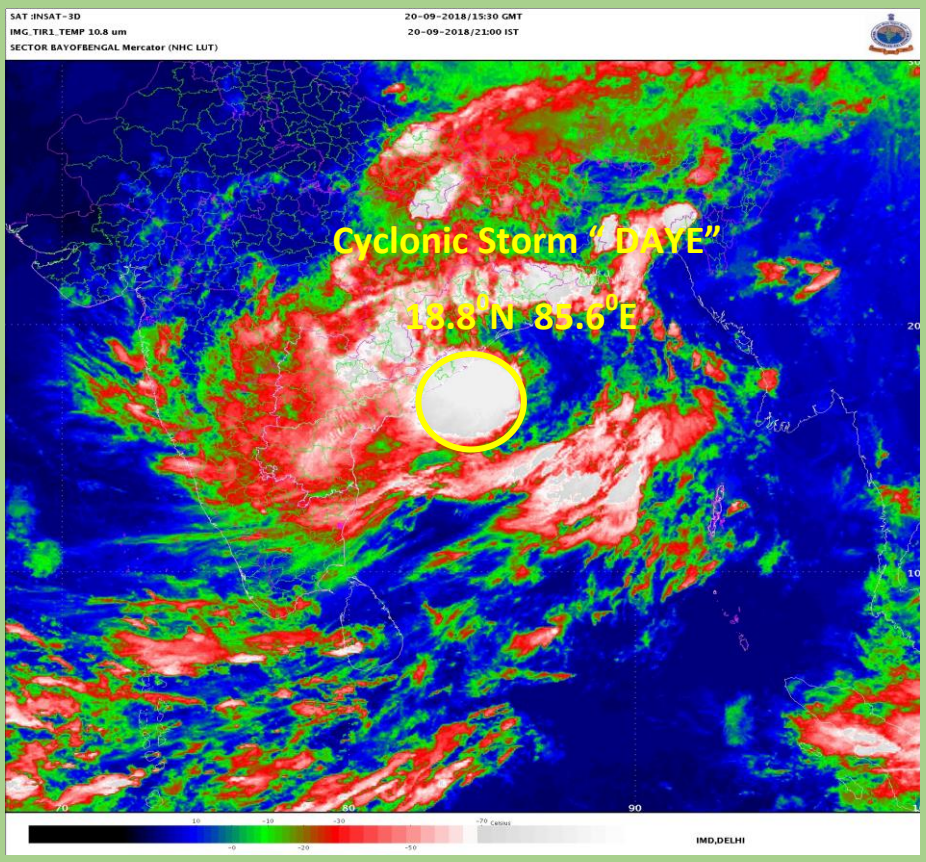
GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
INDIA METEOROLOGICAL DEPARTMENT

Cyclonic Storm, 'DAYE' over the Bay of Bengal (19 – 22 September 2018): A Report



INSAT-3D enhanced colored IR imagery of 20th September, 2018

Cyclone Warning Division

India Meteorological Department

New Delhi

January, 2019

Cyclonic Storm "DAYE" over Bay of Bengal
(19– 22 September 2018)

1. Introduction

Cyclonic Storm (CS) Daye originated from a low pressure area (LPA) which formed over eastcentral Bay of Bengal (BoB) and adjoining Myanmar in the afternoon (0900 UTC) of 18th September. It lay as a well marked low pressure area (WML) over the same region in the morning (0300 UTC) of 19th September.

Under favourable environmental conditions, it concentrated into a Depression (D) over eastcentral BoB in the night (1500 UTC) of 19th September. Moving nearly west-northwestwards, it intensified into a deep depression (DD) over westcentral BoB in the morning (0300 UTC) of 20th September and further into a cyclonic storm (CS) **"Daye**" in the same night (1500 UTC). It crossed south Odisha and north Andhra Pradesh coast close to Gopalpur (Odisha) as a cyclonic storm with a wind speed of 60-70 kmph gusting to 80 kmph during 1900-2000 UTC of 20th September. It continued to move west-northwestwards, weakened into a DD in the early morning (0000 UTC) of 21st , into a D in the same evening (1200 UTC) and into a WML over west Madhya Pradesh and adjoining east Rajasthan in the evening (1200 UTC) of 22nd September. It lay as a WML over southeast Rajasthan in the morning (0300 UTC) of 23rd. It lay over north Rajasthan and adjoining southwest Uttar Pradesh & south Haryana in the early morning (0000 UTC) of 24th and lay as an LPA over south Haryana and neighbourhood on 24th morning. It became less marked on 25th morning.

2. Salient Features:

The salient features of the system were as follows:

- It is the first cyclonic storm to develop over the north Indian Ocean in the month of September after 2005 when the cyclonic storm, Pyarr crossed Andhra Pradesh coast near Kalingapatnam on 21 September 2005.
- The system had intensification close to the coast 4 hrs prior to landfall.
- The system maintained the intensity of cyclonic storm for about six hrs only.
- It had straight and west-northwestward moving track till 0000 UTC of 20th which recurved northwards thereafter.
- The track length of the cyclone was 1550 km.
- It moved faster, as the 12 hour average translational speed of the cyclone was 26.2 kmph against LPA (1990-2013) of 13.7 kmph over north Indian Ocean.
- The peak maximum sustained surface wind speed (MSW) of the cyclone was 60-70 kmph gusting to 80 kmph (35 knots gusting to 45 knots) during 1500 UTC of 21st to 2100 UTC of 21st Sep.
- The lowest estimated central pressure was 992 hPa (from 1500 UTC to 1800 UTC of 21st Sep).
- The life period (D to D) of cyclone was 87 hours (3 days & 15 hours) against long period average (LPA) (1990-2013) of 4.45 days for cyclonic storm over Bay of Bengal.

- The Velocity Flux, Accumulated Cyclone Energy (ACE) and Power Dissipation Index (PDI) were 0.35 $X10^2$ knots, 0.12 X 10^4 $knots^2$ and 0.04 $X10^6$ $knots^3$ respectively against LPA (1990-2013) of 0.49 $X10^2$ knots, 0.2 X 10^4 $knots^2$ and 0.08 $X10^6$ $knots^3$ during monsoon season for BoB.

3. Monitoring of CS, 'DAYE'

The cyclone was monitored & predicted continuously by India Meteorological Department (IMD) prior to it's genesis as low pressure area over BoB from 18th Sep onwards. The system was monitored mainly with satellite observations from INSAT 3D and 3DR, SCAT Sat, polar orbiting satellites, scatterometer observations, Doppler Weather Radar (DWR) and available ships & buoy observations in the region. Various national and international numerical weather prediction models and dynamical-statistical models were utilized to predict the genesis, track and intensity of the cyclone. Tropical Cyclone Module, the digitized forecasting system of IMD was utilized for analysis and comparison of various models guidance, decision making process and warning product generation. IMD issued regular bulletins to WMO/ESCAP Panel member countries including Yemen, Oman and Somalia, National & State Disaster Management Agencies, general public and media since inception of the system over AS.

4. Brief life history

4.1. Genesis

Cyclonic Storm (CS) Daye originated from a low pressure area (LPA) which formed over eastcentral Bay of Bengal (BoB) and adjoining Myanmar in the afternoon (0900 UTC) of 18th September. It lay as a well marked low pressure area (WML) over the same region in the morning (0300 UTC) of 19th September. Under favorable environmental conditions, it concentrated into a Depression (D) over eastcentral BoB in the night (1500 UTC) of 19th September.

According to satellite imageries, intensity of the system was T 1.5. The maximum sustained wind speed is 15-20 kts gusting to 30 knots. The estimated central pressure was 1002 hPa. Associated broken low and medium clouds with embedded intense to very intense convection over west central bay and neighborhood. The minimum cloud top temperature was minus 93^{0}C.

Considering the environmental conditions, the sea surface temperature (SST) was 27-29^{0}C over central BoB & adjoining north BoB. The tropical cyclone heat potential was about 60-80 kj/cm2 over this region. Madden Julian Oscillation index lies in phase 3 with amplitude less than 1 favoring cyclogenesis and further intensification. The low level relative vorticity is about 150x$10^{-6}$$sec^{-1}$to the northeast of system centre. The lower level convergence is about 20 x$10^{-5}$$sec^{-1}$ to the southwest of centre of system.The upper level divergence is about 20 x$10^{-5}$$sec^{-1}$ to the southwest of the centre of system and is about 20 x$10^{-5}$$sec^{-1}$ to the southeast of the centre of system. The vertical wind shear is moderate (10-25 knots) around the system centre and it incerases towards north Andhra and Odisha coasts. The upper tropospheric ridge runs along 260 N. hence, the winds are east southeasterly over the region in upper troposphere. Under these conditions, the well marked low pressure area concentrated into a depression on 19th morning.

4.2. Intensification and movement

According to satellite imageries, intensity of the system was C.I. 2.0 at 0300 UTC of 20th September. Associated Broken low to medium clouds with embedded intense to very intense convection lay over west central bob and neighborhood. The minimum cloud top temperature was minus 93^0C. the maximum sustained wind speed was 25-30 knots gusting to 35 knots. The estimated central pressure was 996 hpa. The sea condition is very rough over the region of the deep depression.

Considering the environmental conditions, the sea surface temperature (SST) was $28\text{-}30^0$C over north BoB & adjoining west central BoB. The tropical cyclone heat potential was about 50-80 kj/cm2 over this region. Madden Julian Oscillation index continued in phase 3 with amplitude less than 1. The low level relative vorticity was about $150x10^{-6}sec^{-1}$ to the northeast of system centre. The lower level convergence was about $30\ x10^{-5}sec^{-1}$ to the southwest of system centre. The upper level divergence was about $20\ x10^{-5}sec^{-1}$ to the southwest of the centre of system. The vertical wind shear was low to moderate (10-20 knots) to the northwest of the system centre and is high elsewhere. The upper tropospheric ridge ran along 26^0 N. Hence, the upper troposphere winds were predominantly east-north easterlies becoming east southeasterly towards the coast. thus, the system intensified into DD and moved west-northwestwards towards south Odisha and adjoining north Andhra coast.

Under similar environmental conditions, it moved west-northwestwards and intensified further into a cyclonic storm (CS) “DAYE” in the night (1500 UTC) of 20th September.

It crossed south Odisha and north Andhra Pradesh coast close to Gopalpur (Odisha) as a cyclonic storm with a wind speed of 60-70 kmph gusting to 80 kmph during 1900-2000 UTC of 20th September. It continued to move west-northwestwards, weakened into a DD in the early morning (0000 UTC) of 21st, into a D in the same evening (1200 UTC) and into a WML over west Madhya Pradesh and adjoining east Rajasthan in the evening (1200 UTC) of 22nd September. It lay as a WML over southeast Rajasthan in the morning (0300 UTC) of 23rd. It lay over north Rajasthan and adjoining southwest Uttar Pradesh & south Haryana in the early morning (0000 UTC) of 24th and lay as an LPA over south Haryana and neighbourhood on 24th morning. It became less marked on 25th morning. Observed track is shown in fig.1

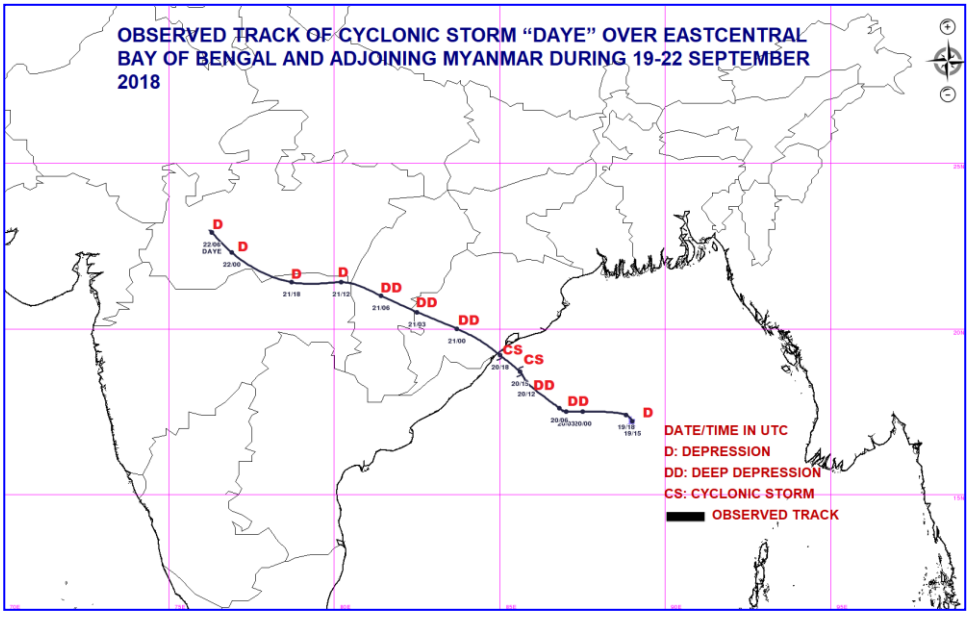


Fig.1 Observed track of CS Daye (19-22 September, 2018) over Bay of Bengal

Table 1: Best track positions and other parameters of the Cyclonic Storm, 'Daye' over the Bay of Bengal during 19-22 September, 2018

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
19/09/2018	1500	17.2	89.0	**1.5**	997	25	3	**D**
	1800	17.4	88.8	**1.5**	996	25	4	D
20/09/2018	0000	17.5	87.5	**1.5**	996	25	4	D
	0300	17.5	87.0	**2.0**	995	30	5	**DD**
	0600	17.6	86.8	**2.0**	995	30	5	DD
	1200	18.4	85.8	**2.0**	994	30	6	DD
	1500	18.7	85.6	**2.5**	992	35	8	**CS**
	1800	19.2	85.0	**2.5**	992	35	8	CS
		Crossed south Odisha and adjoining north Andhra Pradesh coasts close to Gopalpur near 19.27^{0}N/84.92^{0}E between 1900-2000 UTC of 20th September 2018						
21/09/2018	2100	19.6	84.4	-	993	35	7	CS
	0000	20.0	83.7	-	994	30	6	**DD**
	0300	20.5	82.5	-	994	30	6	DD
	0600	21.0	81.4	-	995	30	5	DD
	1200	21.4	80.2	-	996	25	4	**D**
	1800	21.4	78.7	-	996	25	4	D
22/09/2018	0000	22.3	76.9	-	997	25	4	D
	0300	22.9	76.3	-	998	20	3	D
	0600	22.9	76.3	-	999	20	3	D
	1200	Weakened into a well-marked low pressure area over west Madhya Pradesh and adjoining east Rajasthan						

The TPW imageries during 20-21 Sep. 2018 are presented in **Fig.2**. These imageries indicate continuous warm and moist air advection from the southeast sector into the system, even when the system was located over land. However, over the land surface, there was land interaction and moisture supply also reduced relatively. As a result, though the system weakened, it maintained the intensity of depression/deep depression till 22nd September 2018.

