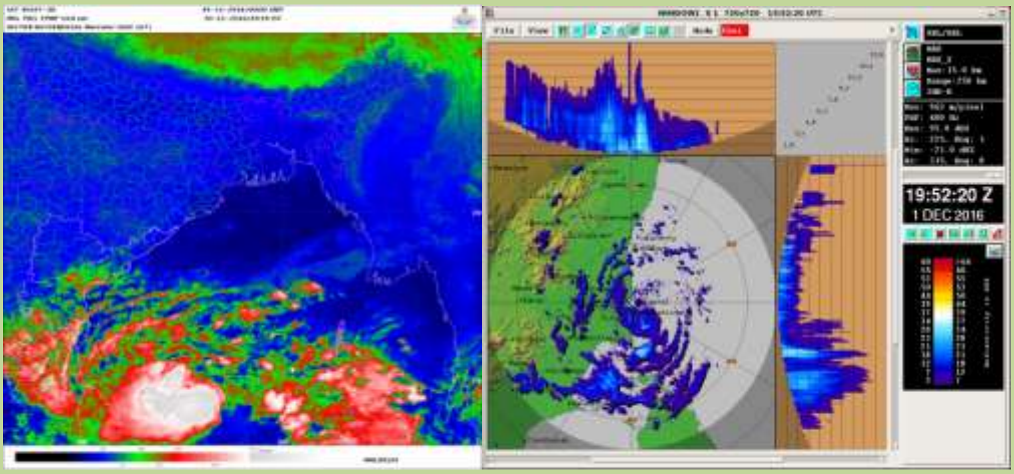
GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
INDIA METEOROLOGICAL DEPARTMENT

# Cyclonic Storm,'Nada' over the Bay of Bengal (29Nov-02Dec2016): A Report




Typical INSAT-3D enhanced colored IR imagery & DWR Karaikal imagery

## Cyclone Warning Division

## India Meteorological Department

## New Delhi

## January 2017

# Cyclonic Storm 'Nada' over the Bay of Bengal
# (29 Nov-02 Dec 2016)

## 1. Introduction

A depression formed over southeast BOB in the evening of 29$^{th}$ November. It moved initially northwestwards and intensified gradually into cyclonic storm (CS) "Nada" over southeast BoB in the morning of 30$^{th}$. It maintained its intensity till the evening of 1$^{st}$ December while moving west-northwestwards. It weakened into a deep depression (DD) in the noon of 1$^{st}$ December and further into a depression in the same midnight. Continuing to move west-northwestwards, it crossed north Tamil Nadu coast near Nagapattinam (about 20 km south of Karaikal) during 0400-0500 hours IST of 2$^{nd}$ December. Continuing to move westwards, it further weakened into a well marked low pressure area over interior Tamil Nadu in the forenoon of 02$^{nd}$ Dec. 2016. The track of the system and typical satellite imagery are presented in fig.1 & fig.2 respectively. The average landfall, track and intensity forecast errors are presented in Table 1,2 & 3 respectively.

### Salient features of the system:

- It was the second CS over BOB during post monsoon season.
- It also weakened over sea under the influence of high vertical wind shear, low sea surface temperature and low ocean heat content over southwest BoB off Tamilnadu coast.

### Forecast performance

- Genesis of depression over southeast BOB was predicted 72 hours in advance (26$^{th}$ November).
- The landfall over north Tamil Nadu coast was predicted from the genesis stage itself, i.e. in the evening of 29$^{th}$ Dec. 2016 (about 60 hrs in advance)
- The weakening of the cyclonic storm into a depression at the time of landfall was predicted 24 hrs in advance of time of landfall
- The point and time of landfall over Tamil Nadu coast was also predicted accurately with 24 hr landfall point forecast error of about 28 km and landfall time forecast error of about 4 hrs.
- The 24 hr track forecast error & skill were 68.9 km & 63.4% against long period average (2011-15) of 97.5 km & 48.5%.
- The 24 hr intensity forecast error & skill were 8.6 kts & 49.6% against long period average (2011-15) of 11.5 kts & 36.4%.
- The realised rainfall at most places with isolated heavy to very heavy rainfall over Tamil Nadu and Puducherry on 01$^{st}$ was also well predicted in the first bulletin itself issued on 29$^{th}$ evening.

## 2. Monitoring of CS,'Nada'

The cyclone was monitored & predicted continuously since its inception by IMD. The observed track of the cyclone, Nada is presented in Fig.1. The best track parameters of the system are presented in Table 1**.**

At the genesis stage, the system was monitored mainly with satellite observations and by DWR, Karaikal when it came under the radar range. The coastal hourly observations along Tamil Nadu and Puducherry coasts were utilized to assess the landfall point, time and intensity. The AWS and conventional observations were utilized to alongwith all above to Various national and international NWP models and dynamical-statistical models including IMD's and NCMRWF's global and meso-scale models, dynamical statistical models for genesis and intensity 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.

## 3. Brief life history

### 3.1. Genesis

A low pressure area lay over southeast Bay of Bengal at 0300UTC of 28$^{th}$ November 2016. It became a well-marked low pressure area over southeast Bay of Bengal at 0300UTC of 29$^{th}$ November 2016.At 0300UTC of 29$^{th}$, the sea surface temperature was 29˚C, Ocean thermal energy was 80-100KJ/cm$^2$, low level convergence was 30 x $10^{-5}$ second$^{-1}$, upper level divergence was about 30x$10^{-5}$ second$^{-1}$, the low level relative vorticity was about (100-120) x$10^{-6}$ second$^{-1}$, vertical wind shear of horizontal wind was moderate (10-20 knots). Upper tropospheric ridge lay along 14.0˚N. Considering large scale features, Madden Julian Oscillation was also favourable and lay in Phase-3 with amplitude about 1. Under these favourable conditions, the well-marked low concentrated into a **depression (D)** and lay centered at 1200 UTC of 29$^{h}$ over southeast BoB near latitude 6.5$^0$N and longitude 87.5$^0$E.

### 3.2. Intensification and Movement

The depression over southeast Bay of Bengal moved west-northwestwards with a speed about 15 kmph, intensified into a **deep depression** and lay centred at 0000 UTC of 30th November, 2016 near latitude 7.8ºN and longitude 85.E. At 0300 UTC of 30th November, 2016, the sea surface temperature was around 29˚C near the system centre and 28˚C near north Tamilnadu coast, Ocean thermal energy was about (80-100) KJ/cm$^2$ around system centre and it decreased towards southwest Bay of Bengal becoming less than 50 KJ/cm$^2$ near north Tamilnadu coast. The low level convergence was (50 x $10^{-5}$ second$^{-1}$), upper level divergence was around (40x$10^{-5}$ second$^{-1}$) in southwest sector of deep depression and low level relative vorticity was 150x$10^{-6}$ second$^{-1}$ near the system centre. The vertical wind shear of horizontal wind was moderate (10-20 knots) around the system centre and increased towards southwest Bay of Bengal near Shri Lanka & Tamilnadu coast. The Madden Julian oscillation (MJO) index was in phase 3 with amplitude <1. It continued in phase 3 and then in phase 2 for next 3-4 days. All the above environmental parameters were favourable for further intensification. The upper tropospheric ridge lay along 14.0$^0$ N and hence the east-southeasterly winds prevailed over the region of deep depression in middle and upper tropospheric levels. It steered the system west-northwestwards.

Under these conditions, the deep depression moved northwestwards and intensified into a **cyclonic storm, "Nada**" over southwest & adjoining southeast Bay of Bengal and lay centred at 0300 UTC of 30$^{th}$ November, 2016 near latitude 8.2ºN and longitude 85. 3ºE.

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The cyclonic storm “Nada” over southwest Bay of Bengal moved west-northwestwards and maintained its cyclonic storm intensity till forenoon of 01st Dec. As it moved close to coast, it encountered the colder sea surface, lower Ocean thermal energy (< 50 KJ/cm$^2$) and also the dry air incursion from the northwest in association with an anticyclone lying to the northwest of the system centre. As a result, while moving west-northwestwards, it weakened into a **deep depression** and lay centred at 0600 UTC of 1st December, 2016 near latitude 10.6ºN and longitude 81.2ºE over southwest Bay of Bengal. The intensity of the system reduced further and it weakened into a **depression** at 1800UTC of 1st December, 2016 over southwest Bay of Bengal.

Moving westward, it crossed north Tamilnadu coast near Nagapattinam (about 20 km south of Karaikal) between 2230 and 2330 UTC of 1st December, 2016 and further weakened into a low pressure-area and layover Interior Tamilnadu and neighbourhood at 0300 UTC of 2nd December,2016.

To illustrate the impact of the dry air incursion, the total precipitatble water (TPW) imageries during the life period of the storm are shown in Fig.2.

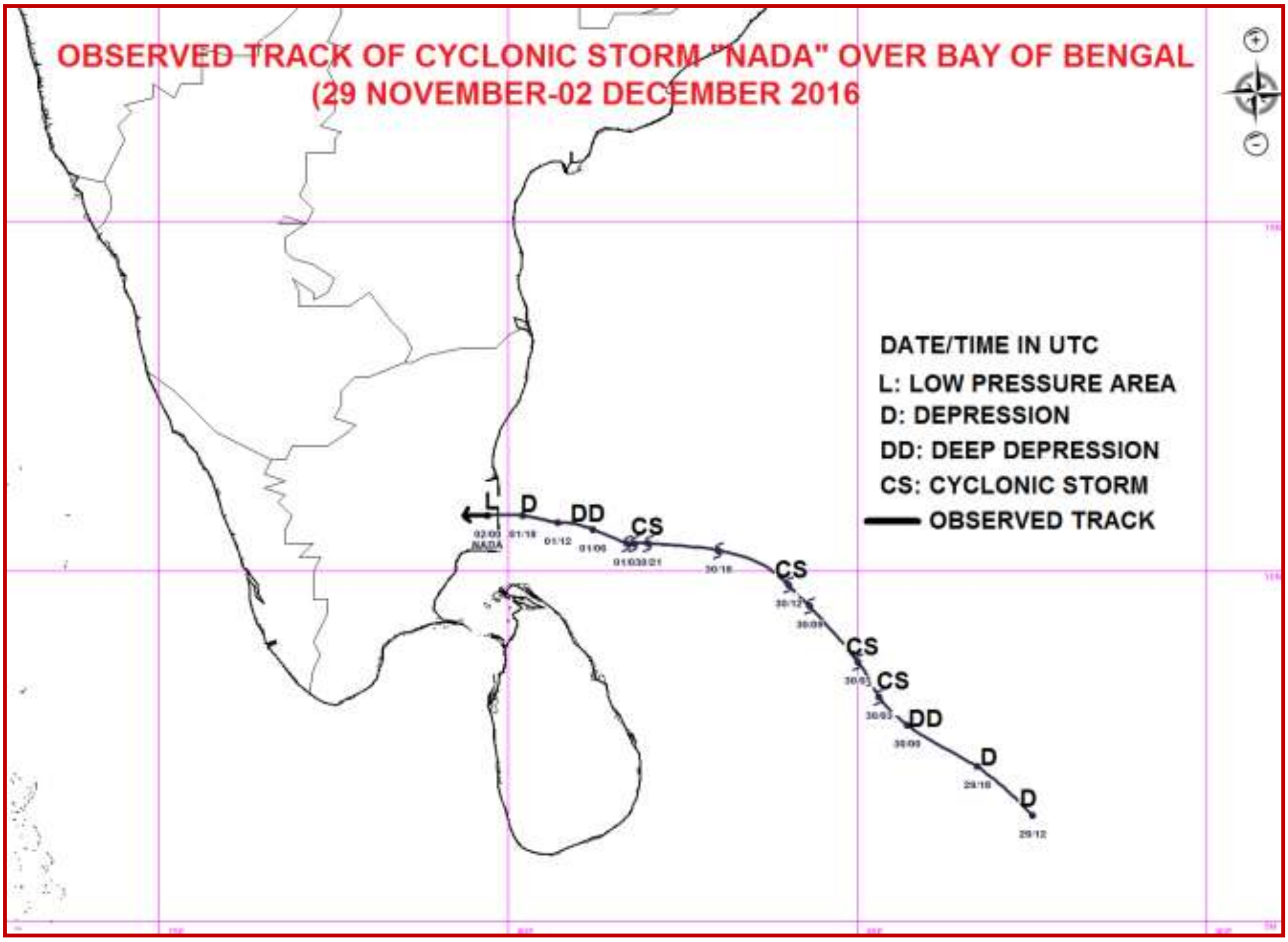


**Fig.1 Observed track of CS,’Nada’ over BoB during 29th Nov-02nd Dec 2016**

**Table 1: Best track positions and other parameters of the Cyclonic Storm, 'NADA' over the Bay of Bengal during 29 November to 02 December, 2016**

| 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 |
|---|---|---|---|---|---|---|---|
| 29/11/2016 | 1200 | 6.5/87.5 | 1.5 | 1004 | 25 | 3 | **D** |
| | 1800 | 7.2/86.7 | 1.5 | 1003 | 25 | 3 | D |
| 30/11/2016 | 0000 | 7.8/85.7 | 2.0 | 1002 | 30 | 4 | **DD** |
| | 0300 | 8.2/85.3 | 2.5 | 1002 | 35 | 6 | **CS** |
| | 0600 | 8.7/85.0 | 2.5 | 1002 | 35 | 7 | CS |
| | 0900 | 9.5/84.3 | 2.5 | 1002 | 35 | 8 | CS |
| | 1200 | 9.8/84.0 | 2.5 | 1000 | 40 | 8 | CS |
| | 1500 | 10.0/83.5 | 2.5 | 1000 | 40 | 8 | CS |
| | 1800 | 10.3/83.0 | 2.5 | 1000 | 40 | 8 | CS |
| | 2100 | 10.4/82.0 | 2.5 | 1000 | 40 | 8 | CS |
| 01/12/2016 | 0000 | 10.5/81.8 | 2.5 | 1001 | 35 | 7 | CS |
| | 0300 | 10.5/81.7 | 2.5 | 1002 | 35 | 6 | **CS** |
| | 0600 | 10.6/81.2 | 2.0 | 1003 | 30 | 4 | **DD** |
| | 1200 | 10.7/80.7 | 2.0 | 1004 | 30 | 4 | DD |
| | 1800 | 10.8/80.2 | 1.5 | 1006 | 25 | 3 | **D** |
| | | **The system crossed north Tamilnadu coast near Nagapattinam (latitude 10.75$^0$N and longitude 79.9$^0$E) between 2230 and 2330 UTC** | | | | | |
| 02/12/2016 | 0000 | 10.8/79.75 | 1.5 | 1006 | 25 | 3 | D |
| | 0300 | **Well Marked Low Pressure Area over interior Tamilnadu and neighbourhood** | | | | | |

