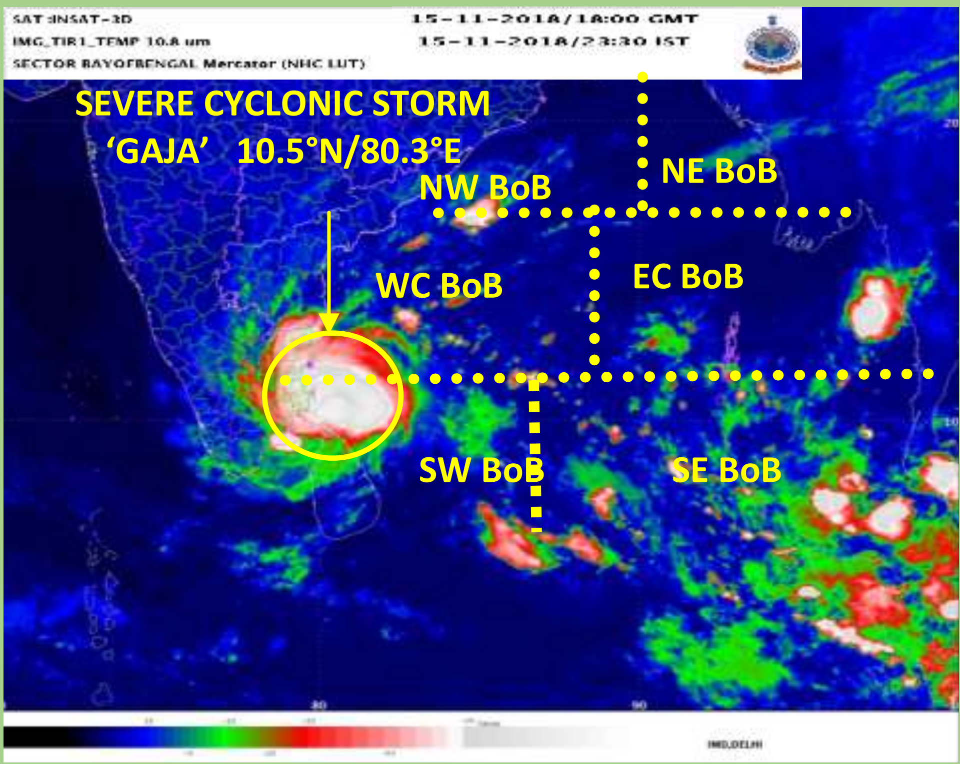
GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
INDIA METEOROLOGICAL DEPARTMENT

Very Severe Cyclonic Storm, 'GAJA' over southeast Bay of Bengal (10 – 19 November 2018): A Report



INSAT-3D enhanced colored IR imagery of 15th November, 2018

Cyclone Warning Division

India Meteorological Department

New Delhi

November 2018

Very Severe Cyclonic Storm "Gaja" over southeast Bay of Bengal (10-19 November 2018)

1. Introduction

Very Severe Cyclonic Storm (VSCS) Gaja originated from a low pressure area (LPA) which formed over Gulf of Thailand and adjoining Malay Peninsula in the morning (0830 IST) of 8th November. It lay as a well marked low pressure area (WML) over north Andaman Sea and neighbourhood in the evening (1730 IST) of 9th November. Under favourable environmental conditions, it concentrated into a Depression (D) over southeast BoB in the morning (0830 IST) of 10th November. Moving west-northwestwards, it intensified into a deep depression (DD) over southeast & adjoining central BoB in the same evening (1730 IST). Moving further west-northwestwards, it intensified into cyclonic storm (CS) "Gaja" over eastcentral and adjoining westcentral & southeast BoB in the early morning (0530 IST) of 11th November, 2018. It then moved nearly westwards till early morning (0530 IST) of 12th. Thereafter it recurved south-southwestwards and followed an anticlockwise looping track till 13th morning. It then moved west-southwestwards and intensified, into a Severe Cyclonic Storm (SCS) over southwest BoB in the morning (0830 IST) of 15th November and into a very severe cyclonic storm in the same night (2030 IST). Moving further west-southwestwards it crossed Tamilnadu & Puducherry coast between Nagapattinam and Vedaranniyam near latitude 10.45˚N and longitude 79.8°E with wind speed of 130 kmph gusting to 145 kmph during 0030 to 0230 hours IST of 16th November. Thereafter, it moved nearly westwards, and weakened rapidly into an VSCS in the early morning (0530 IST), a CS in the morning (0830 IST) and into a DD over interior Tamil Nadu in the forenoon (1130 IST) of 16th November. It then moved west-southwestwards and weakened into a D in the same evening (1730 IST) over central Kerala. Moving nearly westwards, it emerged into southeast Arabian Sea (AS) in the same midnight (2330 IST). Moving nearly westwards, it intensified into a DD over southeast AS in the early morning (0530 IST) of 17th November. Thereafter, it moved nearly west-northwestwards and crossed Lakshadweep Islands in the 17th afternoon (1400-1700 hrs IST) as a deep depression. It continued to move west-northwestwards and weakened into a D over southeast AS around noon (1130 IST) of 19th & into a WML over southwest & adjoining southeast AS in the same midnight (2330 IST). It lay as a low pressure area over southwest Arabian Sea on 21st and became less marked over the same region on 22nd. The observed track of the system during 10th-19th November is presented in Fig.1. The best track parameters of the system are presented in Table 1.

The salient features of the system are as follows.

i. VSCS Gaja was the sixth cyclone over north Indian Ocean during 2018 against the normal frequency of about 4.5 cyclones per year during the satellite era (1961 onwards).
ii. It was the first ever looping track cyclone over the Bay of Bengal after 1996.
iii. The system had one of the longest track length equal to 3418 km.
iv. Despite unfavorable environmental conditions, the system intensified into a VSCS just prior to landfall near to coast.

v. The very severe cyclonic storm intensity of the system was short lived (about 3 hrs). The peak maximum sustained surface wind speed (MSW) of the cyclone was 130 kmph gusting to 145 kmph during 1800 to 2100 UTC of 1^{5th}. The lowest estimated central pressure was 975 hPa with pressure drop of about 31 hPa.

vi. The life period (D to D) of the system was 219 hours (9 days and 3 hours) against long period average (LPA) (1990-2013) of 98 hours for VSCS category over Bay of Bengal during post monsoon season.

vii. It moved with normal speed, as the 12 hour average translational speed of the cyclone was 14.6 kmph against LPA (1990-2013) of 14.7 kmph for VSCS category over north Bay of Bengal.

viii. The Velocity Flux, Accumulated Cyclone Energy (ACE) and Power Dissipation Index (PDI) were 9.4 $X10^2$ knots, 4.35X 10^4 $knots^2$ and $2.1X10^6$ $knots^3$ respectively.

Brief life history, characteristic features and associated weather along with performance of NWP and operational forecast of IMD are presented and discussed in following sections.

2. Monitoring of VSCS, 'GAJA'

The cyclone was monitored & predicted continuously by India Meteorological Department (IMD) prior to its genesis as low pressure area over BoB from 7^{th} November 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) Karaikal, Chennai, Thiruvananthapuram and Kochi along with 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 Bangladesh, Myanmar, Sri Lanka, Maldives National & State Disaster Management Agencies, general public and media since inception of the system over BOB. The system came under Radar surveillance from morning of 15^{th}.

3. Brief life history

3.1. Genesis

VSCS Gaja originated from an **LPA** which formed over Gulf of Thailand and adjoining Malay Peninsula at **0300 UTC of 8^{th} November.** At 0300 UTC of 8^{th} November, the Madden Julian Oscillation (MJO) index lay in phase 3 with amplitude less than 1. It was expected to remain in phase 3 & 4 during next 4 days with amplitude less than 1. Hence MJO phase was expected to support enhancement of convective activity over south BoB & adjoining areas during next 4 days. The environmental conditions like sea surface temperature (28-29^{0}C), lower level convergence ($20x10^{-5}$ $second^{-1}$), lower level vorticity ($100x10^{-6}$ $second^{-1}$), upper level divergence ($15x10^{-5}$ $second^{-1}$) and vertical wind shear (10-15 knots) were also favoring intensification of LPA after its emergence into Andaman Sea. The upper tropospheric ridge ran along 12^{o}N and under its influence the system was expected to move west-northwestwards after its emergence into Andaman Sea. Similar conditions prevailed and the system lay as a **WML** over north Andaman Sea and neighborhood at **1200 UTC of 9th November**.

At **0300 UTC of 10th**, the MJO index lay in phase 4 with amplitude close to 1. MJO phase and amplitude were supporting enhancement of convective activity over south BoB & adjoining areas. The SST was 28-29^{0}C over southeast BoB and adjoining north Andaman Sea. TCHP was 50-80 KJ/cm^{2} over southeast BoB. The lower level vorticity was 50x10^{-6} second^{-1}, lower level convergence was 5-10x10^{-5} second^{-1}, upper level divergence was 10x10^{-5} second^{-1} and low level vertical wind shear was low to moderate (5-15 kt). The upper tropospheric ridge ran along 14°N. Under these supportive conditions, the system intensified into a **depression** over central parts of Andaman Sea near 11.7°N/92.5°E.

3.2. Intensification and movement

At 1200 UTC of 10th, the MJO index lay in phase 4 with amplitude close to 1. Similar sea conditions prevailed. The lower level convergence increased and was of the order of 10-15x10-5 second-1, the lower level vorticity also increased and was of order 100x10-6 second-1 to the south of the system centre, the upper level divergence also increased and was of the order 30x10-5 second-1 around the system centre and vertical wind shear was low (5-10 knots) around the system centre. The total precipitable water vapour (TPW) imagery indicated warm air advection into the core of the system. Under these conditions, the system intensified into a deep depression over southeast & adjoining central BoB near 12.6°N/90.8°E. The upper tropospheric ridge ran along 14°N and favoured west-northwestward movement of the system.

At 0000 UTC of 11th, similar thermo-environmental conditions and MJO phase continued. TPW imagery indicated warm air advection into the core from the southeast sector. Under these conditions the system intensified into a cyclonic storm “Gaja” over eastcentral and adjoining westcentral & southeast BoB near latitude 13.4°N/89.3°E. The upper tropospheric ridge ran along 16°N favoring west-northwestward movement of the system during next 36 hours. The system however, moved nearly westwards till early morning (0000 UTC) of 12th. Thereafter, it recurved south-southwestwards and followed an anticlockwise looping track till 13th morning. It then moved west-southwestwards and intensified, into a VSCS over southwest BoB in the morning (0300 UTC) of 15th November.

At 0300 UTC of 15th, the MJO lay in phase 5 with amplitude close to 1. It was forecast to remain in phase 5 for next 48 hours with amplitude less than 1. MJO phase was favoring intensification of system during next 48 hours. The SST was around 28-29°C and TCHP is 50-80 KJ/cm2 around the system centre. It is less than 50 KJ/cm2 over western parts of southwest BoB north Tamil Nadu coast. The lower level convergence was of the order 10-15 x10-5 second-1 to the southeast of the system centre. The lower level vorticity increased and was of the order of 150x10-6 second-1 around the system centre. The upper level divergence was of the order of 20-30x10-5 second-1 around the system centre. The vertical wind shear was low to moderate (10-15 knots) over the system centre and also along the forecast track.

The TPW imagery indicated warm air advection from the southeast sector into the core of the system centre and advection of cold & dry air near north Tamil Nadu and Andhra Pradesh coasts. The poleward outflow was favouring upper air divergence. Under these favourable conditions, the system intensified into an VSCS over southwest BoB near 11.3°N/82.6°E. Upper level ridge ran along 13°N and two anticyclonic circulations were lying to the east and west of the system centre. The system moved west-southwestwards under the influence of the anticyclone to the west (Arabian Sea) of the system and continued to move west-southwestwards till landfall.

At 1500 UTC of 15th, the SST was around 28-29°C and TCHP was 50-80 KJ/cm2 around the system Centre. It was less than 50 KJ/cm2 over western parts of southwest BoB off north Tamil Nadu coast. The lower level convergence was of the order 20-30 x10-5 second-1 to the southeast of the system centre. The low level vorticity was of the order of 150x10-6 second-1 around the system centre. The upper level divergence was of the order of 30x10-5 second-1 around the system centre. The vertical wind shear was low to moderate (10-15 knots) over the system centre and also along the forecast track. TPW imagery indicated warm air advection into the core from the southeast sector. The poleward outflow was favoring increase in divergence. Under these conditions, the system intensified into a VSCS over southwest BoB near 10.6°N/80.7°E. Upper level ridge ran along latitude 13°N in association with the anticyclonic circulation to the east and west of the system centre. Under the influence of anticyclone to the west (Arabian Sea) of the system centre, it moved west-southwestwards and crossed Tamil Nadu and Puducherry coasts between Nagapattinam & Vedaranniyam near 10.450N/79.80E during 1900 to 2100 UTC. The system maintained its peak intensity for 6 hours during 1500 UTC of 15th to 0000 UTC of 16th.

At 0000 UTC of 16th, the lower level convergence was of the order 30 x10-5 second-1, the lower level vorticity was of the order of 150x10-6 second-1 and the upper level divergence was of the order of 20x10-5 second-1 around the system centre. The vertical wind shear was low to moderate (5-10 knots) over the system centre and also along the forecast track. However, there was cut-off of moisture supply and thus, the system weakened into an VSCS over coastal Tamil Nadu 10.4°N/79.2°E. The upper tropospheric ridge ran along lat 14°N in association with the anticyclonic circulation to the west of the system centre. Under its influence, the system moved nearly westwards. Similar conditions prevailed and the system moving westwards weakened into a CS over coastal Tamil Nadu near 10.4°N/78.5°E and into a DD over interior Tamil Nadu near 10.5°N/77.6°E.

At 1200 UTC of 16th, there was further disorganization of cloud mass and weakening of environmental features with the lower level convergence of order 20x10-5 second-1 to southwest of the system centre, the lower level vorticity of the order 100x10-6 second-1 over the system centre and the upper level divergence of order 10x10-5 second-1 around the system centre. The vertical wind shear was low (5-10 knots) around the system centre. Under these conditions, the system weakened into a D near 10.1°N/76.4°E. The upper tropospheric ridge ran along 15°N and under it’s influence, the system moved nearly westwards and emerged into southeast Arabian Sea at 0000 UTC of 17th.

At 0000 UTC of 17th, the system was over southeast Arabian Sea near 9.8°N/74.3°E as a depression. At that time, the SST was 29-30°C and TCHP was 50-80 KJ/cm2 over southeast Arabian Sea. The lower level convergence was of the order of 10-15x10-5 second-1 to the southwest of the system centre, the lower level vorticity was around 80-100x10-6 second-1 and the upper level divergence was around 10 x 10-5 second-1 around the system centre. The vertical wind shear was low (5-10 knots) around the system centre. The upper tropospheric ridge runs along 13°N and thus favored nearly westward movement of the system across southeast Arabian Sea.

At 0600 UTC of 19th, similar sea conditions prevailed. However, the TCHP was becoming less than 50 KJ/ cm2 to the west of 65°E. The lower level convergence was about 5x10-5 second-1, the lower level vorticity was of the order 100x10-6 second-1, the upper level divergence was 10-20x10-5 second-1 and vertical wind shear was low to moderate (5-15 knots) around the system centre. The TPW imagery was indicating dry air incursion from the western sector up to southern sector and decrease in warm moist air advection from the southeast into the system center. Water vapour imagery also indicated dry mid-level atmosphere. Under these conditions, there was no further intensification of the system. The system continued to move nearly westwards and weakened into a WML over southwest & adjoining southeast Arabian Sea at 1800 UTC of 19th.

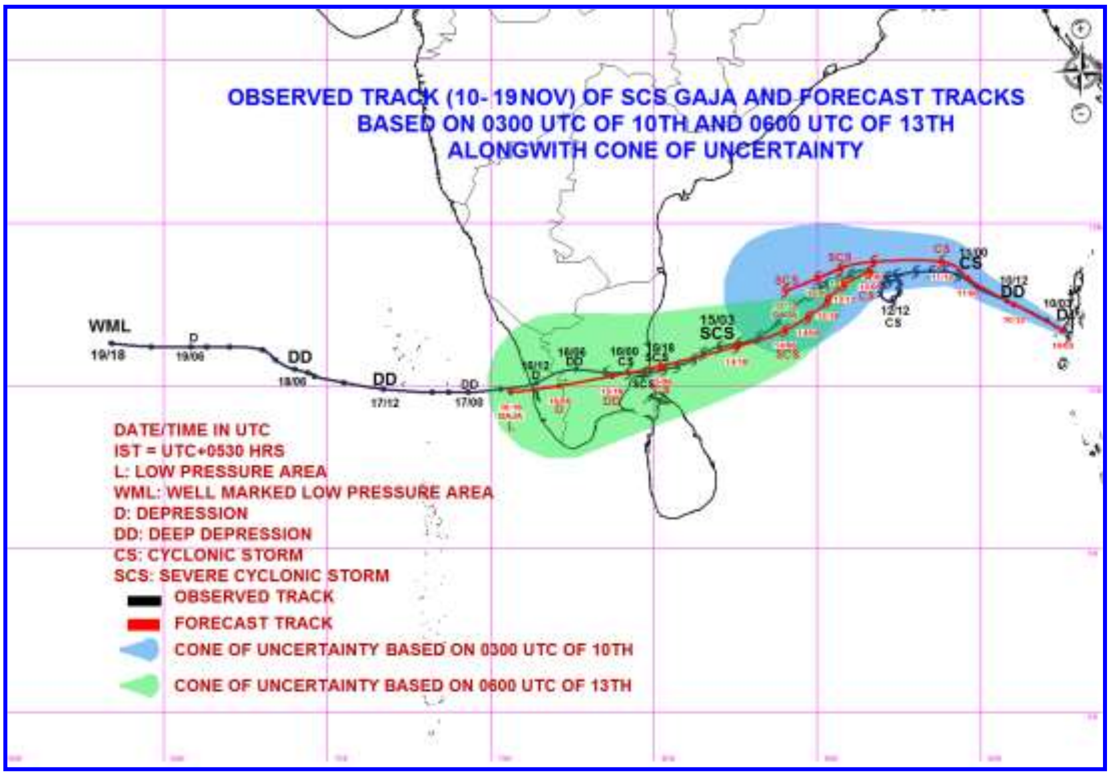


Fig.1 Observed track of VSCS GAJA (10-19 November, 2018) over southeast Bay of Bengal.

Table 1: Best track positions and other parameters of the Very Severe Cyclonic Storm "Gaja" over Bay of Bengal during 10th – 19th November

Date	Date/Time (UTC)	Centre lat.⁰ N/ long. ⁰ E		C.I. NO.	Estimated Maximum Sustained Surface Wind (kt)	Estimated Central Pressure (hPa)	Estimated Pressure drop at the Centre (hPa)	Grade
10/11/2018	0300	11.7	92.5	1.5	25	1003	3	**D**
	600	12	92	1.5	25	1002	4	D
	1200	12.6	90.8	2	30	1001	5	**DD**
	1800	13	89.9	2	30	1000	6	DD
11/11/2018	0000	13.4	89.3	2.5	35	999	7	**CS**
	0300	13.5	88.9	2.5	35	999	7	CS
	0600	13.5	88.5	2.5	40	998	8	CS
	0900	13.5	88.2	2.5	40	998	8	**CS**
	1200	13.5	88	2.5	40	998	8	CS
	1500	13.5	87.7	2.5	40	998	8	CS
	1800	13.4	87.4	2.5	40	998	8	CS
	2100	13.5	87.2	2.5	40	998	8	CS
12/11/2018	0000	13.3	87.1	2.5	40	998	8	CS
	0300	13.1	87	2.5	40	998	8	CS
	0600	12.9	86.9	2.5	40	998	8	CS
	0900	12.9	86.9	2.5	40	998	8	CS
	1200	12.6	87.3	2.5	40	998	8	CS
	1500	12.9	87.5	2.5	40	998	8	CS
	1800	13.2	87.5	2.5	45	996	8	CS
	2100	13.2	87.3	2.5	45	996	8	CS
13/11/2018	0000	13.2	87.2	2.5	40	998	8	CS
	0300	13.3	87.1	2.5	40	998	8	CS
	0600	13.5	86.6	2.5	40	998	8	CS
	0900	13.4	86.4	2.5	40	998	8	CS
	1200	13.4	86	2.5	40	998	8	CS
	1500	13.2	85.8	2.5	40	998	8	CS
	1800	13.2	85.6	2.5	40	998	8	CS
	2100	13.1	85.5	2.5	40	998	8	CS
14/11/2018	0000	13.1	85.3	2.5	40	998	8	CS
	0300	13	85.1	2.5	40	998	8	CS
	0600	12.8	84.8	2.5	45	996	10	CS
	0900	12.6	84.6	2.5	45	996	10	CS
	1200	12.4	84.2	2.5	45	996	10	CS
	1500	12.2	84.2	2.5	45	996	10	CS

	1800	12	83.8	2.5	45	996	10	CS
	2100	11.8	83.4	2.5	45	996	10	CS
15/11/2018	0000	11.5	83.2	2.5	45	996	10	CS
	0300	11.3	82.6	3	50	994	12	**SCS**
	0600	11.2	82	3.5	55	990	15	SCS
	0900	11	81.5	3.5	55	989	16	SCS
	1200	10.8	81.2	3.5	60	988	18	SCS
	1500	10.6	80.7	4	65	984	21	VSCS
	1800	10.5	80.3	4	70	976	30	VSCS
		Crossed Tamil Nadu and Puducherry coasts between Nagapattinam & Vedaranniyam near 10.45^0N and 79.8^0E during 1900 to 2100 UTC						
	2100	10.4	79.7	-	70	976	30	VSCS
16/11/2018	0000	10.4	79.2	-	55	990	15	**SCS**
	0300	10.4	78.5	-	45	996	10	CS
	0600	10.5	77.6	-	30	1000	6	**DD**
	1200	10.1	76.4	1.5	25	1002	4	**D**
	1800	9.9	75.3	1.5	25	1002	4	D
17/11/2018	0000	9.8	74.3	2	30	1003	5	**DD**
	0300	9.8	73.7	2	30	1003	5	DD
	0600	9.8	73.2	2	30	1003	5	DD
	1200	9.9	71.7	2	30	1003	5	DD
	1800	10.1	70.5	2	30	1003	5	DD
18/11/2018	0000	10.3	69.6	2	30	1003	5	DD
	0300	10.4	69.4	2	30	1003	5	DD
	0600	10.5	69	2	30	1003	5	DD
	1200	10.7	68.5	2	30	1003	5	DD
	1800	10.8	67.5	2	30	1003	5	DD
19/11/2018	0000	11	66.6	2	30	1003	5	DD
	0300	11.1	66.3	2	30	1003	5	DD
	0600	11.2	65.8	1.5	25	1004	4	D
	1200	11.2	65	1.5	25	1004	4	**D**
	1800	**Weakened into a well marked low pressure area over southwest & adjoining southeast Arabian Sea**						

The total precipitable water imageries (TPW) during 11^{th}-19^{th} November are presented in **Fig.2**. These imageries indicate continuous warm and moist air advection from the southeast sector into the core of system till 15^{th} November. Thereafter, cold dry air prevailed over north TamilNadu and adjoining Andhra Pradesh. The system was over land during this period and experienced decrease in its intensity. It emerged into AS at 1200 UTC of 16^{th} as a depression. Thereafter, there was warm moist air advection into the core leading to its intensification into a DD at 0000 UTC of 17^{th}. At 0600 UTC of 19^{th}, there was significant decrease in warm moist air advection into the core of system, leading to weakening of the system.