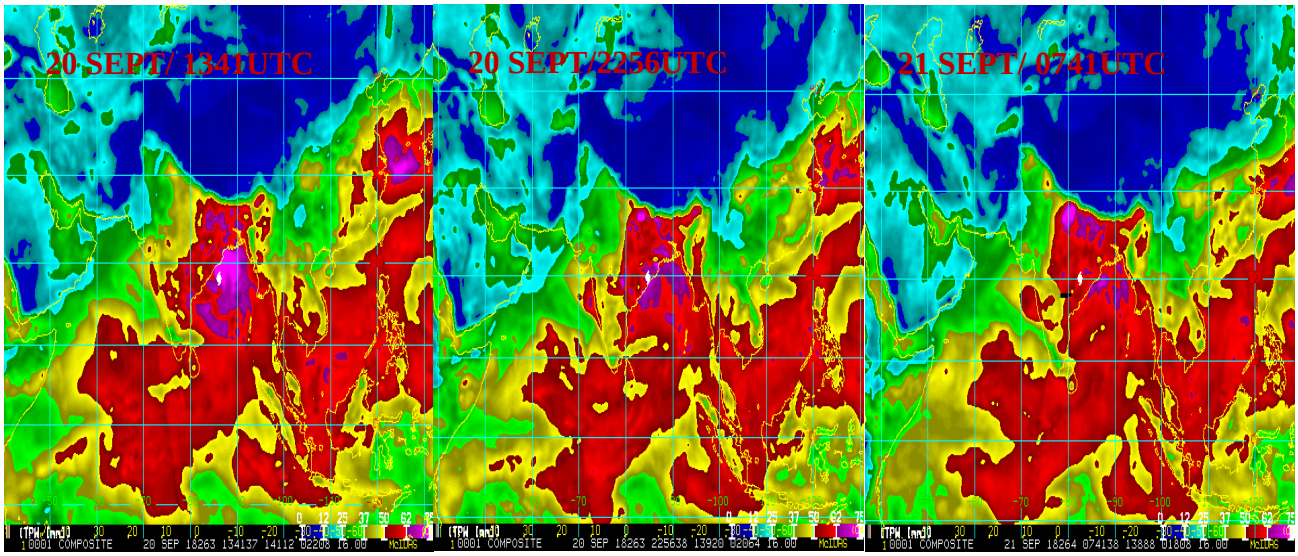


Fig. 2: Total Precipitable Water (TPW) imageries during 19-22 September, 2018

The wind speed in middle and deep layer around the system centre is presented in **Fig.3**. The wind shear around the system between 200 & 850 hPa levels remained high(20-30 knots). However, it decreased gradually from the genesis stage to dissipation stage. The direction of 200-850 hPa wind shear was northeasterly during the period. It caused the convective cloud mass to be sheared to the southwest of the system centre.

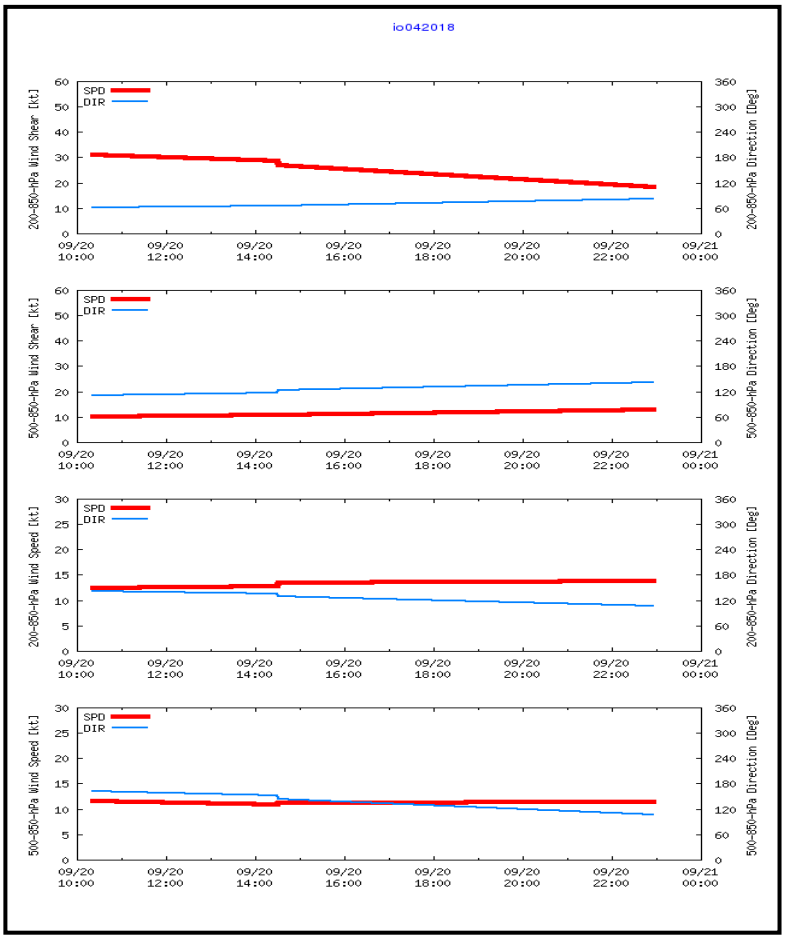


Fig.3 Wind shear and wind speed in the middle and deep layer around the system during 19-22 September 2018.

From **Fig.3**, it indicates that from the genesis stage, the mean deep layer winds between 200-850 hPa levels steered the system initially north-morthwestwards and then northwestwards. till 17th and then southwestwards.

The twelve hourly movement of CS Daye is presented in **Fig.4**. The 12 hour average translational speed of the cyclone was about 26 kmph and hence the cyclone was fast moving in nature.

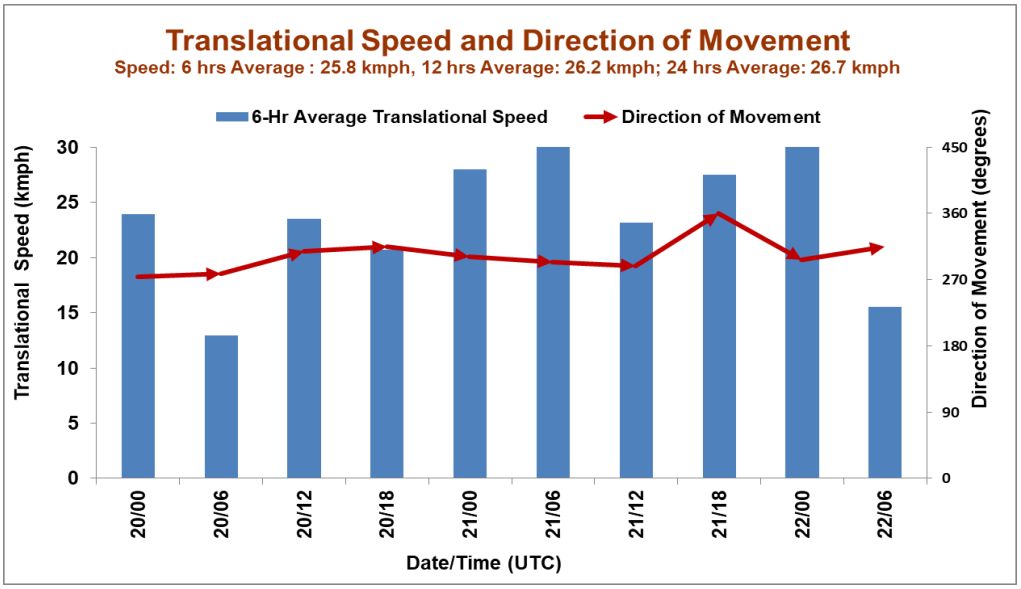


Fig.4 Twelve hourly average translational speed (kmph) and direction of movement in association with CS Daye

5. Maximum Sustained Surface Wind speed and estimated central pressure

The lowest estimated central pressure and the maximum sustained wind speed are presented in **Fig.5**. The lowest estimated central pressure had been 992 hPa during 1500-1800 UTC of 20th. The estimated maximum sustained surface wind speed (MSW) was 35 knots during the same period. At the time of landfall, the ECP was 992 hPa and MSW was 35 knots (cyclonic storm).

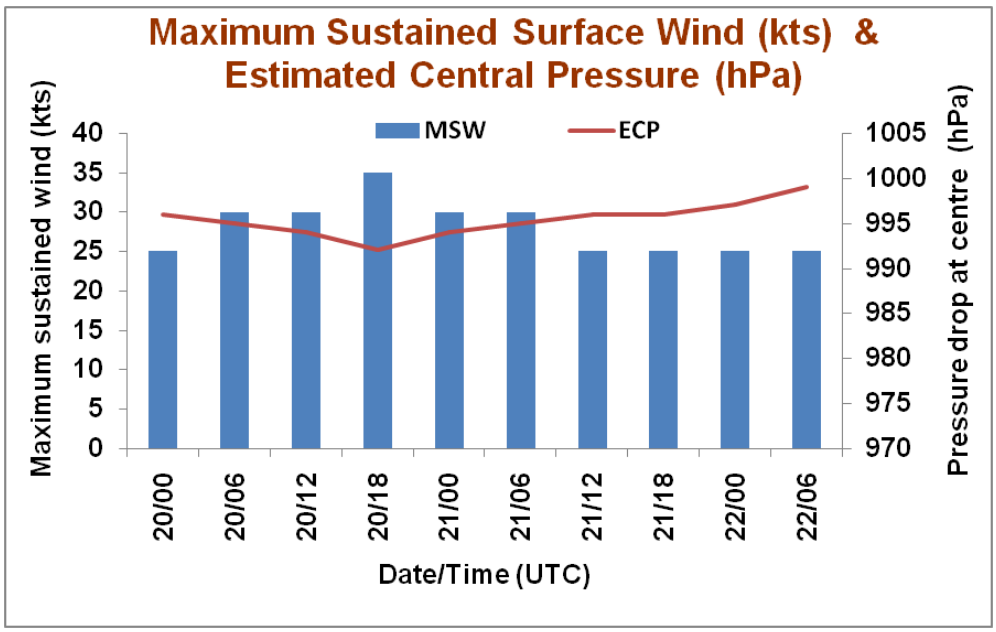


Fig.5. Lowest estimated central pressure and the maximum sustained wind speed

6. 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 & MTSAT and microwave & high resolution images of polar orbiting satellites DMSP, NOAA series, TRMM, Metops were also considered. Typical INSAT-3D visible/IR imageries, enhanced colored imageries and cloud top brightness temperature imageries are presented in **Fig.6**. The imageries indicated the shear patter of the system and the convective clouds were sheared to the southwest of the system centre.