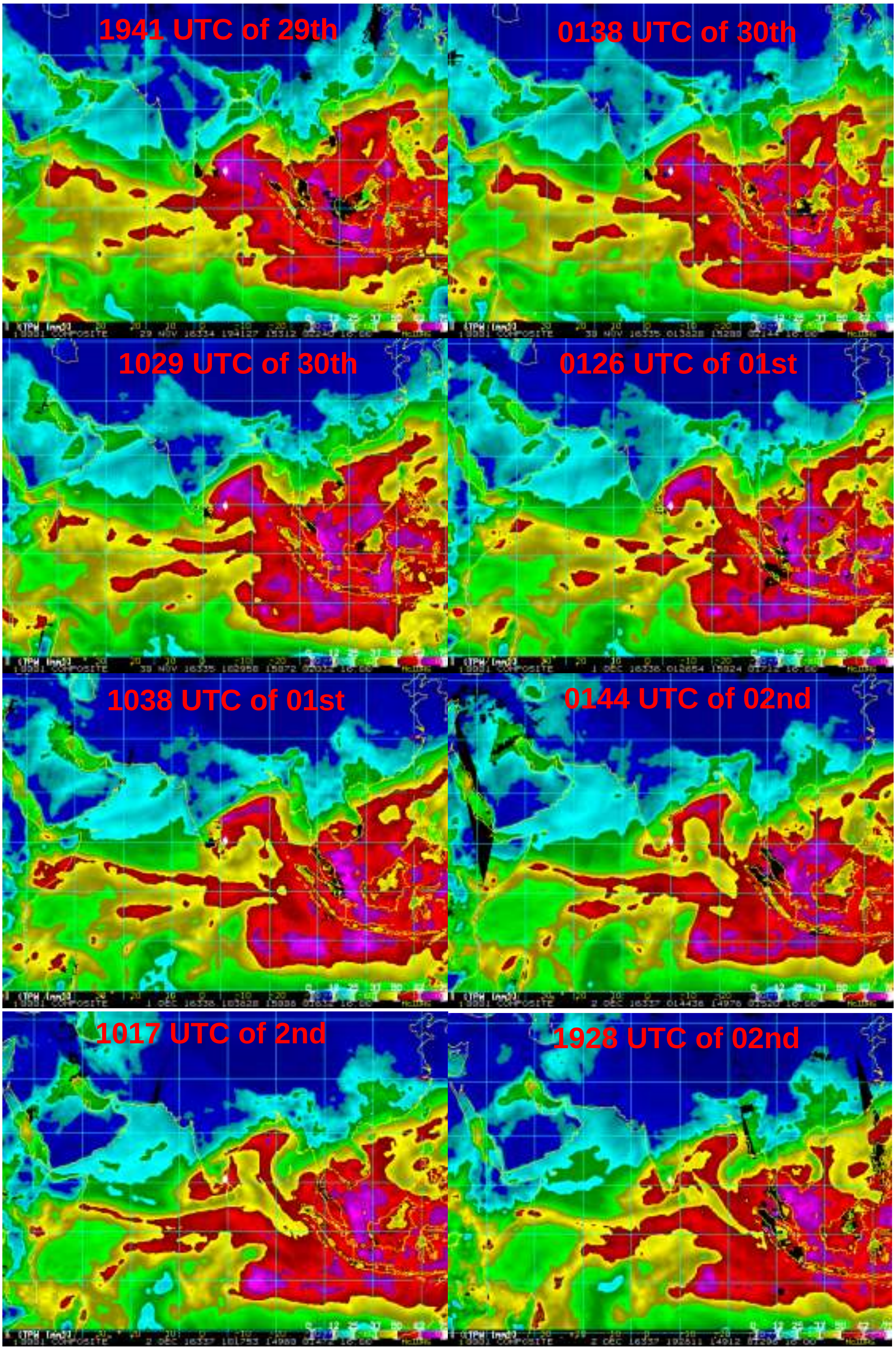


**Fig.2 Total precipitable water imageries during 29th Nov to 02 Dec 2016**

The environmental wind shear between 200-850 hPa and 500-850 hPa are presented in fig.3. It indicates that the vertical wind shear was between 20-50 knots during genesis and intensification stage and then remained around 20 knots during cyclonic storm stage. During the period of dissipation it gradually increased and was about 20-25 knots. The vertical wind shear between lower and middle level also and 500-850 hPa decreased during genesis and intensification stage and then increased during cyclonic storm stage. However unlike the vertical wind shear between upper and lower level, the vertical wind shear between lower and middle level decreased during weakening stage, becoming about 15-20 knots. Thus the vertical wind shear between upper and lower level played a major role in genesis and intensification/weakening of CS Nada.

The mean wind speed and direction between 200-850 hPa and 500-850 hPa are presented in fig.3. It indicates that the mean wind speed between 200-850 hPa was about 10-15 knots during genesis and intensification stage. It then weakened into about 10 knots during weakening of the system. The direction of the wind was nearly $120^0$ indicating west-northwestwards movement. Considering the mean wind speed between 500-850hPa levels, it was initially about 10 knots at the time of genesis and increased to about 15 knots during intensification of the system. Thereafter, it decreased becoming 5-7 knots during weakening stage of the system. The direction of the mean wind was about $120^0$ throughout the life period indicating west-northwestwards movement of the system.

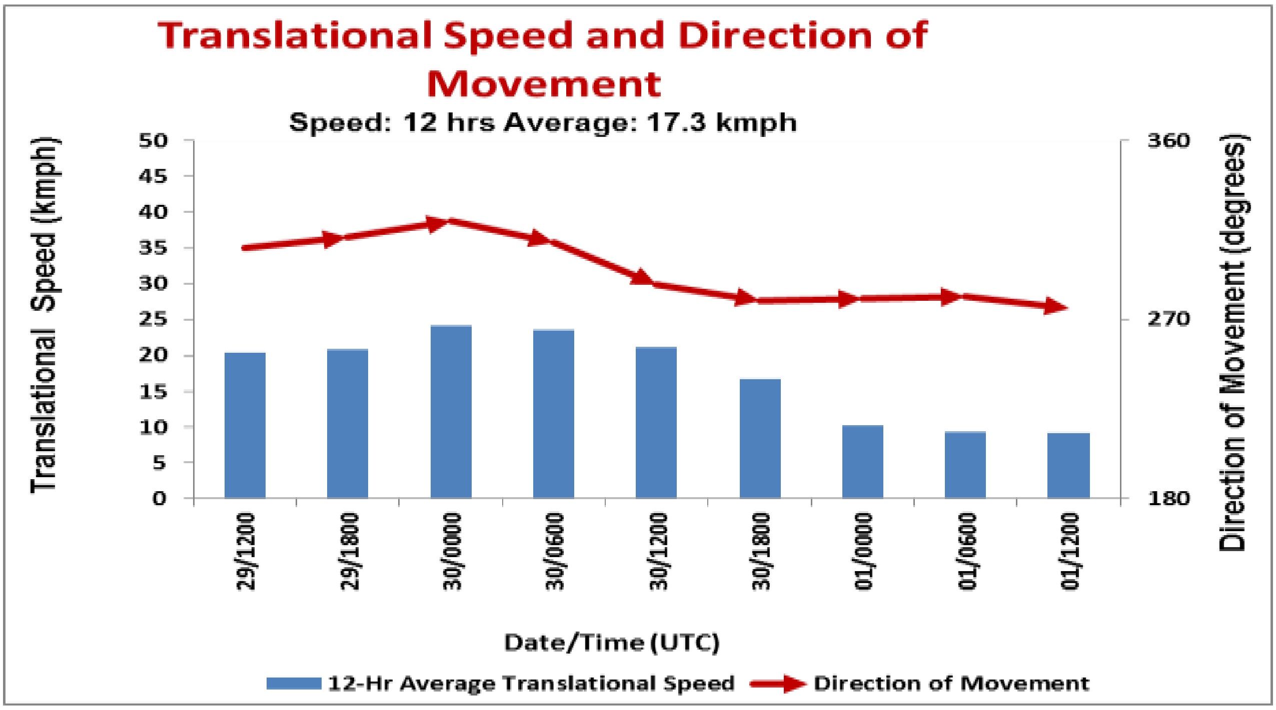


**Fig.4 Twelve hourly average translational speed (kmph) and direction of movement in association with CS Nada**

Comparing with the actual direction of movement and translational speed (Fig.3), the mean wind speed between 200 and 850 hPa levels was identical with the actual translational speed. However, the directions of movement were not in agreement with each other.

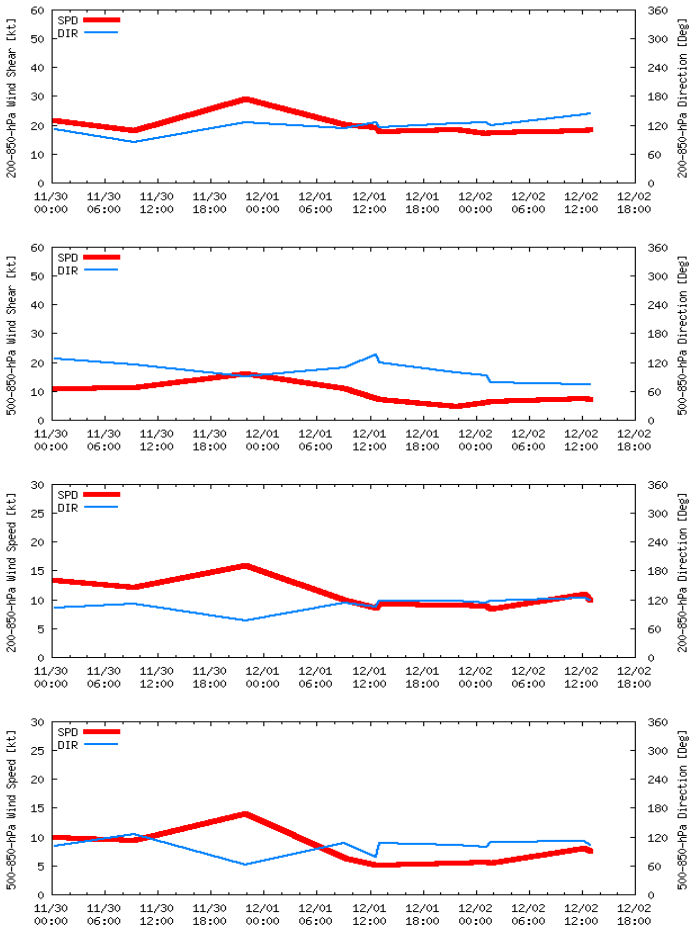


**Fig.4 Wind shear and wind speed in the middle and deep layer around the system during 29th November to 02nd December.**

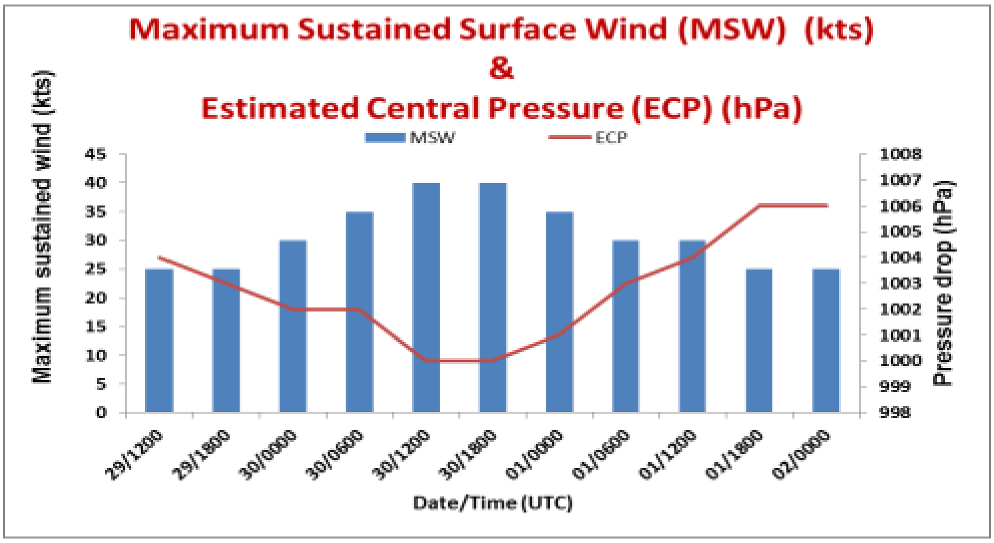


**Fig.5 Lowest estimated central pressure and the maximum sustained wind speed**

### 3.3. 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 1000 hPa. The estimated maximum sustained surface wind speed (MSW) was 40 knots during 1200 UTC of 30th to 2100 UTC of 30th November. At the time of landfall, the ECP was 1006 hPa and MSW was 25 knots (Depression). The figure also indicates that the system did not intensify much despite its long journey over sea mainly because of unfavourable sea condition and dry air incursion from northwest. There was no rapid intensification and rapid weakening of the system throughout its life cycle.

### 4. Climatological aspects

Considering the area of genesis (+/- $2^0$ around the genesis point), the climatological tracks of the TCs during 1891-2015 are presented in Fig.6. It indicates that climatologically, out of 28, only four system recurved northeastwards and remaining moved wet-northwest/ northwestwards. Similarly out of 28, 17 systems intensified into cyclonic storm or higher intensity category.

Most of the system moving northwest/west-northwestwards crossed Tamil Nadu or Sri Lanka coast. Hence the track of Nada was nearly climatological in nature.

