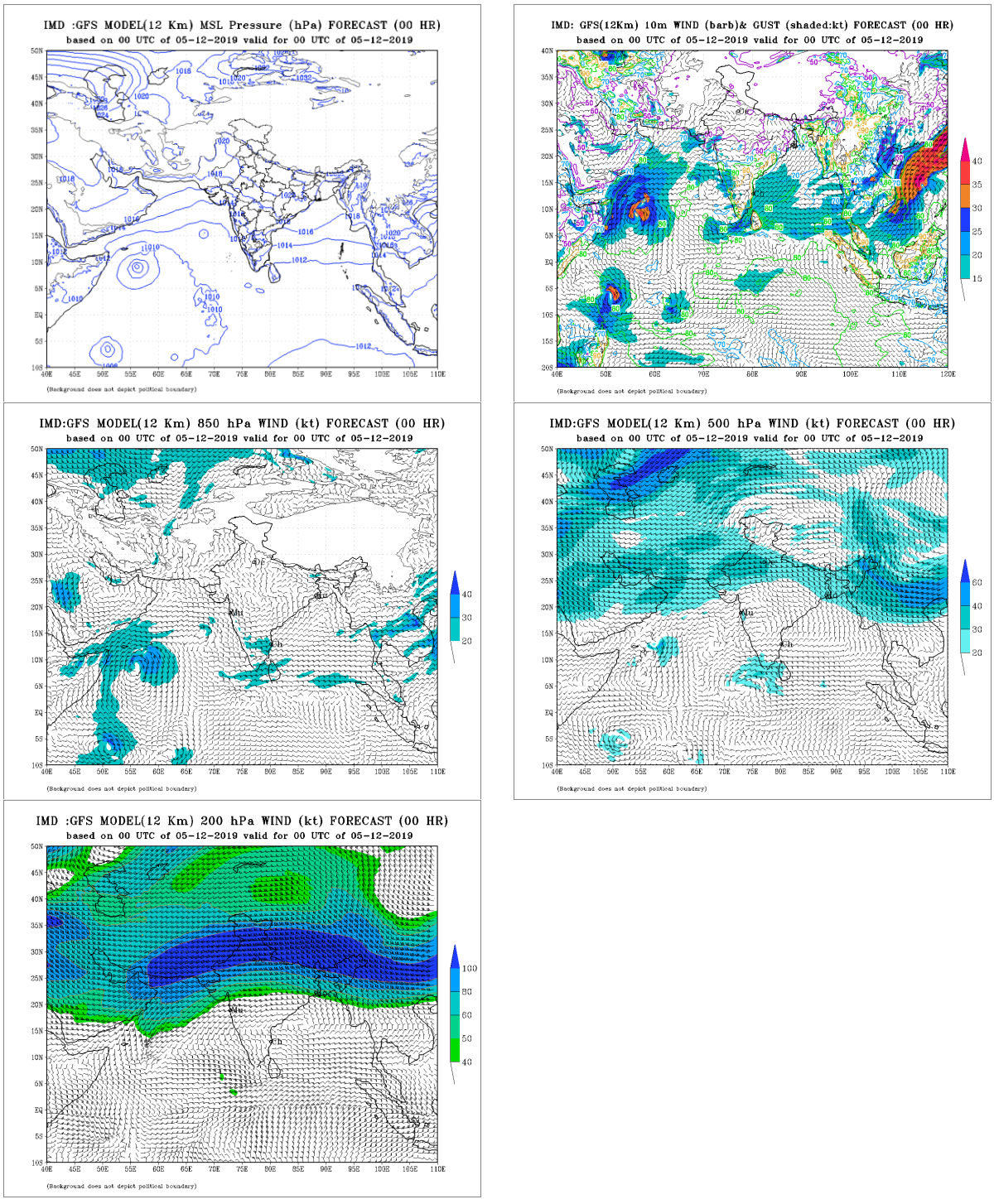


Fig. 8 (d): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 5th December

The analysis field of IMD GFS (T1534) at 0000 UTC of 6th, indicated further weakening of system over southwest AS into a DD. The circulation was extending upto 500 hPa level. Synoptically, the system lay as a CS over southwest AS.

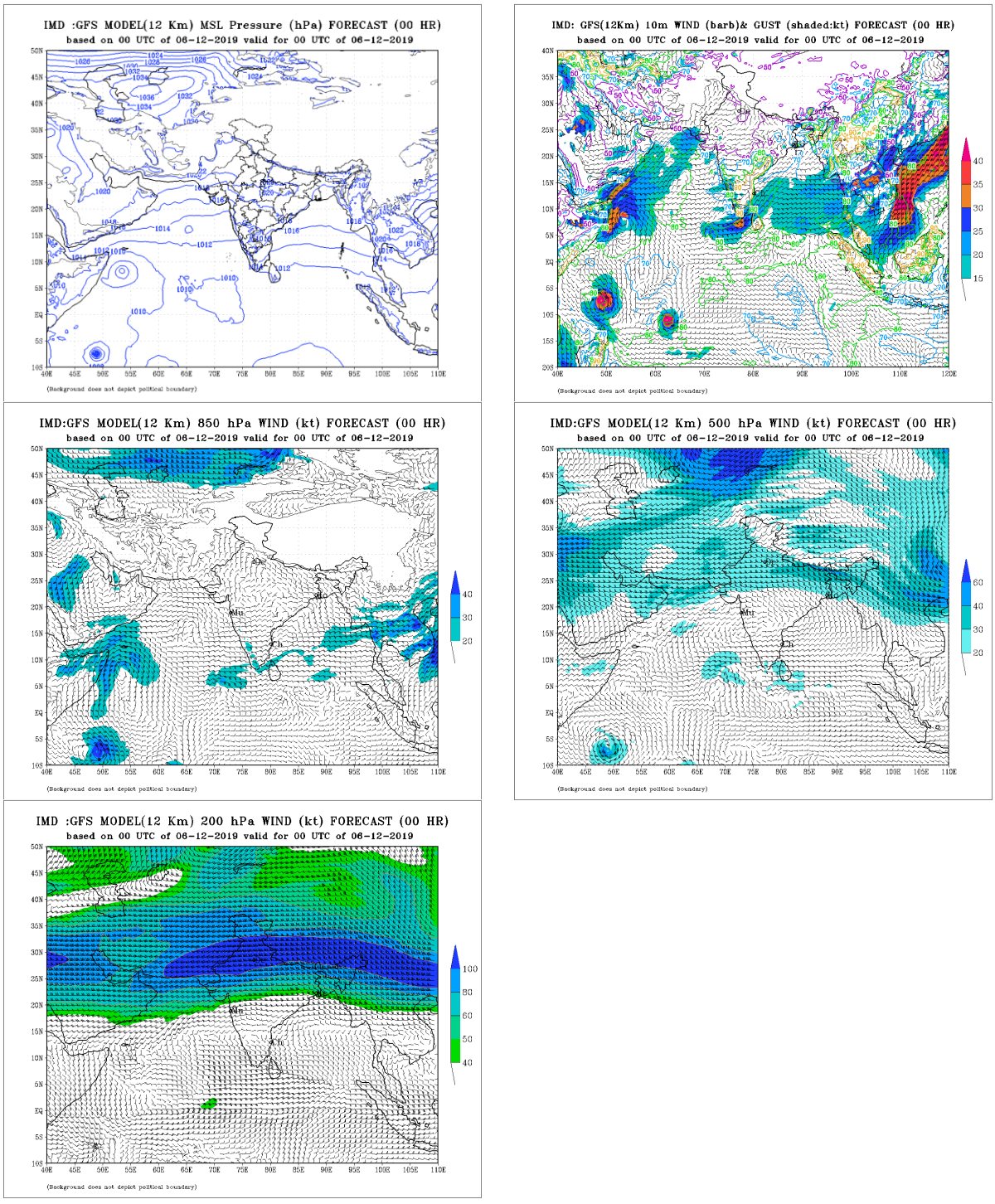


Fig. 8 (e): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 6th December

The analysis field of IMD GFS (T1534) at 0000 UTC of 7th, indicated the system crossing Somalia coast as a DD. The circulation was extending upto 500 hPa level. Synoptically, the system crossed Somalia coast as a CS during 0200-0300 UTC of 7th.