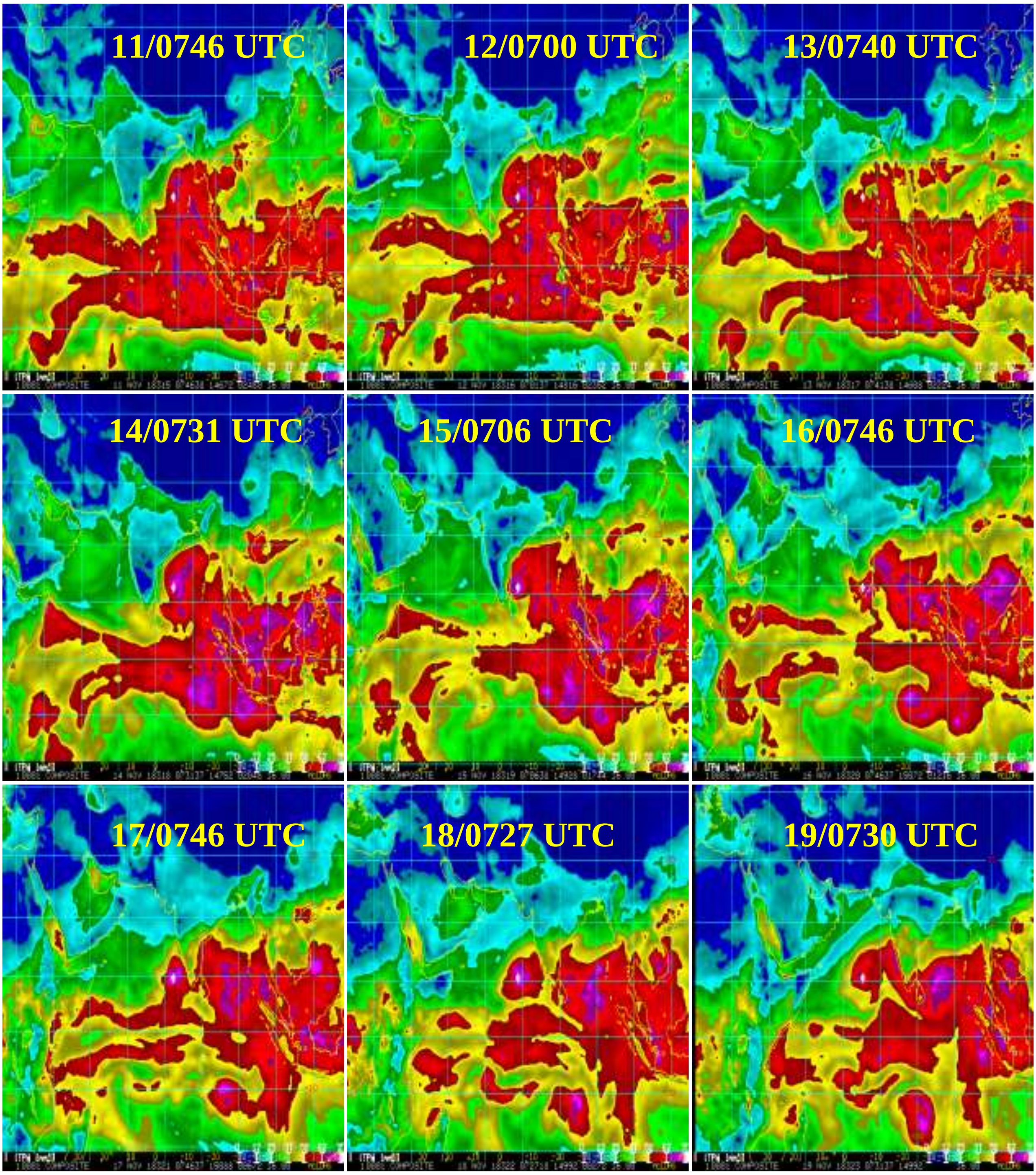


Fig. 2: Total Precipitable Water Imageries during 11-19 November, 2018

The mean wind speed in middle and deep layer around the system centre is presented in **Fig.3**. The wind shear between middle to lower tropospheric levels around the system centre was less than 10 kts till 0000 UTC of 14th and around 15kts till 0000 UTC of 16th. Thereafter, it increased becoming 25 kts at 0600 UTC of 16th. Thereafter, it decreased becoming less than 5 kts till 19th November. The wind shear between upper to lower tropospheric levels was around 15 kts upto 0600 UTC of

15th. It increased slightly upto becoming around 20 kts upto 0600 UTC of 16th. Thereafter, it decreased becoming around 10 kts till 0000 UTC of 19th. Thus, the wind shear between middle to lower tropospheric levels better represents the strengthening/weakening of the system.

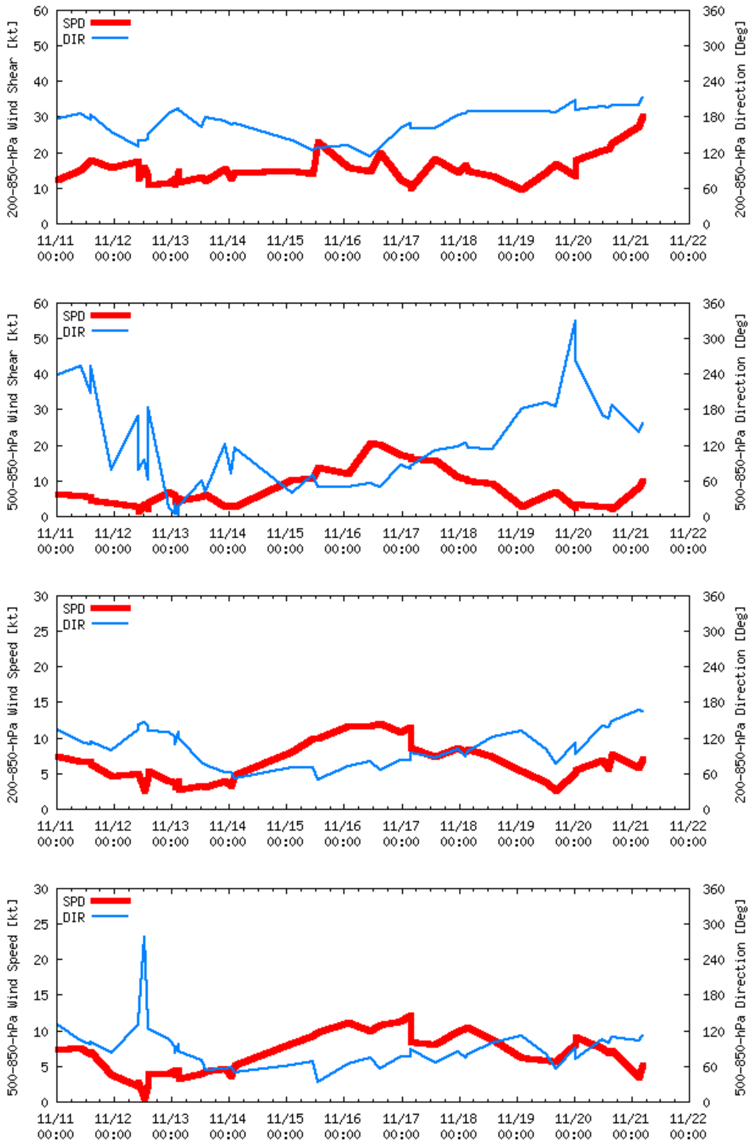


Fig.3 Wind shear and wind speed in the middle and deep layer around the system during 11th to 22nd november 2018.

3.3 Movement

From **Fig.3**, comparing the mean flow pattern between the mean deep layer winds between 200-850 hPa levels and 500-850 hPa levels, it is seen that the flow between 500-850 hPa levels could detect the looping of the system on 12th & 13th with very slow speed becoming stationary during 12th. The mean winds between 500-850 hPa levels steered the system west-southwestwards initially during 11th-12th with a speed of 10 knots or less. Thereafter, the system followed a looping track during

12th-13th and moved with an average speed less than 5 knots. Thereafter, it moved west-southwestwards till 0000UTC of 15th and nearly westwards thereafter and an increase in wind speed. The six hourly movement of VSCS Gaja is presented in **Fig.4 (a)**. The six hourly average translational speed of the cyclone was about 10.5 kmph and hence was slow moving in nature. The system had a track length of about 3418 km during its life period.

Fig.4 (a): Six hourly average translational speed (kmph) and direction of movement in association with VSCS Gaja and (b) Lowest estimated central pressure and the maximum sustained wind speed

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.4 (b)**. The lowest estimated central pressure (ECP) had been 992 hPa at 1800 UTC of 15th. The ECP gradually decreased from 1004 hPa at 1200 UTC of 10th to 992 hPa at 1800 UTC of 15th. Thereafter, there was gradual rise in pressure to 994 hPa at 0000 UTC of 16th. It then increased suddenly to 1002 hPa (at 0600 UTC of 16th) indicating rapid weakening of the system during 0000 to 0600 UTC of 16th. Thereafter it increased gradually to 1006 hPa at 1200 UTC of 19th indicating slow weakening of the system during 0600 UTC of 16th to 1200 UTC of 19th. Similarly, in the wind field it is seen that the maximum sustained wind speed (MSW) had been 70 kts at 1800 UTC of 15th. The MSW gradually increased becoming 35 kts at 0000 UTC of 11th. The system maintained MSW of 40-45 kts till 0000 UTC of 15th. There was rapid intensification of the system during 0000 to 1800 UTC of 15th and the system attained its peak intensity of 70 kts at 1800 UTC of 15th. Thereafter, there was rapid weakening of the system till 0600 UTC of 16th (MSW becoming 30 kts). Thereafter it maintained the intensity of depression/deep depression till 1200 UTC of 19th.

5. Features observed through satellite

At 0300 UTC of 10th, the intensity of the system was characterized by T1.5. Banding features were not clear. Broken low and medium clouds with embedded intense to very intense convection lay over Andaman Sea and adjoining eastcentral BoB. Minimum cloud top temperature (CTT) was minus 93°C. At 1200 UTC of 10th, the system showed curved band pattern. The convective clouds were higher in northern sector. The intensity of the system was T 2.0. Broken low and medium clouds with embedded intense to very intense convection lay over BoB between latitude 11.5°N & 16.0°N and longitude 88.5°E to 93.5°E & northwest Andaman Sea. Minimum CTT was minus 93°C. At 0000 UTC of 11th, the system showed central dense overcast (CDO) pattern. The convective clouds were higher in northern sector. The intensity of the system was T 2.5. Broken low and medium clouds with embedded intense to very intense convection lay over BoB between latitude 13.0°N & 19.0°N and longitude 86.5°E & 95.0°E and northwest Andaman Sea. Minimum cloud top temperature is minus 93°C. At 0300 UTC of 15th, cloud imagery indicated improvement in organization of cloud mass with bands wrapping tightly around the centre from northwest and northeast sectors resulting in curved band pattern. The intensity of the system was T 3.0. Associated broken low and medium clouds with embedded intense to very intense convection lay over BoB between latitude 10.5°N & 13.0°N and longitude 81.0°E & 84.0°E. Minimum CTT was minus 86°C. At 1500 UTC of 15th, there was further improvement in clouds organisation with bands wrapping tightly around the centre in curved band pattern. The intensity of the system was T 3.5. Associated broken low and medium clouds with embedded intense to very intense convection lay over Bob between latitude 9.5°N & 12.5°N and longitude 79.5°E to 82.5°E. Minimum CTT was minus 93°C. At 0000 UTC of 16th, due to land interactions there was disorganization of cloud mass. Entire cloud mass was sheared to the northwest of system centre. Broken low and medium clouds with embedded intense to very intense convection lay between latitude 9.5oN & 12.5oN and west of longitude 81.5oE, Palk Strait, Tamilnadu and south Kerala. Minimum CTT was -89 oC. At 0300 UTC of 16th, the system was over land. More clouds were seen in the southern sector. Broken low and medium clouds with embedded intense to very intense convection lay between latitude 7.5oN & 12.5o N and longitude 76.5oE & 80.5oE. Minimum CTT was -83 oC. At 0000 UT of 17th, the system emerged over southeast Arabian Sea. Curved band features were observed and the system wrapped 0.4 on log10 spiral. Broken low and medium clouds with embedded intense to very intense convection lay between latitude 7.5°N & 12.5°N and longitude 71.5°E and 76.0°E. The minimum CTT was minus 93°C. At 0600 UTC of 19th, there was further disorganization of cloud mass. Shear pattern was observed. The cloud mass was sheared to the west of system centre. The intensity of the system was C.I.1.5. Broken low and medium clouds with embedded intense to very intense convection lay over Arabian Sea between latitude 8.5°N to 14.5°N and longitude 64.0°E to 66.0°E. The minimum cloud top temperature is minus 93°C.

5.1 INSAT-3D features

Typical INSAT-3D visible/IR imageries, enhanced colored imageries and cloud top brightness temperature imageries are presented in **Fig.5 (a-d)**.

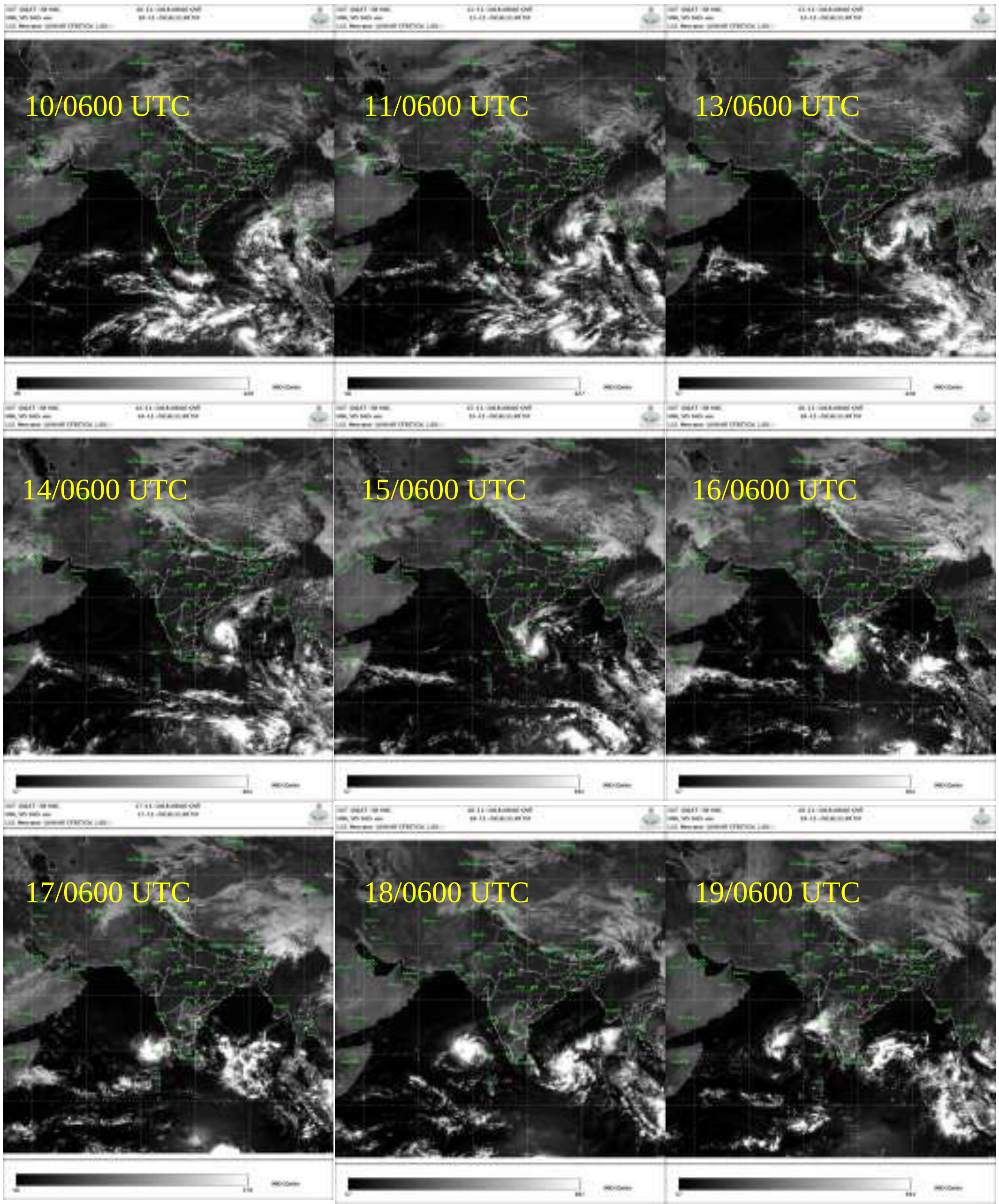


Fig. 5a: INSAT-3D visible imageries during life cycle of VSCS Gaja (10th – 19th November, 2018)

Intensity estimation using Dvorak's technique suggested that the system attained the intensity of **T 1.5** at 1200 UTC of 21st. The convection over south AS further organised and indicated curved banding features from northwest to southeast sector across southwest sector. Minimum cloud top temperature was -93^{0}C. At 0300 UTC of 22nd, the convection further organized and the system attained the intensity

of **T2.0**. The convection showed curved banding features from northeast to southwest sector across northwest sector. Minimum CTT was -93^{0}C.

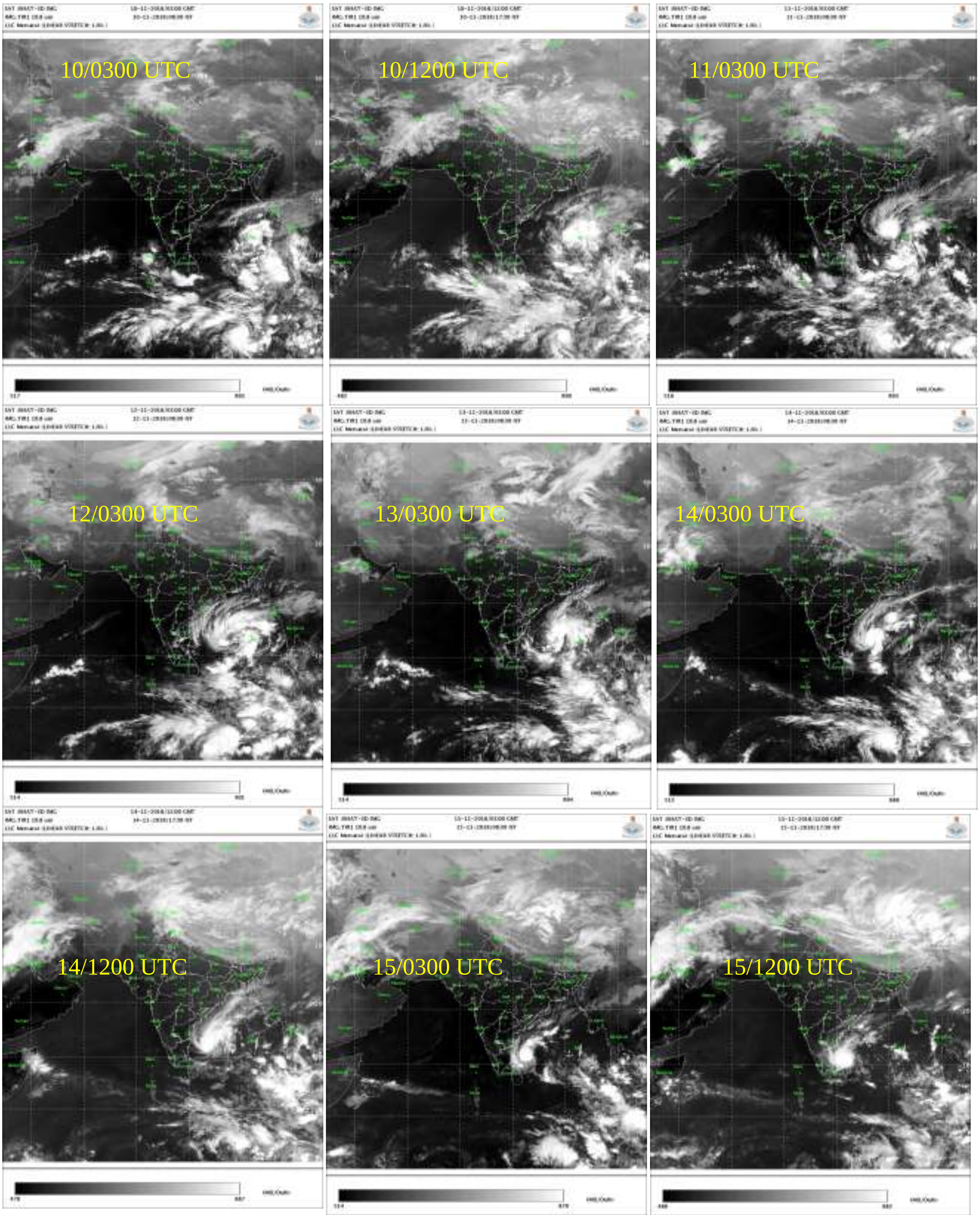


Fig. 5b: INSAT-3D IR imageries during life cycle of VSCS Gaja (10th – 19th November, 2018)

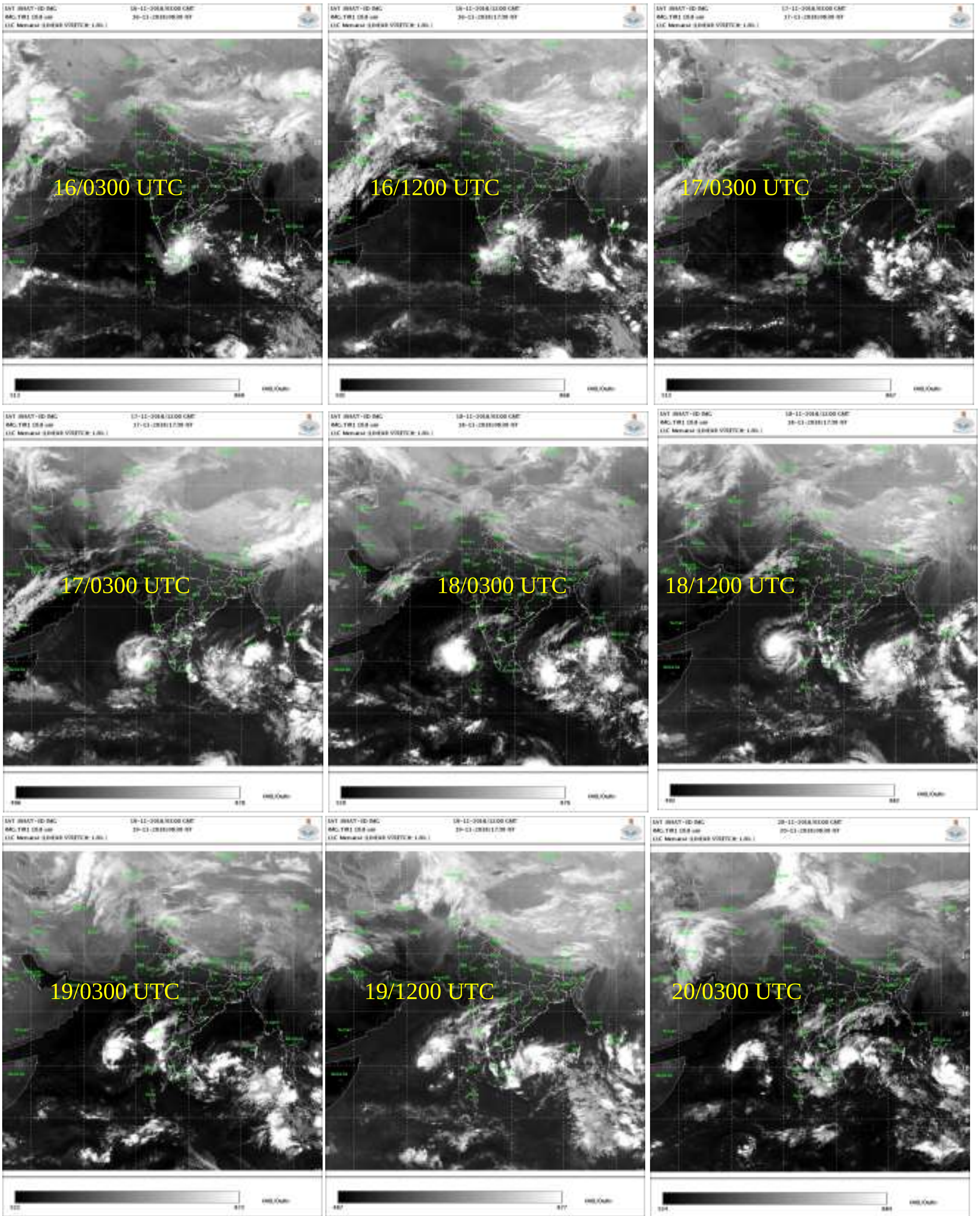


Fig. 5b(cont.): INSAT-3D IR imageries during life cycle of VSCS Gaja (10th – 19th November, 2018)

At 1200 UTC of 22nd, the system attained the intensity **T 2.5**. The cloud pattern indicated banding features from northeast to southwest sector across northwest sector. The intensity of the system was **T3.5**. The convection showed curved banding features from northeast to southwest sector across northwest sector. At 0900 UTC of 23rd, the system attained the intensity **T 4.0**. The convection increased over western and southern sector. With the consolidation of central dense overcast, satellite imagery indicated appearance of eye. It indicated intensification of the system. Minimum CTT was -93^{0}C. At 0300 UTC of 24th, the system further intensified and attained the intensity **T4.5**. The convection showed central dense overcast pattern with well defined spiral bands. Minimum CTT was -93^{0}C.