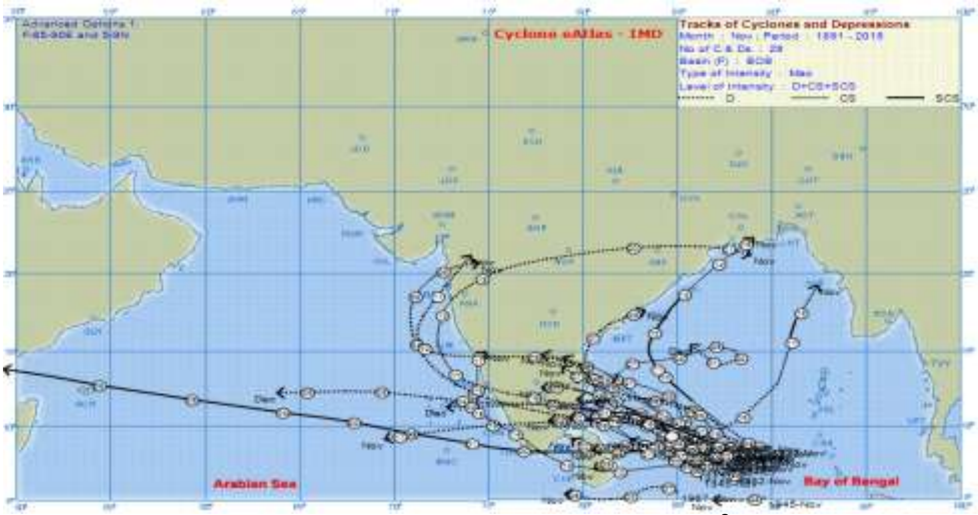


**Fig. 6 Climatological tracks of TCs forming within +/- $2^0$ around the genesis point during 1891-2015.**

### 5. Features observed through satellite and Radar

Satellite monitoring of the system was mainly done by using half hourly Kalpana-1 and 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 enhanced coloured imageries, grey scale enhanced imageries, IR imageries and visible imageries are presented in Fig.7.