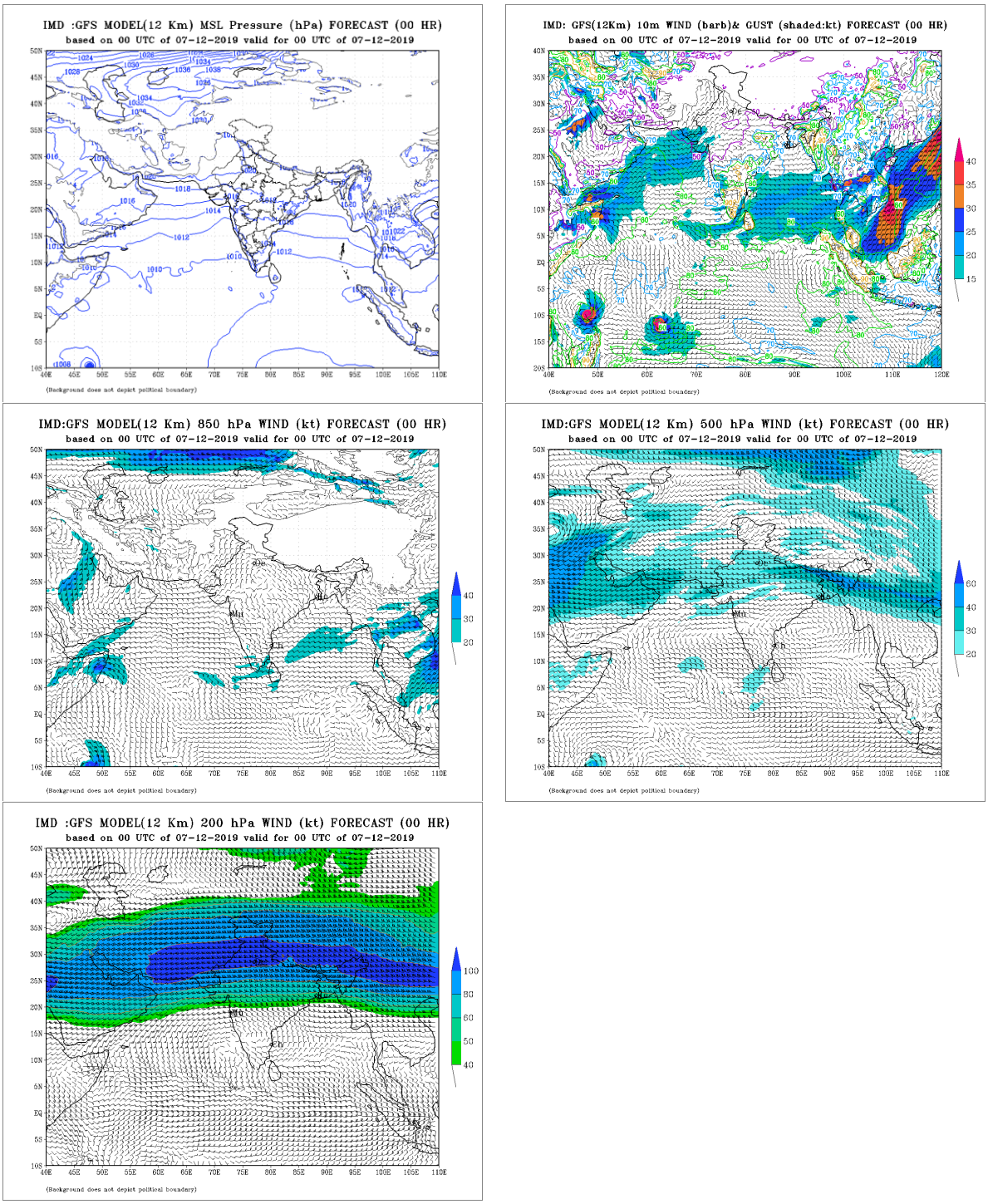


Fig. 8 (f): IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 7th December

Hence to conclude, to a large extent IMD GFS could simulate the genesis, movement and landfall characteristics of the system. However, the intensity was overestimated both during development and decaying stage.

6. Realized Weather:

6.1 Rainfall:

Rainfall associated with CS Pawan based on IMD-NCMRWF GPM merged gauge 24 hours cumulative rainfall ending at 0300 UTC of date is depicted in **Fig 9**. The system developed over southwest Arabian Sea and caused heavy to very rainfall southwest Arabian Sea area during 3rd-4th December. However, rainfall gradually decreased from 4th onwards. On 7th, it caused heavy to very heavy rainfall at few places over coastal parts of northeast Somalia. On 8th, it caused moderate to heavy rainfall at isolated places over interior parts of northeast Somalia. It did not cause any adverse weather over any of the coastal states along west coast of India.

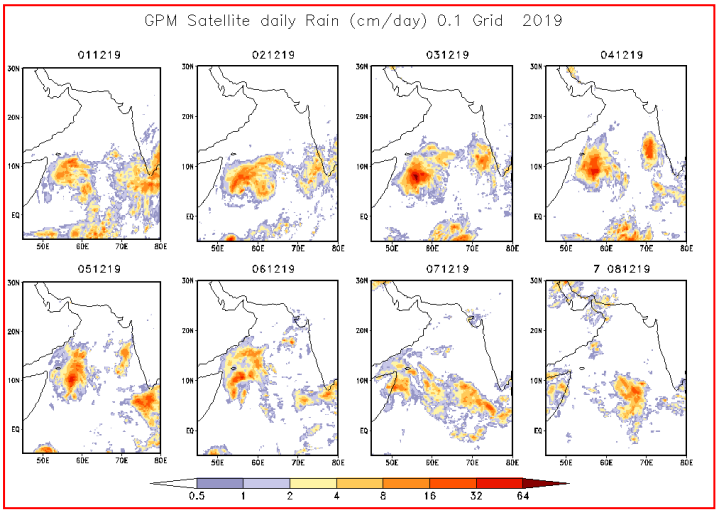


Fig.9: IMD-NCMRWF GPM merged gauge 24 hr cumulative rainfall (cm) ending at 0300 UTC of date during 01-08 December 2019

7. Damage:

No damage was reported in association with this system.

8. 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. 25ºS to 45ºN & long 40º E to 120º 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 120-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. In this report performance of the individual models, MME forecasts, SCIP, GPP, RII for Severe cyclone Pawan are presented and discussed.

8.1 Prediction of cyclogenesis (Genesis Potential Parameter (GPP)) for PAWAN

Fig. 10 shows the predicted zone of cyclogenesis based on 0000 UTC of 28th November to 03rd December upto 120 hours lead period. The GPP index predicted cyclogenesis over southwest AS and adjoining EIO with a lead period of 120 hrs. However, on 2nd (36 hrs prior to genesis), it didn't show any potential zone for cyclogenesis.

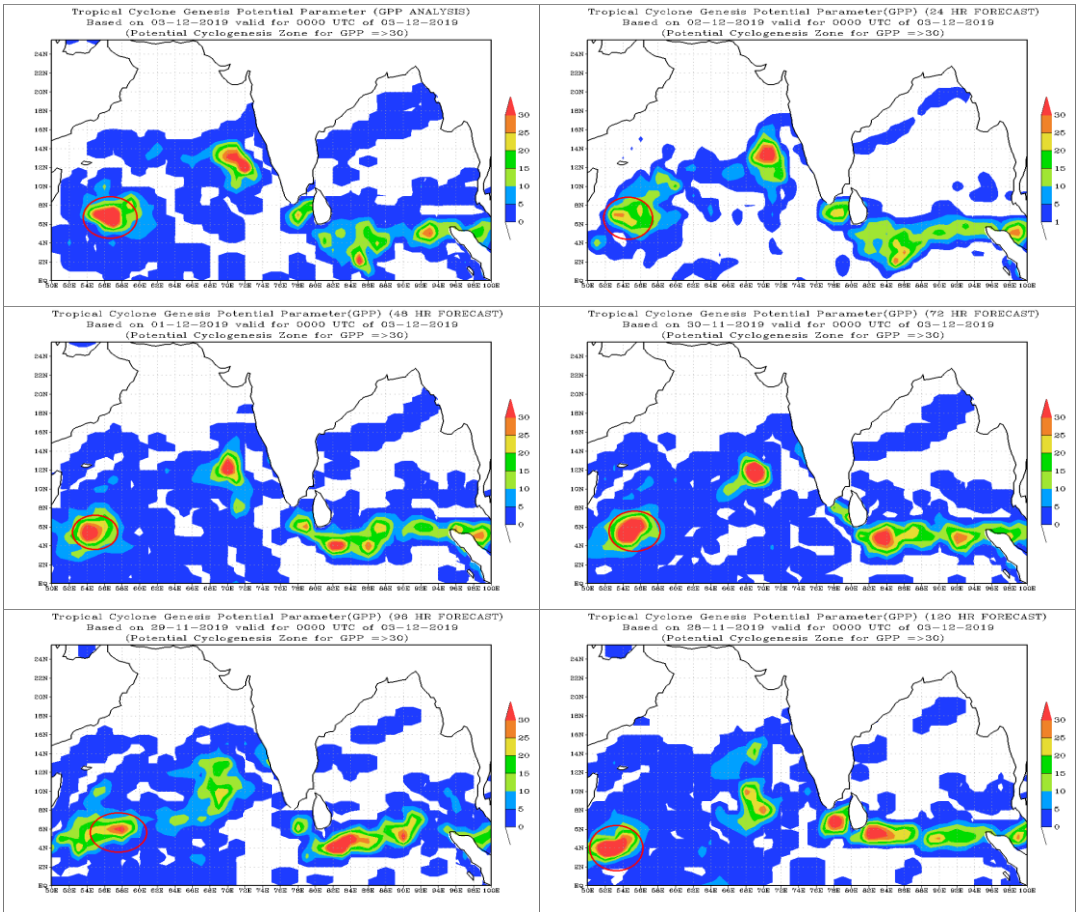


Fig. 10: Predicted zone of cyclogenesis based on 0000 UTC of 3rd December 2019.

8.2 Track prediction by NWP models

Track prediction by various NWP models is presented in Fig.11. At 1200 UTC of 2nd, models like ECMWF, NCEP GFS and IMD GFS were predicting landfall near Somalia coast. All other models like UKMO, JMA, WRF-VAR and MME were predicting weakening over southwest AS.