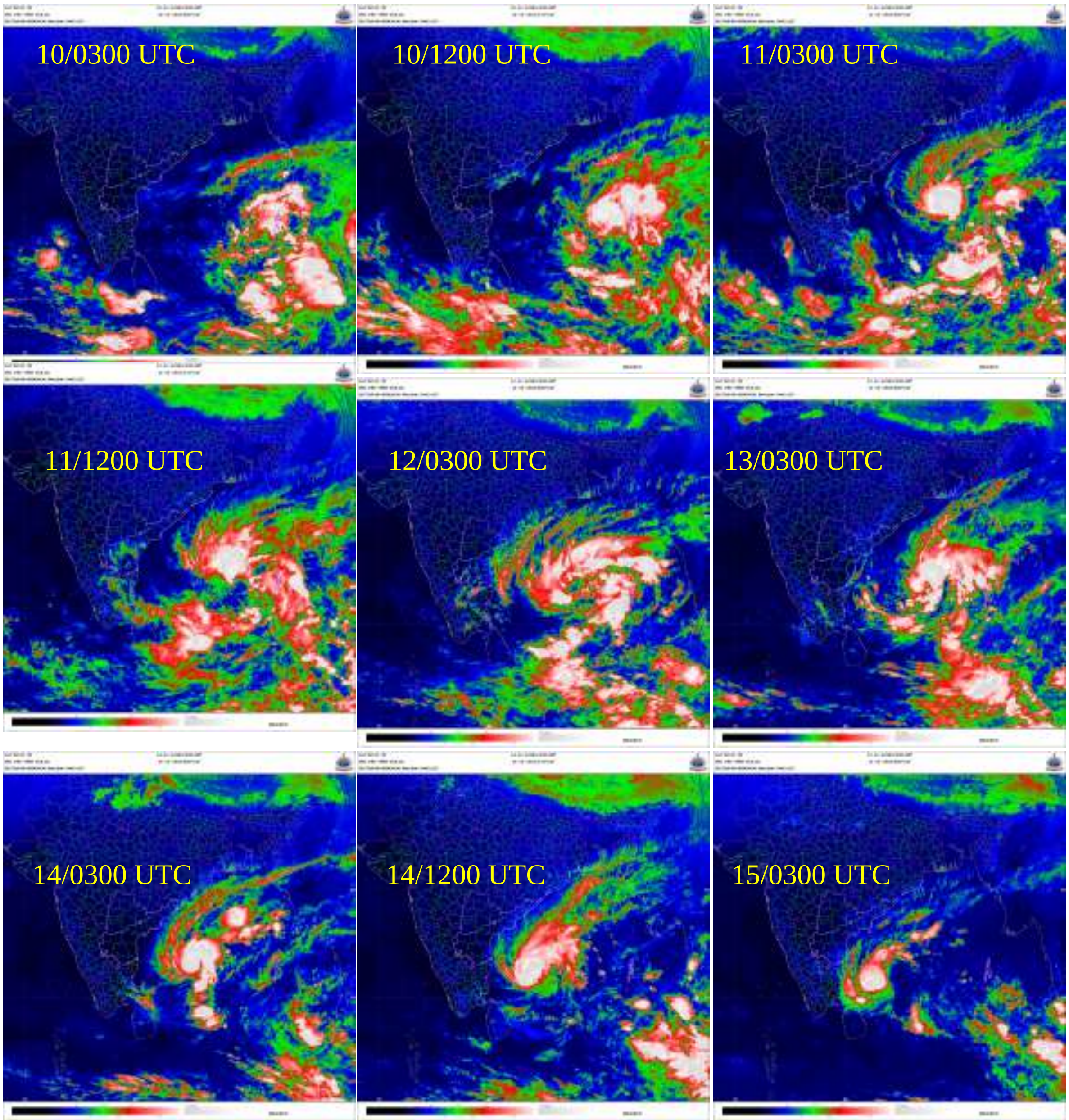


Fig. 5c: INSAT-3D enhanced colored imageries during life cycle of VSCS Gaja (10th – 19th November, 2018)

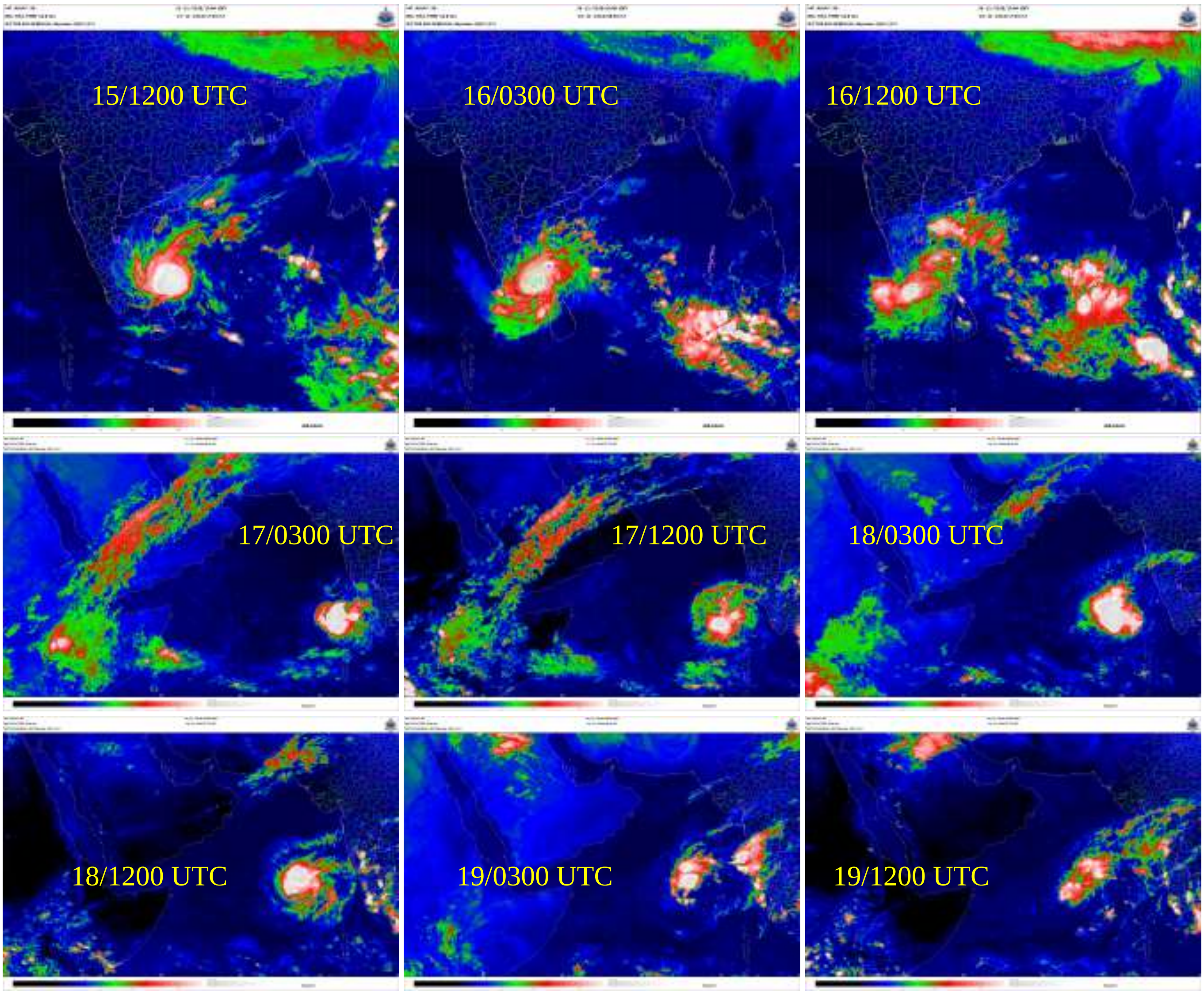


Fig. 5c(Cont): INSAT-3D enhanced colored imageries during life cycle of VSCS Gaja (10th – 19th November, 2018)

At 0300 UTC of 25th, the intensity of the system was **T 5.0**. The convection showed central dense overcast pattern with spiral bands. Associated broken low and medium clouds with embedded intense to very intense convection lay over westcentral and adjoining southwest AS between latitude 10.5^{0}N & 18.5^{0}N and longitude 51.0^{0}E to 58.0^{0}E. At 1800 UTC of 25th, the intensity of the system was **T 5.5**. The clouds got organized further and showed eye pattern. At 1800 UTC of 25th,

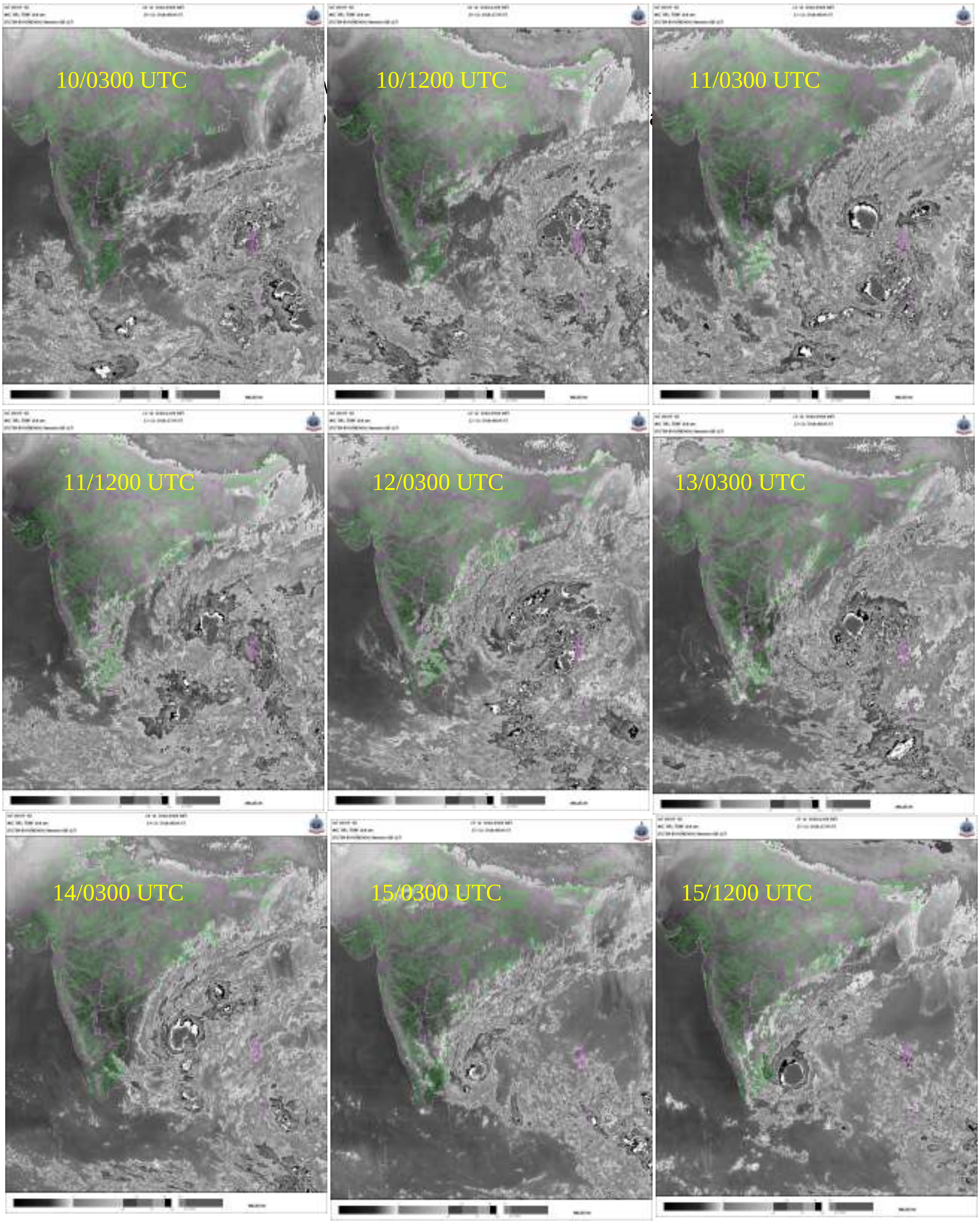


Fig. 5d: INSAT-3D cloud top brightness imageries during life cycle of VSCS Gaja (10th – 19th November, 2018)

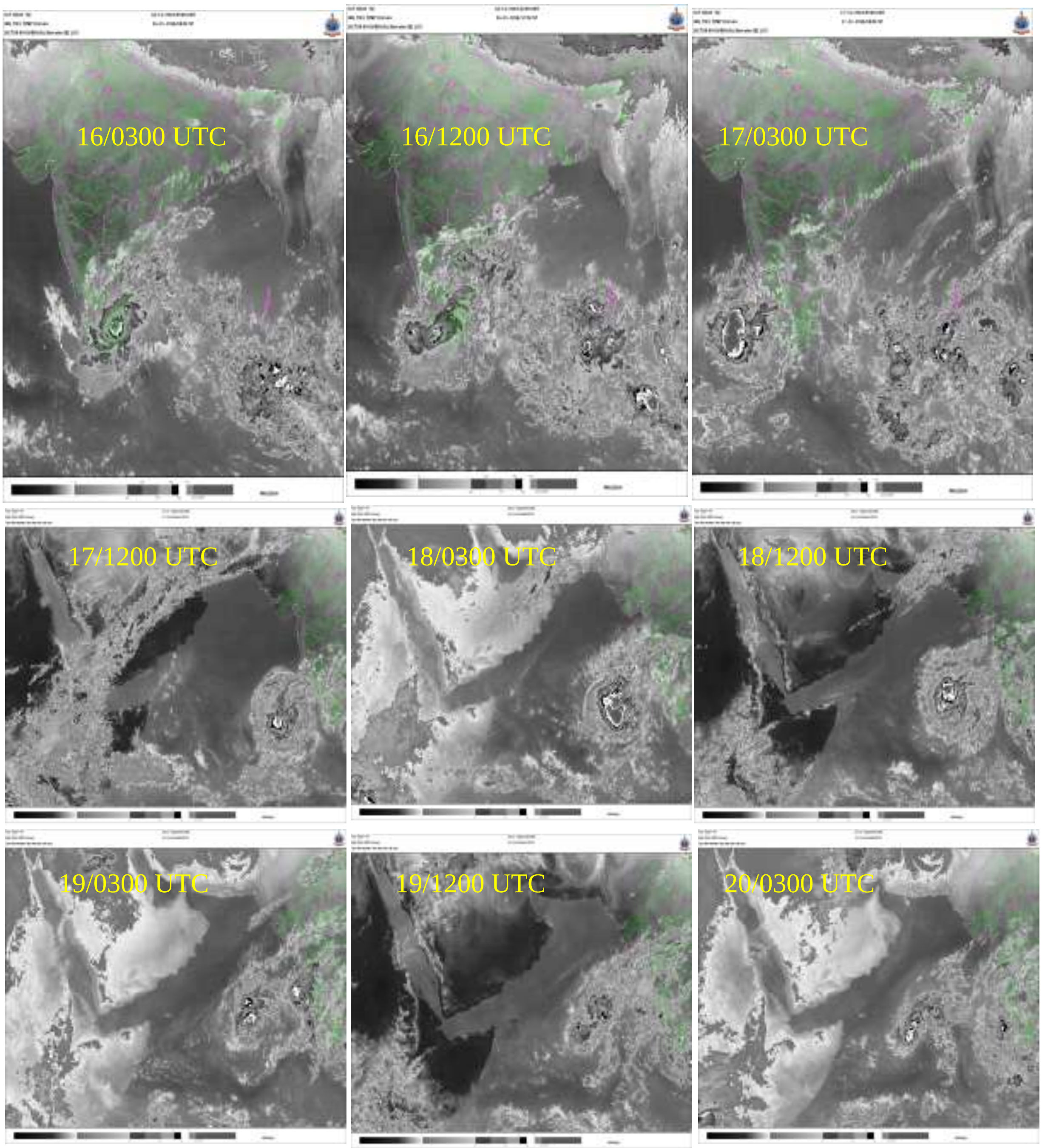


Fig. 5d(Cont): INSAT-3D cloud top brightness imageries during life cycle of VSCS Gaja (10th – 19th November, 2018)

5.2. Radar Imageries:

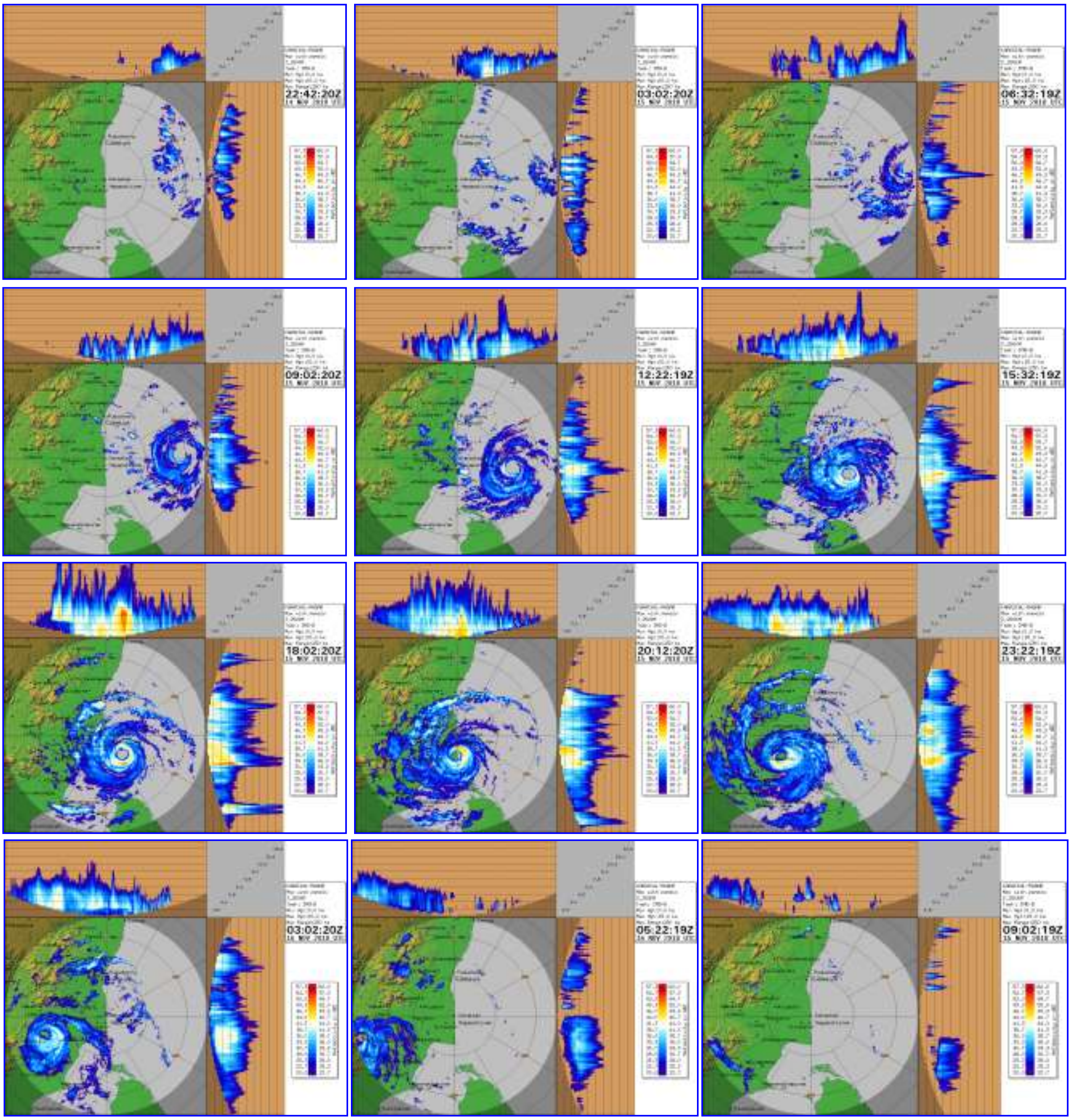


Fig. 5e: Karaikal radar imageries of VSCS Gaja (10th – 19th November, 2018)