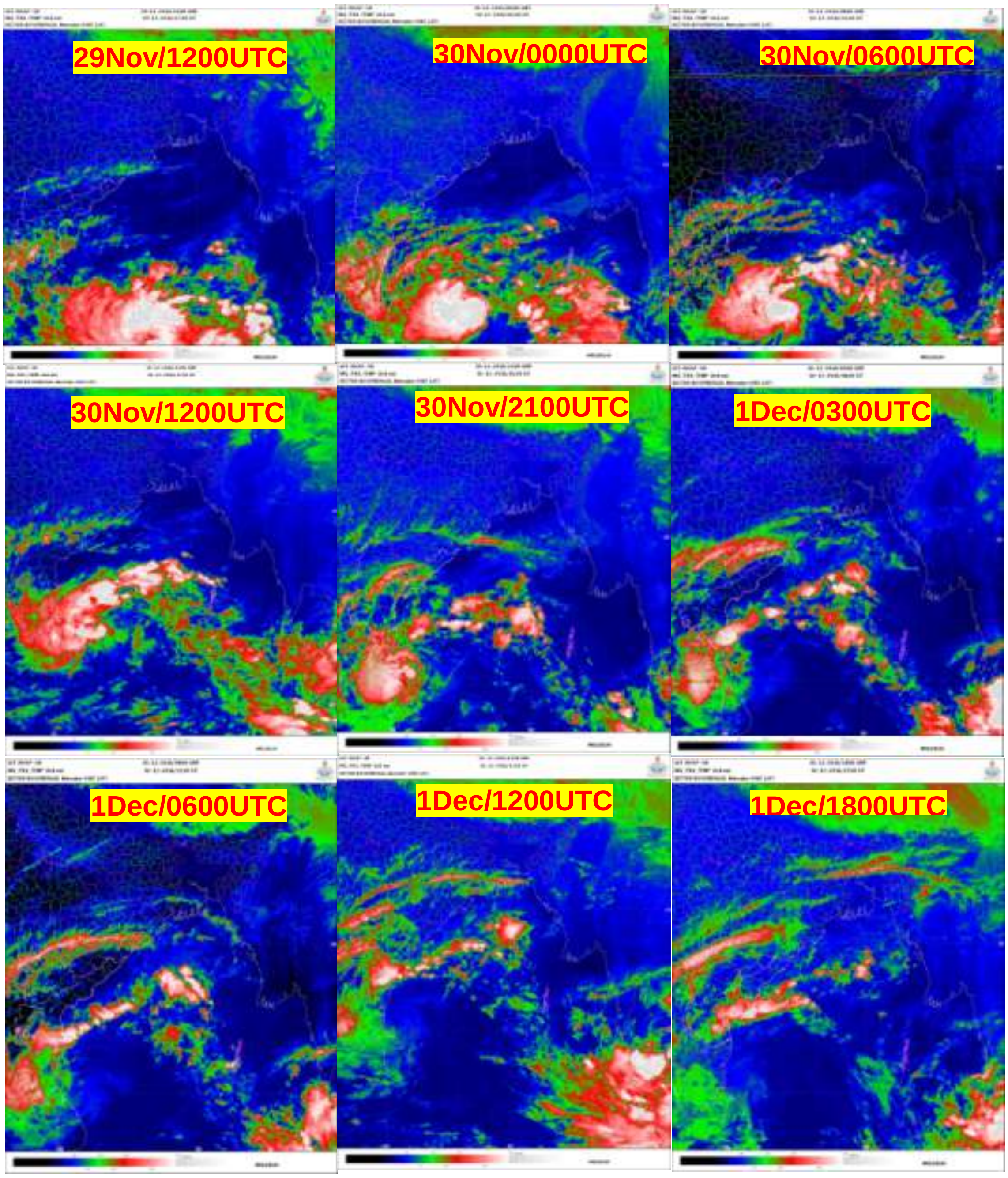


**Fig.7 (a) INSAT-3D enhanced colored imageries based on during 29 Nov – 02 Dec, 2016**

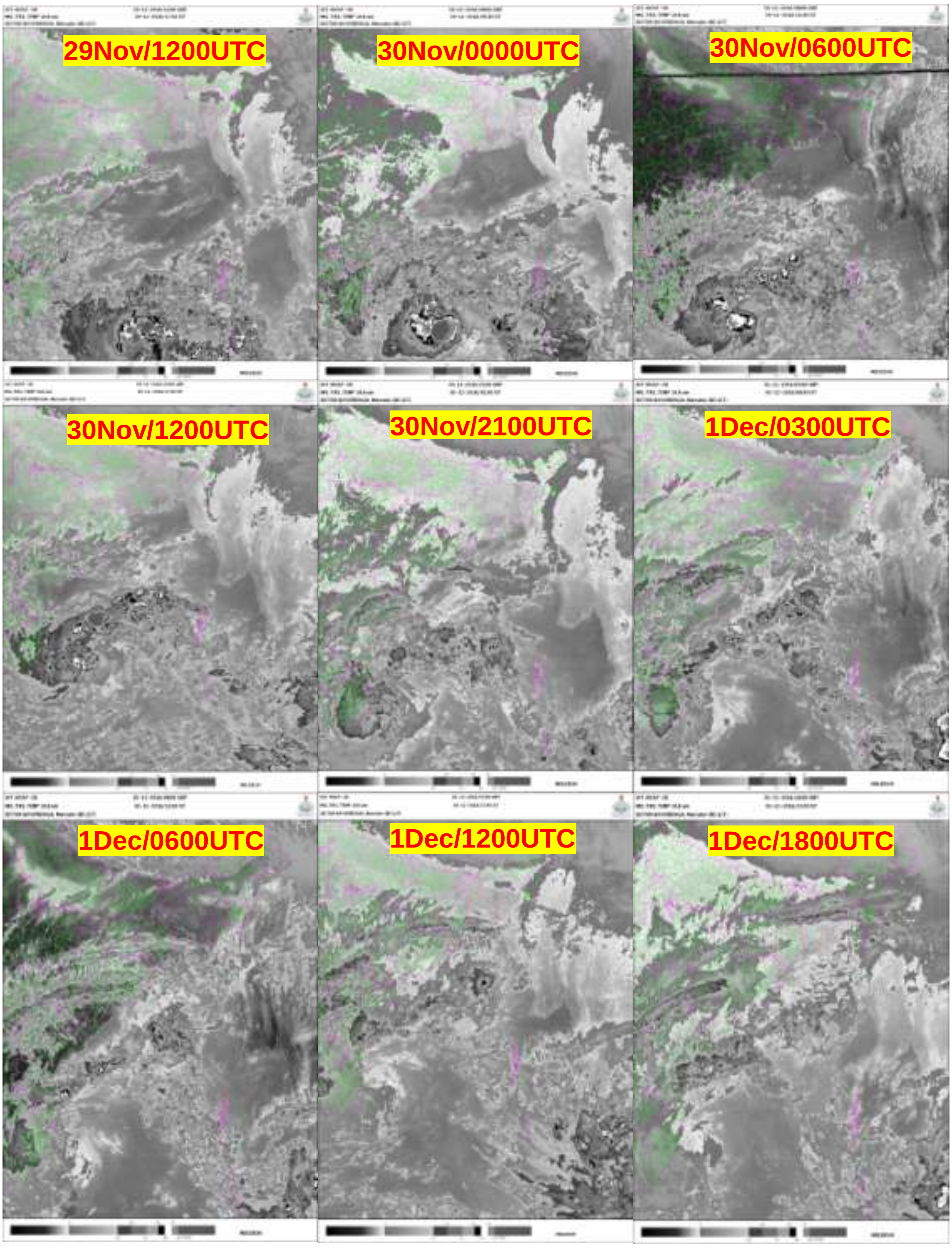


**Fig. 7(b): INSAT-3D enhanced grey scale imageries during 29 Nov – 02 Dec, 2016**

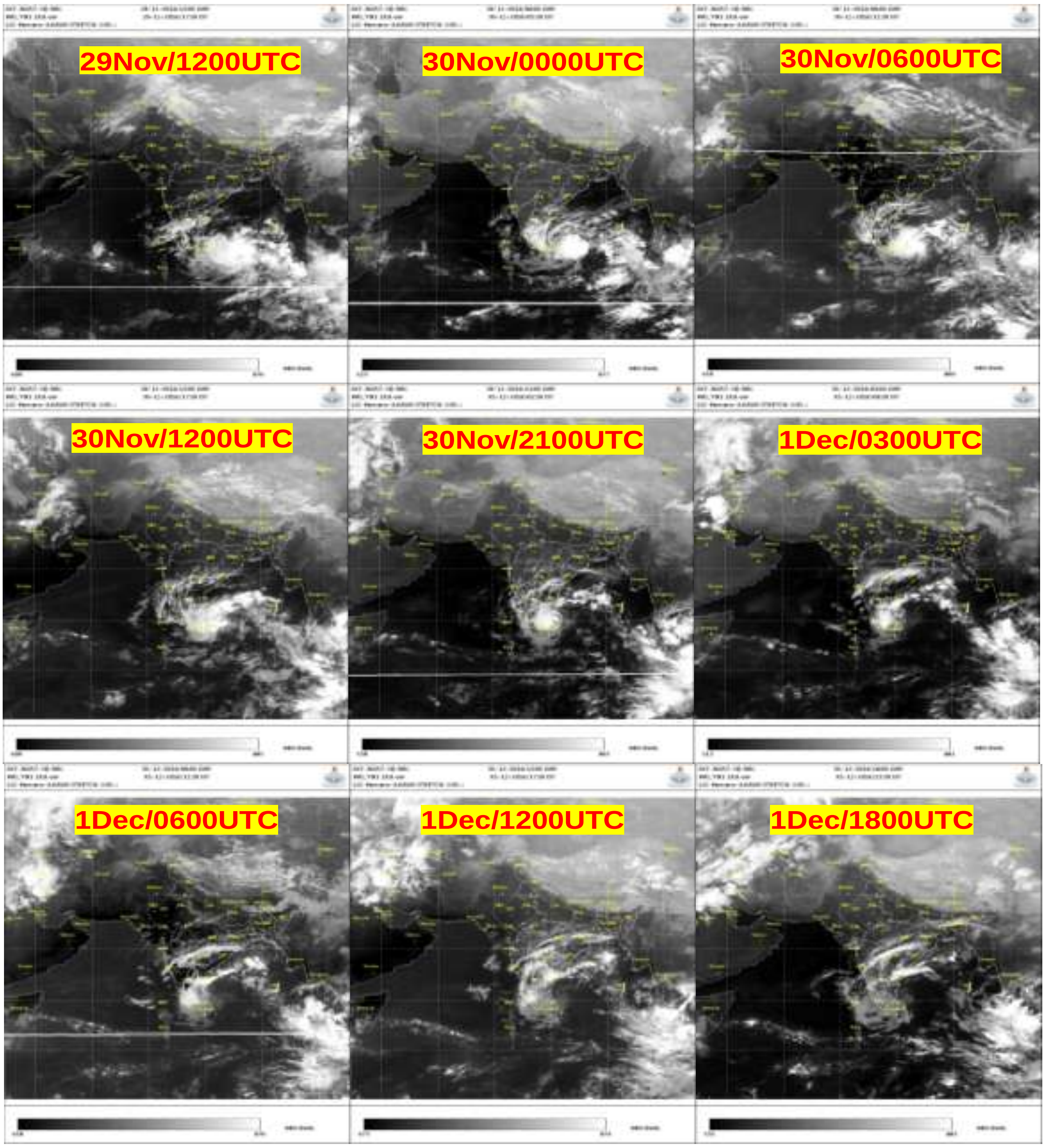


**Fig. 7(c) INSAT-3D IR imageries during 29 Nov- 02 Dec, 2016**

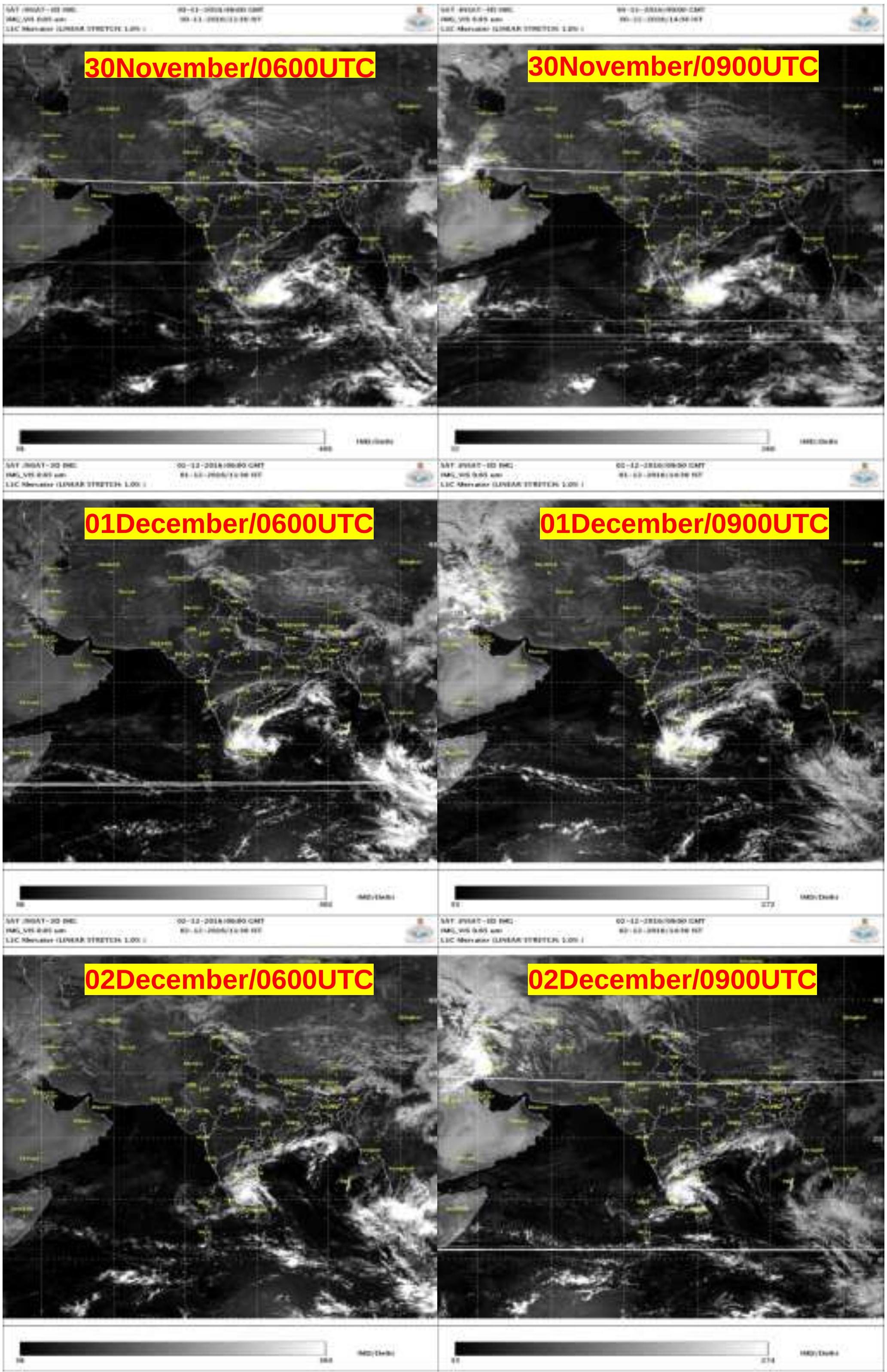


**Fig. 7(d) INSAT-3D Visible imageries during 29 Nov – 02 Dec, 2016**

### 5.3. Features observed through Radar

As the system was tracked by DWR Karaikal Radar imageries during 29th November-02nd December are presented in Fig. 8. The radar imageries helped in detecting the centre of the cyclone accurately, as it could find the spiral band pattern. It also helped in estimating intensity in terms of radial wind observations and the reflectivity of clouds.

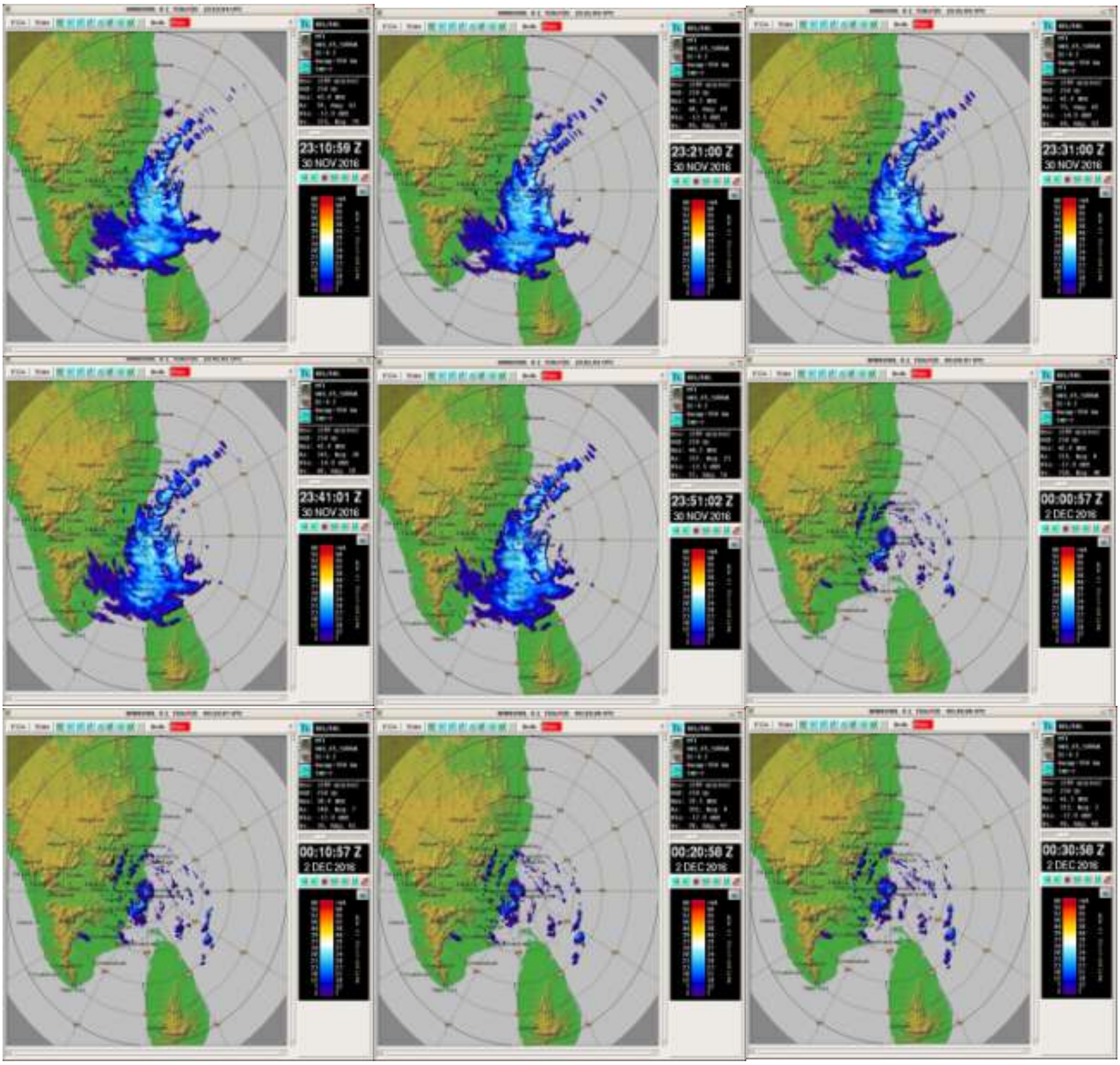


**Fig. 8(a): Plan Position Indicator (PPI) (dBZ) imageries from DWR Karaikal at 2310, 2321, 2331 ,2341, 2351 UTC of 30th November and 0000,0010,0020,00030 UTC of 2nd December,2016**

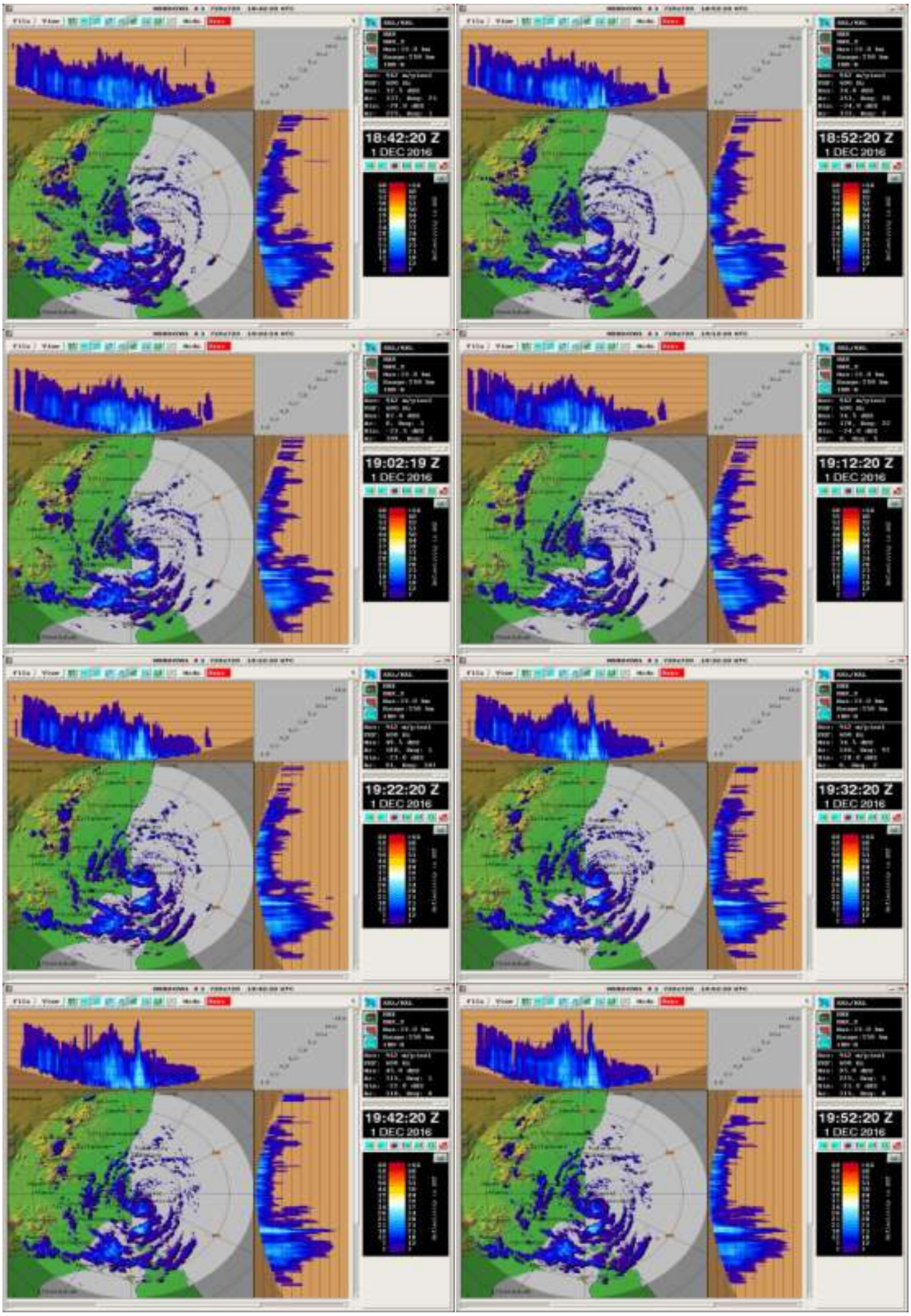


**Fig.8(b): Max(dBZ) imageries from DWR Karaikal at 1842,1852,1902,1912,1922,1932,1942 and 1952 UTC of 1st December 2016.**

## 6. Dynamical features

IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels are presented in Fig.9. GFS (T574) could simulate the genesis of the system and the associated circulation features during the life period of CS Nada.