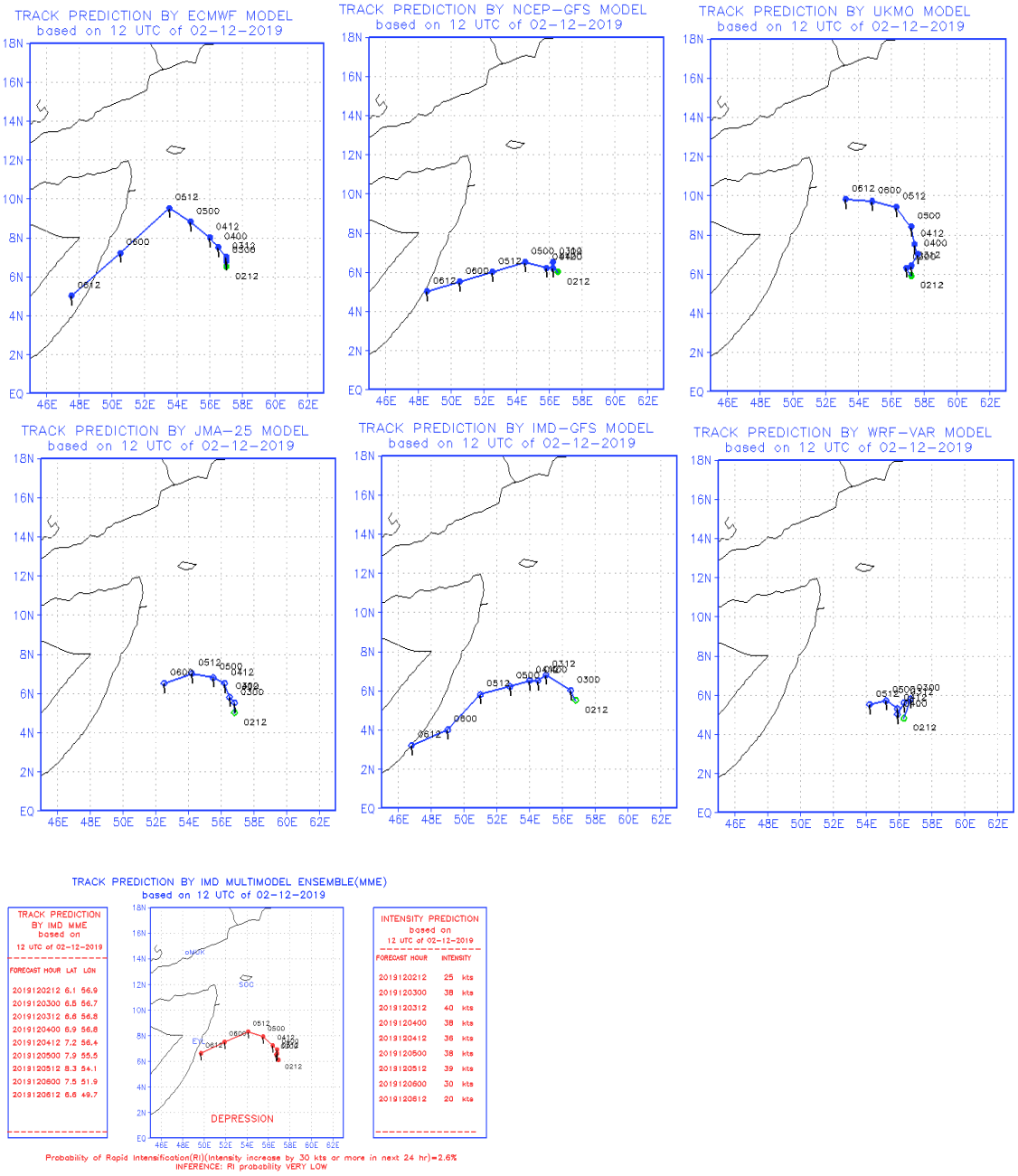


Fig. 11 (a): NWP model track forecast based on 1200 UTC of 02nd December

At 0000 UTC of 3rd, models like ECMWF, MME, NCEP GFS and IMD GFS were predicting landfall near Somalia coast. All other models like UKMO, JMA, WRF-VAR and HWRF were predicting weakening over southwest AS.

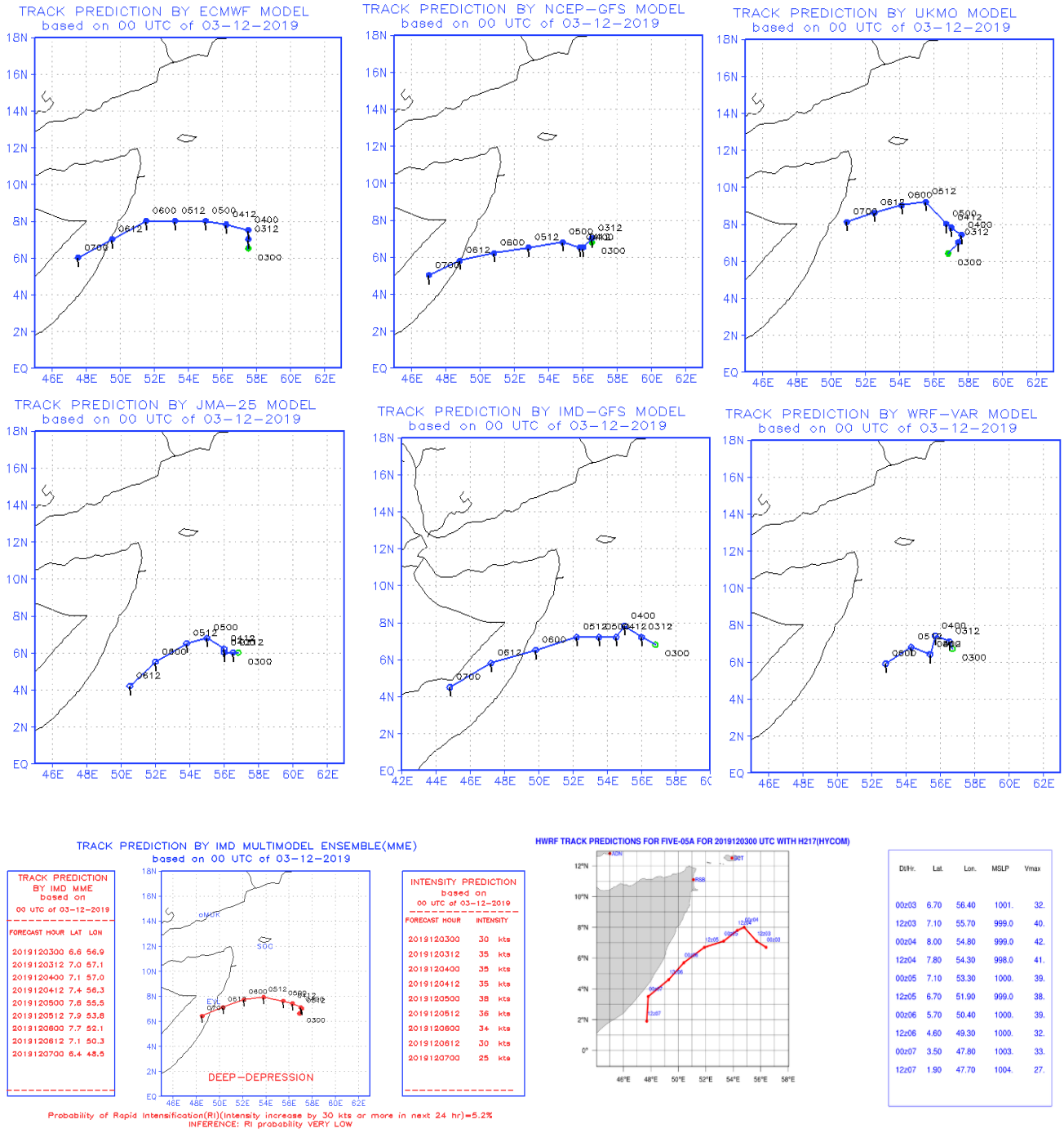


Fig. 11 (b): NWP model track forecast based on 0000 UTC of 3rd December 2019

At 1200 UTC of 3rd, models like ECMWF, MME, NCEP GFS and IMD GFS were predicting landfall near Somalia coast. All other models like UKMO, JMA, WRF-VAR and HWRF were predicting weakening over southwest AS.