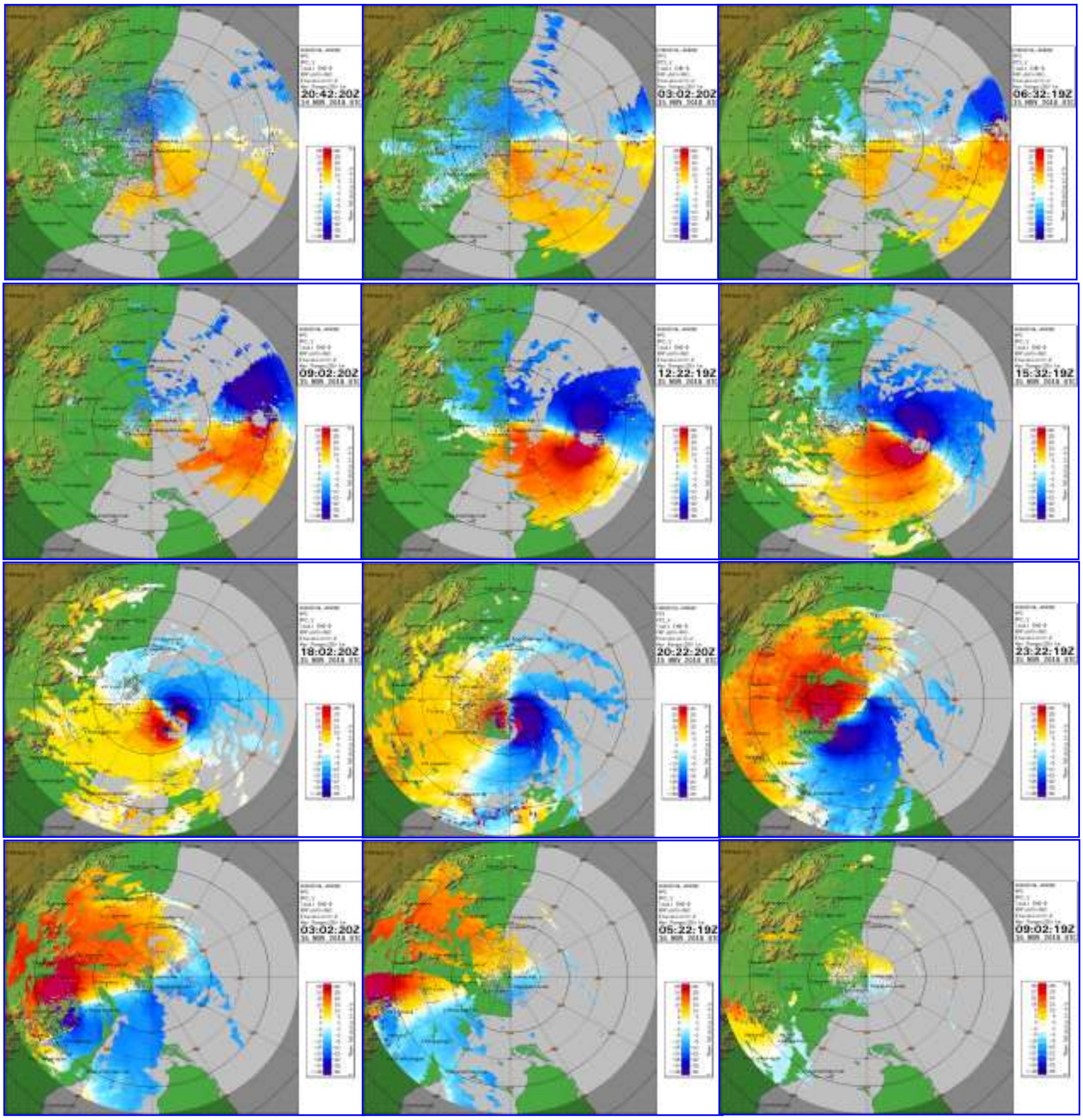


Fig. 5f: Karaikal radar imageries of VSCS Gaja (10th – 19th November, 2018)

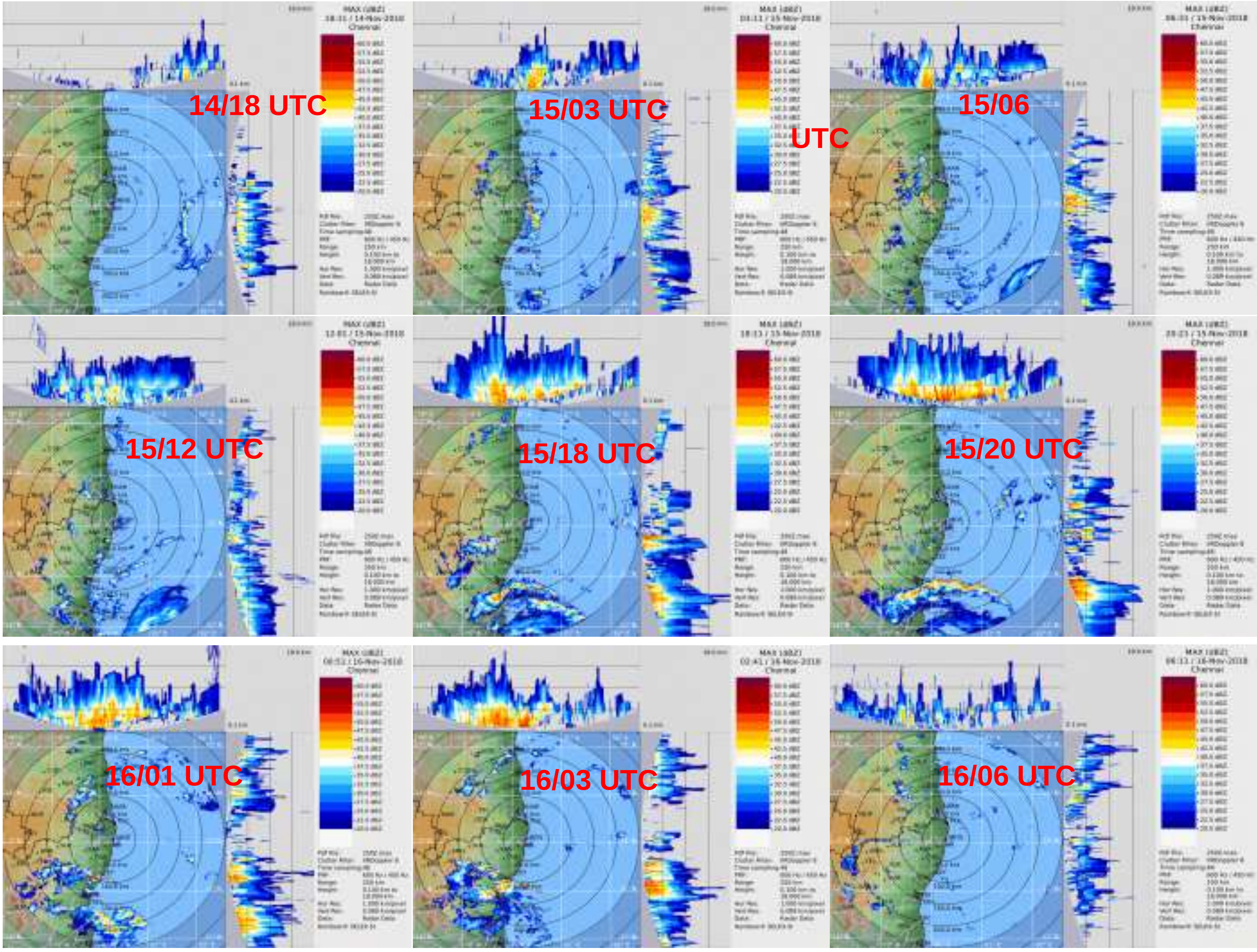


Fig. 5g: Chenni radar imageries of VSCS Gaja (10th – 19th November, 2018)

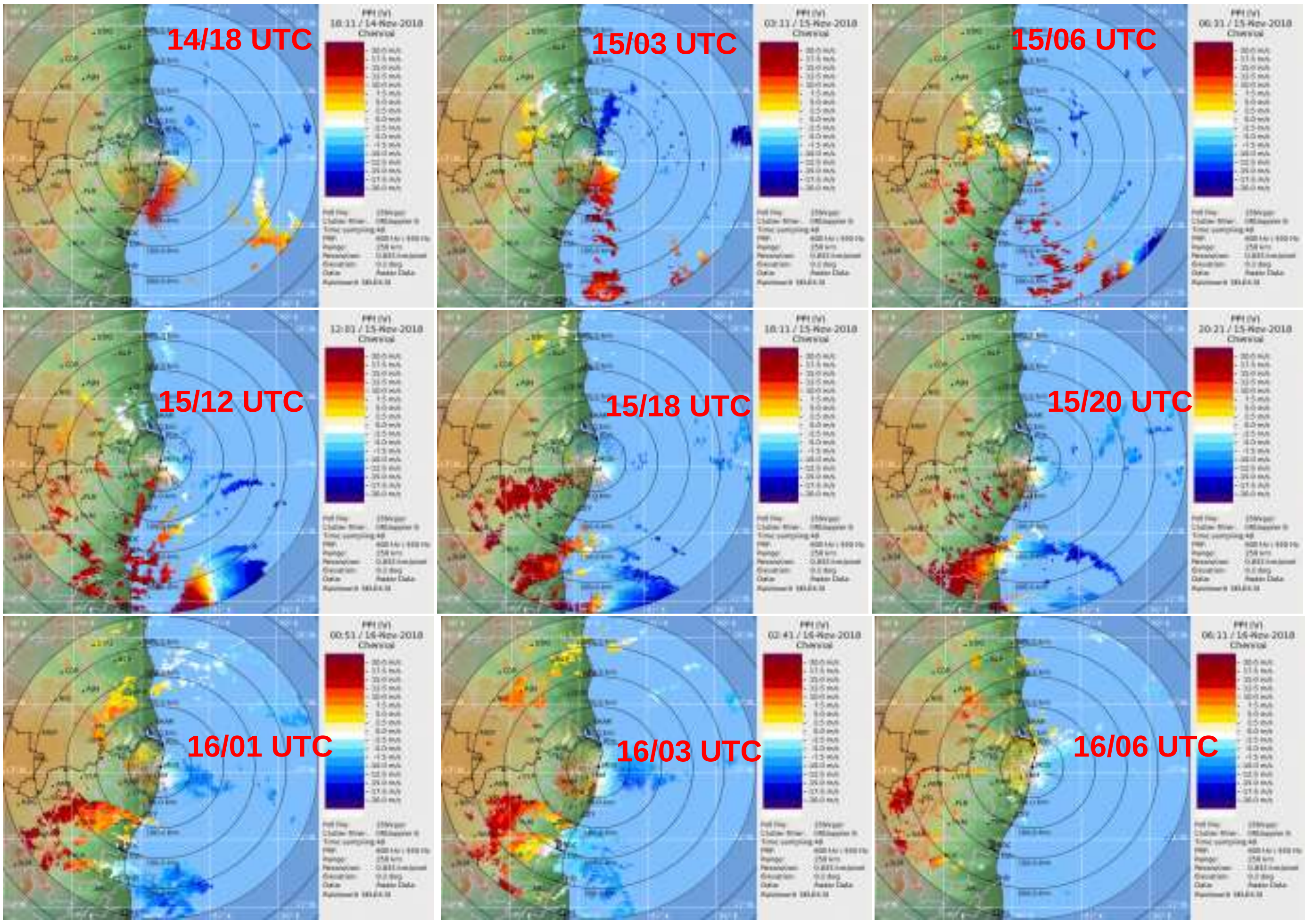


Fig. 5h: Chennai radar imageries of VSCS Gaja (10th – 19th November, 2018)

5.3. Microwave Imageries:

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 VSCS Gaja are presented in **Fig. 5(e).**

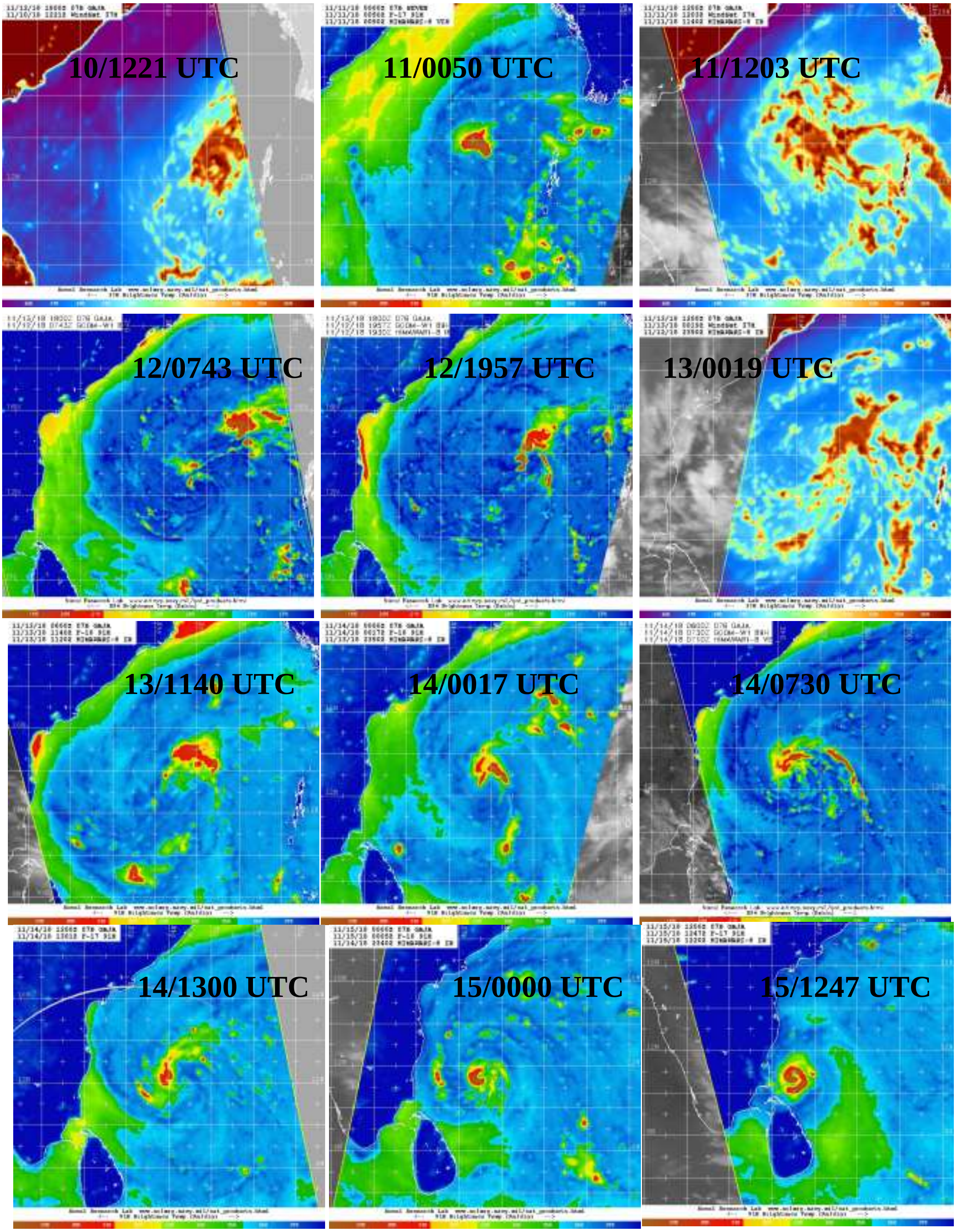


Fig. 5e: Microwave imageries during life cycle VSCS Gaja (10th – 19th November, 2018)

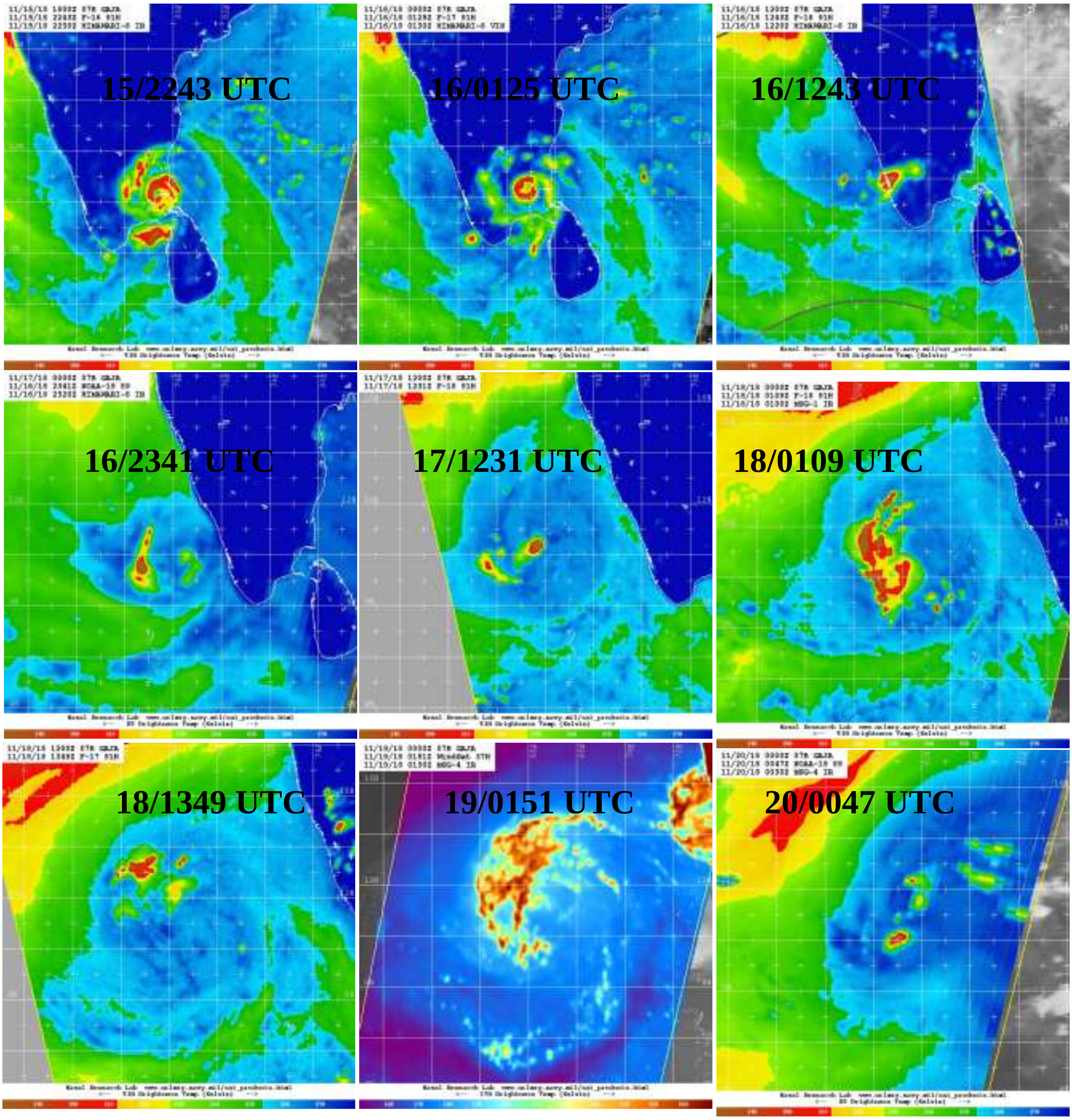


Fig. 5e(Cont.): Microwave imageries during life cycle VSCS Gaja (10th – 19th November, 2018)

When the system was over 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. 5(f).

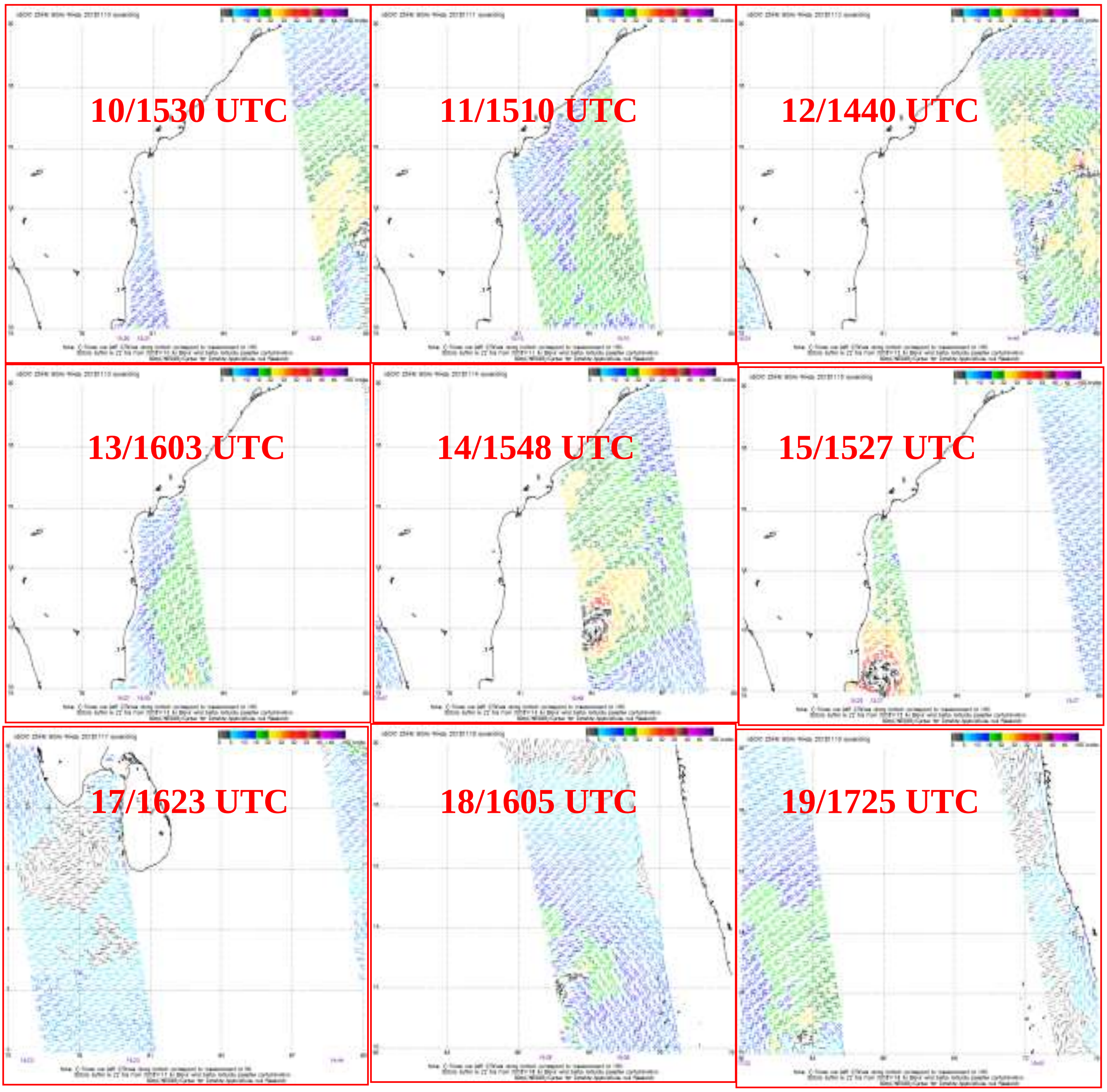


Fig. 5(f): ASCAT (Met-Op B) imageries during life cycle of VSCS Gaja (10th – 19th November, 2018)

Typical imageries from polar satellite, SCATSAT are presented in Fig.9 (b). SCATSAT passes are available twice a day at 0454 UTC and 1636 UTC at http://mosdac.gov.in/scorpio/SCATSAT_Data. The observations based on 1636 UTC of 21st indicated cyclonic circulation over southwest Arabian Sea. Stronger winds were seen in northern sector. The imagery also indicated large scale cross equatorial flow, inflow of warm and moist air into the system centre from southeast sector. At 0454 UTC of 22nd May, the area of strong winds extended to southwest sector. At 1636 UTC of 23rd, stronger winds were seen in the northwest sector. At 0454 UTC of 24th, the centre was seen near 13.5N/56E, warm and moist air advection from southwest to northwest sector was seen. The estimated intensity was more than 60 kts. The maximum size in the southern sector was also due to higher southwesterly winds in the region. On 25th and 26th stronger winds were seen in the northeast sector. SCAT Sat imageries helped in determination of centre to a good extent. Intensity estimates beyond 60 kts cannot be done with the help of these imageries.