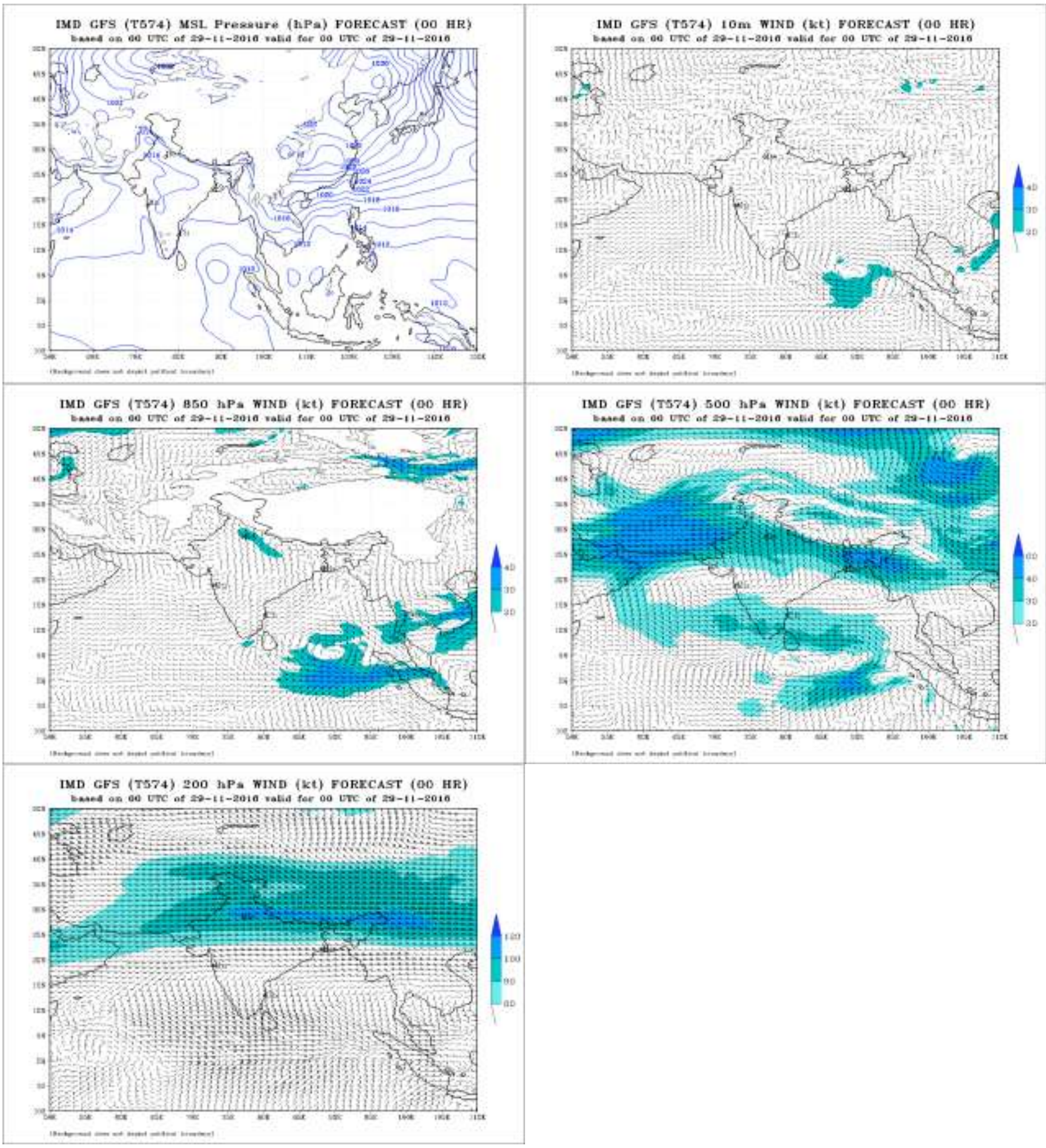


**Fig. 9 (a): IMD GFS MSLP, 10 m wind and winds at 850, 500 and 200 hPa levels based on 0000 UTC of 29th November 2016**

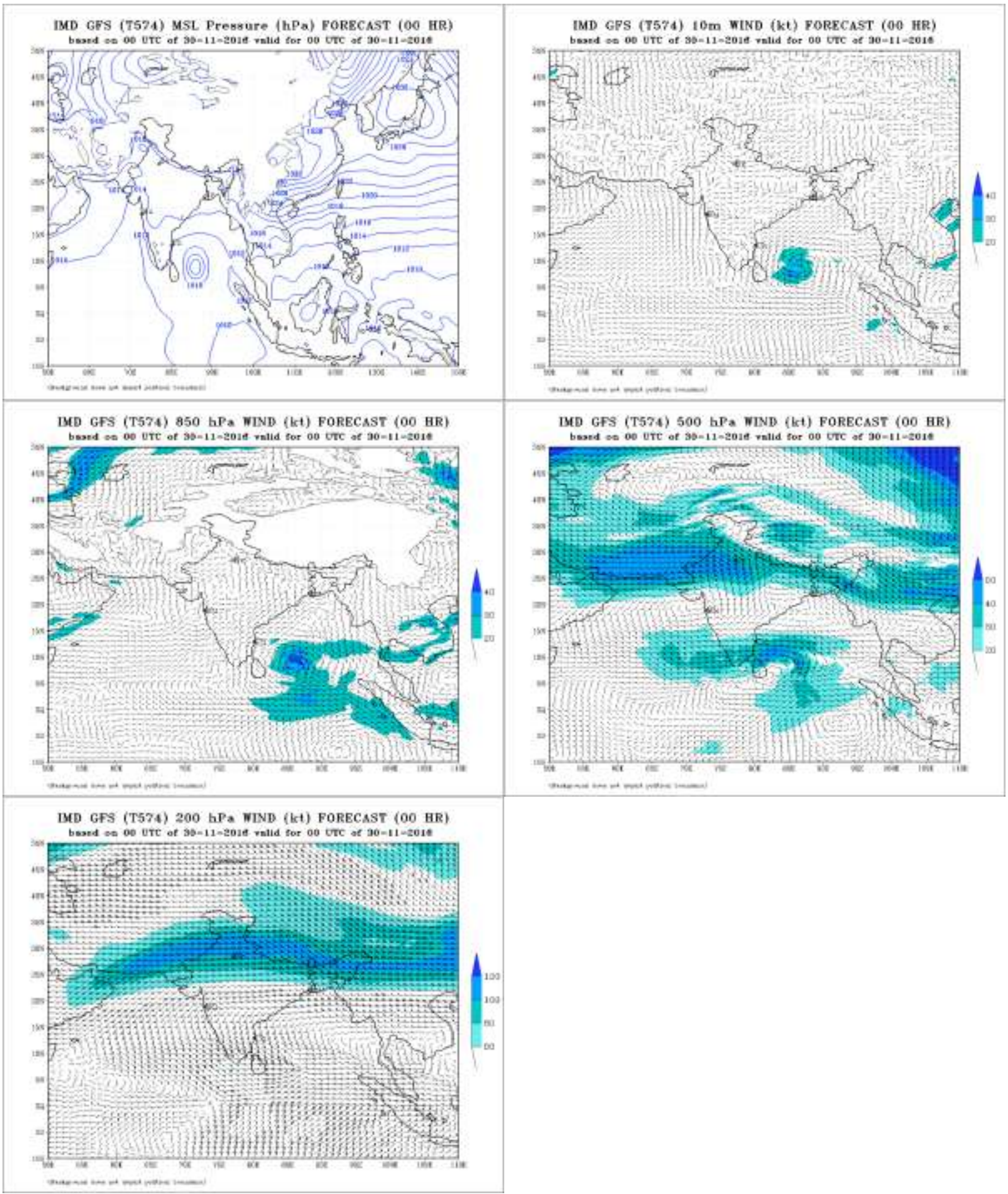


**Fig. 9 (b): IMD GFS MSLP, 10 m wind and winds at 850, 500 and 200 hPa levels based on 0000 UTC of 30th November 2016**

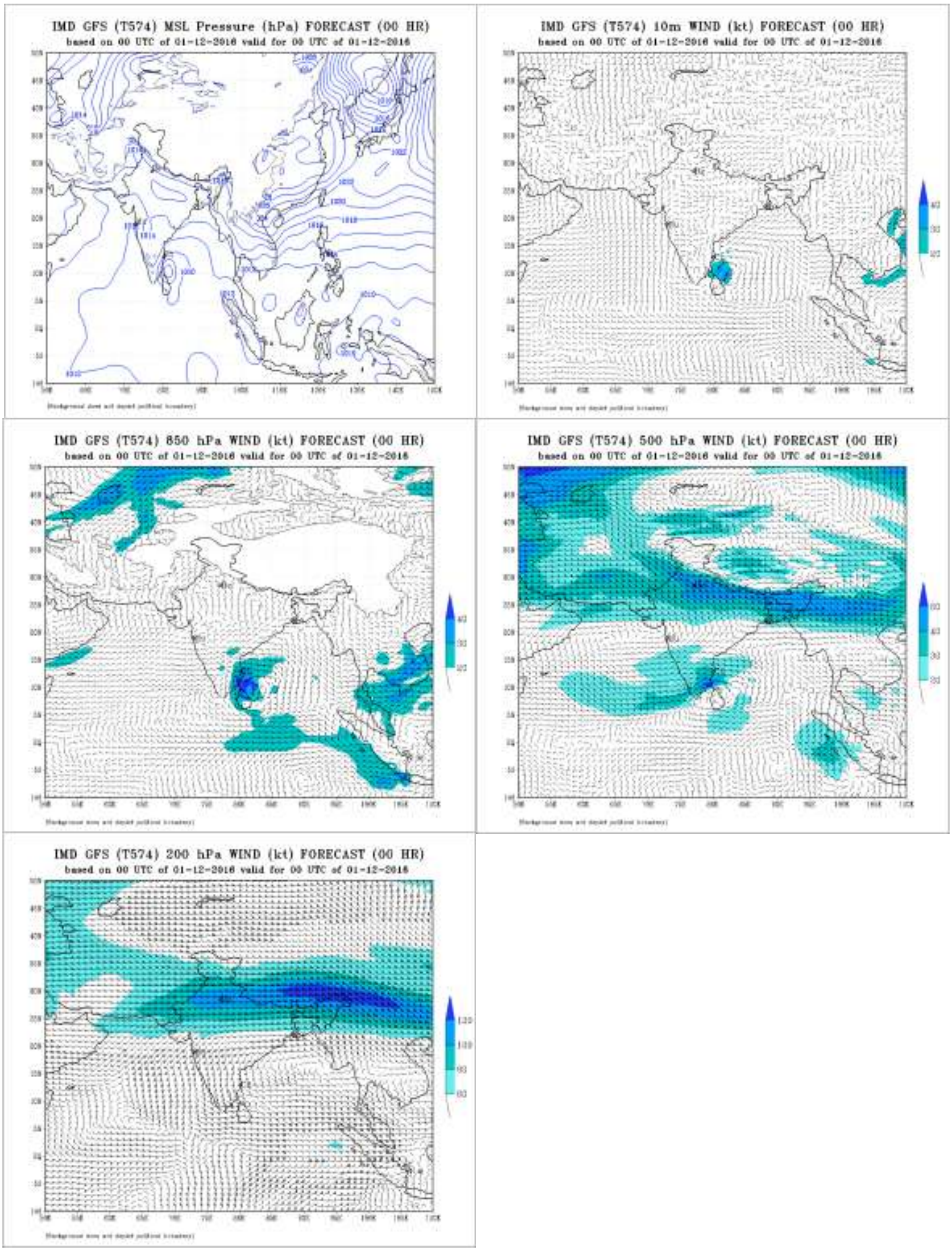


**Fig. 9 (c): IMD GFS MSLP, 10 m wind and winds at 850, 500 and 200 hPa levels based on 0000 UTC of 01st December 2016**

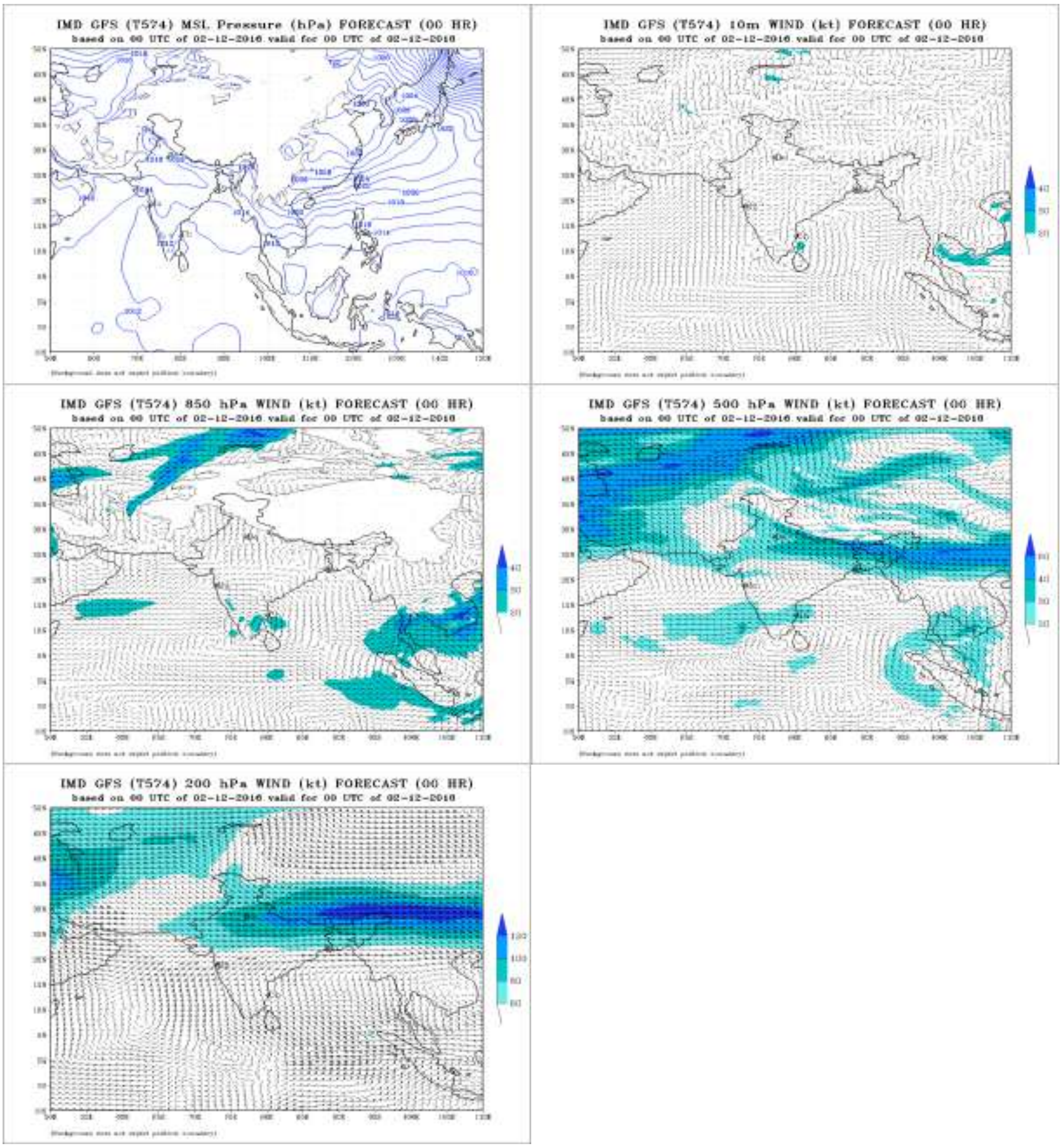


**Fig. 9 (d): IMD GFS MSLP, 10 m wind and winds at 850, 500 and 200 hPa levels based on 0000 UTC of 02nd December 2016**

## 7. Realized Weather:

**Rainfall:**

Rainfall associated with the system is depicted in Fig 10 based on IMD-NCMRWF GPM merged gauge rainfall data. The chief amounts (7 cm or more) of 24 hrs accumulated rainfall ending at 0830 hrs IST of date are given below.

**2nd December**

**COASTAL ANDHRA PRADESH:** Gudur-9
**TAMILNADU & PUDUCHERRY :** Mahabalipuram-11

**3rd December**

**TAMILNADU & PUDUCHERRY:** Kalpakkam and Virudhnagar-8, Madurai Airport, Chennai Airport, Sivakasi, Tirupavnam, Tiruttani, Kancheepuram, Chengalpattu, Metupatti and Tirumangalam-7 each

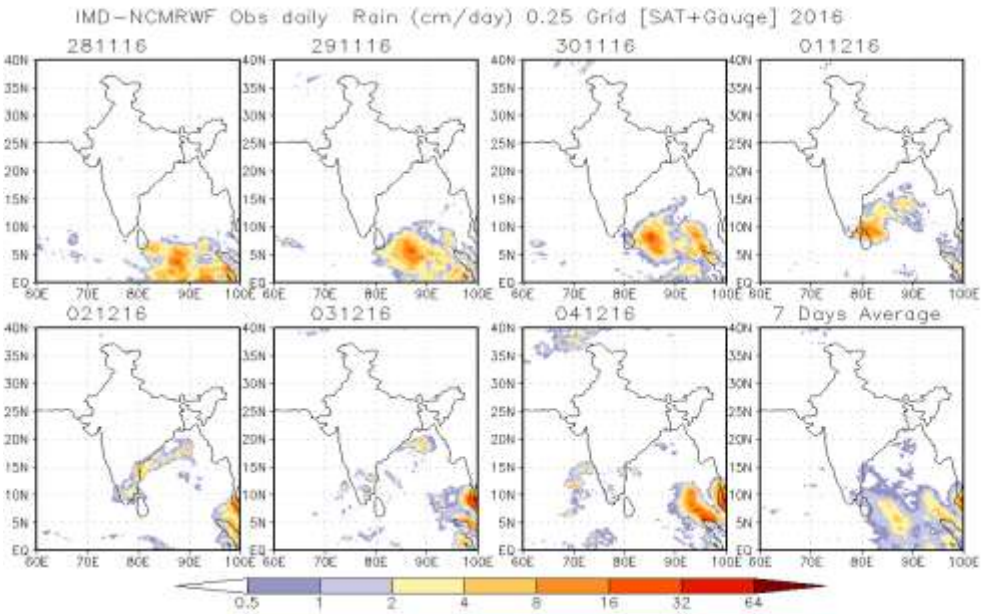


**Fig.10.** IMD-NCMRWF GPM merged gauge rainfall in association with CS, Nada

## 8. Damage due to CS Nada

No damage was reported as Nada weakened and crossed coast as a depression.