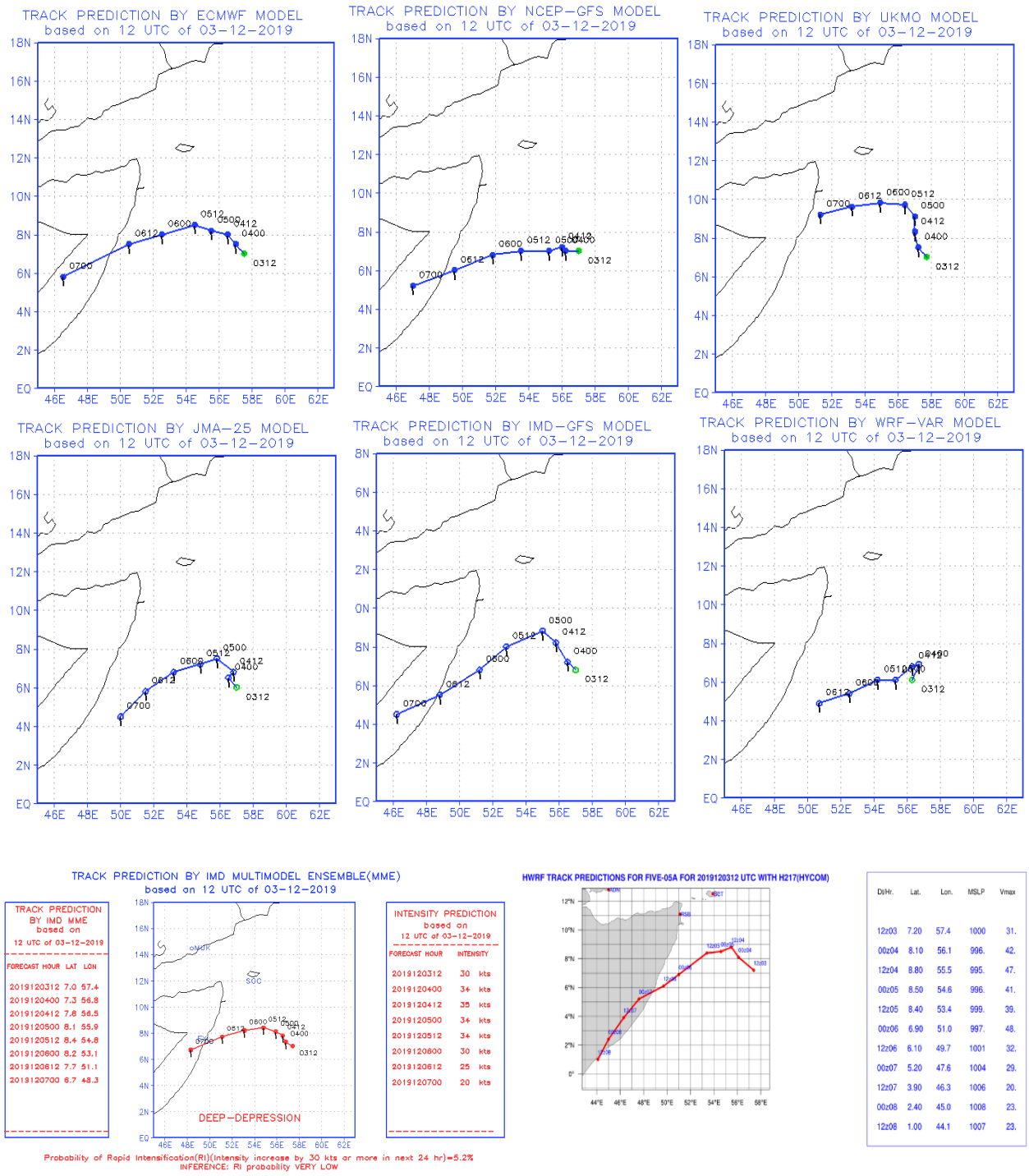


Fig. 11 (c): NWP model track forecast based on 1200 UTC of 3rd December 2019

At 0000 UTC of 4th, models like ECMWF, MME, NCEP GFS, IMD GFS, WRF VAR and HWRF were predicting landfall near Somalia coast. Models like UKMO and JMA were predicting weakening over southwest AS.

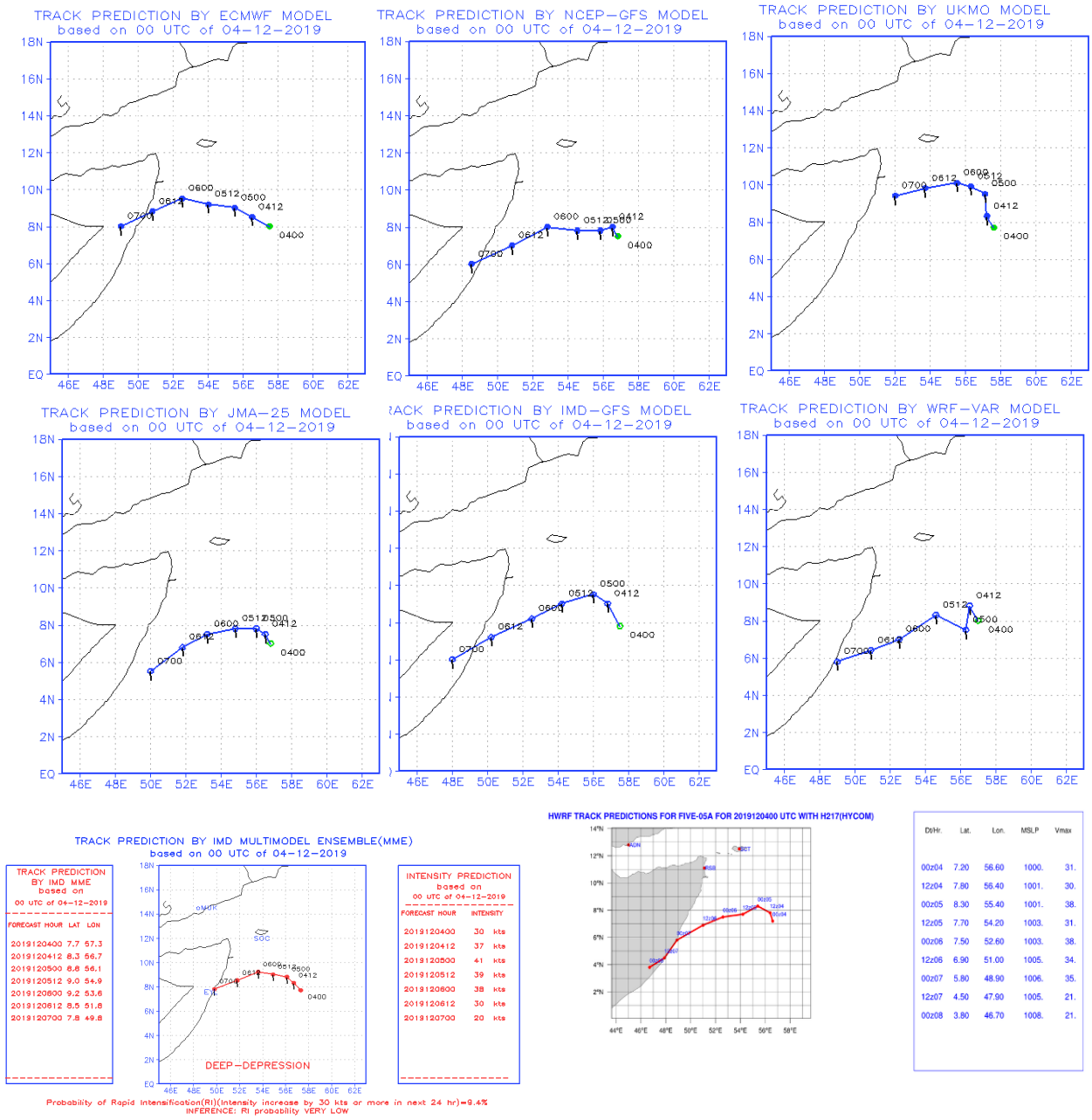


Fig. 11 (d): NWP model track forecast based on 0000 UTC of 4th December 2019

At 1200 UTC of 4th, models like ECMWF, MME, NCEP GFS, IMD GFS and HWRF were predicting landfall near Somalia coast. Models like UKMO, JMA and WRF VAR were predicting weakening over southwest AS.