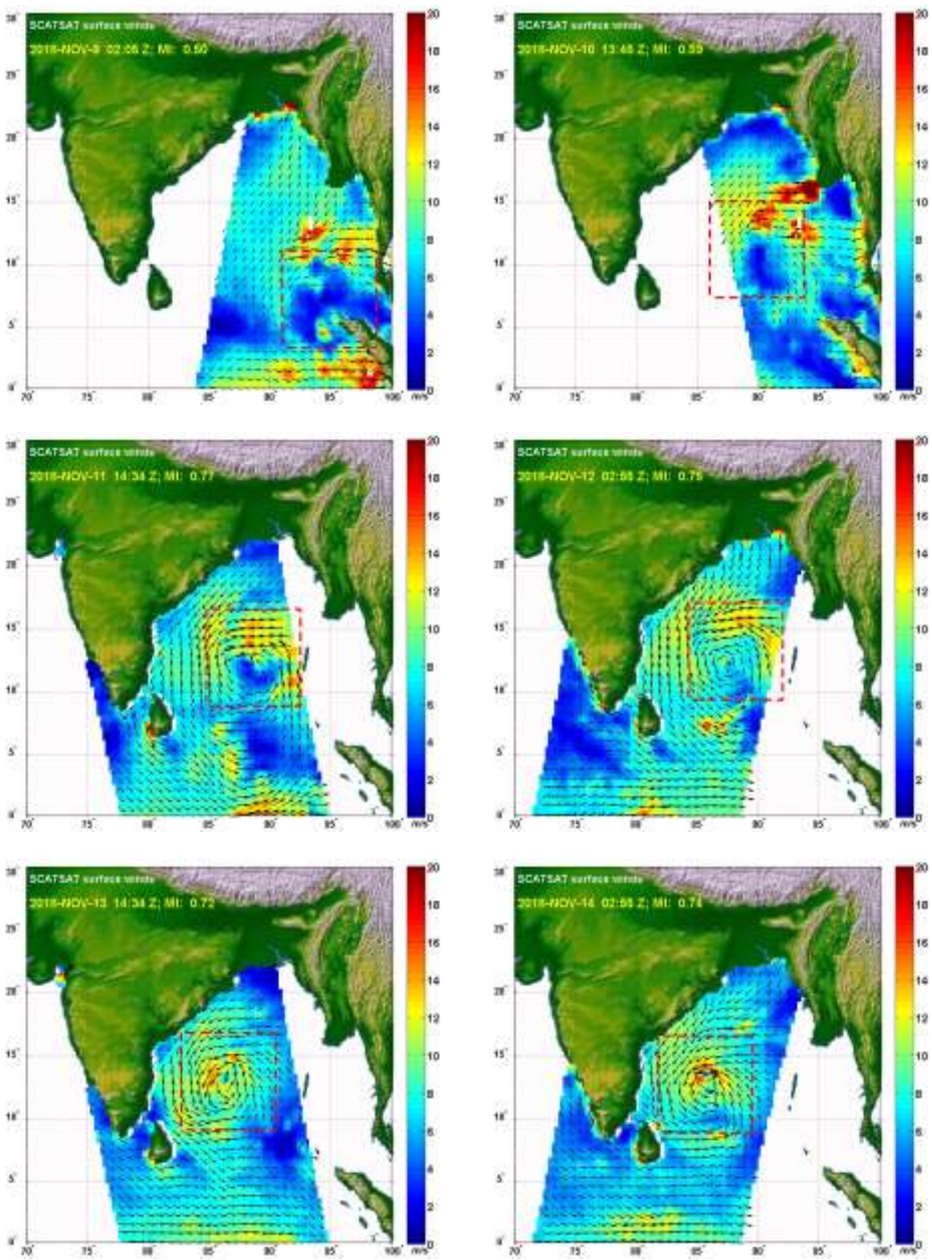


Fig. 5(f): SCAT SAT imageries during life cycle of VSCS Gaja (10th – 19th November, 2018)

6. Dynamical features

IMD GFS (T1534) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels during 10th to 19th November are presented in Fig.6. Based on 0000 UTC observations of 10th, the model predicted a depression over southeast and BoB an adjoining north Andaman Sea. The circulation was extending upto 850 hPa level. Upper tropospheric ridge was seen along 14^0N. The centre, intensity and ridge were correctly captured.

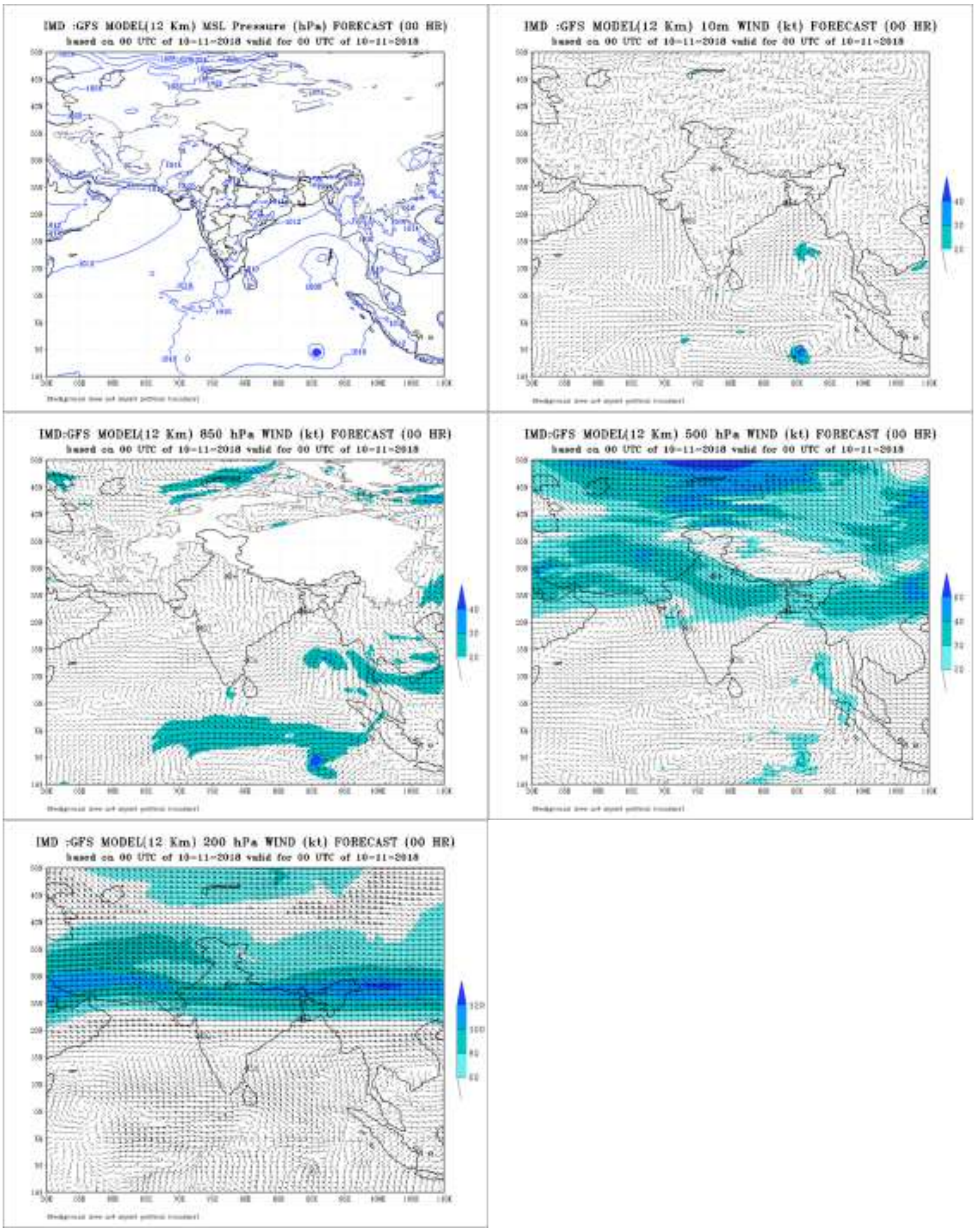


Fig. 6 (a): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 10th November

Analysis based on 0000 UTC of 11th November, predicted slight weakening of system. Vertically the system extended upto 850 hPa levels. However, the system intensified into a deep depression at 1200 UTC of 10th.

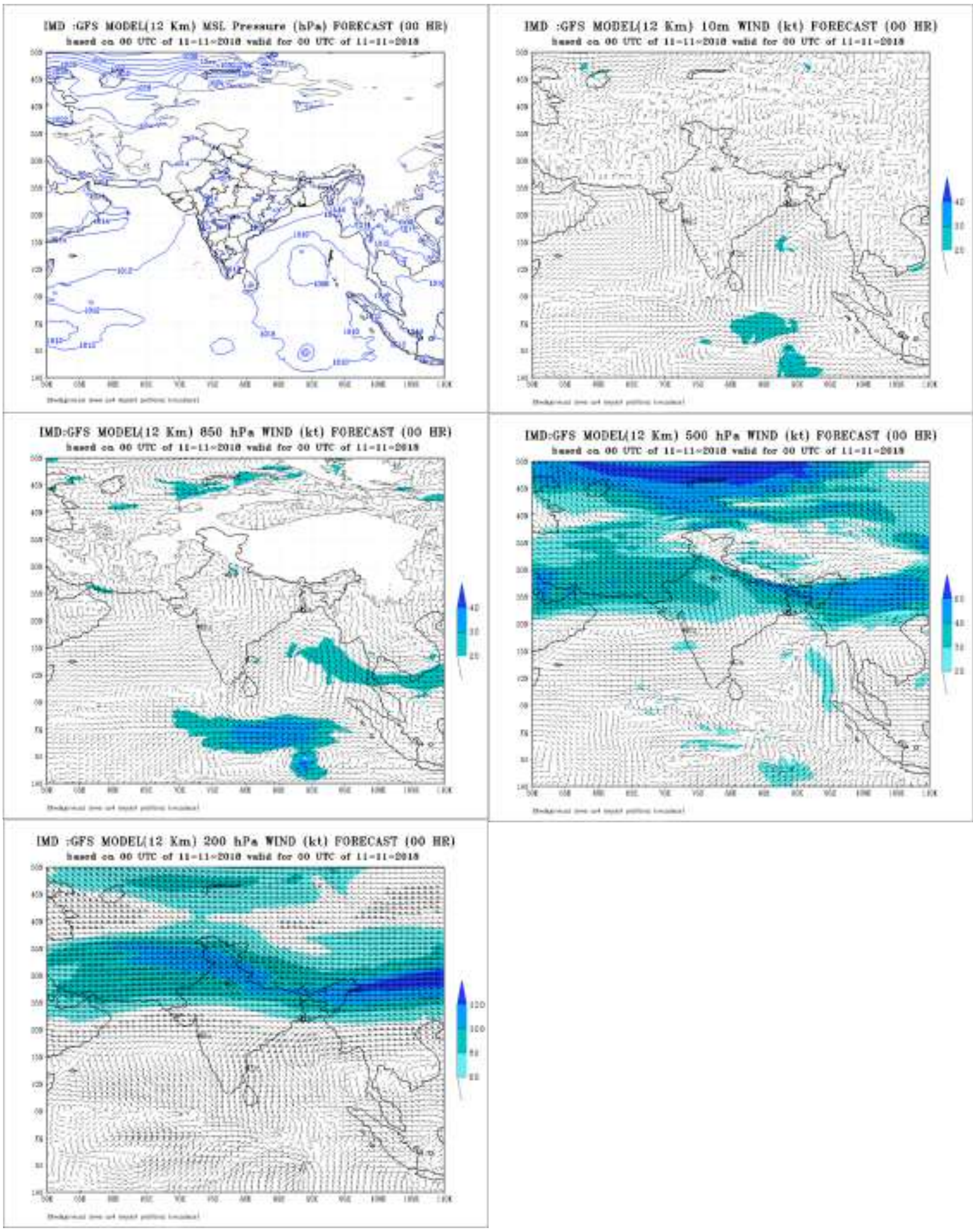


Fig. 6 (b): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 11th November

Analysis based on 0000 UTC of 12th November predicted intensification of the system into a deep depression over westcentral BoB. The circulation extended upto 500 hpa levels. However, the system attained the cyclonic storm intensity at 0000 UTC of 11th. But GFS could capture the centre of the system correctly.

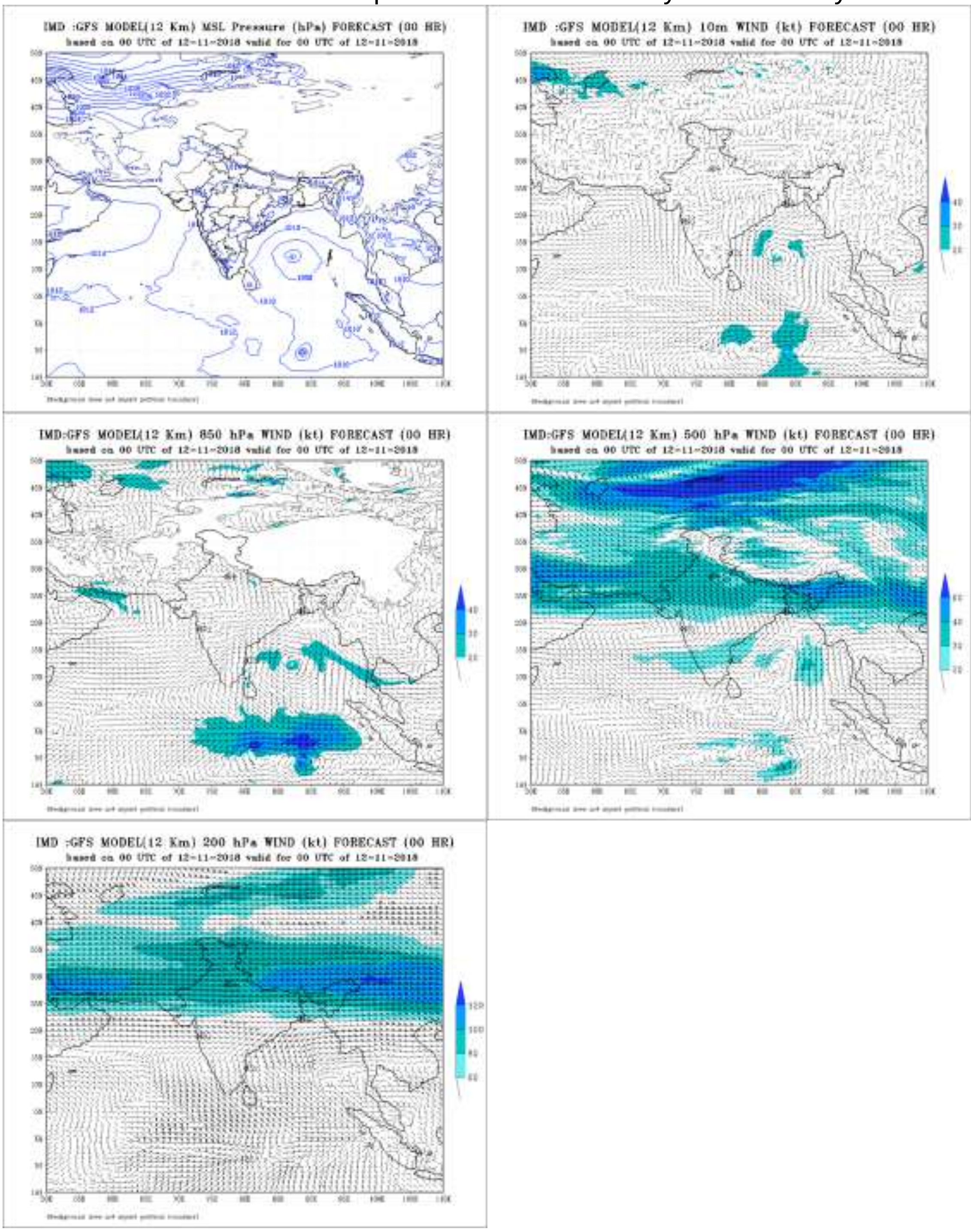


Fig. 6 (c): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 12th November

Initial conditions based on 0000 UTC of 13th November indicated weakening of the system into a depression near 13.5N/87.5E. Vertically the system extension was seen upto 850 hPa level. IMD GFS could capture the location correctly, but underestimated the intensity of the system. The system had the intensity of cyclonic storm at 0000 UTC of 13th.

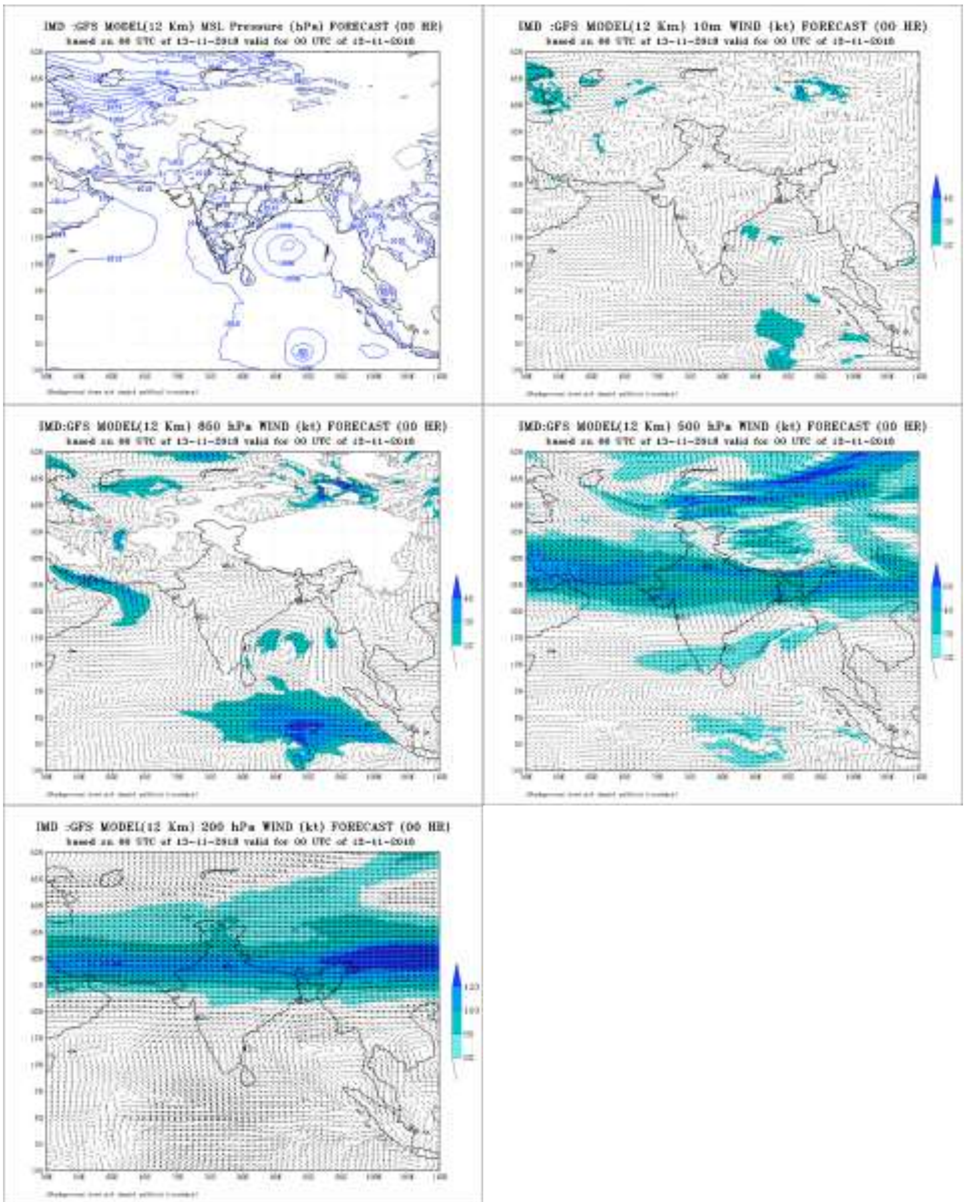


Fig. 6 (d): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 13th November

Analysis based on 0000 UTC of 14th November indicated further weakening of the system into a WML over westcentral and adjoining southwest BoB near 12.5N/85.0E. The system was near 13.5N/85.3E as a cyclonic storm at 0000 UTC of 14th. Thus, IMD GFS could not capture the intensity correctly. Anticyclonic circulation over eastcentral AS and ridge around 15^0N were also seen in GFS analysis charts.

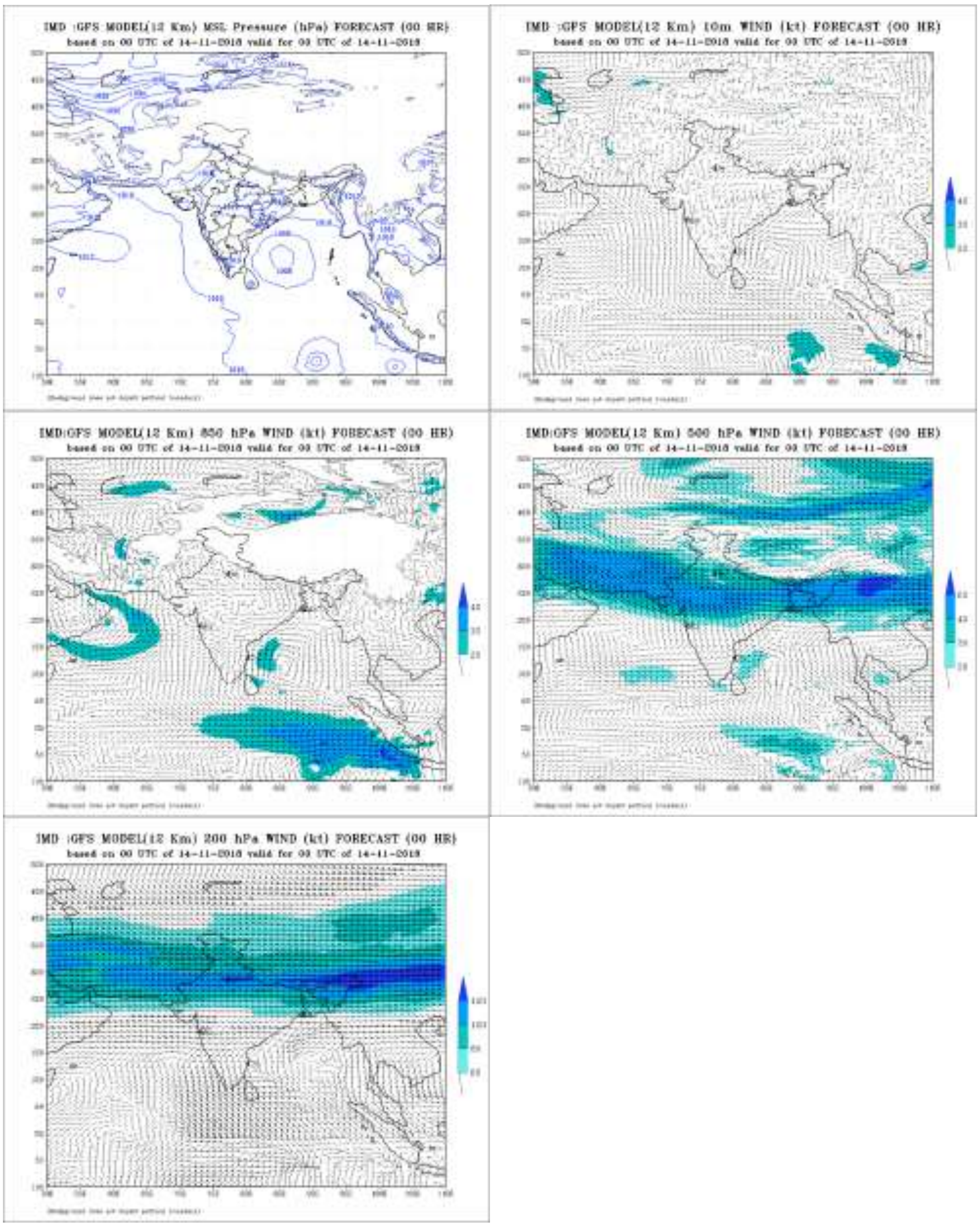


Fig. 6 (e): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 14th November

The initial conditions based on 0000 UTC of 15th indicated intensification of the system into an VSCS over southwest BoB near 11.0N/83.0E. The movement and location was correctly captured. However, the intensity was overestimated. At 0000 UTC of 15th, the system lay over southwest BoB near 11.5N/83.2E as a cyclonic storm. The ridge and anticyclones to the west and east of system centre were also captured by GFS.