## 9. Performance of operational NWP models

IMD operationally runs a regional models, WRF for short-range prediction and one Global model T574L64 for medium range prediction (7 days). The WRF-VAR model is run at the horizontal resolution of 27 km, 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$^o$ S to 45$^o$ N long 40$^o$ E to 120$^o$ E. Initial and boundary conditions are obtained from the IMD Global Forecast System (IMD-GFS) at the resolution of 23 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. Apart from the observations that are used in the earlier system, the new observations assimilated at NCMRWF include (i) Precipitation rates from SSM/I and TRMM (ii) GPSRO occultation (iii) AIRS and AMSRE radiances (iv) MODIS winds. Additionally ASCAT ocean surface winds and INSAT-3D AMVs are also assimilated. NCUM (N768/L70) model features a horizontal resolution of 17km and 70 vertical levels. It uses 4D-Var assimilation and features no cyclone initialization/relocation. NCUM is a grid point model which has a Non-hydrostatic dynamics with a deep atmosphere suitable for all scales. It has semi-implicit time integration with 3D semi-Lagrangian advection, terrain following height coordinates and high order advection. It features mass-flux for shallow convection with convective momentum transport, non-local mixing and entrainment for boundary layer. NCMRWF Ensemble Prediction System (NEPS) is a global medium range probabilistic forecasting system adapted from UK MET Office. The configuration consists of four cycles of assimilation corresponding to 00Z, 06Z, 12Z 18Z and 10-day forecasts are made using the 00Z initial condition. The N400L70 forecast model consists of 800x600 grid points on the horizontal surface and has 70 vertical levels. Horizontal resolution of the model is approximately 33 km in the midlatitudes. The 10 day control forecast run starts with N768L70 analysis of the deterministic assimilation forecast system and 44 ensemble members start from different perturbed initial conditions consistent with the uncertainty in initial conditions. The initial perturbations are generated using Ensemble Transform Kalman Filter (ETKF) method (Bishop et al., 2001).

An important component common to both the deterministic and ensemble model is that they do not use any TC relocation in the analysis.

The Met Office bi-variate approach to tracking TCs is used in the real-time to track the location of the CS ‘Nada’. This method is in contrast to the earlier operational National Centers for Environmental Prediction (NCEP) who use any or all of MSLP, 850 hPa and 700 hPa relative vorticity (RV) and geopotential height to track tropical cyclones (Marchok, 2002). The bi-variate method identifies TCs by examination of the 850RV field, but then fixes the TC centre to the nearest local MSLP minimum (Hamming,2015). Key advantage of the method is that it gives a strong signal of the approximate centre of the TC even for weak systems.

IMD also makes use of NWP products prepared by some other operational NWP centres like, ECMWF (European Centre for Medium Range Weather Forecasting), GFS (NCEP), JMA (Japan Meteorological Agency). Hurricane WRF (HWRF) model and Ensemble prediction system (EPS) has been implemented at the NWP Division of the IMD HQ for operational forecasting of cyclones.

In addition to the above NWP models, IMD also runs 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 I 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 and Decay model for cyclone ROANU are presented and discussed.

### 9.1 Prediction of cyclogenesis (Genesis Potential Parameter (GPP)) for CS Nada

Figure 11 (a-f) shows the predicted zone of cyclogenesis. Grid point analysis and forecasts of GPP could indicate the cyclogenesis zone over south east Bay of Bengal 96 hrs before its formation. 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 forecasts of average GPP (Fig. 12) also showed potential to intensify into a cyclone at early stages of development (T.No. 1.0, 1.5, 2.0).

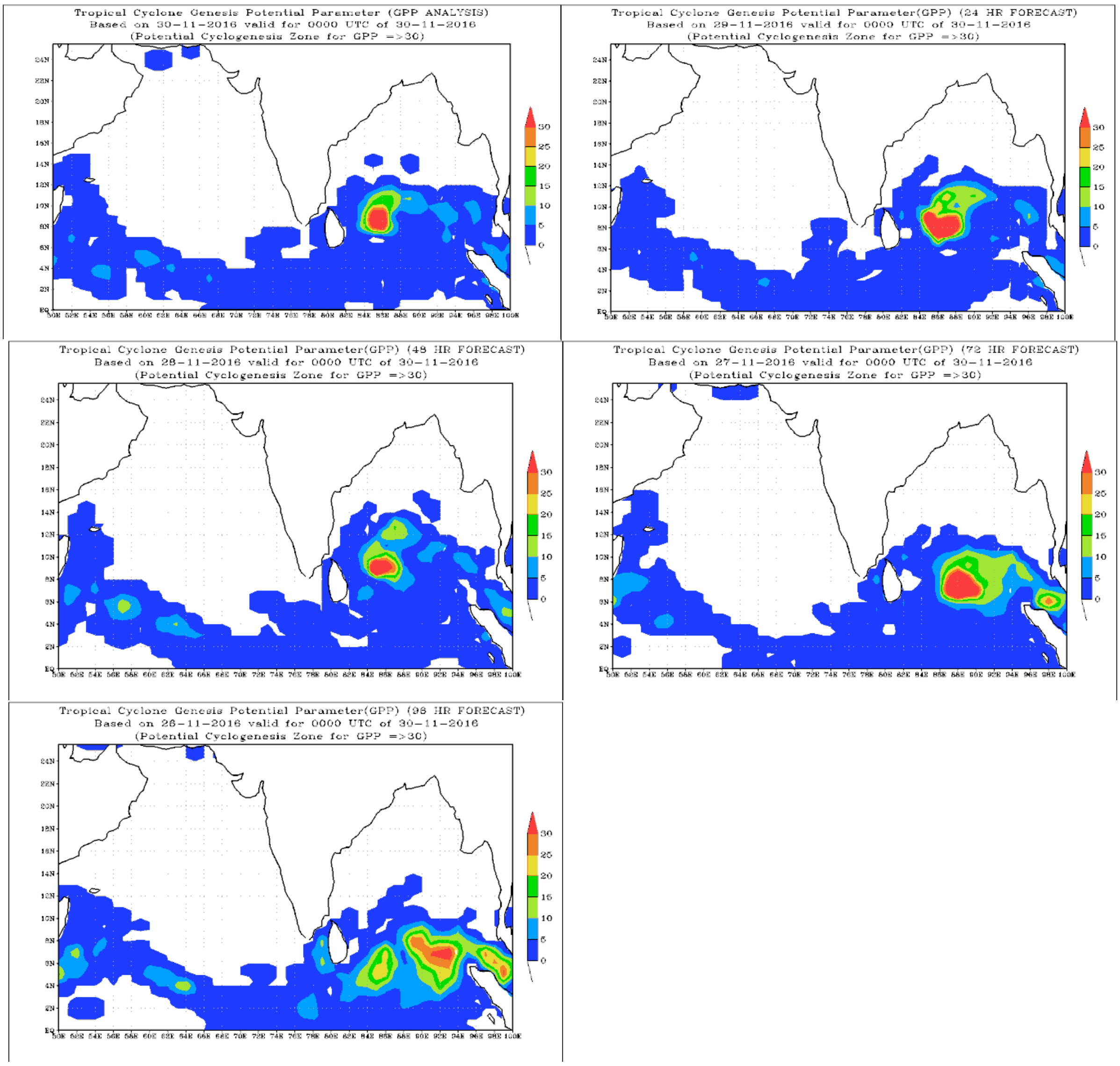


**Figure 11: Predicted zone of cyclogenesis based on 0000 UTC of 26th to 30th November 2016.**

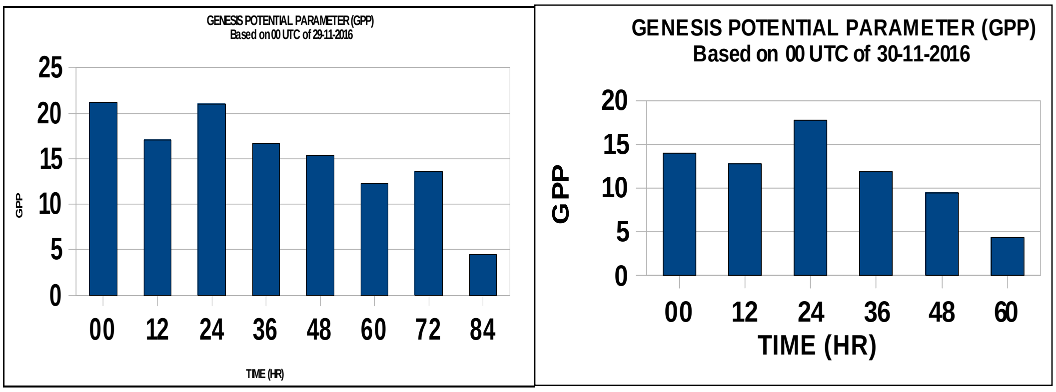


**Fig. 12 : Area average analysis and forecasts of GPP based on 0000 UTC of 29th and 30th November 2016**

## 9.2 Track prediction by NWP models

Track prediction by various NWP models is presented in Fig.13.

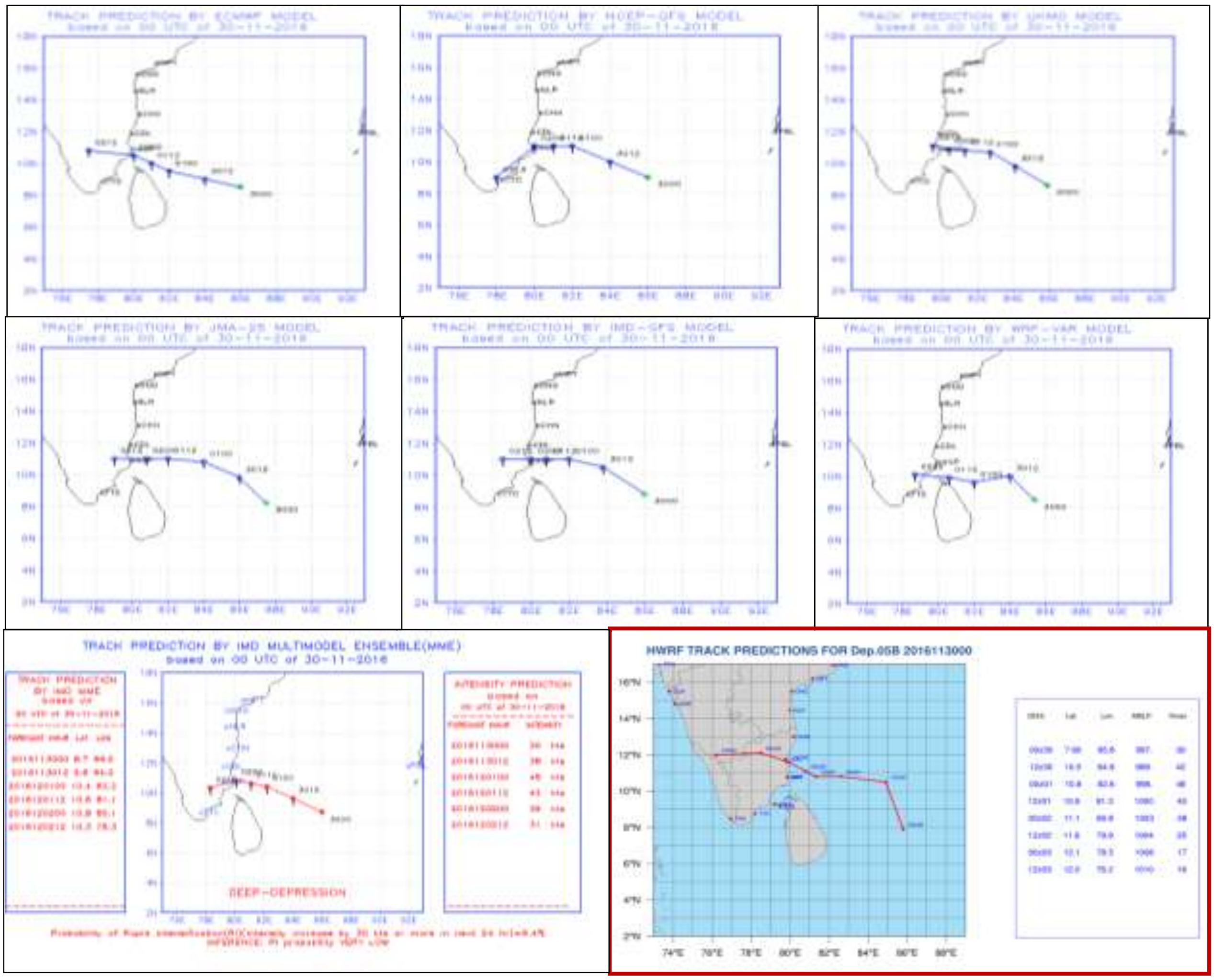


**Fig. 13(a). Track forecast by NWP models based on initial conditions of 0000 UTC of 30th November**

Based on initial conditions of 0000 UTC of 30th November,all models except WRF-Var and HWRF indicated landfall near Karaikal/Nagapattinam. Based on initial conditions of 0000 UTC of 1st December, all models predicted landfall near Nagapattinam or Karaikal except ECMWF and WRF-Var models. The track forecast error of different models are shown in Table 2-4. It indicates that the error was minimum in case of IMD GFS for 24 and 48 hr forecasts. The strike probability and track forecast by individual members of the ensemble are shown in Fig.14.