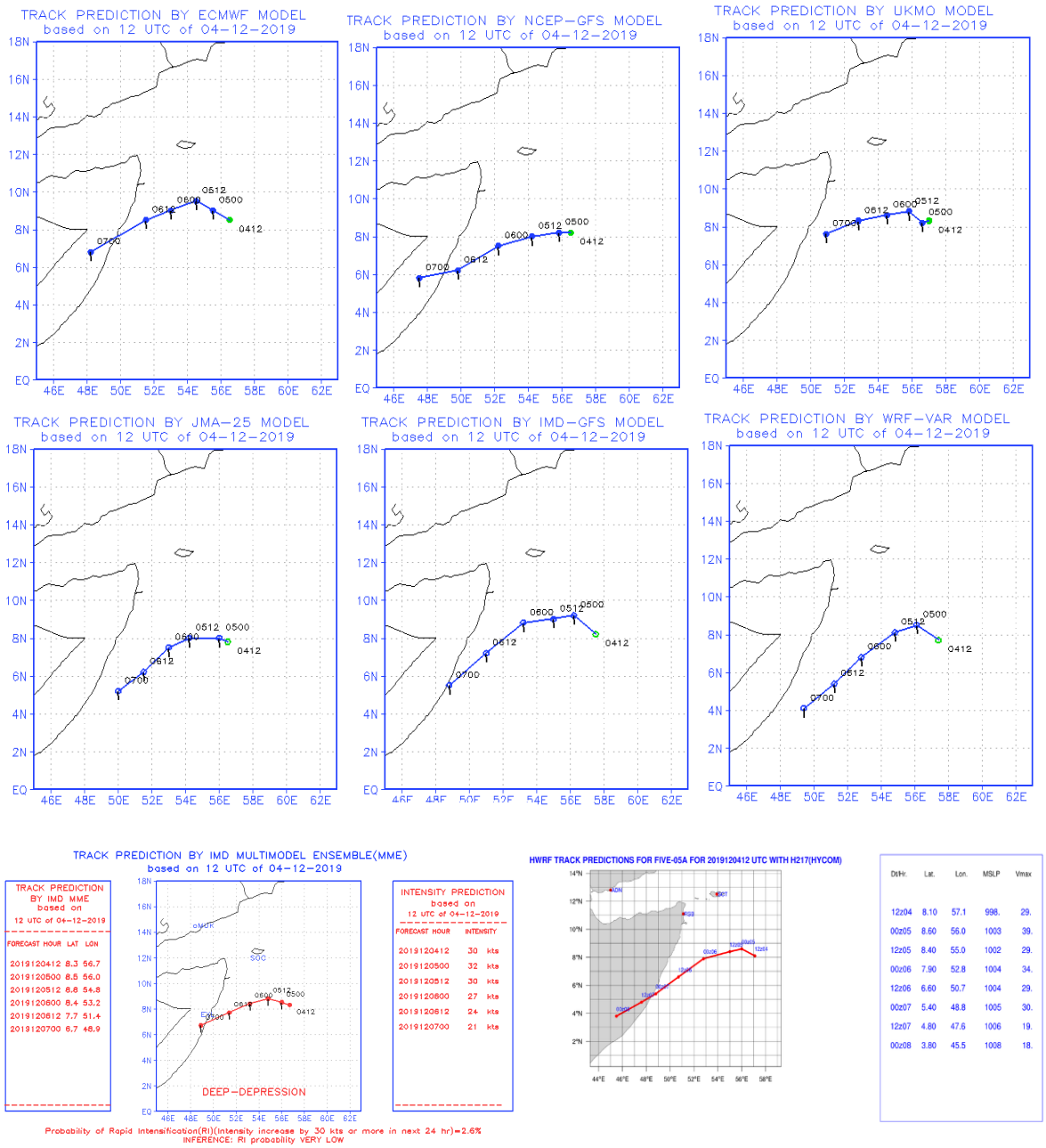


Fig. 11 (e): NWP model track forecast based on 1200 UTC of 4th December 2019

At 0000 UTC of 5th, models like ECMWF, MME, NCEP GFS, IMD GFS and HWRF were predicting landfall near Somalia coast. However, there was large divergence wrt point and time of landfall. Models like UKMO, JMA and WRF VAR were predicting weakening over southwest AS.

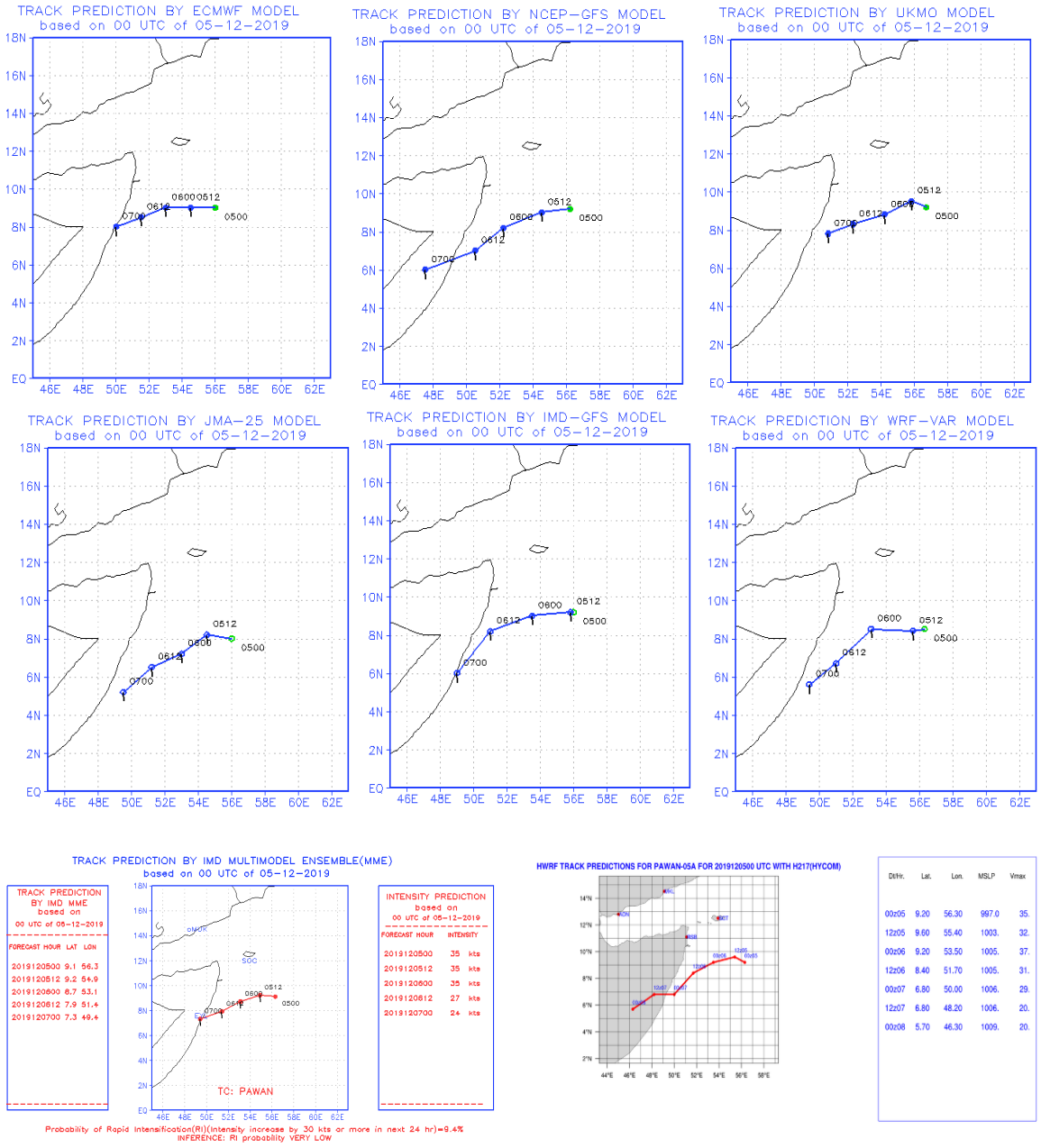


Fig. 11 (f): NWP model track forecast based on 0000 UTC of 5th December 2019

At 1200 UTC of 5th, all models were predicting landfall near Somalia coast. However, there was large divergence wrt point and time of landfall.

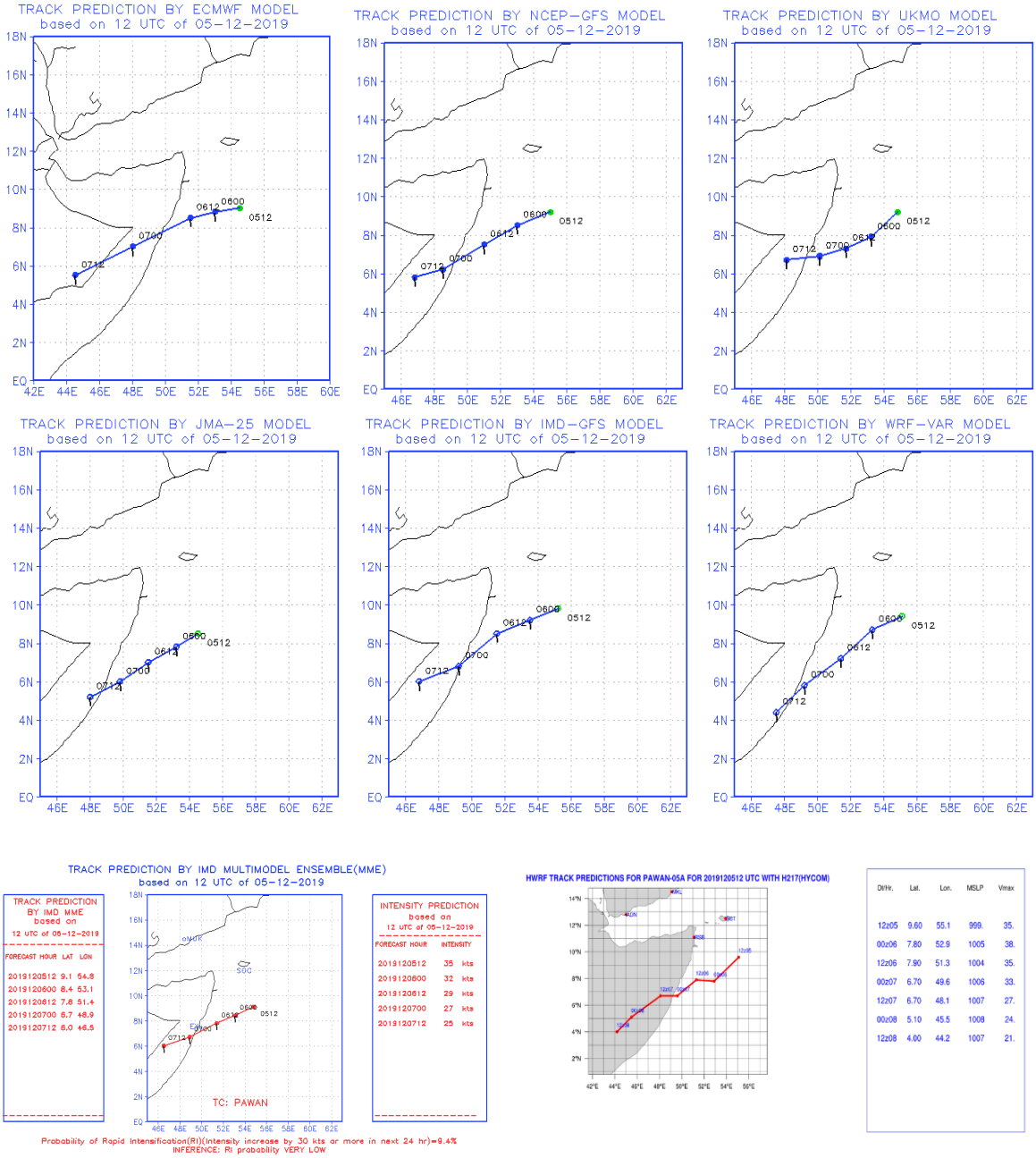


Fig. 11 (g): NWP model track forecast based on 1200 UTC of 5th December 2019

At 0000 UTC of 6th, all models were predicting weakening over sea near Somalia coast. Only HWRF was predicting landfall over Somalia.