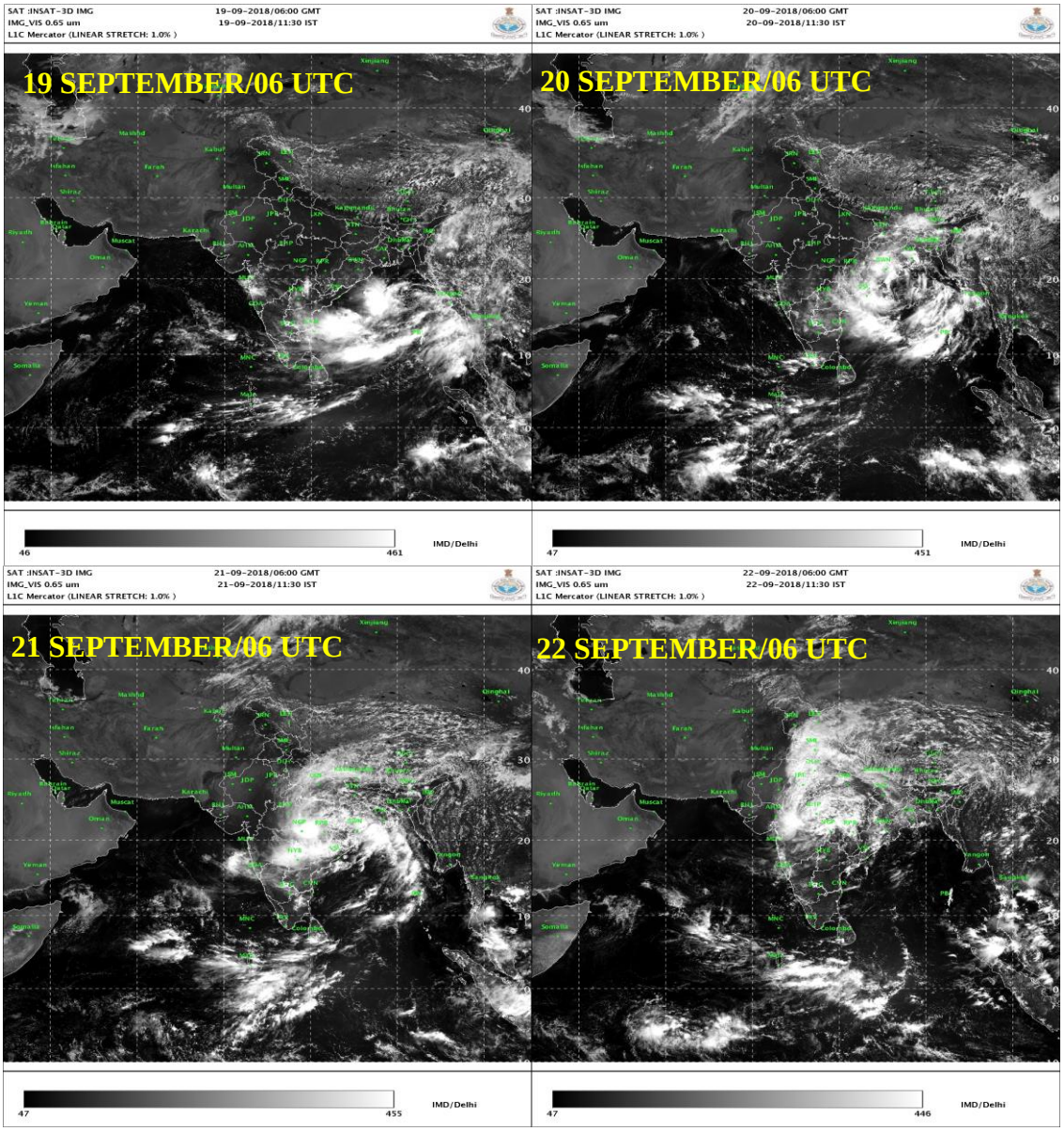


Fig. 6a: INSAT-3D visible imageries during life cycle of CS DAYE (19-22 September, 2018)

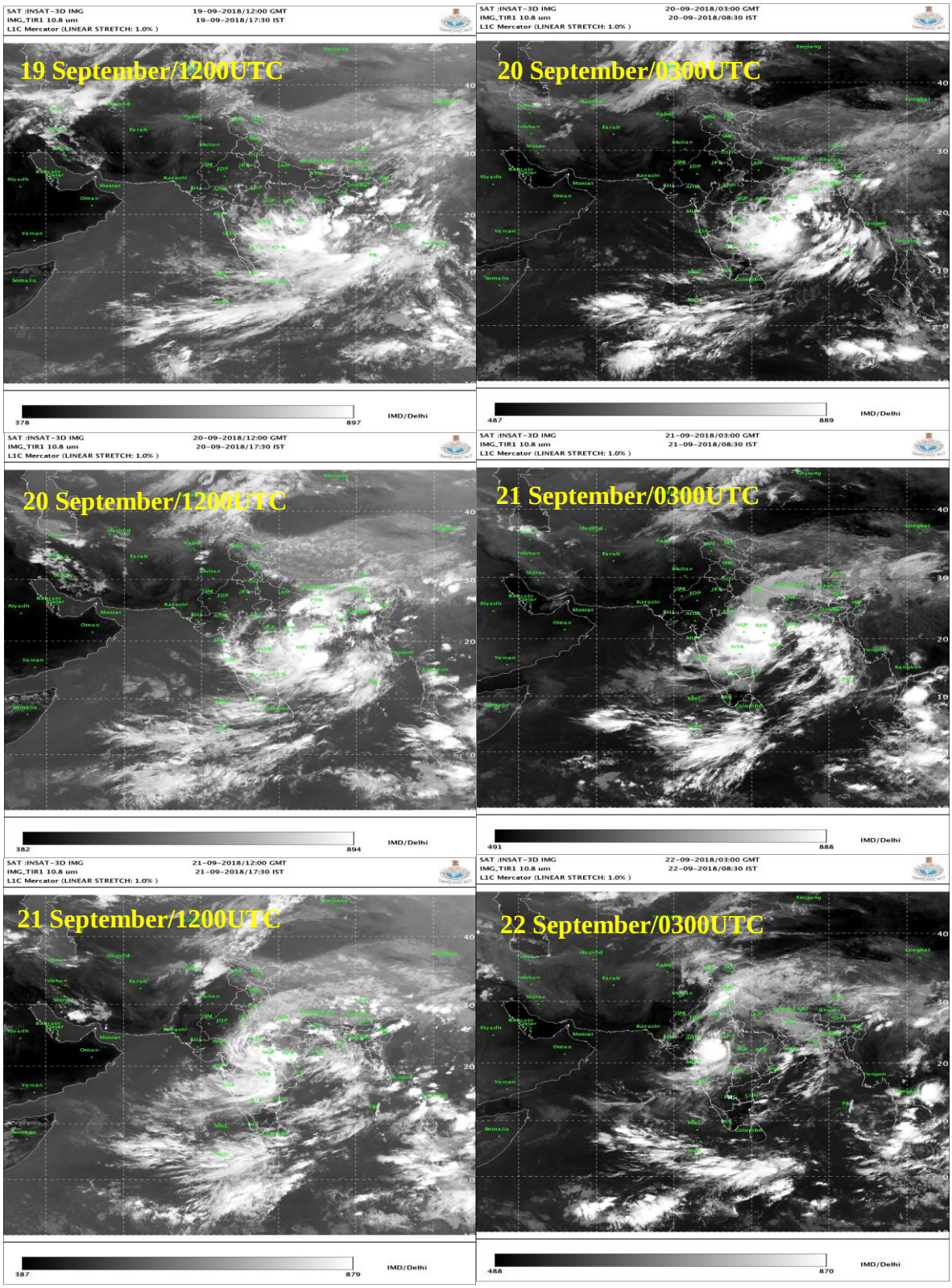


Fig. 6b: INSAT-3D IR imageries during life cycle of CS DAYE (19-22 September, 2018)

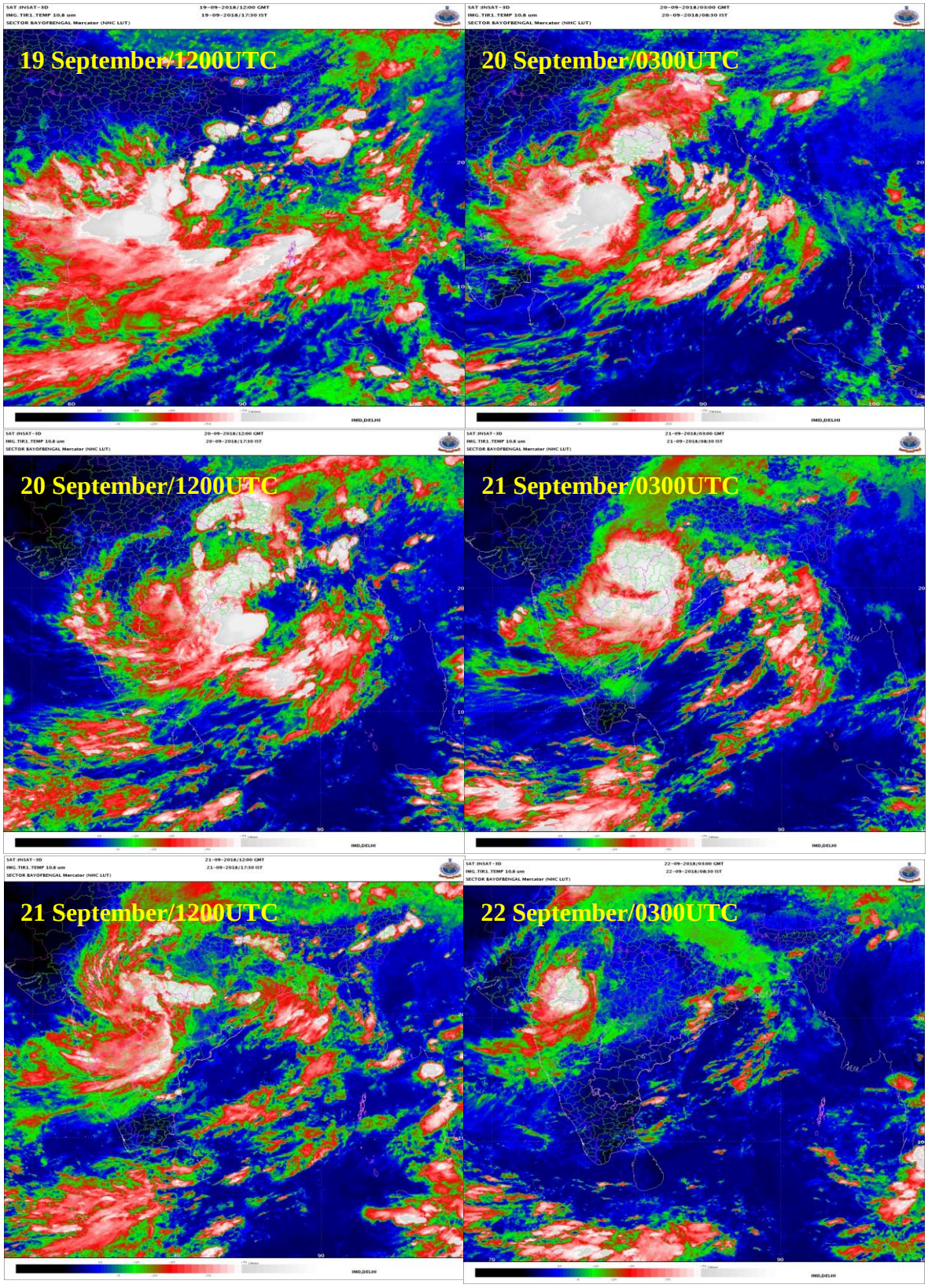


Fig. 6c: INSAT-3D enhanced colored imageries during life cycle of CS DAYE (19-22 September, 2018)

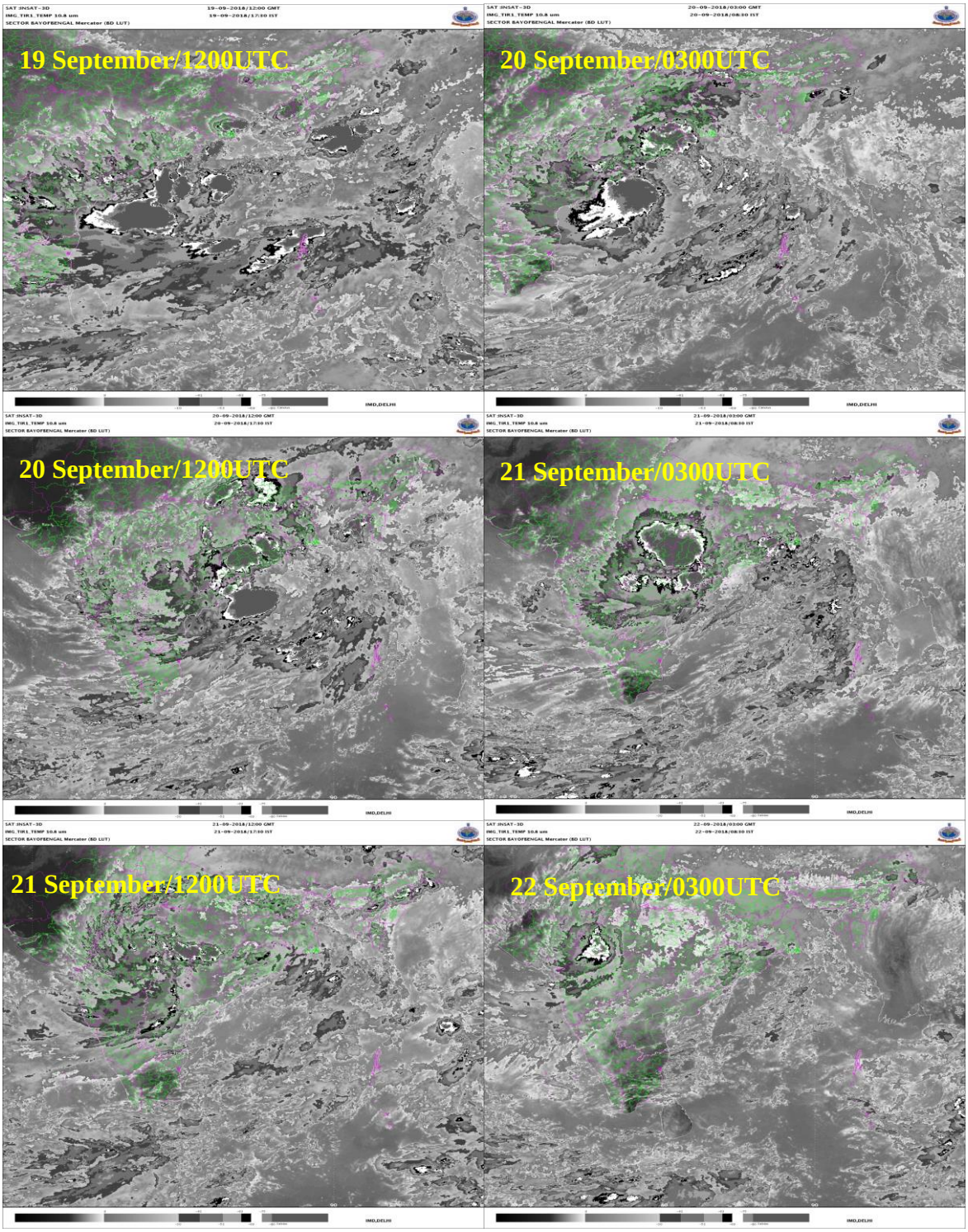


Fig. 6d: INSAT-3D cloud top brightness temperature imageries during life cycle of CS DAYE (19-22 September, 2018)

7. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 19th-21st September are presented in Fig.7. GFS (T1534). Analysis based on 0000 UTC of 19th to 22th September, indicates that the model highly underestimated the intensity of the system. Based on 0000 UTC observations of 19th, the model indicated formation of low over eastcentral BOB with associated cyclonic

circulation extending upto 500 hPa level. Similar was the situation of underestimation of intensity on 20th and 21st. However, the model could detect the track of the system.

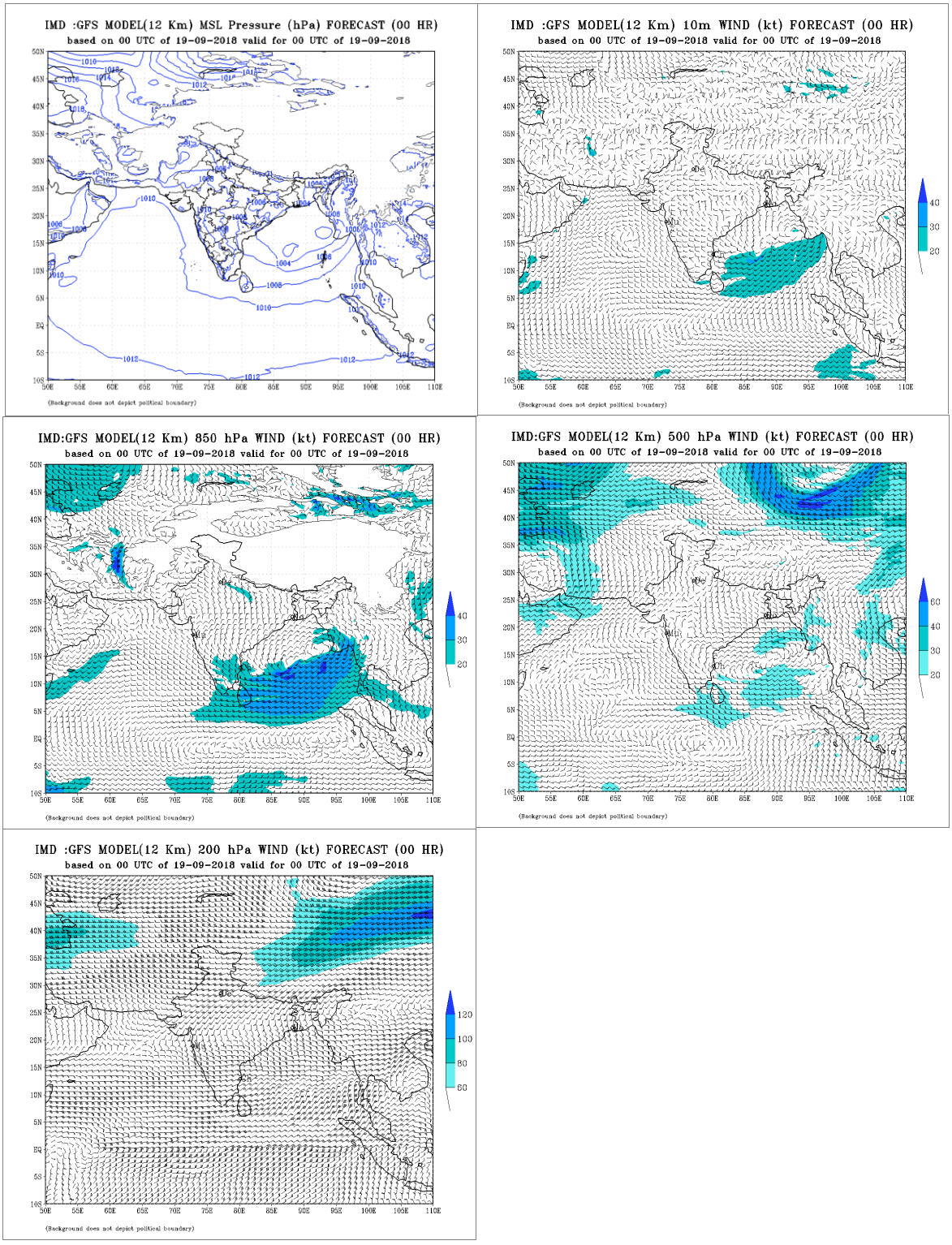


Fig. 7(a): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 19th September 2018

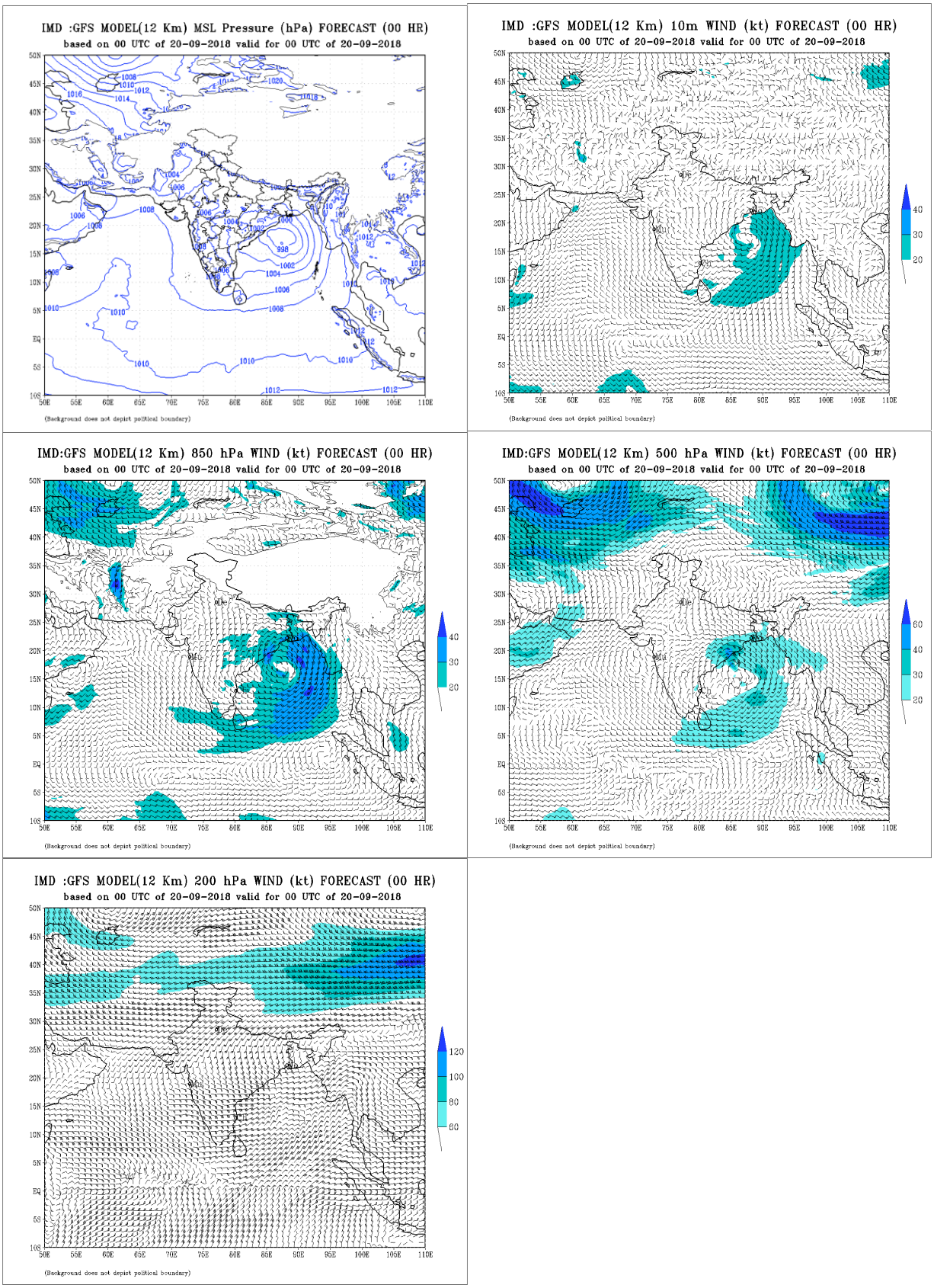


Fig. 7(b): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 20th September 2018

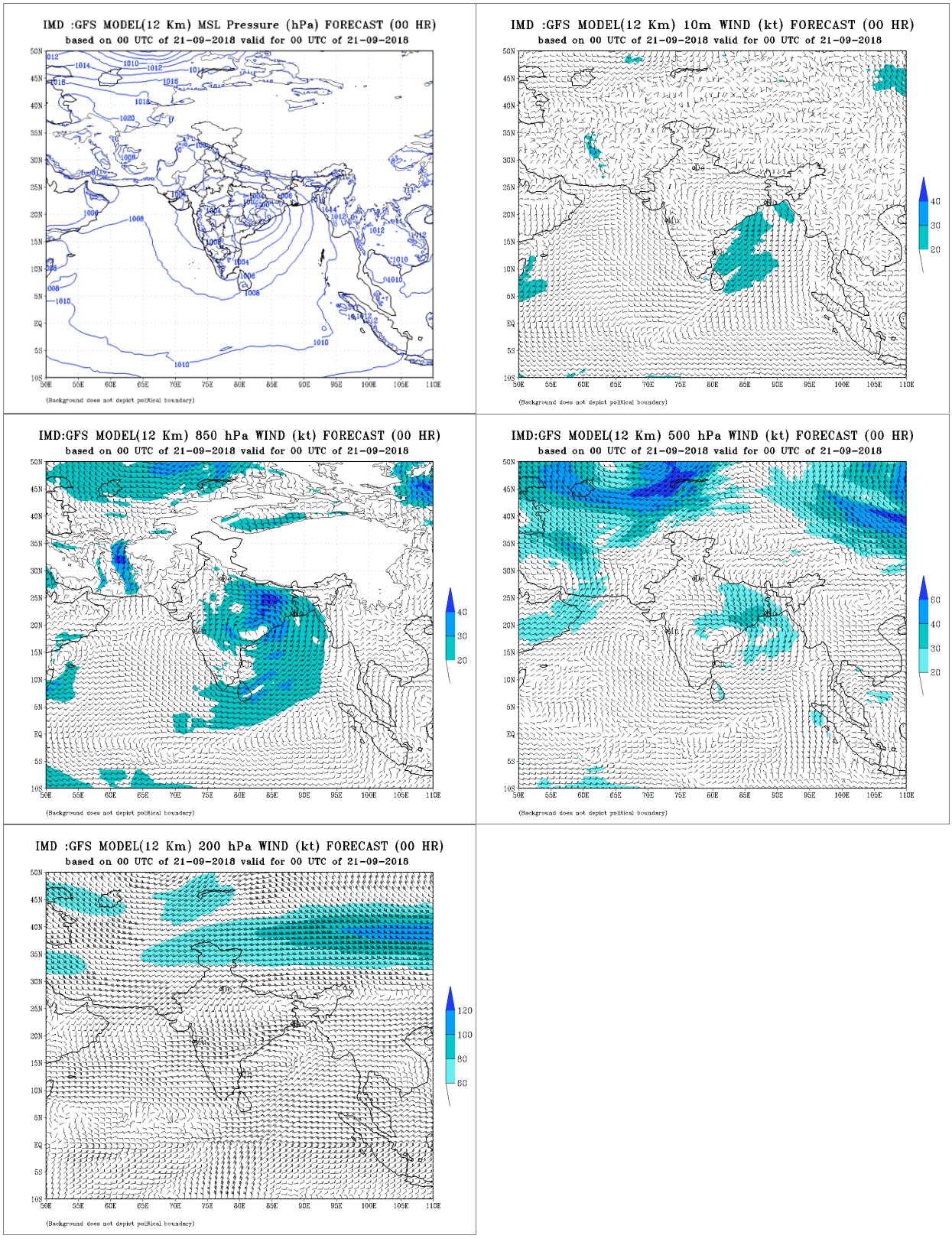


Fig. 7(c): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 21th September 2018