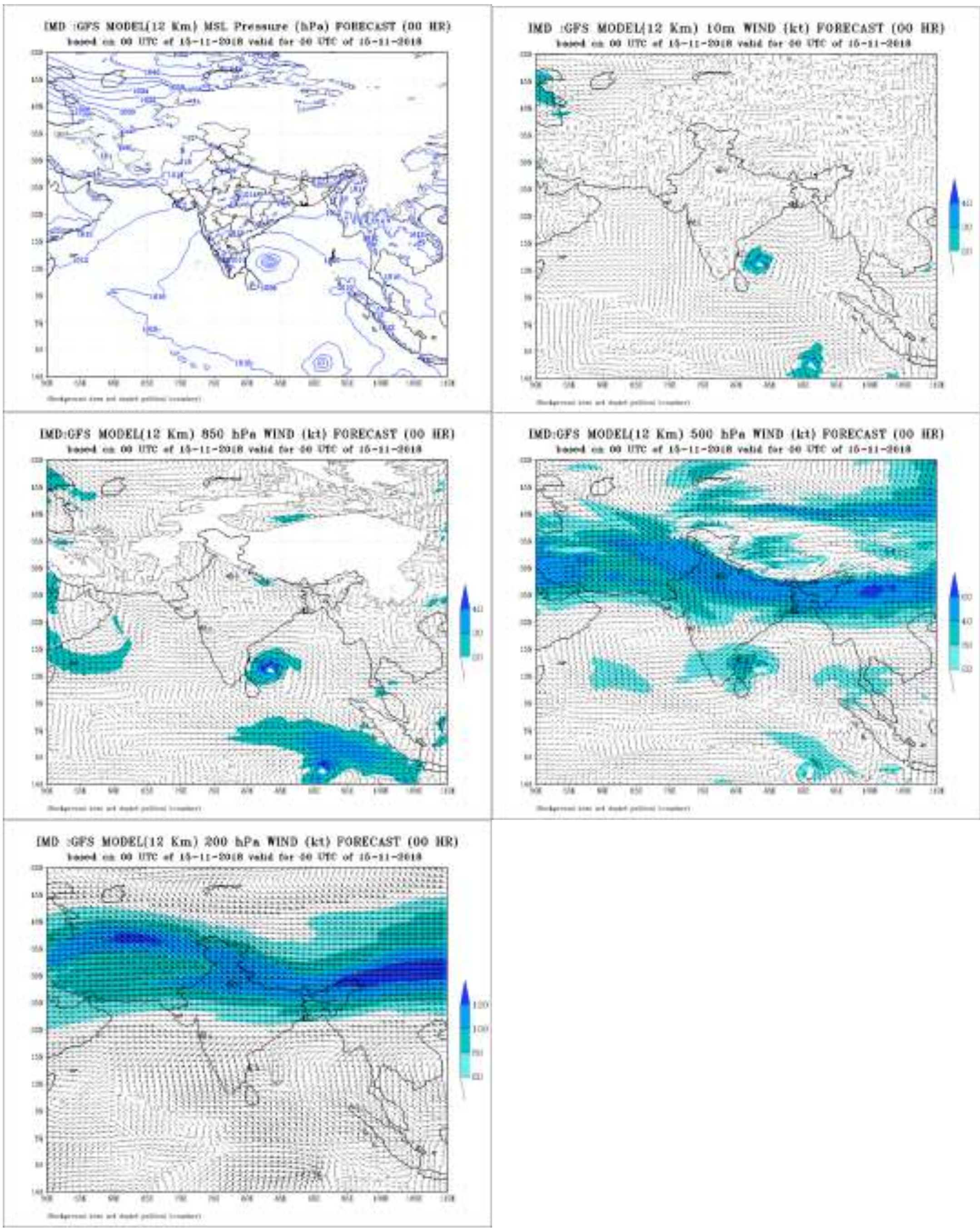


Fig. 6 (f): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 15th November

The initial conditions based on 0000 UTC of 16th indicated that the system crossed near 10.5N/79.5E around 2200 UTC of 15th as a VSCS. The landfall point & time and intensity were correctly predicted. The ridge and anticyclones to the west and east of system centre were also captured by GFS. The anticyclone to the west of system centre was also captured well that led to near westwards movement of the system. It also indicated that vertically the system extended upto 500 hPa level.

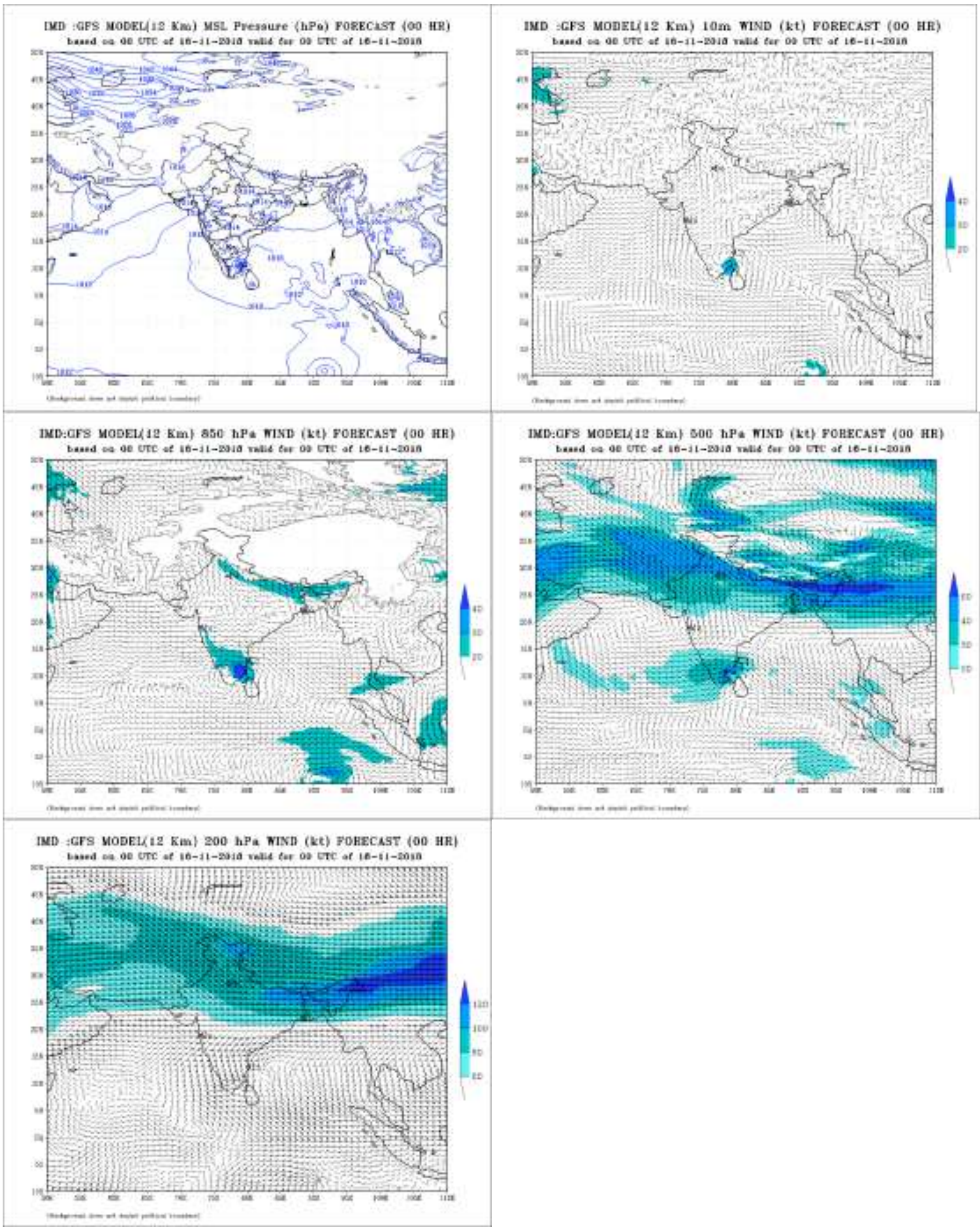


Fig. 6 (f): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 16th November

The initial conditions based on 0000 UTC of 17th captured the movement and location correctly. However, the intensity was underestimated. GFS indicated a depression over southeast AS near 10.0N/74.5E. However, at 0000 UTC of 17th, the system lay as a DD over southeast Arabian Sea near 9.8°N/74.3°E.

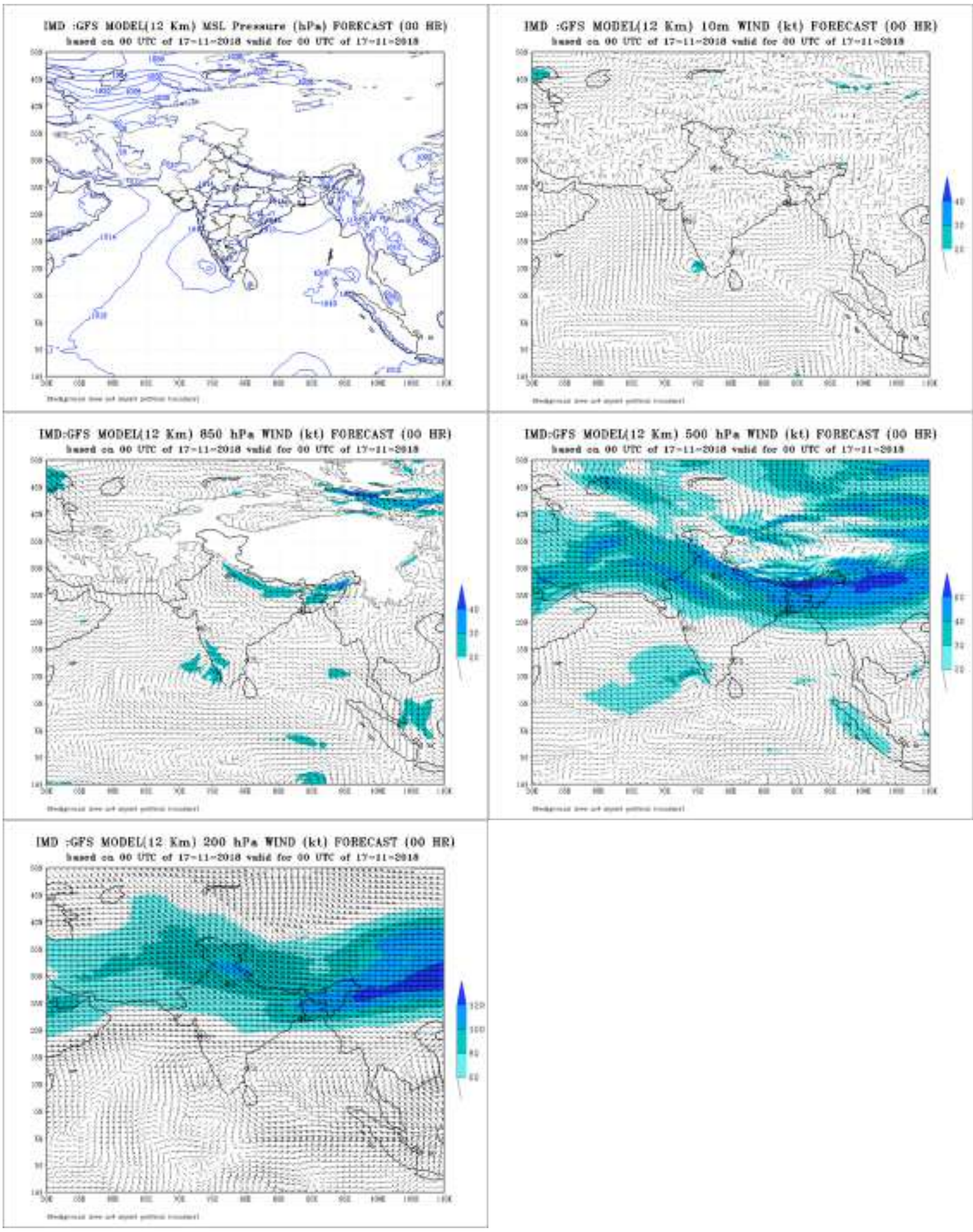


Fig. 6 (g): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 17th November

The initial conditions based on 0000 UTC of 18th captured the movement, location and intensity correctly. GFS predicted the system lay as a DD over southeast AS near 10.5N/69.5E. The best track parameters indicate that at 0000 UTC of 18th, the system lay as a DD over southeast Arabian Sea near 10.3°N/69.5°E.

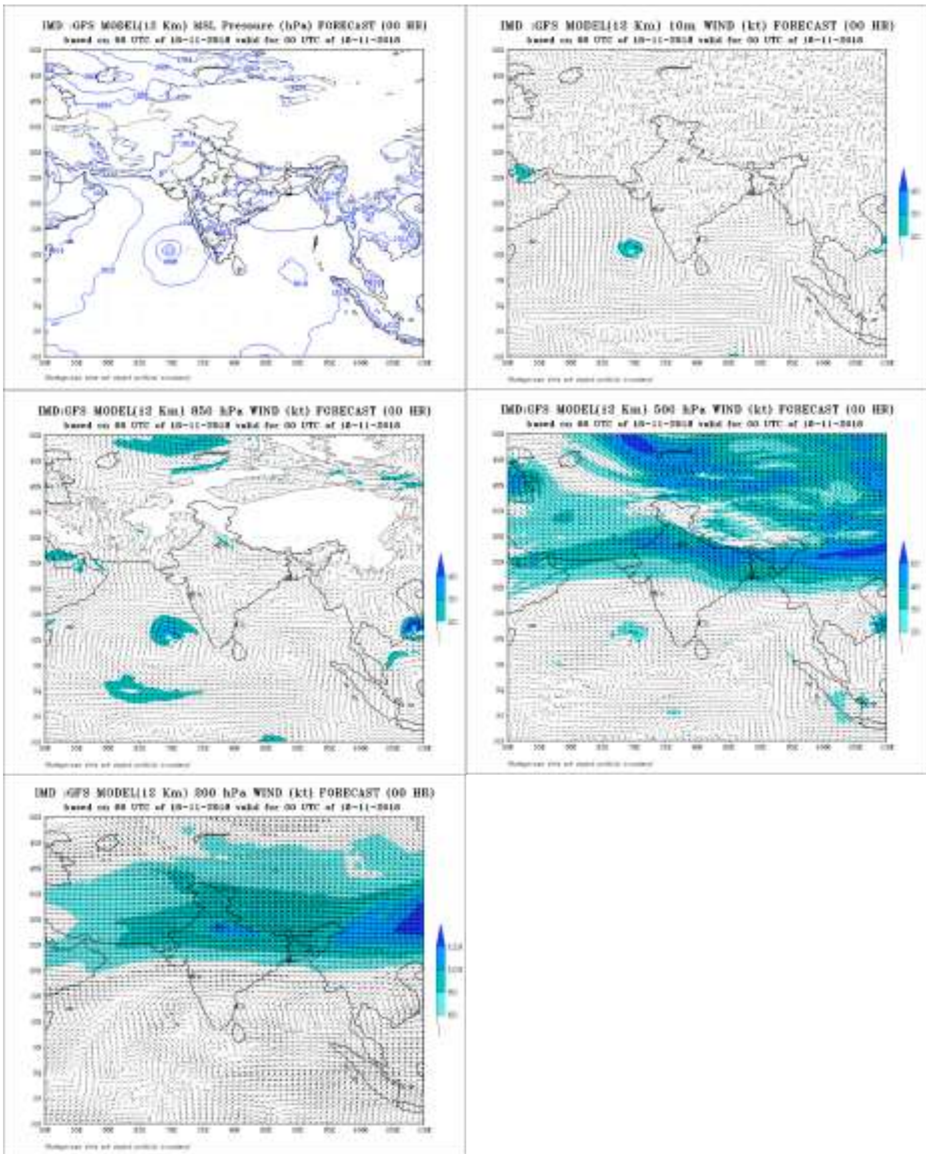


Fig. 6 (h): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 18th November

The initial conditions based on 0000 UTC of 19th indicated weakening of the system into a depression over southeast AS near 10.0N/66.5E. However, best track parameters indicate that the system retained it's intensity of DD and lay near 11.0N/66.0E.

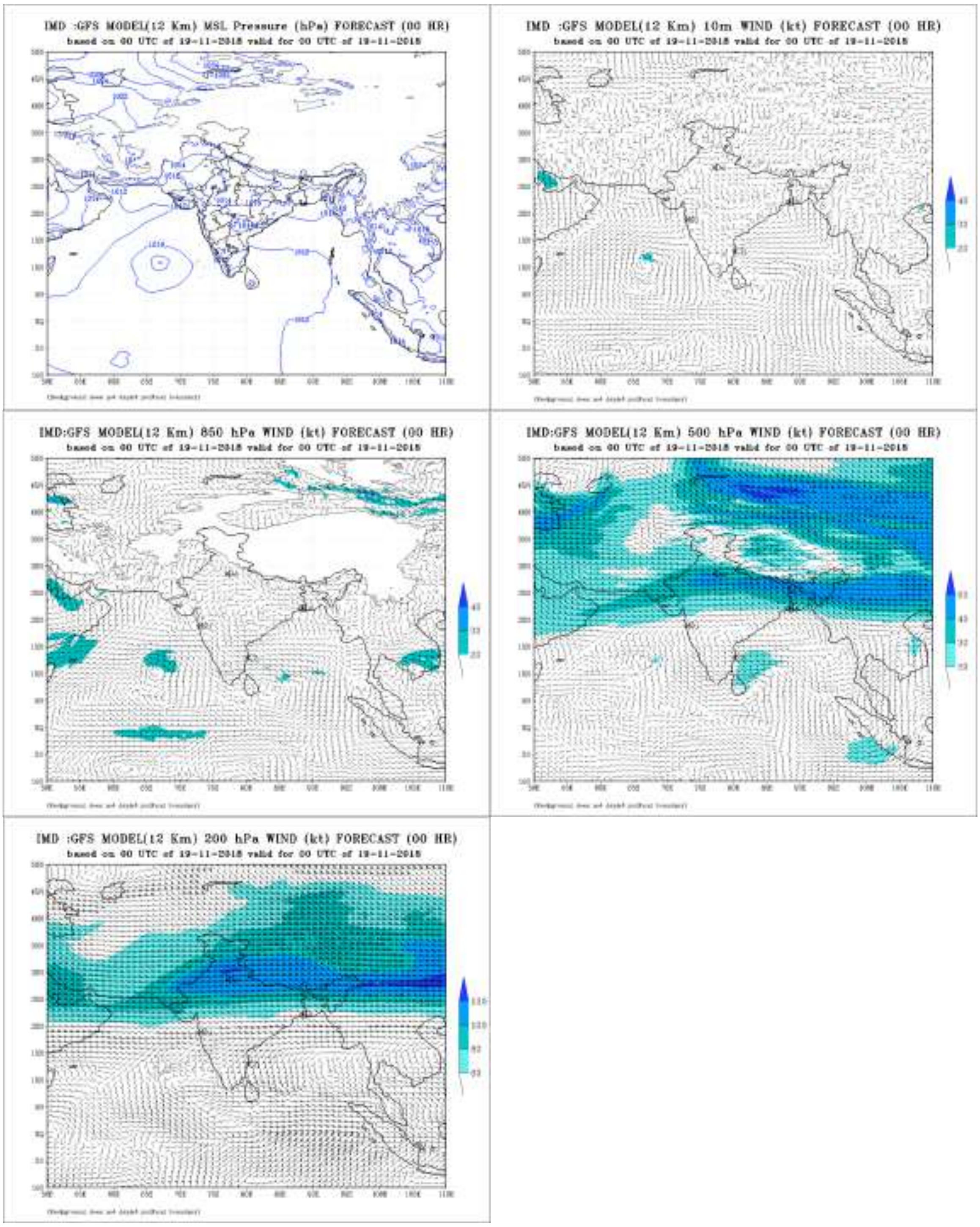


Fig. 6 (i): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 19th November

The initial conditions based on 0000 UTC of 20th indicated further weakening of the system into a WML over southwest AS near 10.5N/63.0E. The system weakened into a WML at 1800 UTC of 20th over southwest & adjoining southeast Arabian Sea.

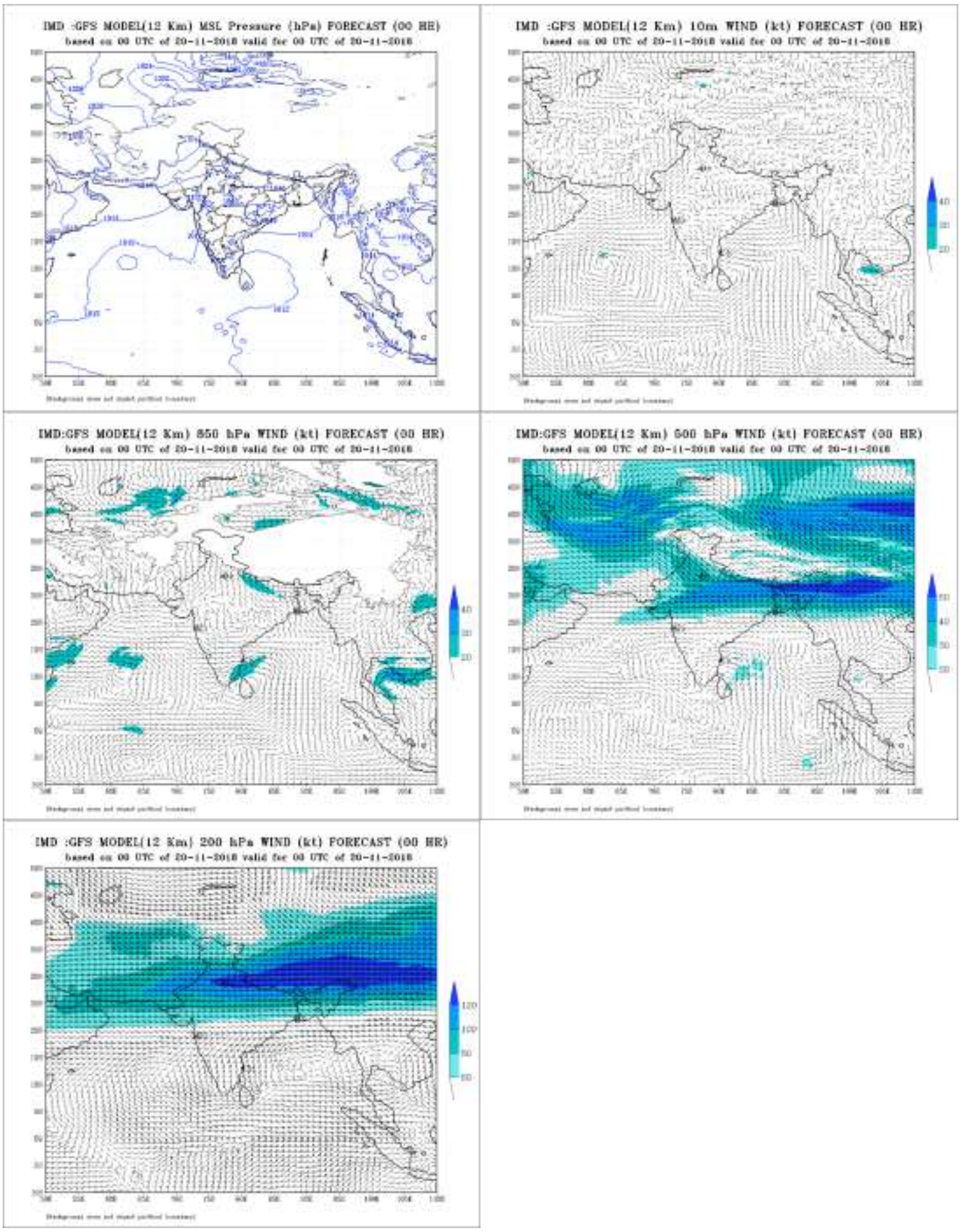


Fig. 6 (f): IMD GFS (T574) mean sea level pressure (MSLP), winds at 10m, 850, 500 and 200 hPa levels based on 0000 UTC of 20th November

Hence to conclude, to a large extent IMD GFS could simulate the genesis, movement and landfall characteristics of the system. However, it could not consistently capture the intensity of the system correctly.