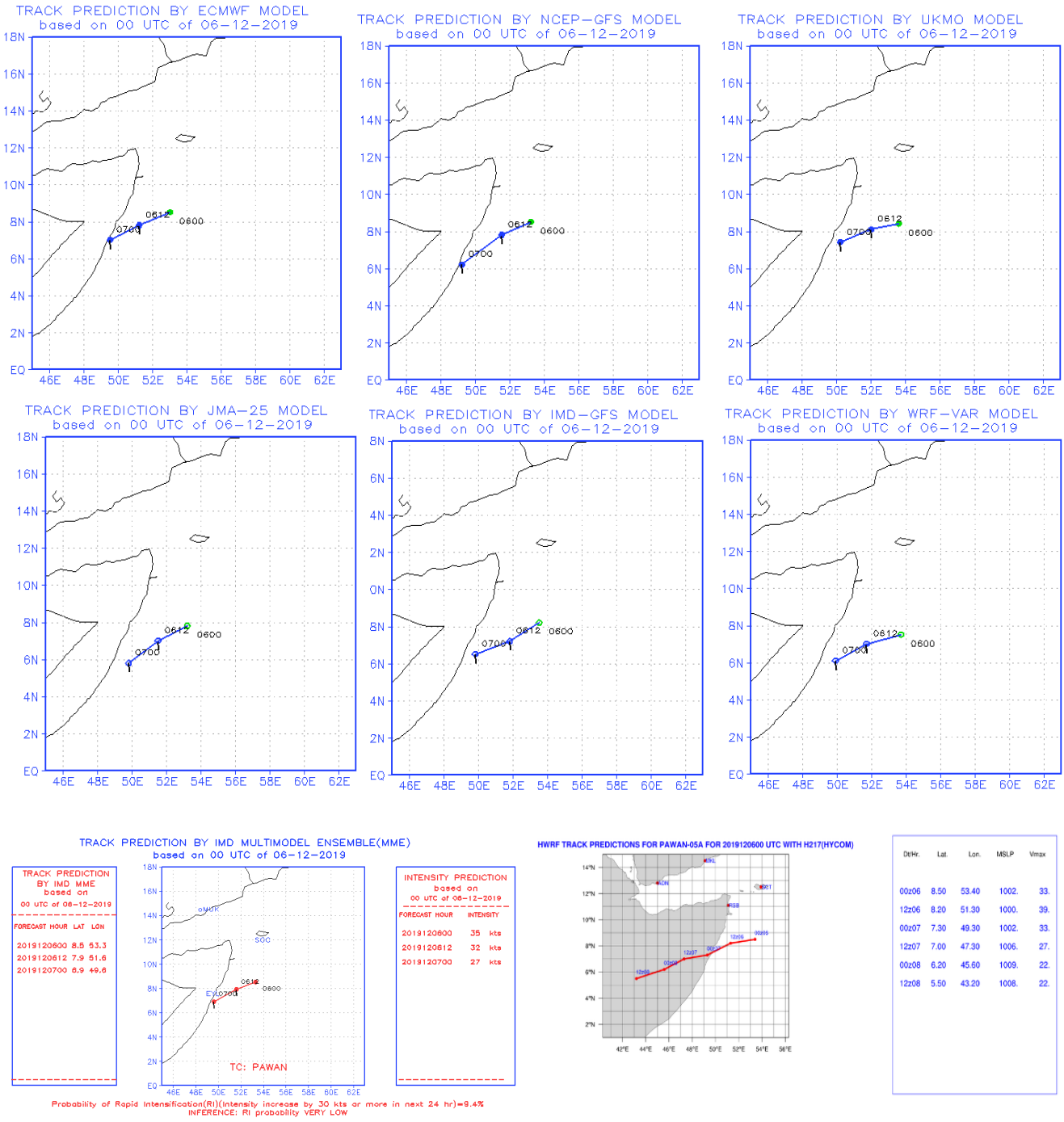


Fig. 11 (h): NWP model track forecast based on 0000 UTC of 6th December 2019

At 1200 UTC of 6th all models except UKMO were predicting landfall over Somalia. even 24 hours prior to landfall, models could not predict landfall. IMD HWRF was consistently predicting landfall since 1200 UTC of 3rd.

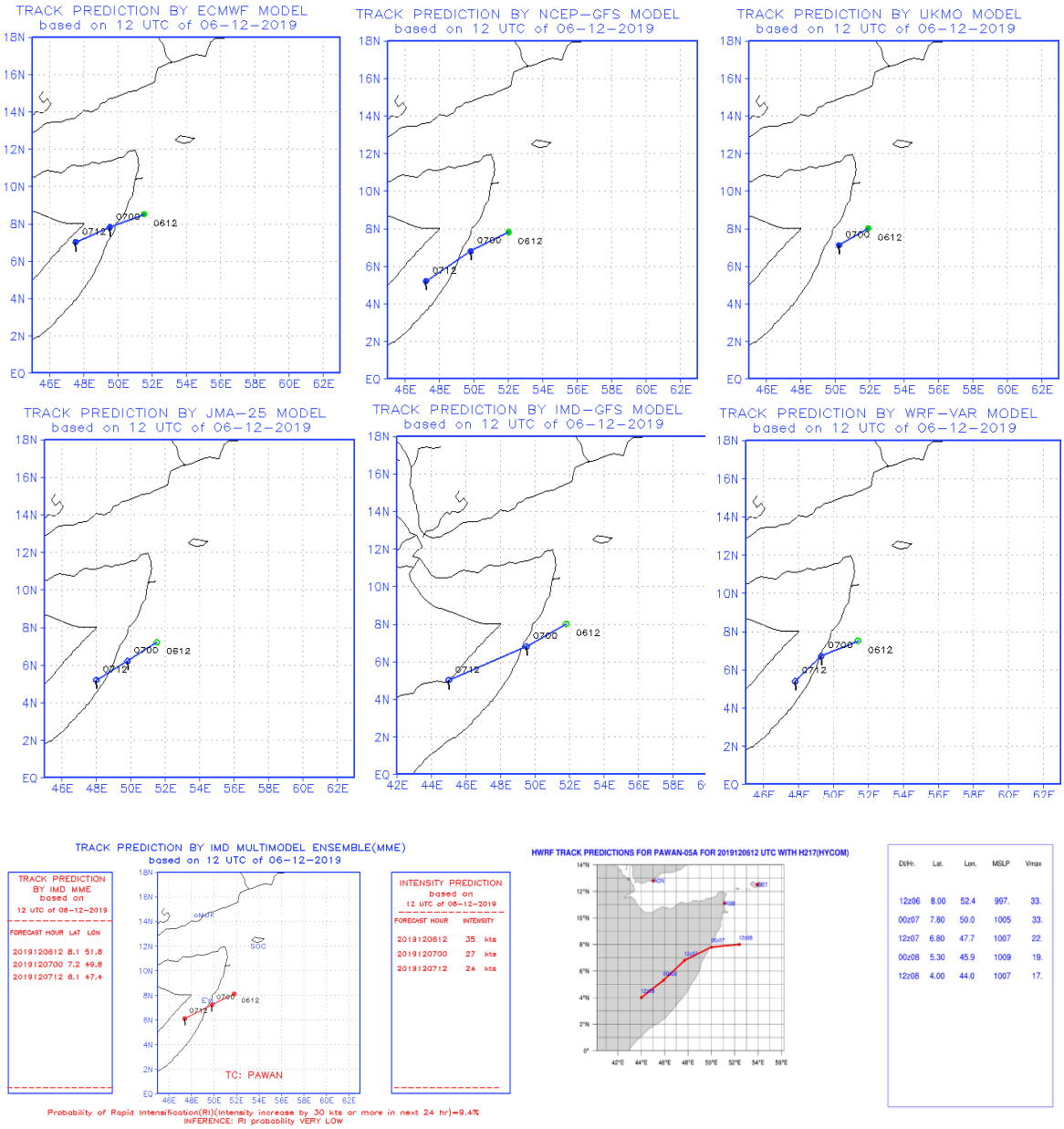


Fig. 11 (i): NWP model track forecast based on 1200 UTC of 6th December 2019

Hence to conclude there was large divergence among various models about the landfall of the system.

9.3 Track and intensity forecast errors by various NWP Models

The average track forecast errors (Direct Position Error) in km at different lead period (hr) of various models are presented in Table 2. From the verification of the forecast guidance available from various NWP models, it is found that the average track forecast errors of MME were the least followed by ECMWF and UKMO for 24, 48 and 72 hours lead period.