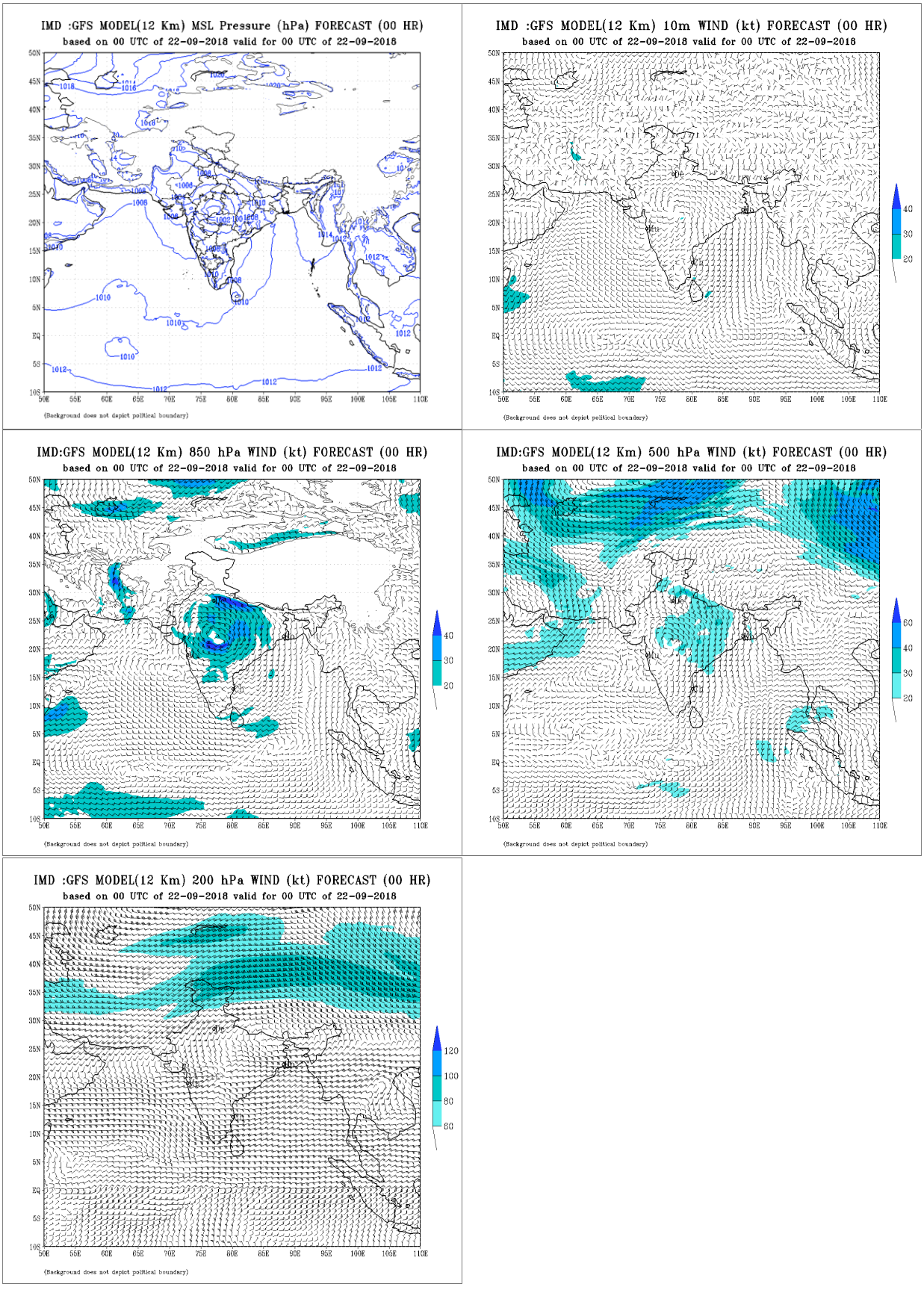


Fig. 7(d): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 19th May

8. Realized Weather:

8.1. Rainfall

Rainfall associated with CS Daye based on IMD-NCMRWF GPM merged gauge rainfall data is depicted in **Fig 8**.

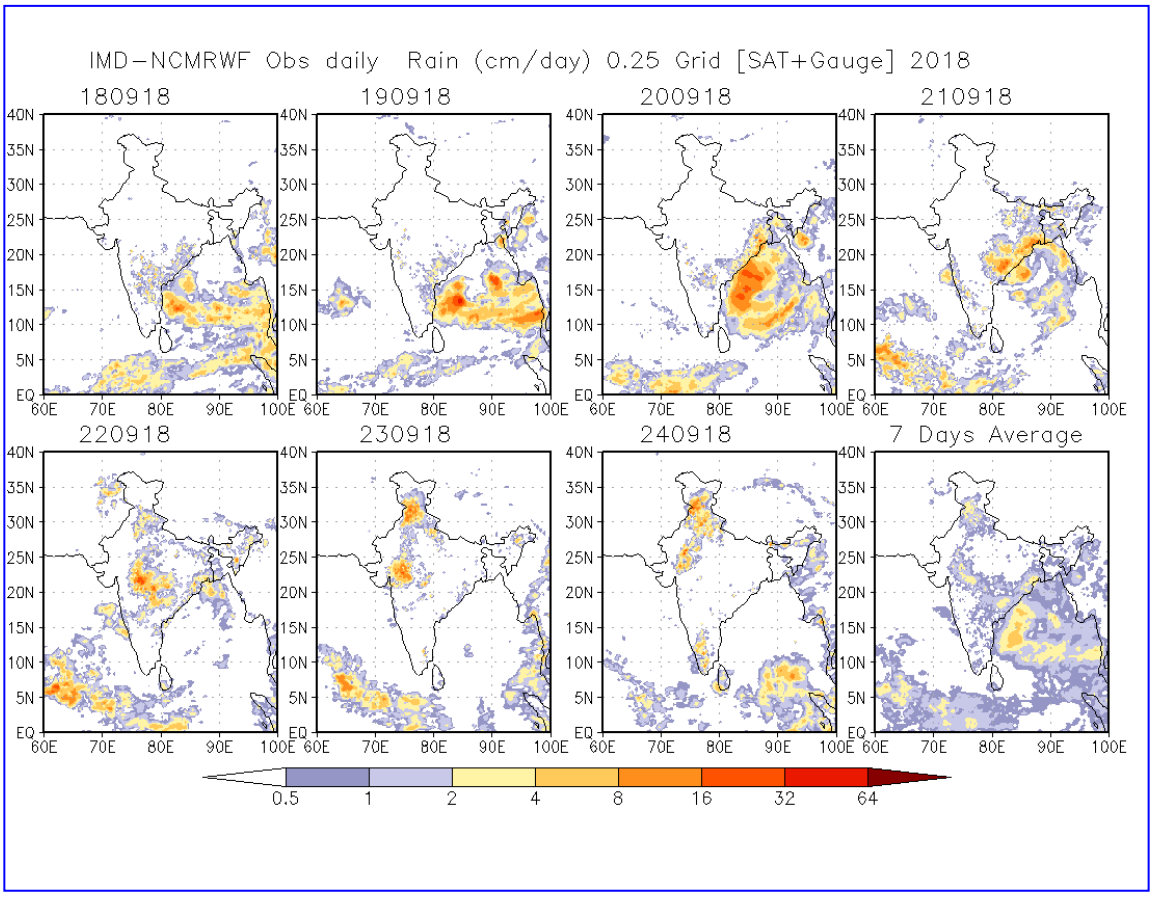


Fig.8: IMD-NCMRWF GPM merged gauge rainfall during during 18 – 24 September and 7 days average rainfall (cm/day)

Under the influence of this system, on 20th rainfall occurred at most places with heavy to extremely heavy rainfall (20 cm or more in 24 hrs) at isolated places over Odisha with heavy to very heavy rainfall at isolated places over north Andhra Pradesh and Chhattisgarh. On 21st, rainfall occurred at most places with heavy to very heavy rainfall at a few places and extremely heavy falls at isolated places over Vidarbha during past 24 hours. It caused rainfall at many places with heavy to very heavy rainfall at a few places over Telangana. Rainfall occurred at many places with isolated heavy falls over Marathwada, Madhya Maharashtra, East Rajasthan, Himachal Pradesh, Chattisgarh and moderate rainfall activity occurred over Uttar Pradesh, Uttrakhand, Haryana, Chandigarh and Delhi. On 22nd, rainfall occurred at most places with heavy to very heavy rainfall at a few places over west Madhya Pradesh, east Rajasthan, Punjab & Himachal Pradesh and heavy to very heavy falls at isolated places over Gujarat during past 24 hours. On 23rd and 24th, It caused rainfall at many places with heavy rainfall at isolated places over west Uttar Pradesh, Uttrakhand and Haryana & Chandigarh and rainfall at a few places with heavy rainfall at isolated places over Jammu & Kashmir. Moderate rainfall activity was observed at a few places over west Rajasthan, east Uttar Pradesh, Madhya Maharashtra and at most places over Delhi. Realized 24 hrs accumulated rainfall (≥5cm) ending at 0830 hrs IST of date during the life cycle of the system is presented below:

21st September

Odisha: Jaipur - 29, Malkangiri - 28, Similiguda - 21, Udala - 19, Remuna - 17, Balasore - 14, Daitari - 13, Kaptipada - 12, Soro, Jeypore, Balimundali, NH5 Gobindpur, Talcher, Anandpur & Nilgiri – 11 each, Narsinghpur, K Nuagaon, Koraput, Tikabali, Rajghat, Bhograi, Hindol & Jaleswar – 10 each, Komna, Harichandanpur, Gania, Pottangi, Berhampur, Jamsolaghat, Parjang, Baripada, Sukinda, Danagadi & Paikmal – 9 each, Betanati, Daspalla, Khandapara, Nawapara, Bonth, Gopalpur & Binjharpur – 8 each, Banki, Chandanpur, Nawarangpur, Satyabadi, Phulbani, Ghatagaon, Batagaon, Akhuapada, Jajpur, Athgarh, Dhamnagar, Ranpur, Raghunathpur, Tikarpara, Mundali, Tangi, Kosagumda, Kalinga, Tentulikhunti, Joshipur & Korei – 7each

Coastal Andhra Pradesh: Chintur - 10, Bobbili - 8, Pathapatnam & Kunavaram – 7 each

Gangetic West Bengal: Contai - 25, Barrackpur & Durgachack – 9 each, Midnapore, Mohanpur & Digha – 8 each, Midnapore & Diamond Harbour – 7 each

Chattisgarh: Konta & Sukma – 9 each and Jagdalpur – 8

22nd September

Himachal Pradesh: Renuka / Dadhau - 7

East Rajasthan: Bakani - 8

Madhya Maharashtra: Raver - 7

Marathwada: Vasmat - 7

Vidarbha: Hinganghat - 23 , Warora - 13 , Deoli, Wardha, Dharni & Chikhalda - 12 each, Chandur & Selu – 9 each, Chandur Bazar - 8 , Samudrapur, Tiwsa, Ralegaon & Kharangha – 7 each ,

Telangana: Utnur - 13 , Manthani - 11 , Shriramsag.Pocha - 10 , Adilabad, Karimnagar, Mallial & Karimnagar - 9 each, Julapalle, Jagtial, Thimmapur, Metpalle, Mogullapalle & Bhupalpalle - 8 each, Nirmal, Sultanabad, Khanpur, Mortad, Sirsilla, Kammar Palle, Sarangapur & Kaleswaram - 7 each

23rd September

West Uttar Pradesh: Shahjahapur & Shahjahanpur – 7 each,

Uttarakhand: Banbasa - 9,

Haryana, Chandigarh & Delhi: Chandigarh & Naraingarh – 8 each, Guhla, Chandigarh, & Chandigarh SASE – 7 each

Punjab: Hoshiarpur - 17, Adampur & Nangal – 15 each, Halwara - 14, Jalandhar - 13, Anandpur Sahib - 12, Hoshiarpur & Salern (District: Hoshiarpur) – 11 each, Nawanshahr & Khanna – 10 each, Balachaur - 9, Patiala Rev, Sirhind, Pathankot , Mukerian & Ludhiana – 8 each, Tibri, Fatehgarh Sahib, Sangrur, Derabassi (Basi), Gurudaspur, Kharar & Malakpur – 7 each

Himachal Pradesh: Naina Davi - 18, Sarkaghat - 14, R L Bbmb, Mehre (Barsar), Manali, Dharmsala & Aghar – 13 each, Una & Barthin – 12 each, Jogindarnagar, Sujanpur Tira, Kasauli & Bharari – 11 each, Nadaun, Kangra & Baijnath – 10 each, Palampur & Seo Bagh – 9 each, Ghamroor, Dharampur, Gulern & Kahu – 8 each, Nagrota Surian, Bhuntar & Sangraha – 7 each