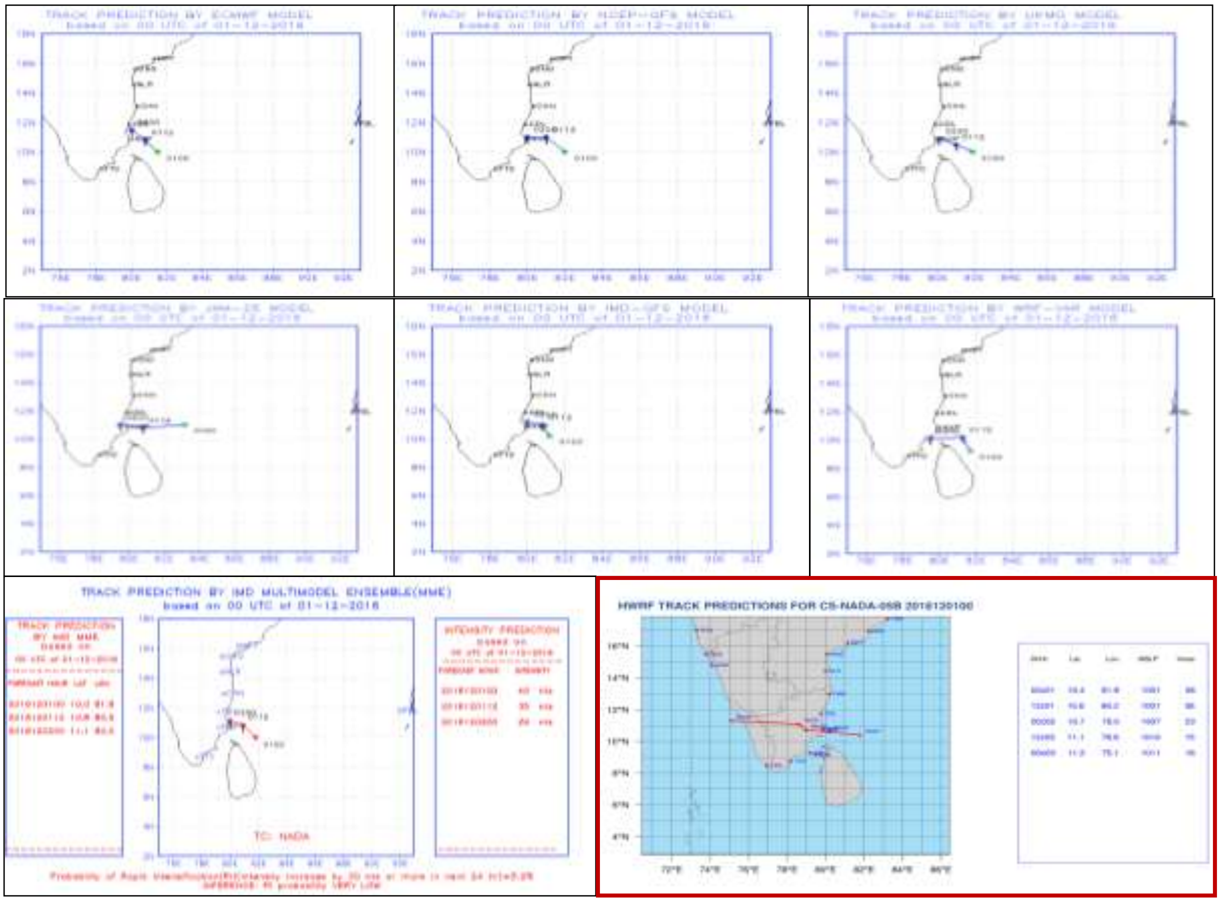

**Fig. 13(b). Track forecast by NWP models based on initial conditions of 0000 UTC of 01st December**

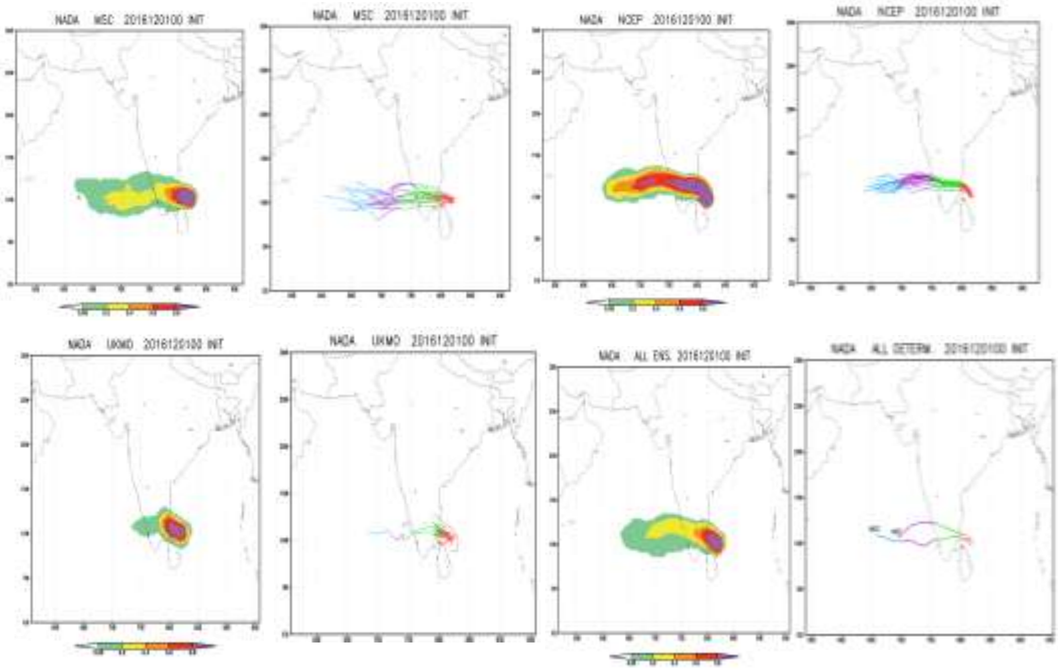

**Fig.14(a): EPS track and strike probability forecast based on 0000 UTC of 01 December**

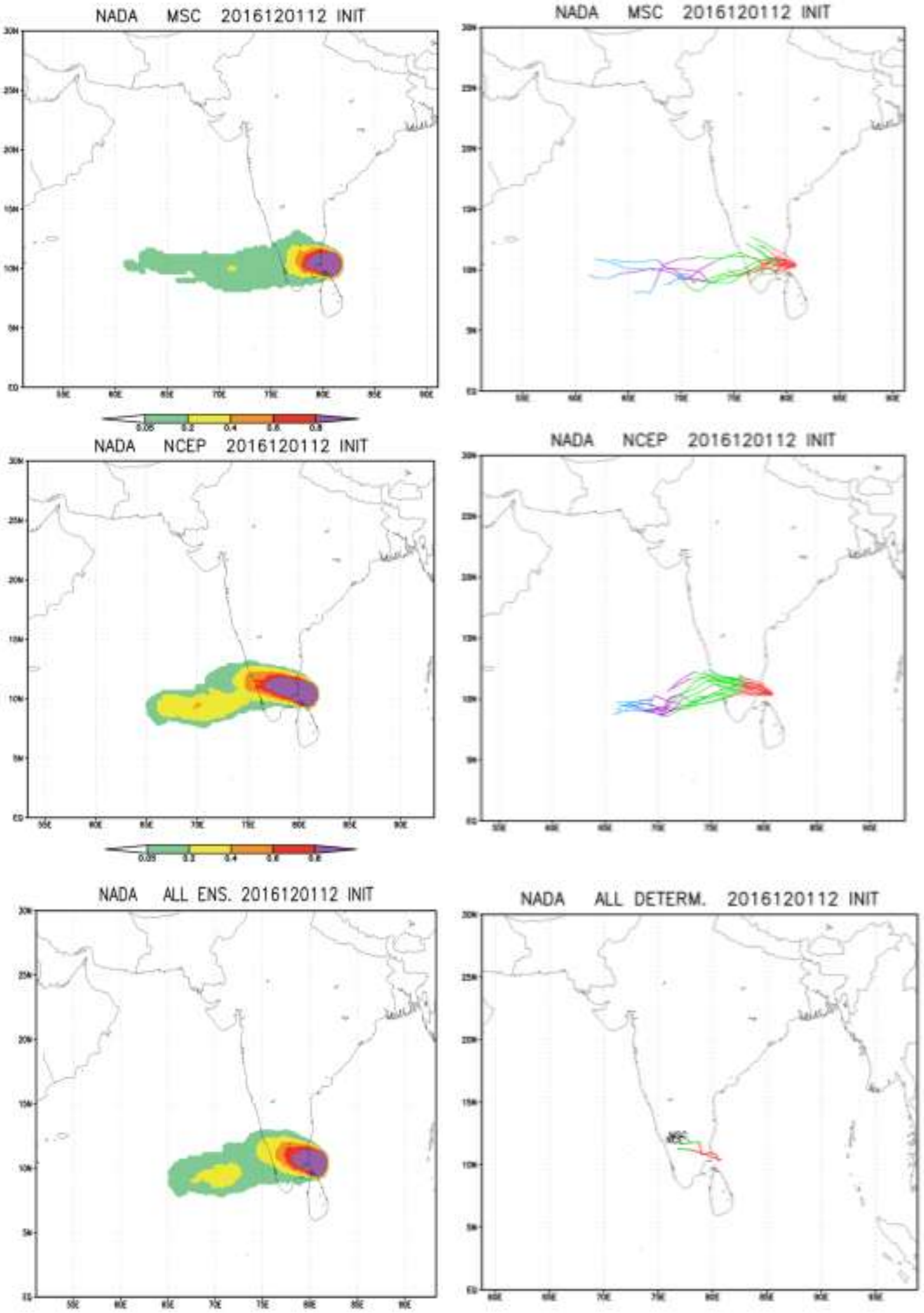


**Fig.14(b): EPS track and strike probability forecast based on 1200 UTC of 01 December**

The landfall point and time forecast errors of different models are shown in Table 5 and 6 respectively. ECMWF and UKMO had better landfall point forecast among different deterministic models. The landfall time error was minimum in case of ECMWF model compared to other deterministic models. The performance was also better for IMD GFS model for 48 hrs forecasts.

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

| Lead time → | 12 hr | 24 hr | 36 hr | 48 hr |
|---|---|---|---|---|
| IMD-GFS | 53(3) | 59(3) | 44(2) | 35(1) |
| IMD-WRF | 56(3) | 106(3) | 106(2) | 139(1) |
| JMA | 143(3) | 119(3) | 99(2) | 117(1) |
| NCEP | 43(3) | 80(3) | 95(2) | 35(1) |
| UKMO | 43(3) | 69(3) | 64(2) | 72(1) |
| ECMWF | 58(3) | 76(3) | 54(2) | 43(1) |
| IMD-HWRF | 69(7) | 69(5) | 65(3) | 119(1) |
| IMD-MME | 34(3) | 51(3) | 55(2) | 38(1) |

**Table 3.** Average cross-track forecast errors (CTE) in km

| Lead time → | 12 hr | 24 hr | 36 hr | 48 hr |
|---|---|---|---|---|
| IMD-GFS | 27 | 51 | 42 | 32 |
| IMD-WRF | 34 | 94 | 101 | 121 |
| JMA | 97 | 84 | 75 | 71 |
| NCEP | 33 | 51 | 60 | 32 |
| UKMO | 19 | 36 | 33 | 42 |
| ECMWF | 37 | 62 | 36 | 18 |
| IMD-HWRF | 45 | 40 | 41 | 81 |
| IMD-MME | 16 | 23 | 24 | 17 |

**Table 4.** Average along-track forecast errors (ATE) in km

| Lead time → | 12 hr | 24 hr | 36 hr | 48 hr |
|---|---|---|---|---|
| IMD-GFS | 40 | 26 | 12 | 14 |
| IMD-WRF | 43 | 38 | 29 | 68 |
| JMA | 103 | 82 | 61 | 92 |
| NCEP | 27 | 55 | 67 | 14 |
| UKMO | 38 | 56 | 54 | 58 |
| ECMWF | 45 | 37 | 39 | 39 |
| IMD-HWRF | 43 | 49 | 49 | 87 |
| IMD-MME | 29 | 43 | 48 | 34 |

**Table 5:** Landfall point forecast errors (km) of NWP Models at different lead time (hour)

| Forecast Lead Time (hour) → | 23 hr | 35 hr | 47 hr |
|---|---|---|---|
| **Based on→** | **01Dec/00z** | **30 Nov/12z** | **30 Nov/00z** |
| **IMD-GFS** | - | 65 | 30 |
| **IMD-WRF** | - | 122 | 129 |
| **JMA** | 30 | 65 | 30 |
| **NCEP** | - | 40 | 39 |
| **UKMO** | - | 12 | 39 |
| **ECMWF** | - | 12 | 30 |
| **IMD-HWRF** | 17 | 119 | 106 |
| **IMD-MME** | 40 | 30 | 12 |

Landfall Point Error: Landfall Forecast Point- Actual Landfall Point
-: No forecast issued

**Table 6.** Landfall time forecast errors (hour) at different lead time (hr)

| Forecast Lead Time (hour) → | 23 hr | 35 hr | 47 hr |
|---|---|---|---|
| **Based on→** | **01Dec/00z** | **30 Nov/12z** | **30 Nov/00z** |
| **IMD-GFS** | - | +3 | +2 |
| **IMD-WRF** | - | +2 | -2 |
| **JMA** | -2 | +3 | +8 |
| **NCEP** | - | +8 | +2 |
| **UKMO** | - | +6 | +8 |
| **ECMWF** | - | -2 | +2 |
| **IMD-HWRF** | -9 | +13 | +14 |
| **IMD-MME** | +1 | +6 | +1 |

Landfall Time Error: Landfall Forecast Time- Actual Landfall Time
- : No forecast issued

('+' indicates delay landfall, '-' indicates early landfall)

**Intensity prediction**

The intensity forecasts of IMD-SCIP model and HWRF model are shown in Table 7. The errors were relatively higher in case of HWRF. The probability of rapid intensification (RI) index of IMD is shown in Table 8. It correctly predicted no RI for cyclone, Nada.