7. Realized Weather:

7.1 Rainfall:

Rainfall associated with VSCS Gaja based on IMD-NCMRWF GPM merged gauge rainfall data is depicted in **Fig 7**.

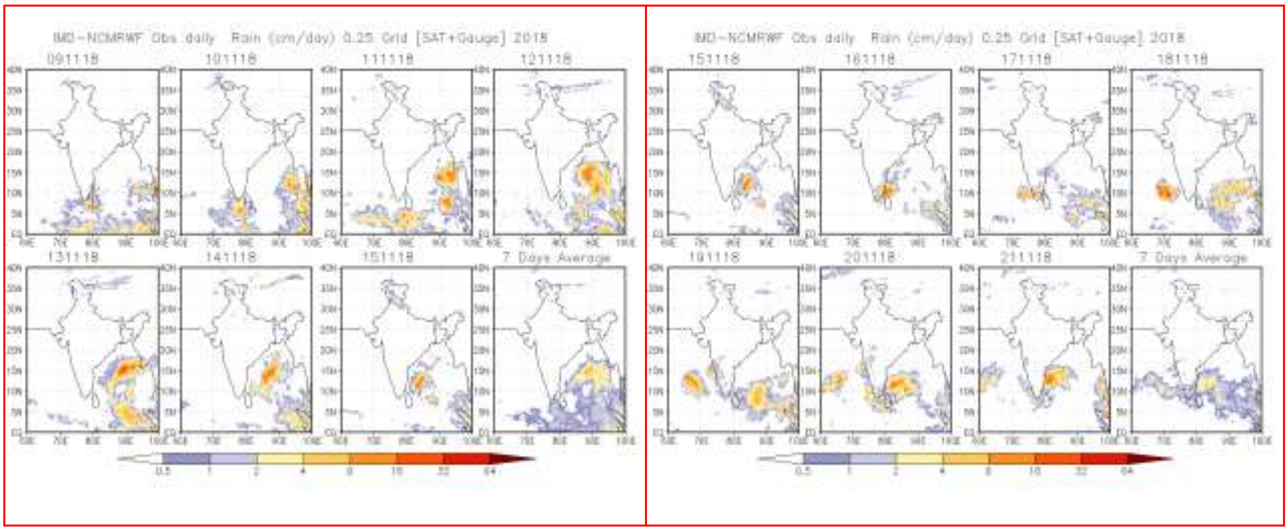


Fig.7: IMD-NCMRWF merged satellite and rain gauge observed rainfall (cm/day) during 10-18 November in association with VSCS Gaja

Under the influence of the system, on 16th November, rainfall occurred at most places with heavy falls at a few places and very heavy falls at isolated places over Tamil Nadu. Moderate rainfall occurred over Kerala, south coastal Andhra Pradesh, Rayalaseema and south interior Karnataka. On 17th, rainfall occurred at most places with isolated heavy to very heavy rainfall over Kerala and Tamilnadu. Isolated extremely heavy rainfall also occurred over Kerala and isolated heavy rainfall over coastal Andhra Pradesh.

Realized 24 hrs accumulated rainfall (≥7cm) ending at 0830 hrs IST of date during the life cycle of the system is presented below:

10 November 2018

Andaman & Nicobar Islands: Long Island-14, Maya Bandar-10, Port Blair-9

11 November 2018

Andaman & Nicobar Islands: Maya Bandar-7,

16 November:

Tamilnadu & Puducherry: Thiruthuraipoondi & Muthupet-17 each, Adirampatnam-16, Peravurani, Pattukottai & Neyveli-14 each, Virudachalam-12, Chengalpattu-11, Cuddalore-9, Madukkur, Arantangi & Vandavasi-8 each, and Srimushnam, Valinokkam, Nagercoil, Uthiramerur, Orthanad, Needamangalam, Thuckalay, Sethiathope, Pondicherry & Tozhudur-7 each

17 November:

Coastal Andhra Pradesh: Kandukur and Gudivada-7 each,

Telangana: Aswaraopeta-7,

Tamilnadu & Puducherry: Sivaganga-17, Kodaikanal-14, Thammampatty-10, Nilakottai, Illuppur, Periyakulam & Bodinaickanur-9 each, Tirupathur-8 and Chinnakalar, Vadipatti-7 each

Kerala: Kozha-28, Piravam-19, Thodupuzha-15, Cherthala & Munnar Kseb-12 each, Kumarakam-11, Idukki-10, Vaikom, & Myladumpara-9 each, Kottayam-8, Peermade -7

7.2. Wind

Atiramapattinam reported maximum wind speed of 117 kmph at 0330 hrs IST, Nagapattinam reported 100 kmph during 0230-0330 IST and Karaikal reported 92 kmph at 0130 IST of 16th. Estimated maximum wind speed at the time of landfall was 130 kmph gusting to 145 kmph.

7.3. Storm surge

Storm surge of about 1 metre above astronomical tide inundated low lying areas upto about 1 km from the coast near the landfall point.

8. Damage due to VSCS Gaja

As per media reports (Source: The News Minute dated the 21st November, 2018), about 46 people lost their lives as an aftermath of cyclonic storm Gaja. Tamil Nadu suffered loss of around 88,102 hectares of agriculture lands, 86702 electric poles, 841 transformers, 201 electricity substations and 4844 fishing boats. The impact of the cyclonic storm Gaja, particularly on perennial crops such as coconut in the Cauvery Delta region, appears insurmountable. Coconut farmers do not see light at the end of the tunnel at this juncture as more than 80 per cent of the trees, many over 20 years old, have fallen flat. (Source: Business Line dated 19 November, 2018). More than 80 per cent of the palms in the region were uprooted, affecting the livelihood of the small and marginal farmers. Around 75 lakh trees were damaged either fully or partially in the gale winds. Nagapattinam, Thanjavur, Tiruvarur, Pudukottai were the worst affected places in Tamil Nadu. Typical damage photographs are presented in **Fig.8**.

Fig.8 (a): Coconut trees felled by cyclone Gaja in Peruvurani area in the Thanjavur district (Business Line 19.11.2018 and The News Minute 18.11.2018)

Fig.8 (b): Damaged Poles and felled Trees in Tamil Nadu (India Today 16.11.2018 and Deccan Chronicle 24.11.2018)

Fig.8 (c): Damaged beaches and boats in Tamil Nadu (Hindustan Times 16.11.2018 and The Economic Times 18.11.2018)

Fig.8 (d): Damaged Karaikudi Tollways and blocked roads in Tamil Nadu (The Indian Express 15.11.2018)

Fig.8 (e): Flooded streets in Tamil Nadu and NDRF team clearing the debris (The Times of India 17.11.2018)

9. 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 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. 25^0S 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. IMD also runs operationally, the cyclone specific Hurricane Weather Research & Forecast (HWRF) model (resolution 18 km, 6 km and 2 km) for cyclone track & intensity prediction in case of cyclone situation in the north Indian Ocean.

Global models are also run at NCMRWF. These include GFS and unified model adapted from UK Meteorological Office. 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. NCMRWF Ensemble Prediction System (NEPS) is a global medium range probabilistic forecasting system adapted from UK MET Office. The configuration consists of 220 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 mid-latitudes. 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.

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 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.

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

In this report performance of the individual models, MME forecasts, SCIP, GPP, RII and Decay model for cyclone Gaja are presented and discussed.

9.1 Prediction of cyclogenesis (Genesis Potential Parameter (GPP)) for GAJA

Fig. 9 (a-f) shows the predicted zone of cyclogenesis based on 0000 UTC of 5th to 10th November for 0000 UTC of 10th November. The model could predict cyclogenesis zone correctly and consistently at 0000 UTC of 10th based on 0000 UTC of 5th – 10th November over southeast and adjoining north Andaman Sea (120 hrs in advance of actual genesis). The analysis and 6 days forecast based on initial conditions of 0000 UTC of 9th November is presented in Fig. 9 (g-m). It can be seen that movement of potential zone of cyclogenesis was correctly captured by the model.

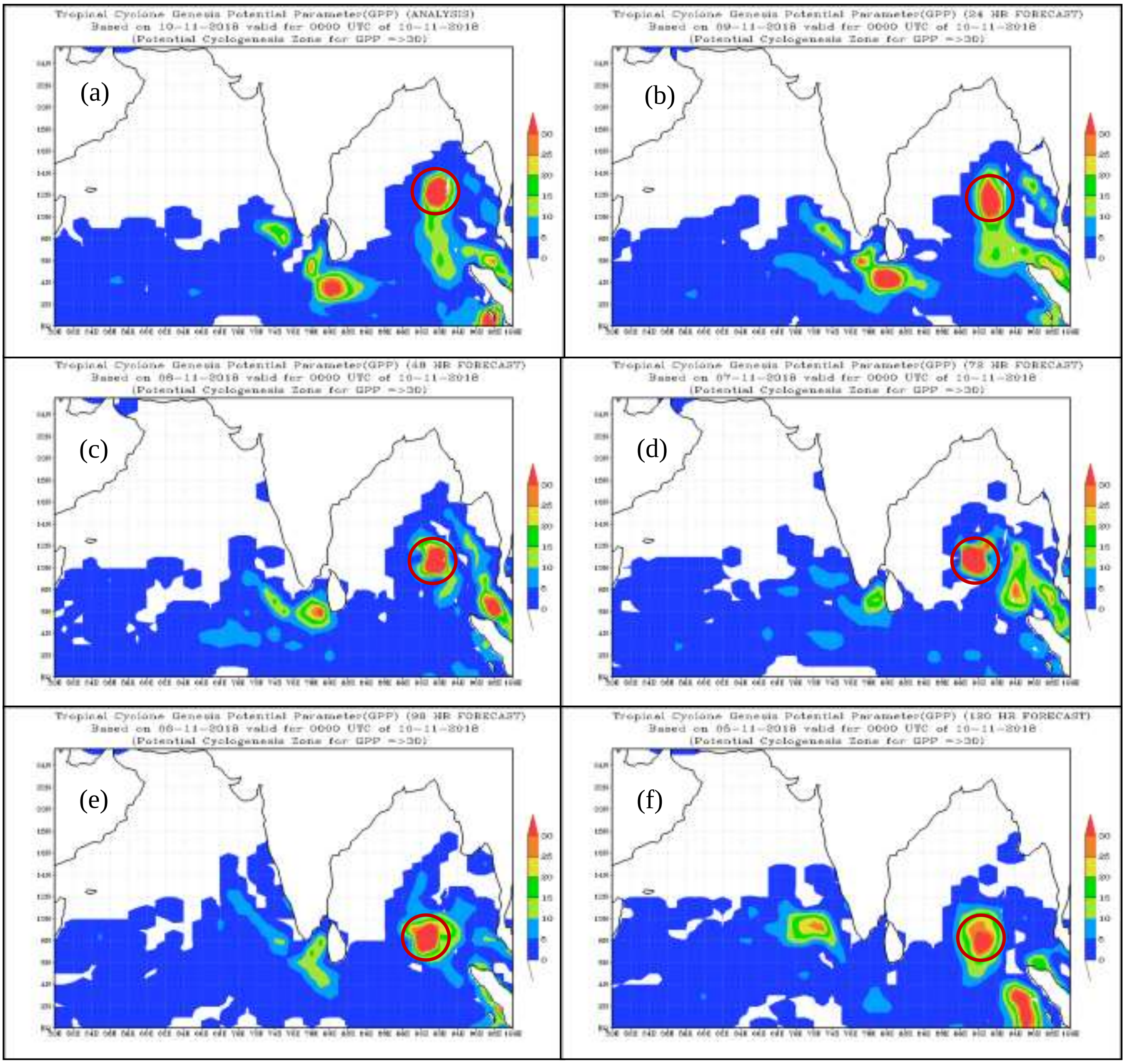


Fig. 9 (a-f): Predicted zone of cyclogenesis for 10th November based on 0000 UTC of 5th -10th November initial conditions

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 was also predicted. 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 GPP (Fig. 10) showed potential to intensify into a cyclone at early stages of development (T.No. 1.0, 1.5, 2.0). However, based on 0000 UTC analysis of 10th, the model predicted intensification upto 36 hrs and weakening trend thereafter. Similarly, the area average analysis based on 1200 UTC of 10th predicted weakening trends around 11th and 13th morning. However, the system didn't show any weakening signal till landfall. However, till 15th, the model predicted the system to maintain cyclonic storm intensity.

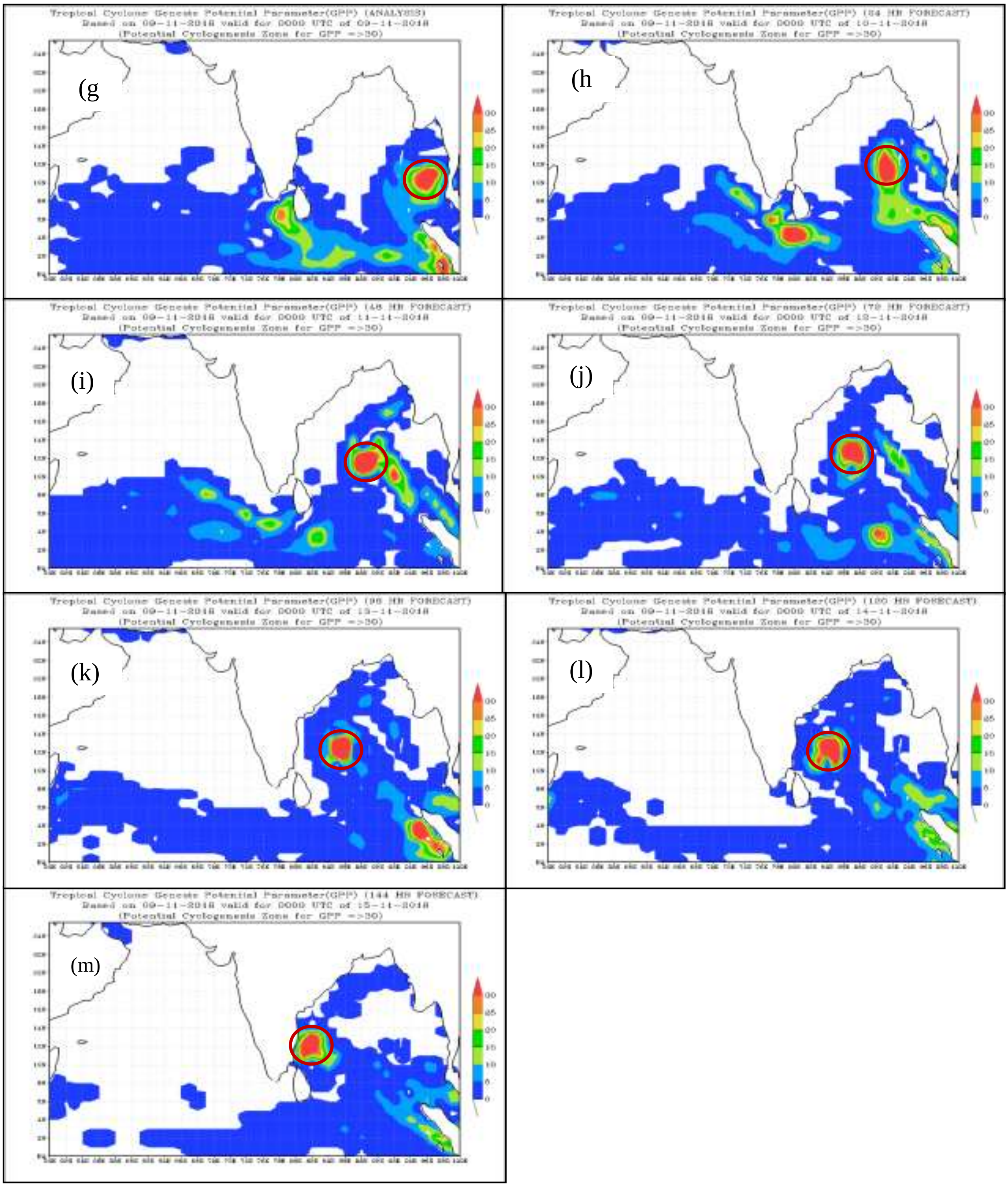


Fig. 9 (h-m): 24-hrly Predicted zone of cyclogenesis based on 0000 UTC of 9th upto144 hours

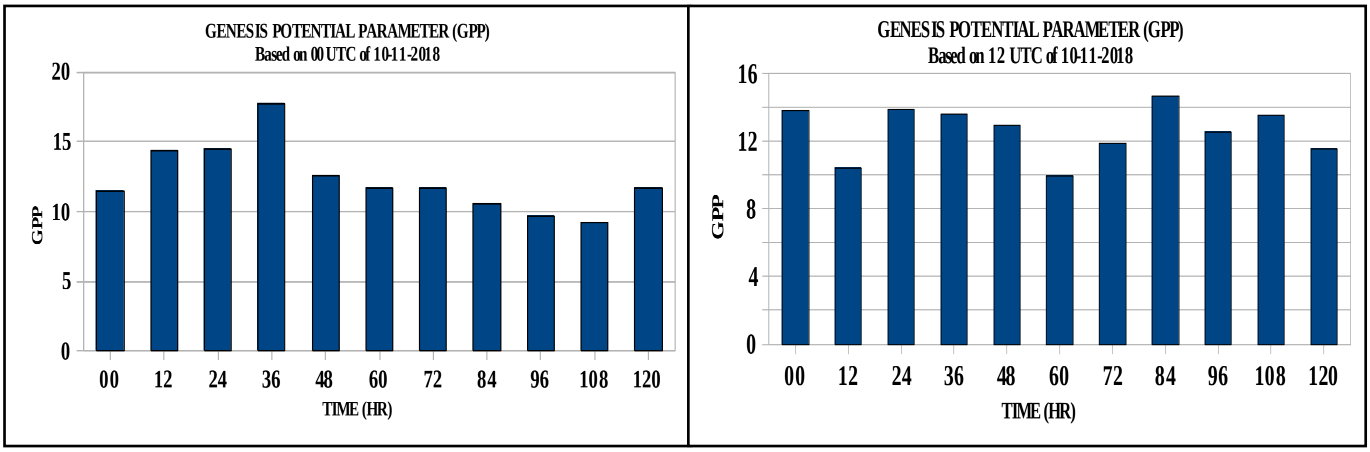


Fig. 10: Area average analysis and forecasts of GPP based on 0000 & 1200 UTC of 10th November, 2018

9.2 Track prediction by NWP models

Track prediction by various NWP models is presented in Fig.11. Based on initial conditions of 0000 UTC of 10th November, all models except IMD-GFS and UKMO were predicting weakening of the system over sea. Both the models were predicting landfall around 0600 UTC of 15th over north Tamil Nadu.

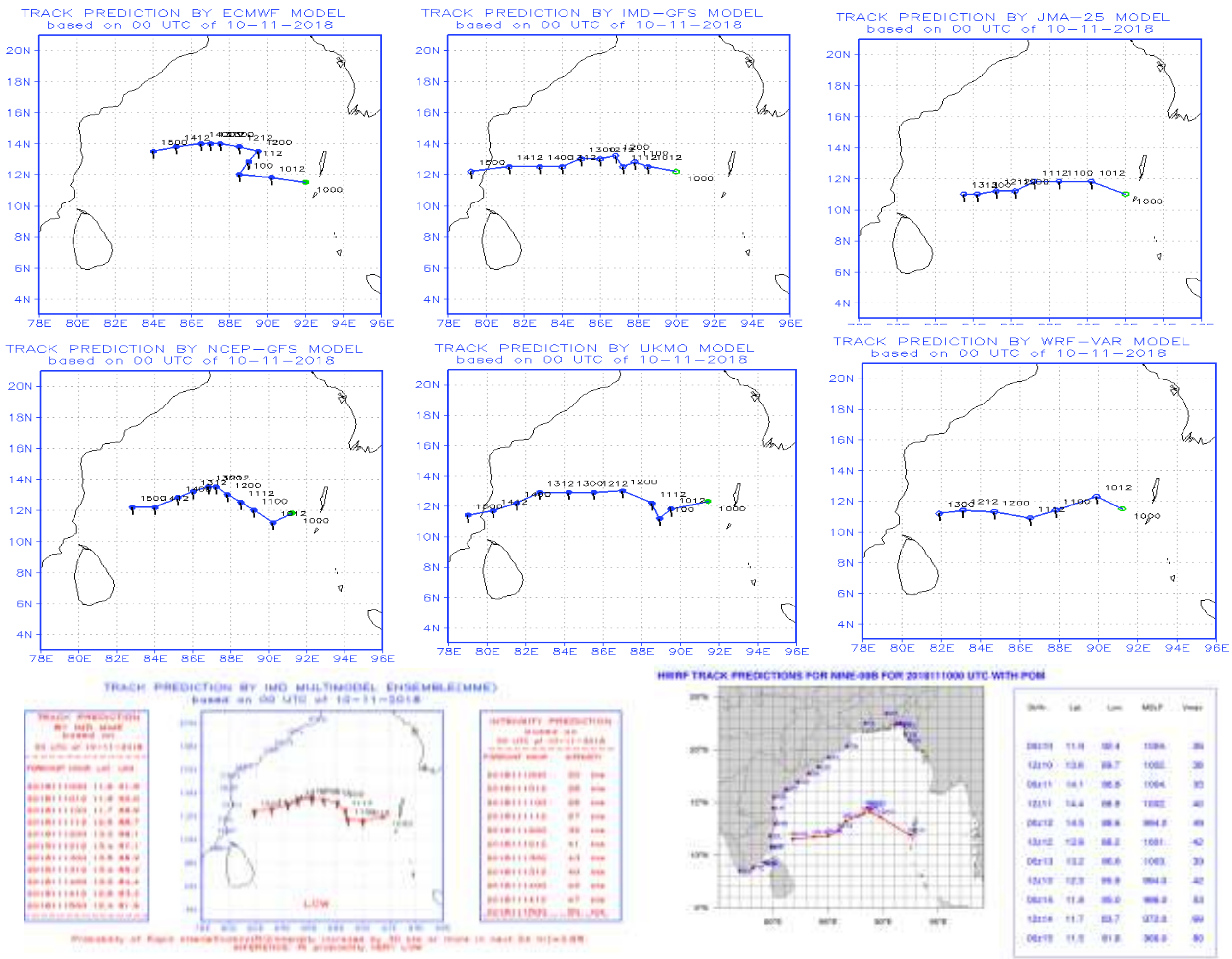


Fig. 11 (a): NWP model track forecast based on 0000 UTC of 10th November

Based on initial conditions of 0000 UTC of 11th November, WRF-VAR, NCEP GFS, HWRF and JMA were predicting weakening over sea prior to landfall. All other models including ECMWF, IMD-GFS, MME, UKMO were predicting landfall over north Tamil Nadu to the north of Nagapattinam between 0600 to 1200 UTC of 15th.