Table 2: Average track forecast errors (Direct Position Error (DPE)) in km

LEAD-TIME	12h	24h	36h	48h	60h	72h	84h	96h
IMD-MME*	53(9)	61(8)	74(7)	101(6)	133(5)	130(4)	203(3)	251(2)
ECMWF	86	78	108	126	188	174	357	459
NCEP-GFS	62	129	189	255	309	363	433	469
UKMO	77	96	88	143	160	195	184	189
JMA-25	108	147	168	209	245	282	340	---
IMD-GFS	74	109	147	240	343	446	603	721
WRF-VAR	83	123	219	279	337	334	---	---
HWRF	91 (15)	153 (13)	161(11)	199(9)	242(7)	287(5)	320(3)	---

( ): Number of forecasts verified; -: No forecast issued

10. Operational Forecast Performance

10.1. Genesis Forecast

- First information about the expected cyclogenesis over southwest AS and adjoining EIO around 3rd December and movement of the system towards Somalia coast was indicated in the extended range outlook issued on 28th November.
- Further, in the Tropical Weather Outlook (TWO) issued at 0600 UTC of 29th November, it was indicated that a LPA would form over EIO and adjoining southwest AS by 1st December. Actually, the LPA formed over southwest AS and adjoining EIO at 0300 UTC of 30th November.
- In the TWO issued at 0600 UTC of 30th November, it was indicated that the system would become more marked by 2nd December. Actually, the system lay as a WML over the same region at 0000 UTC of 2nd December and as a D over southwest AS & adjoining EIO at 1200 UTC of 2nd.
- Thus, cyclogenesis could be predicted well in advance about 5 days in advance since 28th November.

10.2 Track, Intensity and Landfall Forecast

- In the first bulletin issued at 2040 hrs IST (around 1500 UTC) of 2nd December, it was indicated that the system would move initially northwards till 0530 hrs IST (0000 UTC) of 3rd and then northwestwards towards Somalia

coast. However, system moved nearly northwards till 0830 hrs IST (0300 UTC) of 5th.

- In the subsequent bulletin issued at 0850 hrs IST (around 0300 UTC) of 3rd December, it was predicted that the system would move nearly north-northwestwards till 5th morning (0830 hrs IST/0300 UTC) and thereafter gradually recurve southwestwards from 5th evening (1730 hrs IST/1200 UTC). Actually, the system moved north-northwestwards till noon (1130 hrs IST) of 5th and gradually recurved west-southwestwards from 5th night (2030 hrs IST/1500 UTC). Thus, track was correctly predicted since 3rd December.
- In the bulletin issued at 1430 hrs IST (0900 UTC) of 3rd December, first information about the landfall of system over Somalia coast near 7.1^0 N/49.4^0 E around 1800 UTC of 6th was predicted. Actually, system crossed Somalia coast near 7.5^0 N/49.6^0 E around 0730 hrs IST/0200 UTC of 7th. Thus, landfall of the system was predicted about 89 hrs in advance.
- In the first bulletin issued at 2040 hrs IST (around 1500 UTC) of 2nd December, it was indicated that the system would intensify upto cyclonic storm stage with maximum sustained wind speed within the range 35-40 kts. Thus, the peak intensity of the system was well predicted since beginning. However, system would maintain CS intensity for about 51 hrs could not be predicted.
- Since the first bulletin issued at 2040 hrs IST (around 1500 UTC) of 2nd December, fishermen of the coastal states along west coast of India were advised not to venture into southwest Arabian Sea and along & off Somalia coast till 7th December.
- Typical observed and forecast track along with cone of uncertainty and wind distribution indicating accuracy in track prediction is presented in **Fig. 12**.

Thus, the genesis, track, intensity and associated adverse weather like rainfall, strong wind were well predicted by IMD. Since first bulletin, state of sea and warnings for fishermen in deep seas of southwest AS were issued both in textual and graphical form

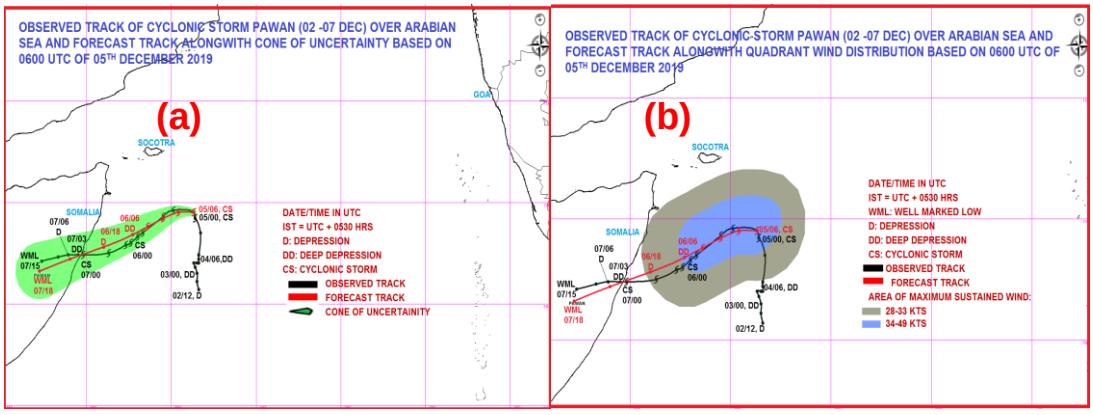


Fig.12: Observed and forecast track of CS 'PAWAN' along with (a) cone of uncertainty and (b) wind distribution indicating accuracy in track and intensity predictions during life cycle of PAWAN.

10.3. Track Forecast Errors:

- The track forecast errors for 24, 48 and 72 hrs lead period were 99, 139, and 183 km respectively against the average track forecast errors of 86, 132 and 178 km during last five years (2014-18) respectively (**Fig.13a)**.
- The track forecast skill was about 69%, 75%, and 70% against the long period average (LPA) of 58%, 70%, and 74% during 2014-18 for 24, 48 and 72 hrs lead period respectively (**Fig.13b)**.
- Fig. 13 (a & b) indicate that for all lead periods the track forecast errors was slightly higher than the LPA. It may be attributed mainly to the fact that, Pawan was a weak system. The skill was better or comparable to LPA for all lead periods.

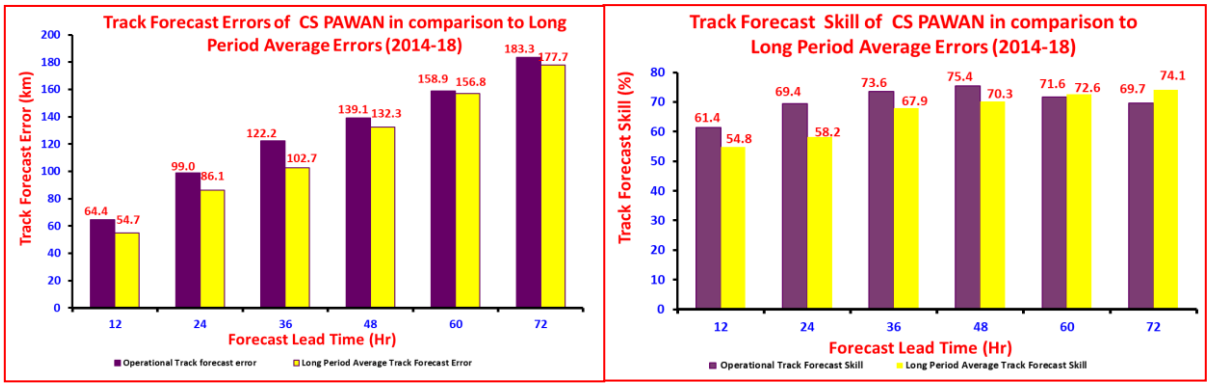


Fig. 13: Track forecast (a) Errors and (b) skill of CS 'PAWAN' as compared to long period average (2014-18)

10.4. Landfall Forecast Errors:

- The landfall point forecast errors for 24, 48 and 72 hrs lead period were 69, 69, and 45 km respectively against the average forecast errors of 46, 70 and 104 km during last five years (2014-18) respectively (**Fig.14a)**.
- The landfall time forecast errors for 24, 48 and 72 hrs lead period were 0.5, 1.0, and 7.0 hrs respectively against the average forecast errors of 3.0, 5.1 and 5.8 hrs during last five years (2014-18) respectively (**Fig.14b)**.

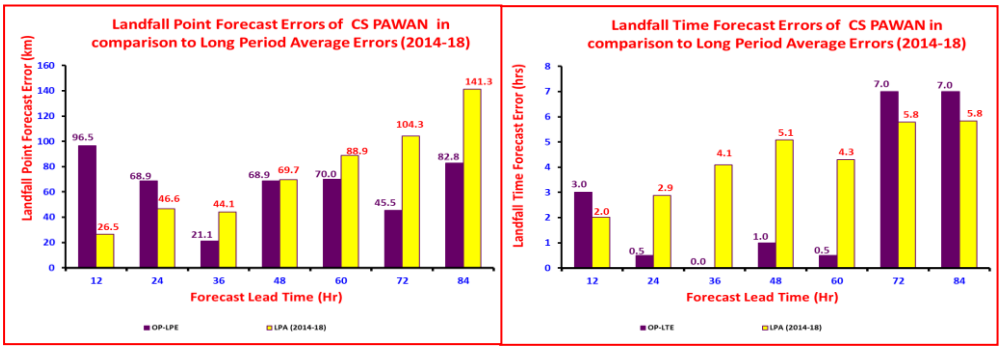


Fig. 14: Track forecast (a) Errors and (b) skill of CS 'PAWAN' as compared to long period average (2014-18)

- Fig. 14 (a & b) indicate that for all lead periods beyond 36 hrs the landfall point forecast errors was less than the LPA. The landfall time errors were less than LPA for 24 to 60 hrs lead period. For longer lead period beyond 72 hrs, the landfall time error was more than LPA mainly because the system moved slower than the LPA.