Jammu & Kashmir: Udhampur - 10, Jammu & Katra – 9 each, Samba - 7

East Rajasthan: Bhungra - 15, Pipalkhunt - 14, Banswara, Khushalgarh, Sallopat - 13, Pratapgarh - 11, Arnod - 10, Ghatol & Shergarh – 9 each, Bhilwara Tehsil, Bhilwara, Garhi, Dug, Aspur, Jagpura, Salumber, Loharia, Gangdhar, Arthuna, Kherwara & Chhotisadri – 7 each,

Gujarat Region: Godhra - 10, Dahod - 9, Morva Hadaf - 8, Quant, Meghraj, Santrampur, Modasa, Chhota Udepur, Jhalod, Garbada & Fatepura – 7 each

West Madhya Pradesh: Jhabua AWS - 19, Badnagar - 14, Jaora, Khachrod & Gandhwani - 13 each, Sailana & Kasarwad - 12 each, Depalpur - 11, Manawar, Nalchha, Dhar-AWS, Sardarpur & Thandla - 10 each, Neemuch AWS, Badnawar, Maheshwar, Mahidpur & Gautampura - 9 each, Bhikangaon & Mandsaur AWS - 8 each, Jabot, Jawad, Ratlam-Aws, Thikri & Petlawad - 7 each,

24 September 2018
West Madhya Pradesh: Jawad - 9,
Gujarat Region: Bhiloda - 14, Vijaynagar - 8, Idar - 7
East Rajasthan: Deogarh - 17, Jawaja - 17, Nayanagar/Beawar - 16, Tatgarh, Bhim – 11 each, Amet, Pipalkhunt, Veja, Arnod, Kanva, Pratapgarh – 9 each, Raipur, Nimarana, Chittorgarh – 8 each, Gangrar, Rashmi, Aspur, Sahada – 7 each
West Rajasthan: Raipur - 7,
Punjab: Pathankot - 24, Gurudaspur - 24, Kapurthala - 23, Taran Taran - 21, Amritsar - 20, Tibri - 18, Mukerian - 17, Ranjit Sagar Dam Site - 15, Malakpur - 15, Madhopur - 15, Shahpur Kandi - 14, Phangota - 14, Nakodar - 9, Salern - 9, Hoshiarpur - 9, Rajpura - 8, Patiala Rev - 8, Adampur, Samana, Khanna, Raya, Patiala, Faridkot, Faridkot, Muktsar – 7 each
Himachal Pradesh: Dalhousi Alha - 17, Kheri - 16, Dharmshala - 14, Dehra Gopipur, Manali, Kangra, Naina Davi, Chamba – 12 each, Guler, Palampur – 11 each, Ghamroor - 10, Nagrota Surian, Bangana, Amb – 9 each, Tissa, Bharwain, Nadaun, Baijnath – 8 each, Sujanpur Tira - 7,
Haryana, Chandigarh and Delhi: Assandh - 16, Karnal - 14, Thanesar - 12, Kurukshetra - 12, Nilokheri - 11, Jagadhari, Radaur – 9 each, Safidon - 8, Bilaspur, Karnal Rev, Indri, Gurgaon Rev, Chhachhrauli, Panipat, Bhiwani, Bhiwani Rev, Guhla – 7 each
West Uttar Pradesh: Gautam Buddha Nagar - 12, Moradabad, Gunnaur – 7 each,
Uttarakhand: Banbasa - 8, Purola, Roorkee-7 each

25th September
West Uttar Pradesh: Muzaffarnagar - 16, Thakurdwara - 13, Budhana, Dhampur, Bijnor – 10 each, Meerut, Mawana – 8 each, Moradabad, Gautam Buddha Nagar – 7 each
Uttarakhand:
Banbasa - 11, Pantnagar, Haldwani – 7 each,
Haryana, Chandigarh & Delhi: Guhla - 11, Sonepat - 9, Pilukhera - 8, Chandigarh - 7
Punjab: Hoshiarpur - 15, Nangal, Hoshiarpur – 14 each, Khanna - 13, Fatehgarh Sahib - 10, Patiala - 9, Anandpur Sahib, Ludhiana – 8 each, Samrala, Ropar, Patiala Rev – 7 each
Himachal Pradesh: Jhandutta - 19, Naina Davi - 18, Una, Mehre (Barsar) – 14 each, Una Rampur - 13, R L Bbmb, Dharampur – 10 each, Banjar, Sarkaghat – 9 each, Gohar, Barthin, Bharari – 8 each, Aghar, Ghumarwin, Bangana - 7 each,

8.2 Wind

The maximum sustained wind speed of 35 knots has been reported by high wind speed recorder at Puri during the time of landfall.

9. Damage due to CS, Daye

No significant damage has been reported due to this storm. However, it caused flood over Odisha due to heavy rainfall.

10. Performance of operational NWP models

IMD operationally runs a regional models, 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. In this report performance of the individual models, MME forecasts, SCIP, GPP, RII for cyclone Sagar are presented and discussed.

10.1 Prediction of cyclogenesis (Genesis Potential Parameter (GPP)) for DAYE

The predicted zone of cyclogenesis for 0000 UTC of 20th September based on 0000 UTC of 15th-20th Sep. 2018 (upto 120 hrs lead period) are shown in Fig.9

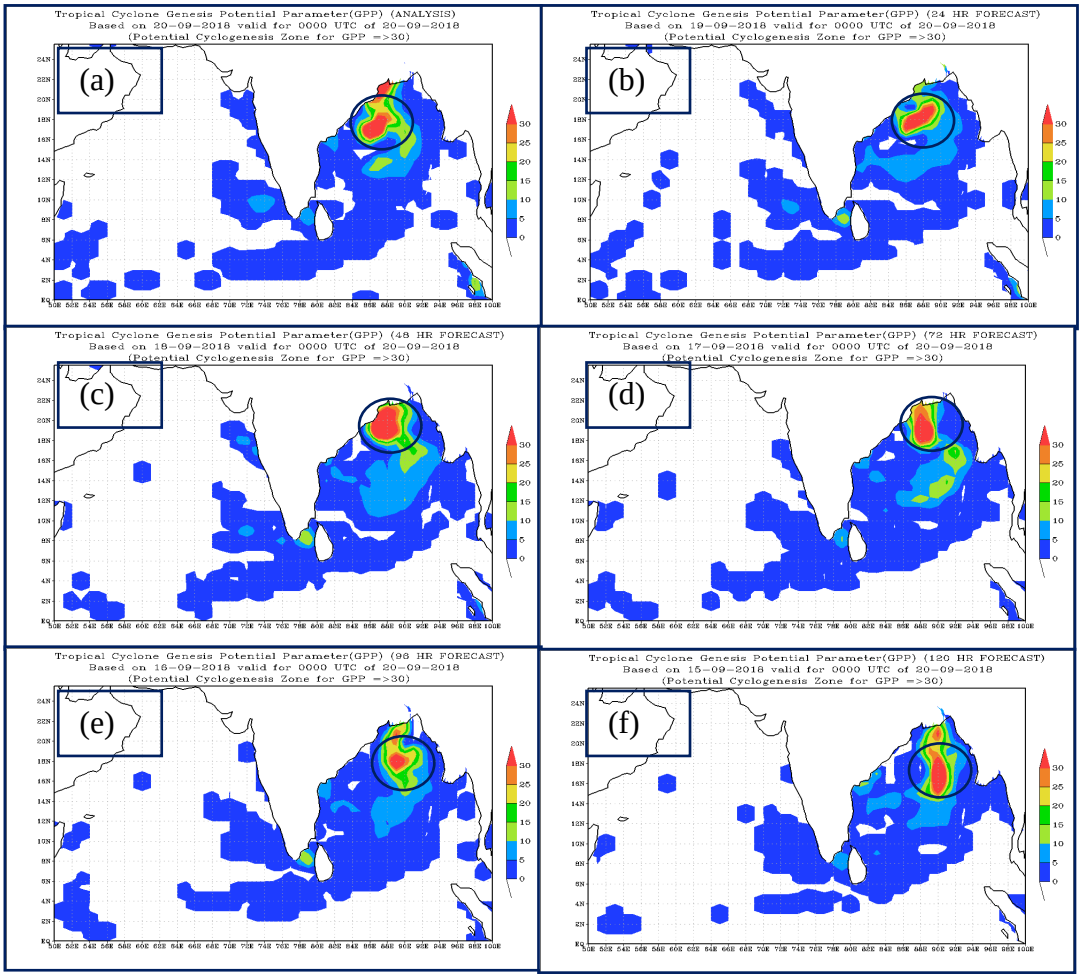


Fig.9 (a-f): Predicted zone of cyclogenesis based on 0000 UTC of 15-20th Sep. 2018 for 20th Sep. 2018

. The model could predict cyclogenesis zone correctly about 72 hrs in advance. Since all low pressure systems do not intensify into cyclones, it is important to identify the potential of intensification (into cyclone) of a low pressure system at the early stages (T No. 1.0, 1.5, 2.0) of development. Conditions for (i) Developed system: Threshold value of average GPP ≥ 8.0 and (ii) Non-developed system: Threshold value of GPP < 8.0. The prediction of intensification of depression into cyclonic storm based on the above is presented in Fig.10.

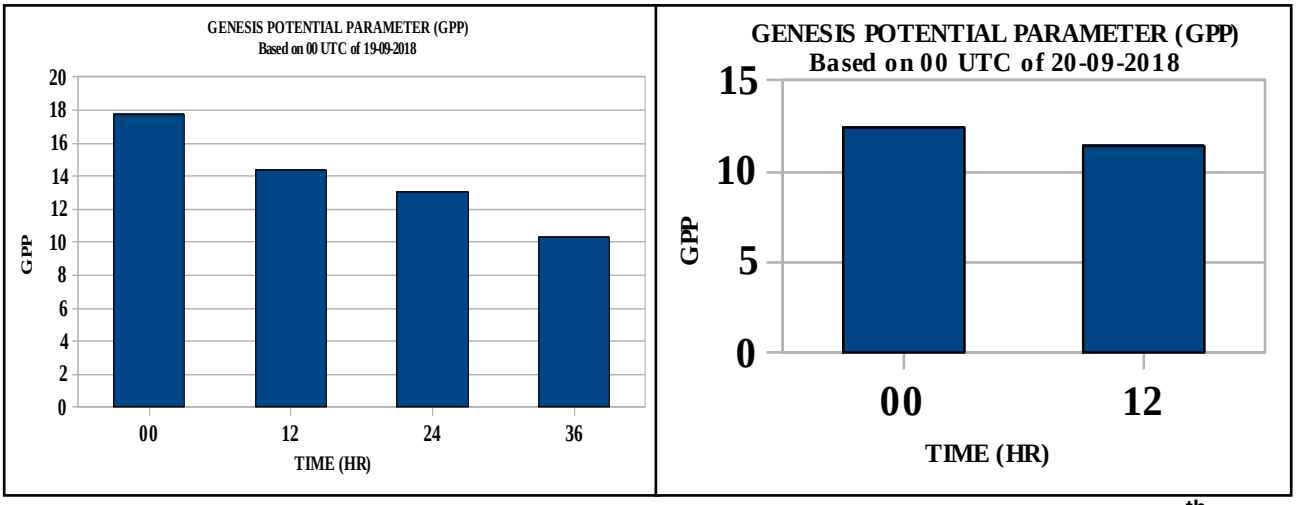


Fig. 10: Area average analysis and forecasts of GPP based on 0000 UTC of 19th and 20th September 2018

10.2 Track prediction by NWP models

Track prediction by various NWP models is presented in **Fig.11**. Based on initial conditions of 0000 UTC of 20th September, most of the models indicated northwestward or west-northwestward movement and the landfall between Kalingapatnam and Gopalpur.