**Table 7:** 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 → | 12 hr | 24 hr | 36 hr |
|---|---|---|---|
| IMD-HWRF (AAE) | 6.0 (7) | 9.0 (5) | 9.6 (3) |
| IMD-HWRF (RMSE) | 7.4 (7) | 10.4 (5) | 10.7 (3) |

( ) : No of forecasts verified

**Table 8:** Probability of Rapid intensification

| Forecast based on | Probability of RI predicted | Chances of occurrence predicted | Intensity changes(kt) occurred in 24h |
|---|---|---|---|
| 00UTC/30.11.2016 | 9.4 % | VERY LOW | 5 |
| 12UTC/30.11.2016 | 9.4 % | VERY LOW | -10 |
| 00UTC/01.12.2016 | 5.2 % | VERY LOW | -10 |

**Heavy rainfall forecast by HWRF model**

The forecast rainfall swaths by HWRF model are presented in Fig.15. It indicates that the HWRF model predicted the occurrence of rainfall along Indian coast (north Tamil Nadu and Andhra Pradesh) based on initial conditions of 0000 UTC of 30 November and 01 December. However, the predicted rainfall intensity was less based on initial condition of 01 Dec as the model predicted weakening of the system

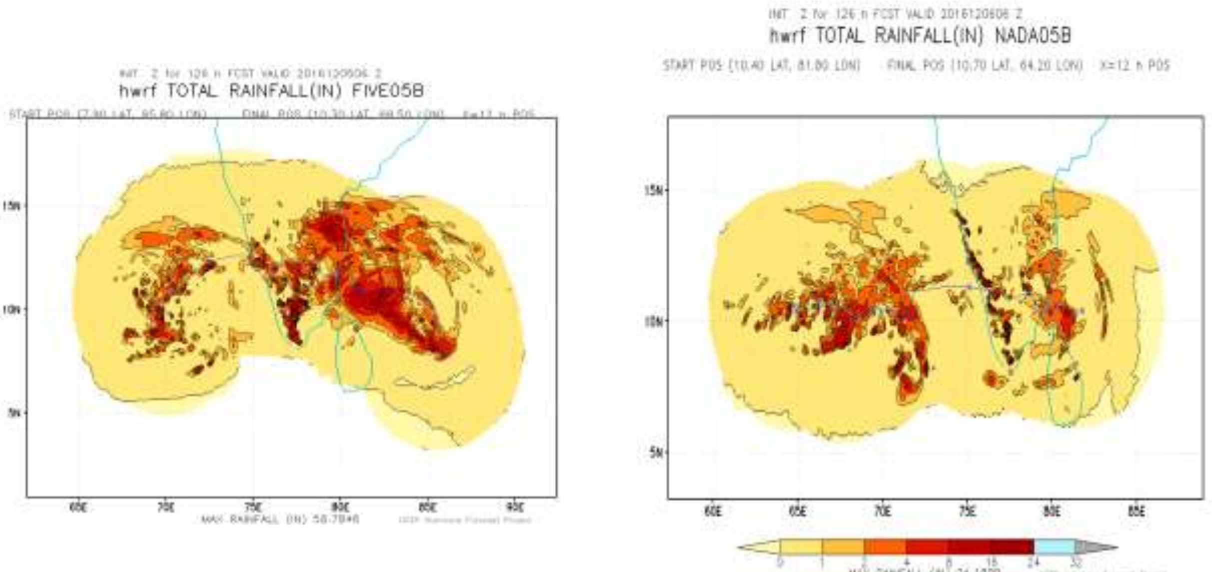


**Fig.15. Rainfall swath predicted by HWRF model based on initial condition of 0000 UTC of 30th November and 01st December 2016.**

## 10. Operational Forecast Performance

### 10.1 Operational Genesis forecast

IMD first predicted genesis of depression over southeast Bay of Bengal (BoB) on 29th November based on the observations of 0000 hours IST of 27th November .

### 10.2. Operational landfall forecast error and skill

The operational landfall forecast errors and skill are presented in Table 8. The point and time of landfall over Tamil Nadu coast was also predicted accurately with 24 hr landfall point forecast error of about 28 km and landfall time forecast error of about 4 hrs (Table 9).

**Table 9: Landfall Point and Time Error in association with CS Nada**

| Lead Period (hrs) | Base Time | Landfall Point (degrees) | | Landfall Time (hours) | | Operational Error | | LPA error (2011-15) | |
|---|---|---|---|---|---|---|---|---|---|
| | | Forecast | Actual | Forecast | Actual | LPE (km) | LTE (hours) | LPE (km) | LTE (hours) |
| 12 | 01/1200 | 10.9/79.9 | 10.75/79.9 | 01/2000 | 01/2300 | 17 | 3.0 | 36.5 | 2.5 |
| 24 | 01/0000 | 11.0/79.9 | 10.75/79.9 | 01/1800 | 01/2300 | 28 | 5.0 | 56.3 | 4.2 |
| 36 | 30/1200 | 11.3/79.9 | 10.75/79.9 | 01/2200 | 01/2300 | 61 | 1.0 | 60.6 | 4.7 |
| 48 | 30/0000 | 11.4/79.9 | 10.75/79.9 | 01/2100 | 01/2300 | 72 | 2.0 | 93.5 | 4.7 |

The LPA error is based on 12, 24,…72 hours lead period.
LPE: Landfall Point Error, LTE: Landfall Time Error, LPA: Long Period Average,
LPE= Forecast Landfall Point-Actual Landfall Point
LTE= Forecast Landfall Time-Actual Landfall Time

### 10.3 Operational track forecast error and skill

The operational average track forecast errors and skills (compared to climatological and persistence (CLIPER) forecasts) are shown in Table 10. The 24 hr track forecast error & skill were 68.9 km & 63.4% against long period average (2011-15) of 97.5 km & 48.5%.

**Table 10: Average Track forecast error and skill in association with CS Nada**

| Lead Period (hrs) | N | Average track forecast error (km) | Skill (%) | LPA (2011-15) | |
|---|---|---|---|---|---|
| | | | | Track forecast error (km) | Skill (%) |
| 12 | 7 | 63.7 | 27.1 | 59.1 | 41.4 |
| 24 | 5 | 68.9 | 63.4 | 97.5 | 48.5 |
| 36 | 3 | 54.9 | 80.1 | 120.0 | 58.1 |
| 48 | 1 | 98.4 | 65.8 | 145.5 | 62.7 |

N: No. of observations verified, LPA: Long Period Average

### 10.4 Operational Intensity forecast error and skill

The operational intensity forecast errors and skill compared to persistence forecast in terms of absolute error (AE) and root mean square error (RMSE) are presented in Table 11. The operational AE and RMSE in intensity forecast has been significantly less than LPA for 24 and 48 hours lead period. The skill in intensity forecast with reference to AE and RMSE is also higher than LPA for these lead periods.

**Table 11: Average Intensity forecast error in association with CS Nada**

| Lead Period (hrs) | N | Average Intensity Error (kts) | | LPA Intensity forecast Error (kts) (2011-15) | | Gain in Skill (%) against Persistence | | LPA Gain in Skill (%) against Persistence (2011-15) | |
|---|---|---|---|---|---|---|---|---|---|
| | | AE | RMSE | AE | RMSE | AE | RMSE | AE | RMSE |
| 12 | 7 | 3.8 | 5.0 | 7.1 | 9.4 | 40.6 | 42.4 | 20.9 | 27.9 |
| 24 | 5 | 8.6 | 9.7 | 11.5 | 14.9 | 49.6 | 53.6 | 36.4 | 40.1 |
| 36 | 3 | 12.1 | 12.5 | 14.8 | 19.2 | 63.7 | 65.0 | 49.4 | 52.0 |
| 48 | 1 | 10.1 | 10.1 | 16.9 | 21.6 | 59.5 | 59.5 | 55.8 | 59.6 |

N: No. of observations verified; AE: Absolute Error; RMSE: Root Mean Square Error, LPA: Long Period Average (2011-15). There was no track forecast verification for 96-120 hours due to short track of the CS.

### 10.4. Adverse weather forecast verification

The verifications of adverse weather like heavy rainfall and gale wind forecast issued by IMD are presented in Table 12-13. It is found that adverse weather was predicted accurately and well in advance.

**Table – 12. Verification of heavy rainfall warning in case of CS, Nada**

| Date/ Time(IST) | Heavy rainfall warning issued | 24-hour Heavy rainfall realized ending at 0300UTC |
|---|---|---|
| **30.11.2016 0300 UTC** | Heavy to very rainfall at a few places over Tamilnadu and Puducherry and isolated heavy to very rainfall over interior Tamilnadu on 1st and 2nd December. | Isolated heavy rainfall over Tamilnadu, Puducherry & coastal Andhra Pradesh |
| **01.12.2016 0300 UTC** | Isolated heavy to very heavy rainfall over Tamilnadu and Puducherry during next 48 hours. | |

The verification of gale wind forecasts (Table 13) indicate that, the wind along the coast at the time of landfall was correctly predicted as, weakening of the system at the time of landfall was well predicted by IMD.

**Table 13. Verification of Gale Wind Forecast**

| Date/ Time(IST) | Sqall/ Gale wind Forecast | Recorded wind speed (knots) |
|---|---|---|
| **30.11.2016 0300 UTC** | Squally wind speed reaching 45-55 kmph gusting to 65kmph along and off Tamil Nadu & Puducherry coasts from 1st December morning. | 35-45 kmph along Tamil Nadu coast |
| **01.12.2016 0300 UTC** | Squally wind speed reaching 45-55 kmph gusting to 65kmph along and off Tamil Nadu & Puducherry coasts during next 24 hours. | |

## 11. Bulletins issued by IMD

- **Track, intensity and landfall forecast:** IMD continuously monitored, predicted and issued bulletins containing track, intensity, and landfall forecast upto 96hrs or till the system weakened into a low pressure area. The above forecasts were issued from the stage of deep 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 knots, ≥50 knots and ≥64 knots wind in four quadrants of cyclone was issued every six hourly giving forecast for +06, +12, +18, +24, +36, +48, +60, +72, +84 and +96 hrs lead period.
- **Diagnostic and prognostic features of cyclone:** The prognostics and diagnostics of the systems were described in the RSMC bulletins and tropical cyclone advisory bulletins.
- **TC Vital:** Tropical cyclone vitals were prepared every six hourly from deep 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.
- **Tropical cyclone forecasts and adverse weather warning bulletins:** The tropical cyclone forecasts alongwith expected adverse weather like heavy rain, gale wind were issued with every three hourly update during cyclone period to the central, state and district level disaster management agencies including MHA, NDRF, NDMA, Tamil Nadu, Andhra Pradesh Kerala & Puducherry. The bulletin also contained the expected damage and suggested action by disaster managers and general public. These bulletins were also issued to Railways, surface transport, Defence including Indian Navy & Indian Air Force, Ministry of Agriculture, Ministry of Information and Broadcasting etc.
- **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. Typical graphical products displaying track with cone of uncertainty and wind distribution forecast are presented in Fig 3.
- **Warning and advisory through social media:** Daily updates were uploaded on facebook 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.
- **Warning and advisory for marine community:** The three/six hourly bulletins were issued by the cyclone warning division at New Delhi and cyclone warning centres of IMD at Chennai to ports, fishermen, coastal and high sea shipping community
- **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.

Statistics of bulletins issued by Cyclone Warning services of IMD in association with the cyclone Nada are given in Table 14

**Table 14(a): Bulletins issued by Cyclone Warning Division, New Delhi**

| S.N. | Bulletin | No. of Bulletins | Issued to |
|---|---|---|---|
| 1 | National Bulletin | 17 | 1. IMD's website<br>2. FAX and e-mail to Control Room NDMA, Cabinet Secretariat, Minister of Sc. & Tech, Secretary MoES &DST, HQ Integrated Defence Staff & CDS, DG Doordarshan, DG All India Radio, DG-NDRF, Dir. Indian Railways, Indian Navy, IAF, Chief Secretary-Tamil Nadu, Kerala, Andhra Pradesh, Puducherry. |
| 2 | RSMC Bulletin for WMO/ ESCAP Panel countries | 15 | 1. IMD's website<br>2. All WMO/ESCAP member countries through GTS and E-mail.<br>3. Indian Navy, IAF by E-mail |
| 3 | Tropical Cyclone Advisory Centre Bulletin (Text & Graphics) | 12 | 1. Met Watch offices in Asia Pacific regions though GTS to issue Significant Meteorological information for International Civil Aviation<br>2. WMO's Aviation Disaster Risk Reduction (ADRR), Hong Kong through ftp<br>3. RSMC website |
| 4 | Cyclone Warnings through SMS | 35,634 by IMD 1,63,394 by Kisan portal , 36944 by INCOIS | SMS through (i) IMD network for disaster managers (once daily), (ii) IMD's public registration using Department of Electronics and Information Technology network, (iii) INCOIS network (36,944) for fishermen and Kisan Portal for farmers (1,63,394).<br>No. of SMS issued to public by Department of Electronics and Information Technology network is about 2,35,15 |
| 5 | Cyclone Warnings through Social Media | Twice daily | Cyclone Warnings were uploaded on Social networking sites like Face book and Tweeter. |

**Table 14 (b): Bulletins issued by ACWC Chennai**

| S.No. | Type of Bulletin Number | No. of Bulletins issued |
|---|---|---|
| | | ACWC Chennai |
| 1. | Sea Area Bulletins | 18 |
| 2. | Coastal Weather Bulletins | 16 |
| 3. | Fishermen Warnings issued | 18 |
| 4. | Port Warnings | 8 |
| 5. | Heavy Rainfall Warning | 9 |
| 6. | Gale Wind Warning | - |
| 7. | Information & Warning issued to State Government and other Agencies | 14 |
| 8. | SMS | 20 |

## 12. Summary and Conclusion:

The CS Nada formed from as a depression over southeast Bay of Bengal in the evening of 29th November and then concentrated into a deep depression in the 0000UTC of 30th. The system gradually intensified into a cyclonic storm at 0300 UTC of 30th. It moved west-northwestwards initially and then, northwestwards, west north-westwards and finally westwards. It crossed north Tamil Nadu coast near Nagapattinam between 2230 and 2330 UTC of 1st December.

IMD utilised all its resources to monitor and predict the genesis, track and intensification of CS Nada. The forecast of its genesis (formation of Depression) on 29th November, its track, intensity, point & time of landfall, were predicted well with sufficient lead time. Its movement away from Indian coast was also predicted well in advance with high confidence.

## 13. Acknowledgements:

RSMC New Delhi duly acknowledges the contribution of Bangladesh Meteorological Department for providing real time Radar products for tracking the system and valuable information for preparation of report. It is worth mentioning here that, DWR products from Karaikal helped especially in monitoring the system prior to and during landfall in better estimation of location, intensity and landfall processes like heavy rainfall, gale wind etc. We also acknowledge the observational support from Department of Meteorology, Sri Lanka for the cyclone Nada. The contribution of the valuable inputs and guidance from NCMRWF, IIT Bhubaneswar, IIT-Delhi, INCOIS and NIOT Chennai is also recognized. The inputs from Agrometeorology Division, Pune, NWP Division, & Satellite Division at IMD HQ New Delhi, Area Cyclone Warning Centre (ACWC) Chennai are appreciated for their timely inputs required for compilation of this report.