10.5. Intensity Forecast Errors:

- The absolute error (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 07, 05 and 11 knots against the LPA of 10, 14 and 14 knots respectively **(Fig. 15a).**
- The root mean square error (RMSE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 08, 07 and 11 knots against the LPA of 13, 19 and 19 knots respectively **(Fig. 15b).**
- For all lead periods, the intensity forecast errors were significantly less than the long period average errors of 2014-18.

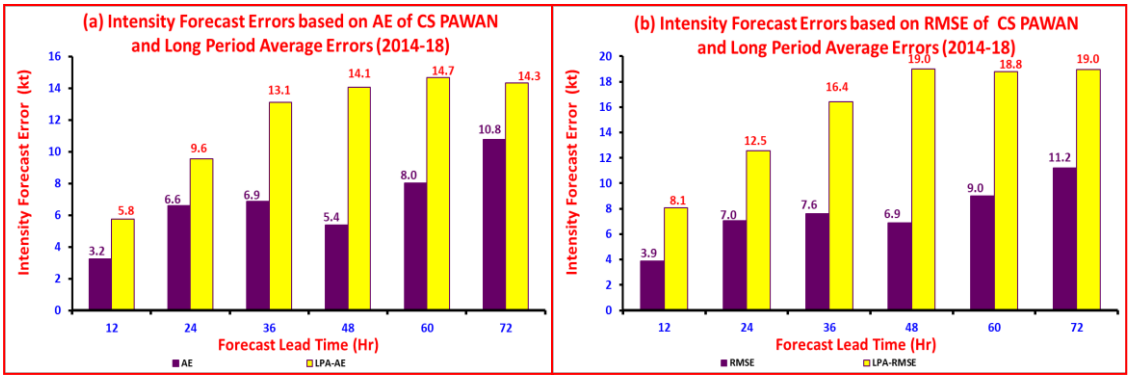


Fig. 15: (a) Absolute errors (AE) and (b) Root Mean Square errors (RMSE) in intensity forecast (winds in knots) in association with CS 'PAWAN' as compared to long period average (2014-18)

- The skill in intensity forecast based on AE for 24, 48 and 72 hrs lead period was 02, 51 and 01 % against the LPA of 43, 68 and 72 % respectively **(Fig. 16 a).**

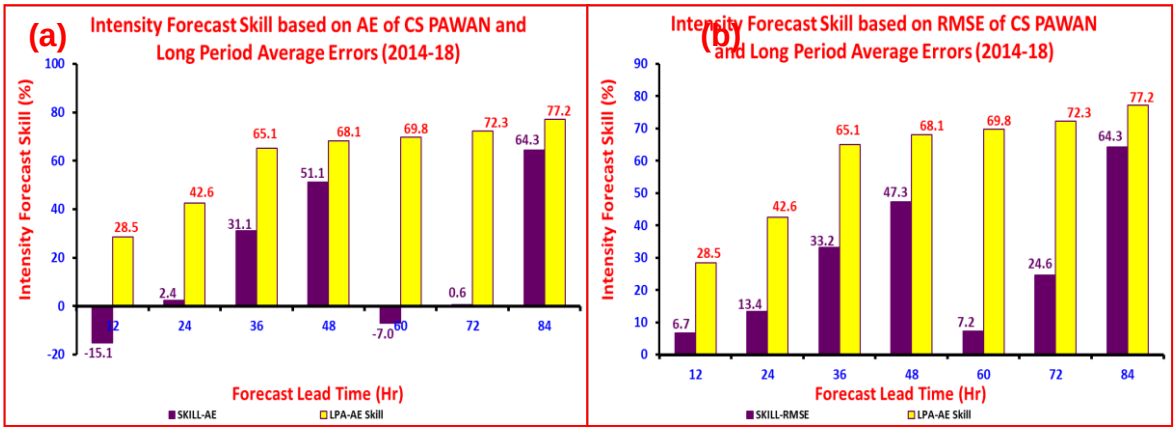


Fig. 16: Skill in intensity forecast (%) based on (a) Absolute errors (AE) and (b) Root Mean Square errors (RMSE) in association with CS 'PAWAN' as compared to long period average (2014-18)

- The skill in intensity forecast based on RMSE for 24, 48 and 72 hrs lead period was 23, 47 and 25 % against LPA of 49, 59 and 69 % respectively **(Fig. 16 b).**
- For all lead periods the skill in intensity forecast was less than the LPA. It is mainly due to the fact that the system would maintain CS intensity for nearly 2 days could not be captured well.

11. 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 etc. upto 120 hours 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.
- **Cyclone structure forecast for shipping and coastal hazard management** The radius of maximum wind and radii of MSW ≥28 knots, ≥34, ≥50 and ≥64 knots wind in four geographical quadrants (NE, NW, SW, SE) of cyclone was issued every six hour giving forecast for +06, +12, +18, +24, +36 … upto 120 hours lead period.
- **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.
- **Adverse weather warning bulletins:** The tropical cyclone forecasts along with expected adverse weather like gale wind was issued with every three hourly update during cyclone period to the central agencies including MHA, NDRF, NDMA and State level disaster management agencies of all the states along west coast of India including Tamil Nadu, Andhra Pradesh, Kerala, Karnataka, Goa, Maharashtra, Gujarat, Lakshadweep Islands, Daman & Diu and Dadra & Nagar Haveli. The bulletin also contained the suggested action for disaster managers and general public in particular for fishermen. These bulletins were also issued to Defense authorities including Indian Navy & Indian Air Force.
- **Warning and advisory for marine community:** The three/six hourly Global Maritime Distress Safety System (GMDSS) bulletins were issued by the cyclone warning division at New Delhi. Similarly, Sea Area and Coastal Weather bulletins, Port Warnings and Fishermen warnings were issued by cyclone warning centres of IMD at Chennai, Meteorological Centre, Thiruvananthapuram, Goa, Area Cyclone Warning Centre Mumbai and Cyclone Warning Centre Ahmedabad to fishermen, coastal and high sea shipping community.
- **Fishermen Warning:** Fishermen warnings for not to venture into southwest Arabian Sea & adjoining equatorial Indian ocean was issued since prior to the formation of the Depression over the area.

- **Warning and advisory through social media:** Daily updates were uploaded on Facebook and twitter regularly during the life period of the system.
- **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.
- **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 and middle east 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 system were described in the RSMC bulletins.
- **TC Vital:** Tropical cyclone vital parameters were prepared every six hour from depression stage onwards and provided to various NWP modeling groups in India for generation/relocation of vortex in the model so as to improve the track and intensity forecast by the numerical models

Statistics of bulletins issued by RSMC New Delhi in association with the CS Pawan are given in **Table 3.**

Table 3: Bulletins issued by RSMC New Delhi

S.N	Bulletin	No. of Bulletins	Issued to
1	National Bulletin	31	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 and Administrator Lakshadweep Islands.
2	RSMC Bulletin	31	1. IMD's website 2. WMO/ESCAP member countries including Somalia and WMO through GTS and E-mail.
3	GMDSS Bulletins	7	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 &	18	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

	Graphics)		
5	Tropical Cyclone Vital Statistics	18	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 four times and when intensity changed	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- 7,80,051 To farmers of Gujarat & Maharashtra through Kisaan Portal
6.	Warnings through Social Media	Daily four times and when intensity changed	Cyclone Warnings were uploaded on Social networking sites (Face book, Twitter and Whatsapp) since inception to weakening of system (every time when there was change in track, intensity and landfall characteristics)
7.	Press Release	5 (once a day)	Disaster Managers, Media persons by email and uploaded on website
8.	Press Briefings	Frequently	Regular briefing daily

12. Summary and Conclusion:

The Cyclonic Storm (CS) 'PAWAN' originated from an LPA over southwest AS and adjoining EIO on 30th November, 2019. It concentrated into a depression over southwest AS & adjoining EIO on 2nd December and into the CS "PAWAN" on 5th December over southwest AS. It crossed Somalia coast near latitude 7.4°N and longitude 49.6°E during 0200 – 0300 UTC of 07th December 2019 as a CS with maximum sustained wind speed (MSW) of 60-70 kmph gusting to 80 kmph. It weakened into a WML area over north Somalia & adjoining Ethiopia on 7th December. The system was monitored since 28th November. The track forecast errors for 24, 48 and 72 hrs lead period were 99, 139, and 183 km respectively against the average track forecast errors of 86, 132 and 178 km during last five years (2014-18) respectively.

13. Acknowledgements:

IMD and RSMC New Delhi duly acknowledge the contribution from all the stake holders and disaster management agencies who contributed to the successful monitoring, prediction and early warning service of CS 'PAWAN'. 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 Office Goa, Bengaluru. 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.