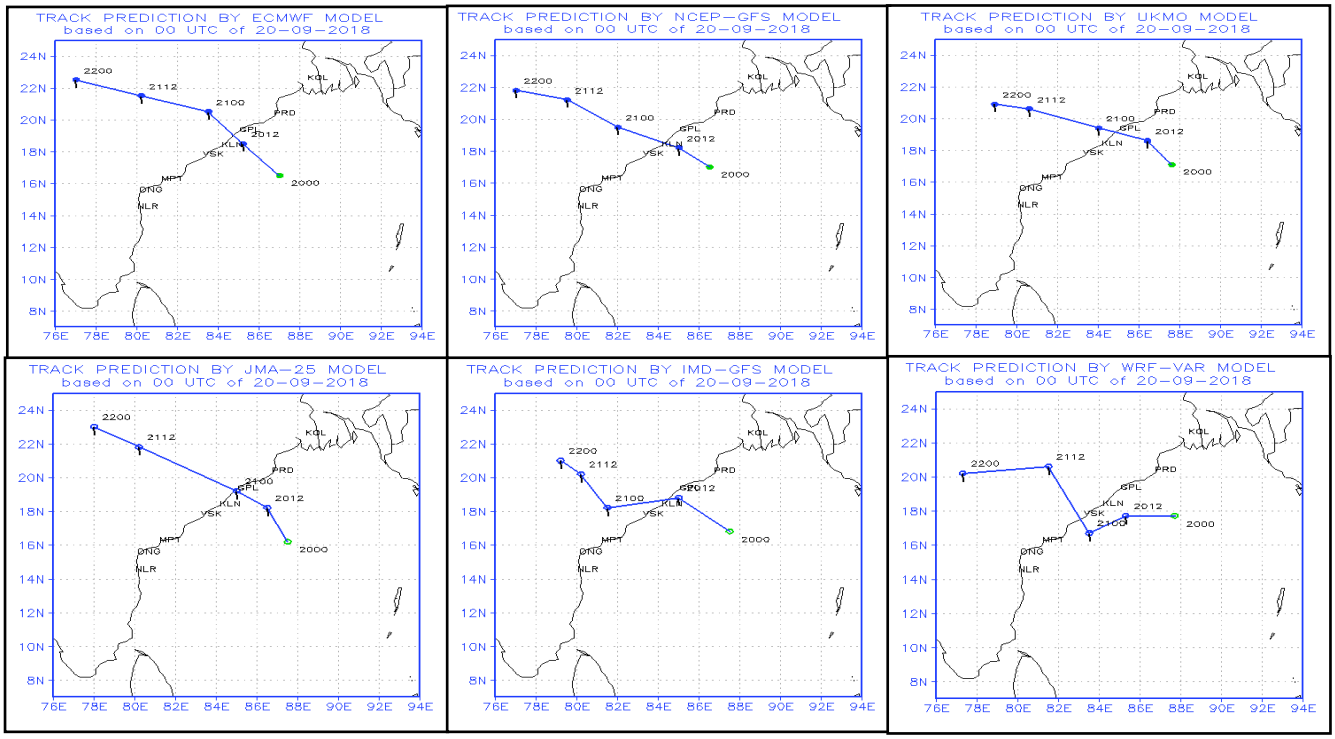


Fig. 11 (a): NWP model track forecast based on 0000 UTC of 20.09.2018

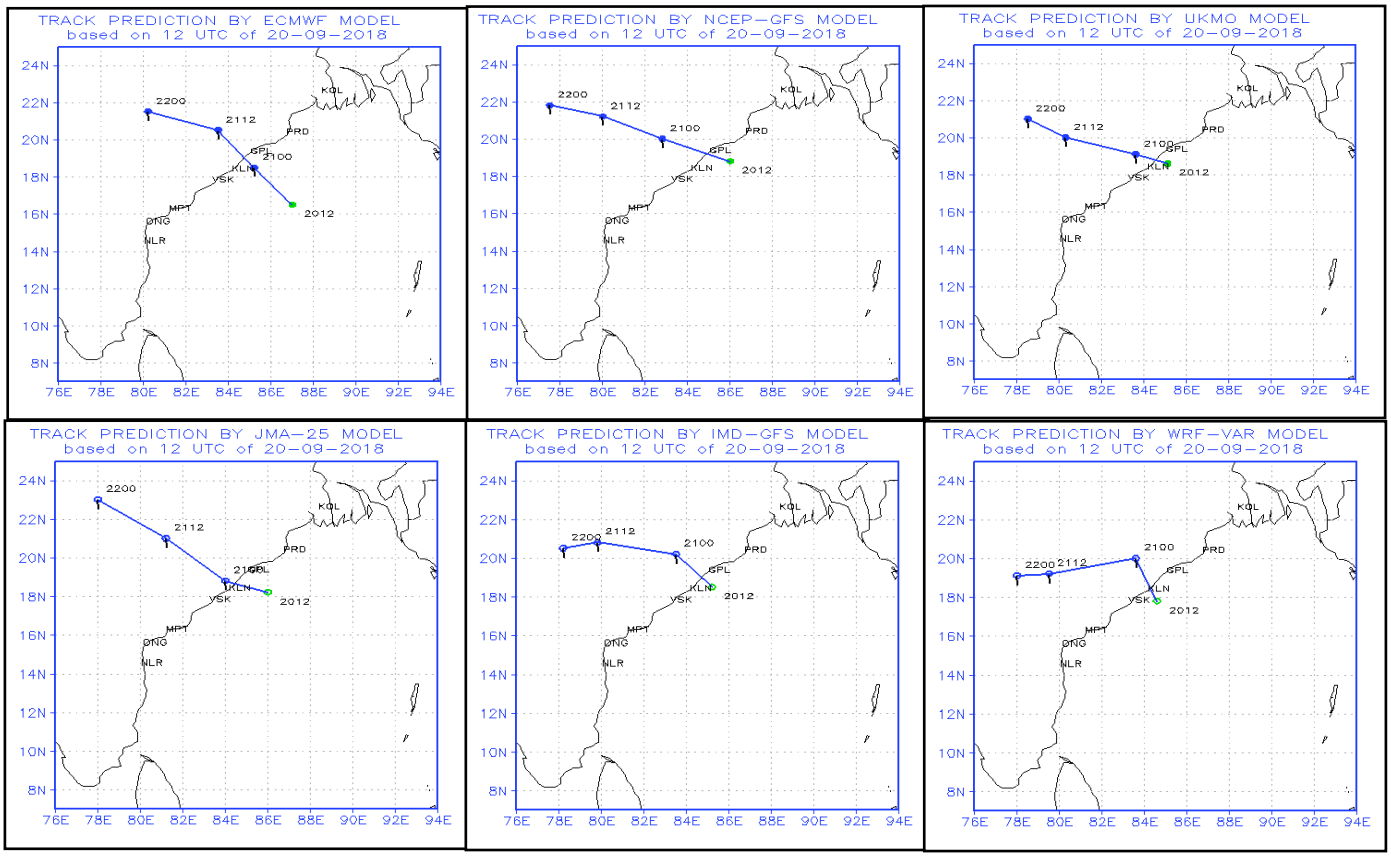


Fig. 11 (b): NWP model track forecast based on 1200 UTC of 20.09.2018

10.3 Track 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 for 24 hours lead period was minimum for MME followed by NCEP (GFS) model and for 48 hours lead period the errors were the least by ECMWF followed by NCEP (GFS). The landfall forecast errors are presented in Table 3. The landfall point errors for 7 hours lead period were the least for GFS group of models followed by ECMWF and for 20 hours lead period, errors were the least by JMA & UKMO followed by ECMWF. The landfall time errors for 7 hours lead period were the least for IMD MME followed by JMA and for 20 hours lead period, errors were the least by UKMO followed by IMD MME.

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
IMD-GFS	63(2)	192(2)	187(2)	278(1)	-
IMD-WRF	52(2)	311(2)	267(2)	237(1)	-
JMA	107(2)	138(2)	91(2)	137(1)	-
NCEP-GFS	91(2)	108(2)	79(2)	57(1)	-
UKMO	84(2)	115(2)	159(2)	259(1)	-
ECMWF	147(2)	208(2)	181(2)	24(1)	-
IMD-HWRF	83(5)	159(5)	167(5)	136(3)	160(1)
IMD-MME	61(2)	101(2)	123(2)	98(1)	-

Table-3a. Landfall point forecast errors (km) of NWP Models at different lead time (hour)

Forecast Lead Time (hour) →	7:30 hr	19:30 hr
Based on	**20 September 12z**	**20 September 00z**
IMD-GFS	33	96
IMD-WRF	123	282
JMA	92	11
NCEP	11	123
UKMO	57	15
ECMWF	38	38
IMD-MME	72	62

Table-3b. Landfall time forecast errors (hour) at different lead time (hr)
('+' indicates delay landfall, '-' indicates early landfall)

Forecast Lead Time (hour) →	**7:30 hr**	**19:30 hr**
Based on	**20 September, 12z**	**20 September, 00z**
IMD-GFS	-4:30	-5:30
IMD-WRF	-4:30	+7:30
JMA	+1:30	+4:30
NCEP	-4:30	-4:30
UKMO	-2:30	+0:30
ECMWF	+8:30	-4:30
IMD-MME	+0:30	-2:30

10.4 Intensity forecast errors by various NWP Models

The intensity forecast errors of IMD-SCIP model and HWRF model are shown in Table **4(a-b).** The errors in intensity forecast were significantly less for IMD SCIP as compared to HWRF upto 24 hours lead period. However, for 36 hours lead period, the errors were less by HWRF as compared to IMD SCIP.

Table 4(a). 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**
IMD-SCIP (AAE)	3.5(2)	3.0(2)	3.0(1)
IMD-SCIP (RMSE)	3.8	3.6	3.0

Table 4(b) Average absolute errors (AAE) and Root Mean Square (RMSE) errors in knots of HWRF model (Number of forecasts verified is given in the parentheses)

Lead time →	**12H**	**24H**	**36H**	**48H**	**60H**
IMD-HWRF (AAE)	6.6(5)	5.4(5)	2.2(5)	2.3(3)	5.0(1)
IMD-HWRF (RMSE)	8.0(5)	7.2(5)	2.7(5)	3.5(3)	5.0(1)

11. Operational Forecast Performance

11.1. Genesis Forecast

- First information regarding formation of an LPA over the central & adjoining north BoB around 18th and low (1-25%) probability of it's intensification into depression around 19th was issued in the Tropical Weather Outlook at 0600 UTC of 16th September (about 54 hours in advance of formation of LPA & 84 hours in advance of formation of depression). Thereafrer, the probability of formation of depression was upgrated to moderate and high in the tropical weather outlook issued on 17th and 18th September. The LPA formed over eastcentral BoB and adjoining Myanmar at 0900 UTC of 18th and depression formed over eastcentral BoB in the night (1500 UTC) of 19th.

11.2. Landfall Forecast

- First information regarding west-northwestwards movement of system towards south Odisha-north Andhra Pradesh coasts was issued in Tropical Weather Outlook issued at 0600 UTC of 17th Sep. (about 30 hours prior to landfall).
- The information regarding landfall of system near south Odisha-north Andhra Pradesh coasts between Kalingapatnam and Paradip close to Puri during late night of 20th & early morning of 21st was given in the first bulletin issued at 1700 UTC of 19th (about 24 hours in advance). The system crossed south Odisha and adjoining north Andhra Pradesh coasts close to Gopalpur near 19.27^{0}N/84.92^{0}E during 1900-2000 UTC of 20th September 2018.
- The landfall point was further updated in the bulletin issued on 20th at 0330 UTC that the system would cross south Odisha-north Andhra Pradesh coasts between Kalingapatnam and Puri close to Gopalpur around midnight of 20th (about 16 hours prior to landfall) with maximum sustained wind speed of 55-65 kmph gusting to 75 kmph. Pre-Cyclone Watch was issued for Odisha and north Andhra Pradesh coasts.
- The warning was further updated in the bulletin issued at 0700 UTC of 20th that the system would cross south Odisha-north Andhra Pradesh coasts between Kalingapatnam and Puri close to Gopalpur around midnight of 20th (about 12 hours prior to landfall) with maximum sustained wind speed of 60-70 kmph gusting to 80 kmph. Cyclone Alert for south Odisha and north Andhra Pradesh coasts was issued. It was upgraded to Cyclone Warning for south Odisha and north Andhra Pradesh coasts at 1630 UTC of 20th.
- The error in landfall point for 12 hours lead period was 39.7 km against long period average (LPA) (2013-17) of 29.7 km and the error in landfall time for 12 hours lead period was 3.5 hours against LPA of 2.3 hours.

11.3. Track Forecast

- The track forecast error for 24, and 48 hrs lead period were 63.1, and 58.5 km respectively, which is significantly less than the average track forecast errors of 93 and 144 km during last five years (2013-17). The track forecast skill was significantly higher being about 85%, and 93% against the long period average (LPA) of 55%, and 68% during 2013-17 for 24 and 48 hrs lead period respectively. (**Fig.13, Table 6**).

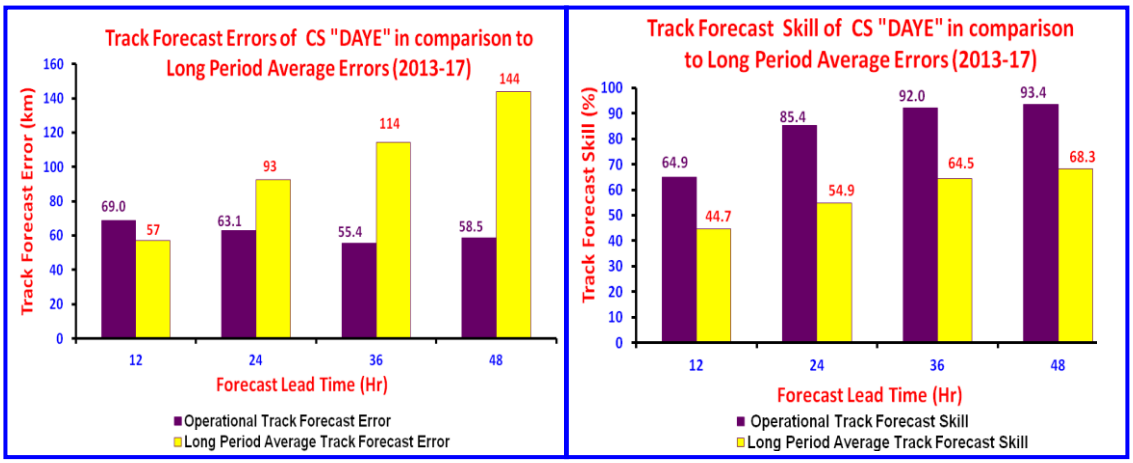


Fig.12: Track Forecast Errors and Skill for CS Daye

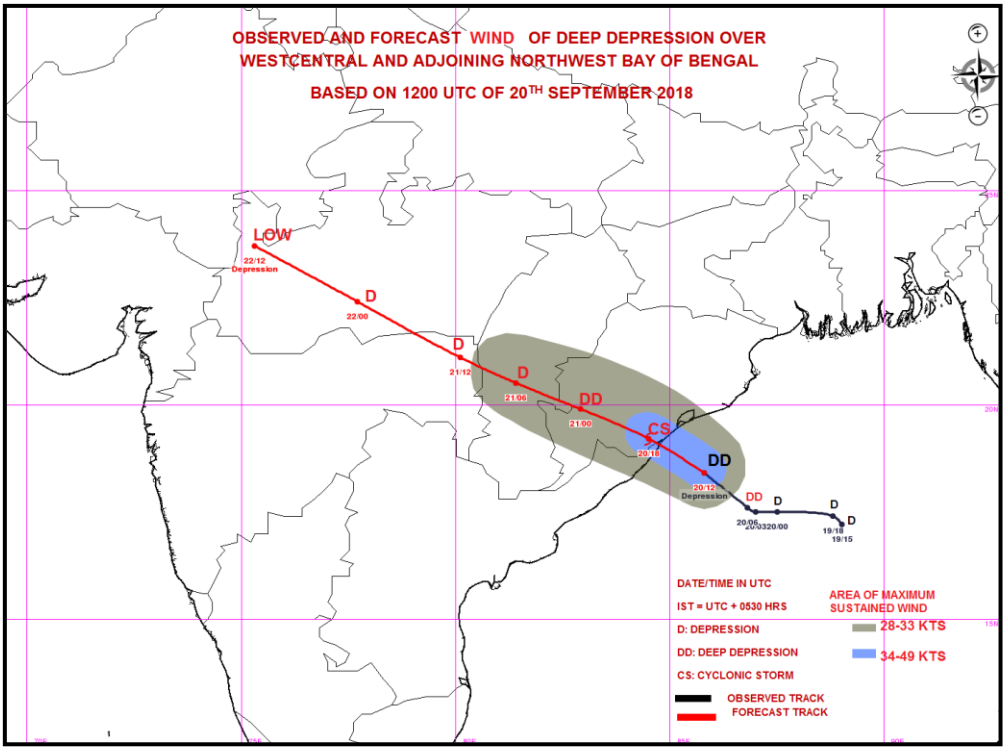


Fig.13: Observed and forecast track with cone of uncertainty based on 1800 UTC of 19th Sep. 2018 in association with CS Daye

Table 6: Average Track forecast error in association with CS Daye

Lead Period (hrs)	N	Average track forecast error (km)	Skill (%)	LPA (2013-17)	
				Track forecast error (km)	Skill (%)
12	5	67.5	65.6	57	44.7
24	4	70.9	83.5	93	54.9
36	4	54.2	92.2	114	64.5
48	3	58.5	93.4	144	68.3

14.4. Intensity Forecast

- The absolute error (AE) of intensity (wind) forecast for 24 and 48 hrs lead period were 1.1 and 6.1 knots against the LPA of 10.4 and 15.5 knots respectively. The skill in intensity (wind) forecast based on AE for 24 and 48 hrs lead period was 92.3 and 81.3% against the LPA of 37.1 and 56.8% respectively (**Fig.14, Table 7**).
- The root mean square error (RMSE) of intensity (wind) forecast for 24 and 48 hrs lead period were 1.6 and 6.1 knots against the LPA of 14.0, and 20.6 knots respectively. The skill based on RMSE of intensity (wind) forecast for 24 and 48 hrs lead period was 89.8 and 81.8% against the LPA of 40.1 and 60.0% respectively (**Fig.6**).

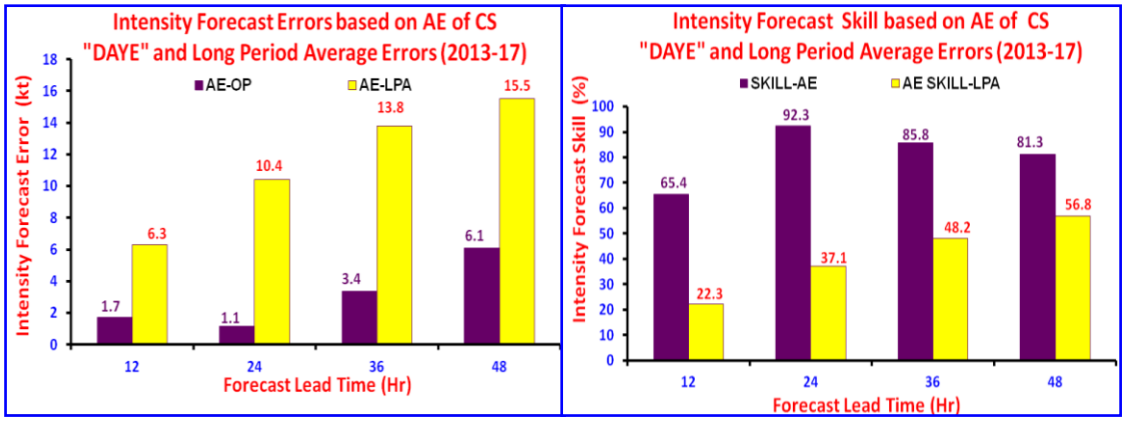


Fig. 15: Absolute errors (AE) of intensity forecast and skill for CS Daye

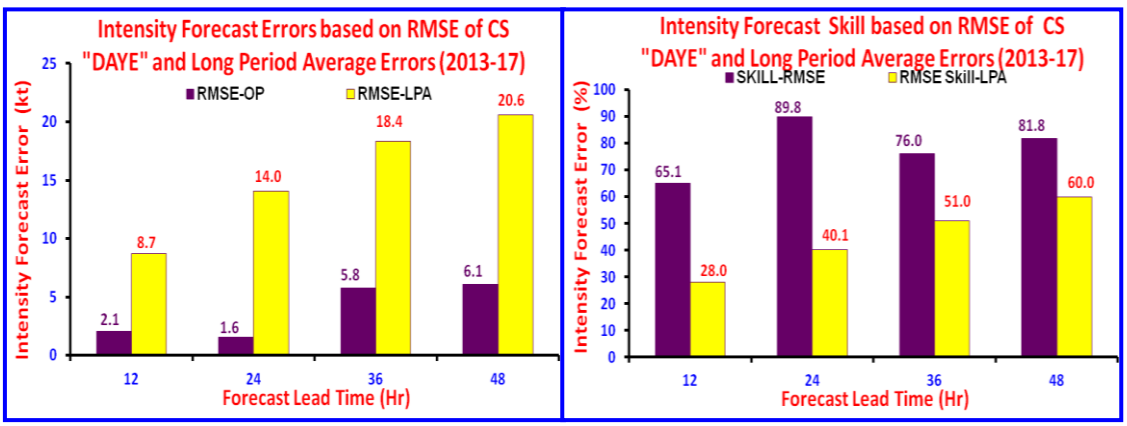


Fig. 16: RMSE of intensity forecast and skill for CS Daye

Table 7: Average Intensity forecast error in association with CS Daye

Lead Period (hrs)	N	Average Intensity Error (kts)		Skill (%) in intensity forecast		LPA Intensity forecast Error (kts) (2013-17)		LPA Skill (%) in Intensity forecast (2013-17)	
		AE	RMSE	AE	RMSE	AE	RMSE	AE	RMSE
12	5	1.7	2.1	65.4	65.1	6.3	8.7	22.3	28.0
24	4	1.1	1.6	92.3	89.8	10.4	14.0	37.1	40.1
36	4	3.4	5.8	85.8	76.0	13.8	18.4	48.2	51.0
48	2	6.1	6.1	81.3	81.8	15.5	20.6	56.8	60.0

N: No. of observations verified; AE: Absolute Error; RMSE: Root Mean Square Error, LPA: Long Period Average (2013-17)

12. 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 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.
- **Cyclone structure forecast for shipping and coastal hazard management** The radius of maximum wind and radii of MSW ≥28 knots and ≥34 knots wind in four quadrants of cyclone was issued every six hourly giving forecast for +06, +12, +18, +24, +36 and +48 hrs lead period.
- **Adverse weather warning bulletins:** The tropical cyclone forecasts alongwith expected adverse weather like gale wind was issued with every three hourly update during cyclone period to the central, state and district level disaster management agencies including MHA NDRF, NDMA for all the states along west coast of India, Lakshadweep Islands and Daman & Diu and Dadar 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 Defence 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.
- **Warning and advisory through social media:** Daily updates were uploaded on face book and tweeter 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.
- **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, Kolkata and Cyclone warning centres at Bhubaneswar and Visakhapatnam to ports, fishermen, coastal and high sea shipping community.
- **Fishermen Warning:** First warning for fishermen of the states of West Bengal, Odisha and Andhra Pradesh was issued at 1500 UTC of 16th May.
- **Advisory for international Civil Aviation :** The Tropical Cyclone Advisory Centre (TCAC) bulletin for International Civil Aviation were issued every six hourly to all meteorological watch offices in Asia Pacific region for issue of significant meteorological information (SIGMET). It was also sent to Aviation Disaster Risk Reduction (ADRR) centre of WMO at Hong Kong.
- **Diagnostic and prognostic features of cyclone:** The prognostics and diagnostics of the systems were described in the RSMC bulletins and tropical cyclone advisory bulletins.

Statistics of bulletins issued by RSMC New Delhi in association with the cyclonic storm Sagar are given in **Table 8.**

Table 8 : Bulletins issued by RSMC New Delhi

S.N	Bulletin	No. of Bulletins	Issued to
1	National Bulletin	18	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 Defence Staff, Director General Doordarshan, All India Radio, National Disaster Response Force, Chief Secretary-Telangana, Andhra Pradesh, Odisha, West Bengal, Chhattisgarh, Madhya Pradesh, Jharkhand, Maharashtra, Rajasthan, Gujarat, Uttar Pradesh, Uttarakhand, Haryana, Punjab, Delhi,.
2	RSMC Bulletin	07	1. IMD's website 2. WMO/ESCAP member countries 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)	05	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	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 (97,488) to users registered with RSMC website from the states of Odisha, Andhra Pradesh, Chattisgarh, and Maharashtra
6	Warnings through Social Media	Daily	Cyclone Warnings were uploaded on Social networking sites (Face book and Tweeter) since inception to weakening of system (every time when there was change in intensity).
7	Message through Whatsapp	14	Everyday based on observation of 00, 03, 06, 12, 18 UTC observations to central level disaster managers
8	Press Release	4	Disaster Managers, Media persons by email and uploaded on website
9	Press Briefings	Daily	Regular briefing daily

13. Summary and Conclusion:

Cyclonic Storm (CS) Daye originated from a low pressure area (LPA) which formed over eastcentral Bay of Bengal (BoB) and adjoining Myanmar in the afternoon (0900 UTC) of 18th September. It lay as a well marked low pressure area (WML) over the same region in the morning (0300 UTC) of 19th September.

Under favourable environmental conditions, it concentrated into a Depression (D) over eastcentral BoB in the night (1500 UTC) of 19th September. Moving nearly west-northwestwards, it intensified into a deep depression (DD) over westcentral BoB in the morning (0300 UTC) of 20th September and further into a cyclonic storm (CS) “Daye” in the same night (1500 UTC). It crossed south Odisha and north Andhra Pradesh coast close to Gopalpur (Odisha) as a cyclonic storm with a wind speed of 60-70 kmph gusting to 80 kmph during 1900-2000 UTC of 20th September. It continued to move west-northwestwards, weakened into a DD in the early morning (0000 UTC) of 21st , into a D in the same evening (1200 UTC) and into a WML over west Madhya Pradesh and adjoining east Rajasthan in the evening (1200 UTC) of 22nd September. It lay as a WML over southeast Rajasthan in the morning (0300 UTC) of 23rd. It lay over north Rajasthan and adjoining southwest Uttar Pradesh & south Haryana in the early morning (0000 UTC) of 24th and lay as an LPA over south Haryana and neighbourhood on 24th morning. It became less marked on 25th morning.

IMD utilised all its resources to monitor and predict the genesis, track and intensification of CS Daye. The track forecast error for 12, 24,36 and 48 hrs lead period were 67.5, 70.9,54.2 and 58.5 km respectively, which is significantly less than the average track forecast errors of 57, 93,114 and 144 km during last five years (2013-17). The absolute error (AE) of intensity (wind) forecast for 12, 24,36 and 48 hrs lead period were 1.7, 1.1,3.4 and 6.1 knots against the LPA of 6.3, 10.4,13.8 and 15.5 knots respectively.

14. Acknowledgements:

India Meteorological Department (IMD) and RSMC New Delhi duly acknowledges the contribution from all the stake holders and disaster management agencies who contributed to the successful monitoring, prediction and early warning service of CS Daye. 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), 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, Kolkata, Cyclone Warning Centre (CWC) Bhubaneswar, Visakhapatnam, Meteorological Centre (MC) Raipur, Ranchi, Bhopal, Hyderabad, Regional Meteorological Centre Nagpur, New Delhi Numerical Weather Prediction Division, Satellite and Radar Division, surface and upper air instruments divisions and Information System and Services Division at IMD is also duly acknowledged.