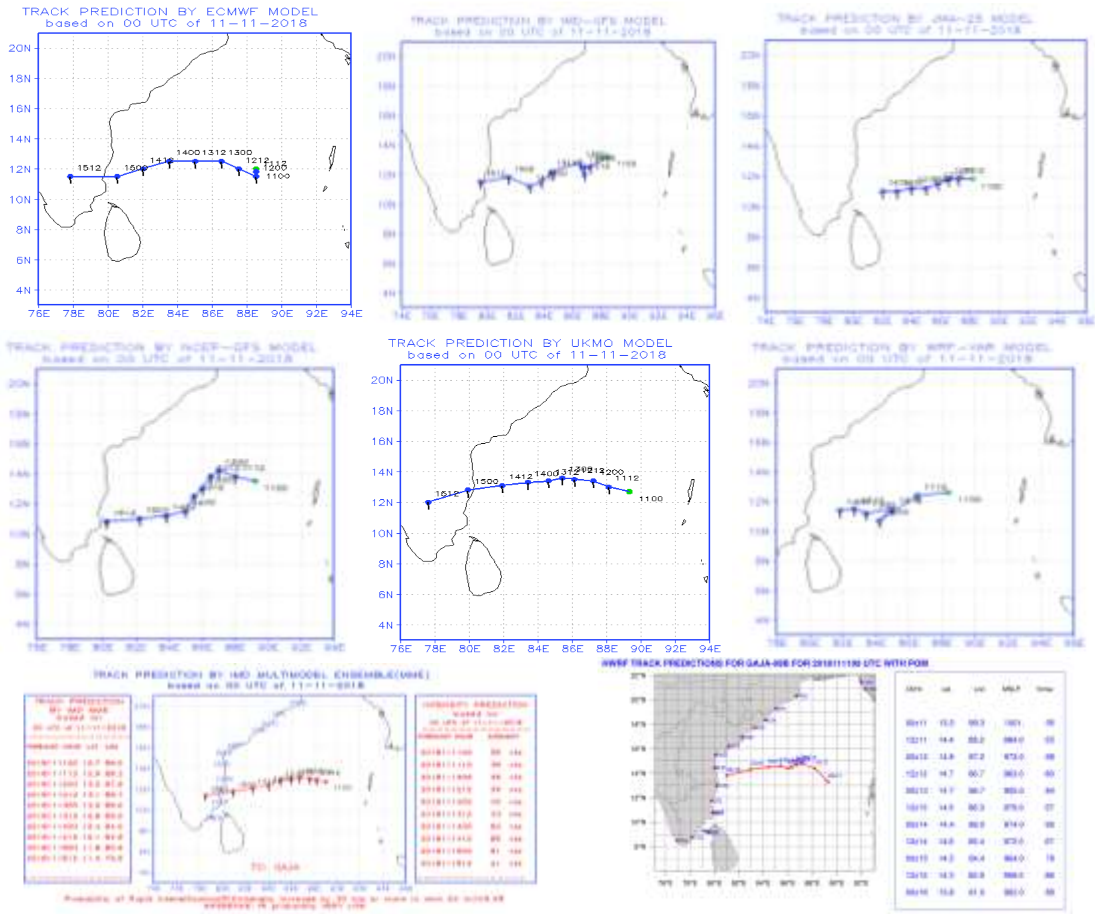


Fig. 11 (b): NWP model track forecast based on 0000 UTC of 11th November

Based on initial conditions of 0000 UTC of 12th November, none of the models could capture looping during 12th-13th. Models like IMD-GFS, JMA indicated landfall to the north of Nagapattinam. HWRF predicted landfall over Chennai. MME and ECMW predicted landfall to the south of Nagapattinam. NCEP GFS and UKMO predicted the southwestwards movement with the system entering Palk Strait and hitting coast near Kanyakumari and Tuticorin respectively. There was also large variation w.r.t. landfall time.

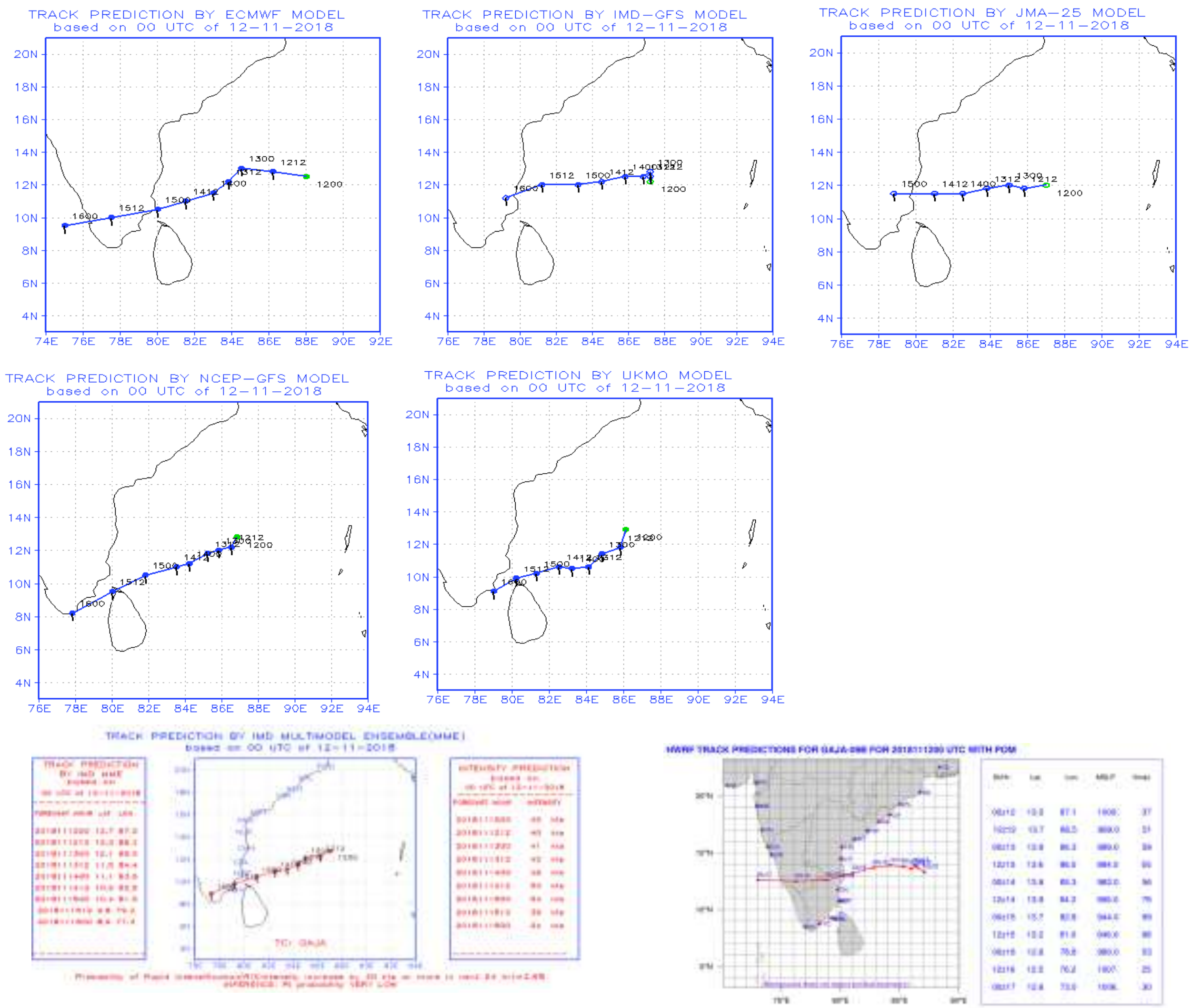


Fig. 11 (c): NWP model track forecast based on 0000 UTC of 12th November

Based on initial conditions of 0000 UTC of 13th November, IMD-GFS and NCEP-GFS predicted landfall over north Sri Lanka. All other models were predicting landfall to the north of Nagapattinam. HWRF and UKMO even predicted emergence of the system into Arabian Sea.

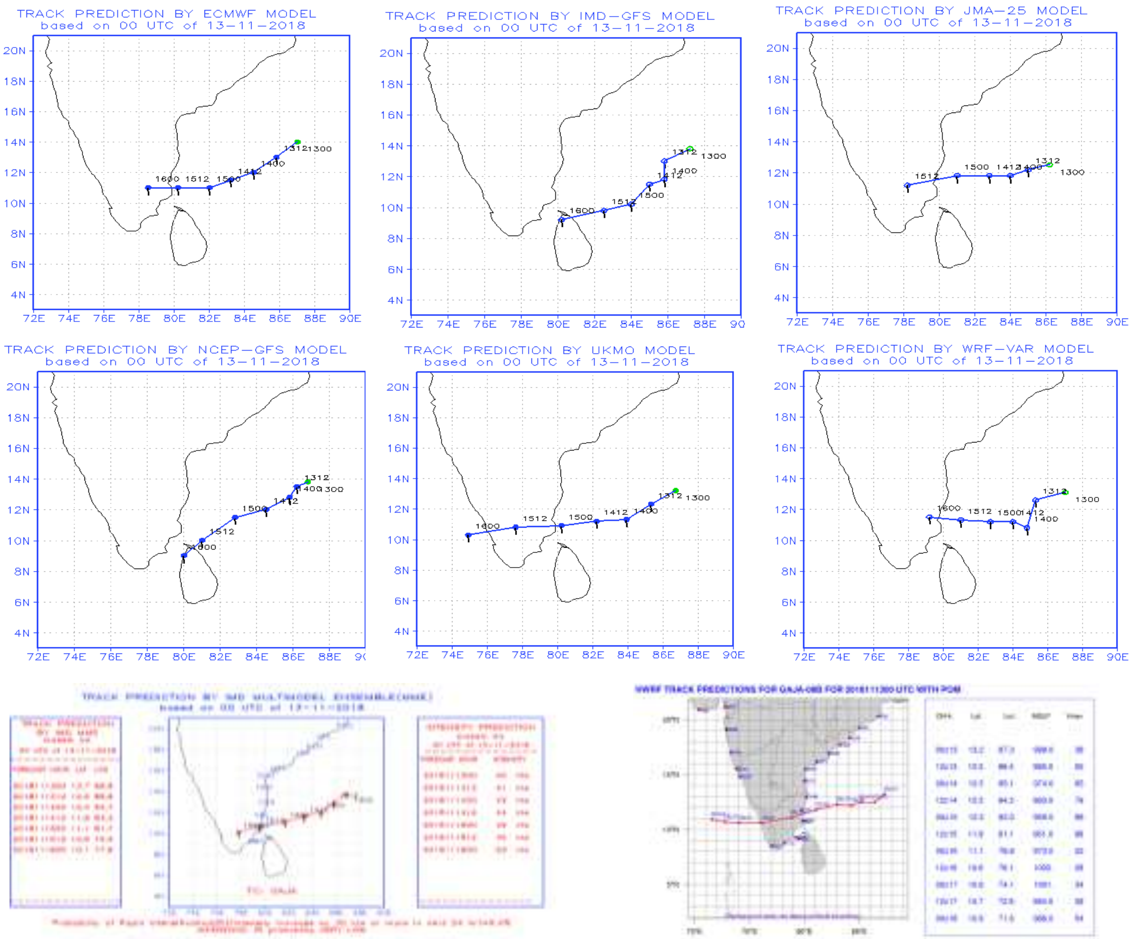


Fig. 11 (d): NWP model track forecast based on 0000 UTC of 13th November

Based on initial conditions of 0000 UTC of 14th November, NCEP-GFS and IMD GFS predicted weakening of the system over southwest BoB. Only HWRF was predicting emergence of the system into Arabian Sea. All other models like ECMWF, UKMO, WRF-VAR, JMA, HWRF & MME predicted landfall close to Nagapattinam between 1800 UTC of 15th to 0600 UTC of 16th. The intensity predicted at the time of landfall by HWRF was around 80 kts and that by MME was around 34 kts.

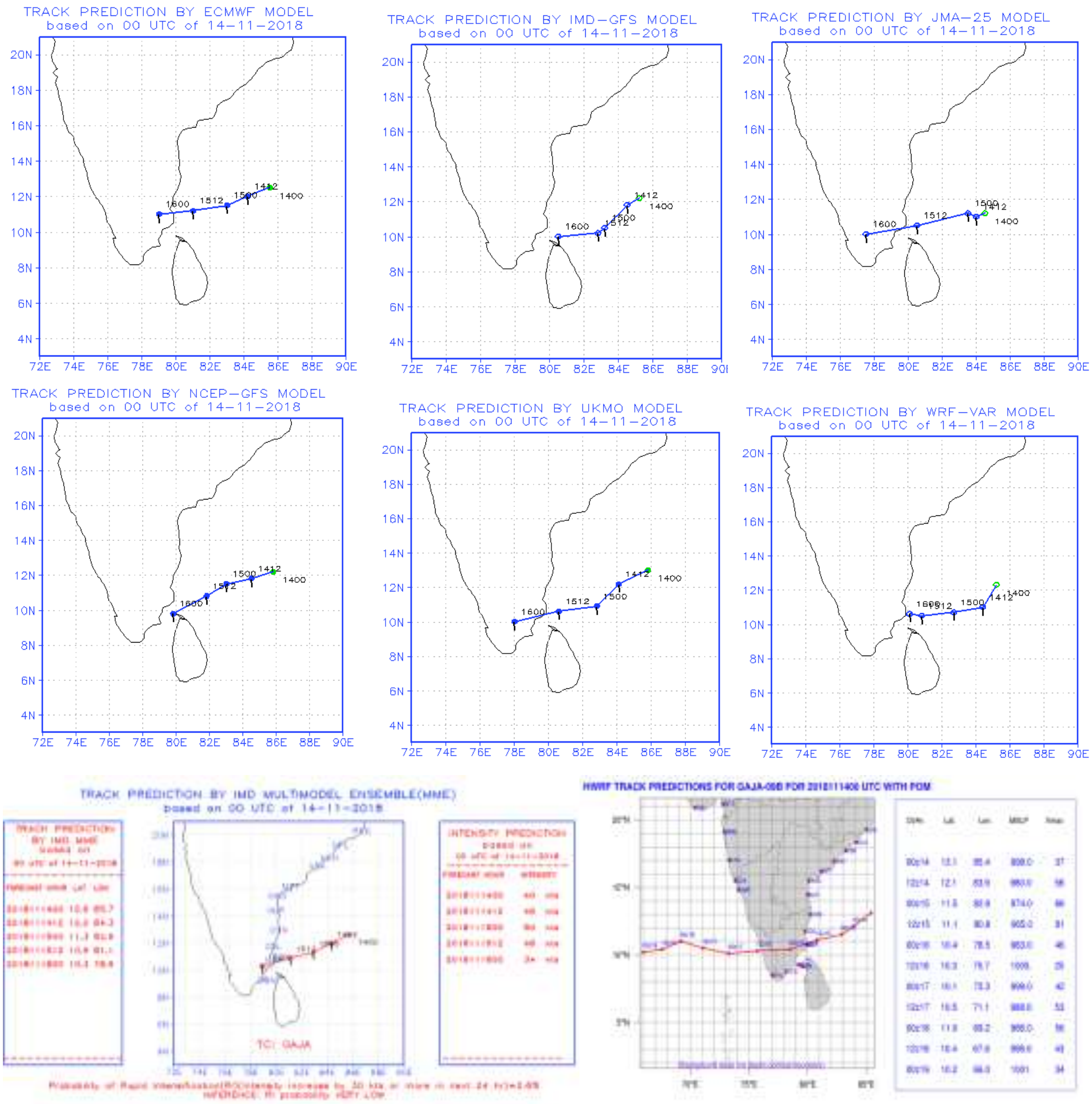


Fig. 11 (e): NWP model track forecast based on 0000 UTC of 14th November

Based on initial conditions of 0000 UTC of 15th November, models like ECMWF, JMA, HWRF & MME predicted landfall close to Nagapattinam around 0000 UTC of 16th. NCEP-GFS, IMD GFS, WRF-VAR and UKMO predicted landfall to the south of Nagapattinam between 0000 & 0600 UTC of 16th. The intensity predicted at the time of landfall by HWRF was around 80 kts and that by MME was around 54 kts. Only HWRF and NCEP GFS were predicting emergence of the system into Arabian Sea.

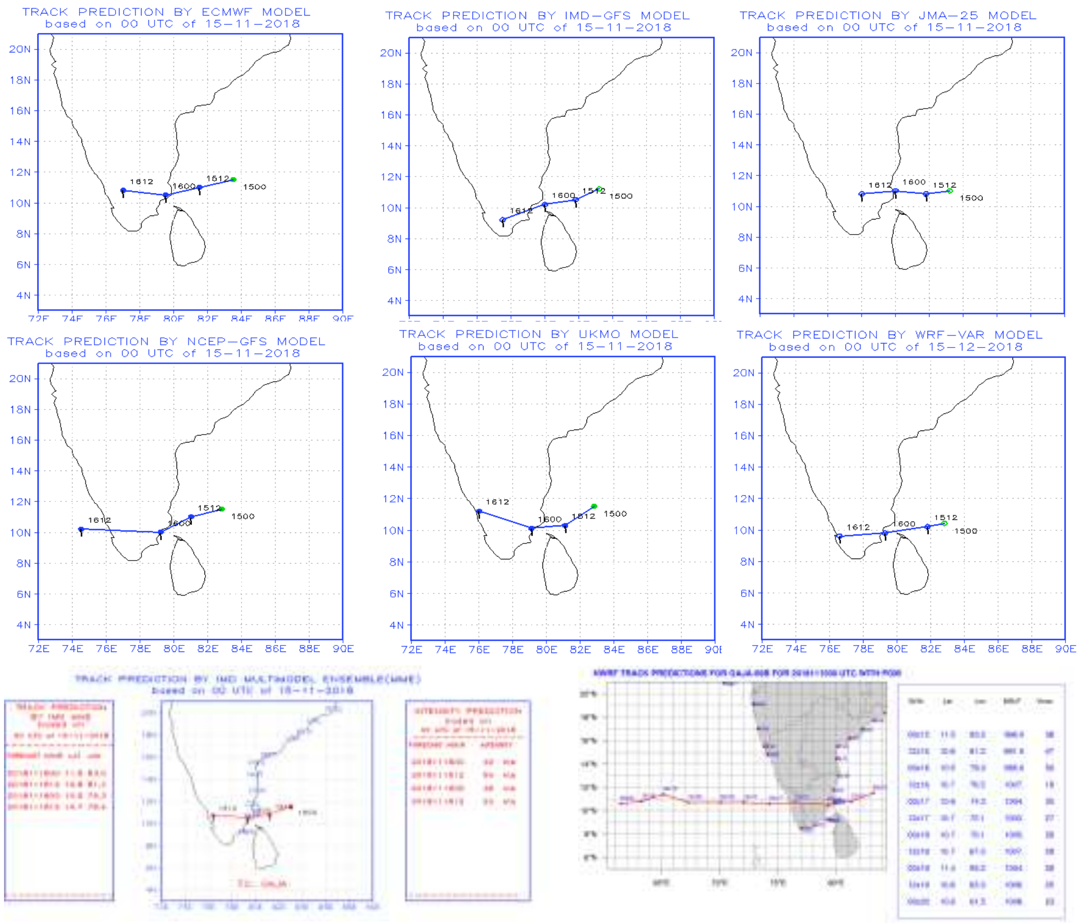


Fig. 11 (f): NWP model track forecast based on 0000 UTC of 15th November

Based on initial conditions of 0000 UTC of 17th November, all the models were indicating near westwards movement of the system upto southwest AS and weakening over sea. Both MME and HWRF were capturing initial intensity as 30 kts and predicting the system to intensify upto cyclonic storm intensity by 0000 UTC of 18th. The system was predicted to weaken gradually thereafter.

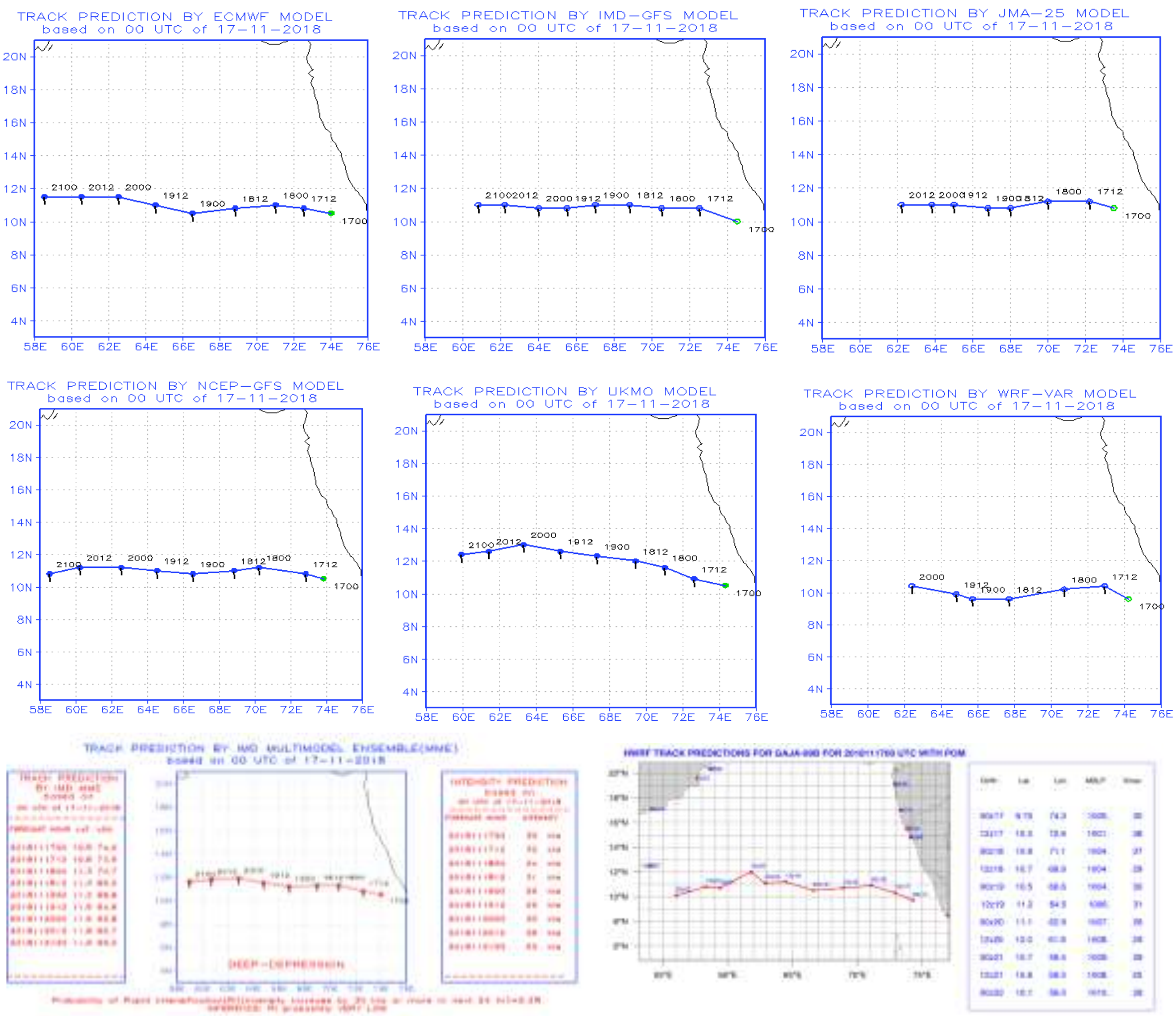


Fig. 11 (g): NWP model track forecast based on 0000 UTC of 17th November

Based on initial conditions of 0000 UTC of 18th November, models like ECMWF, JMA, NCEP-GFS, WRF-VAR and MME were indicating near westwards movement of the system upto southwest AS and weakening over sea. However, IMD GFS was predicting initial westwards movement followed by northwestwards movement. While HWRF was predicting initial westwards movement followed by southwestwards movement. MME was predicting the system to retain depression stage till 1200 UTC of 21st and HWRF predicted the same till 0000 UTC of 24th.

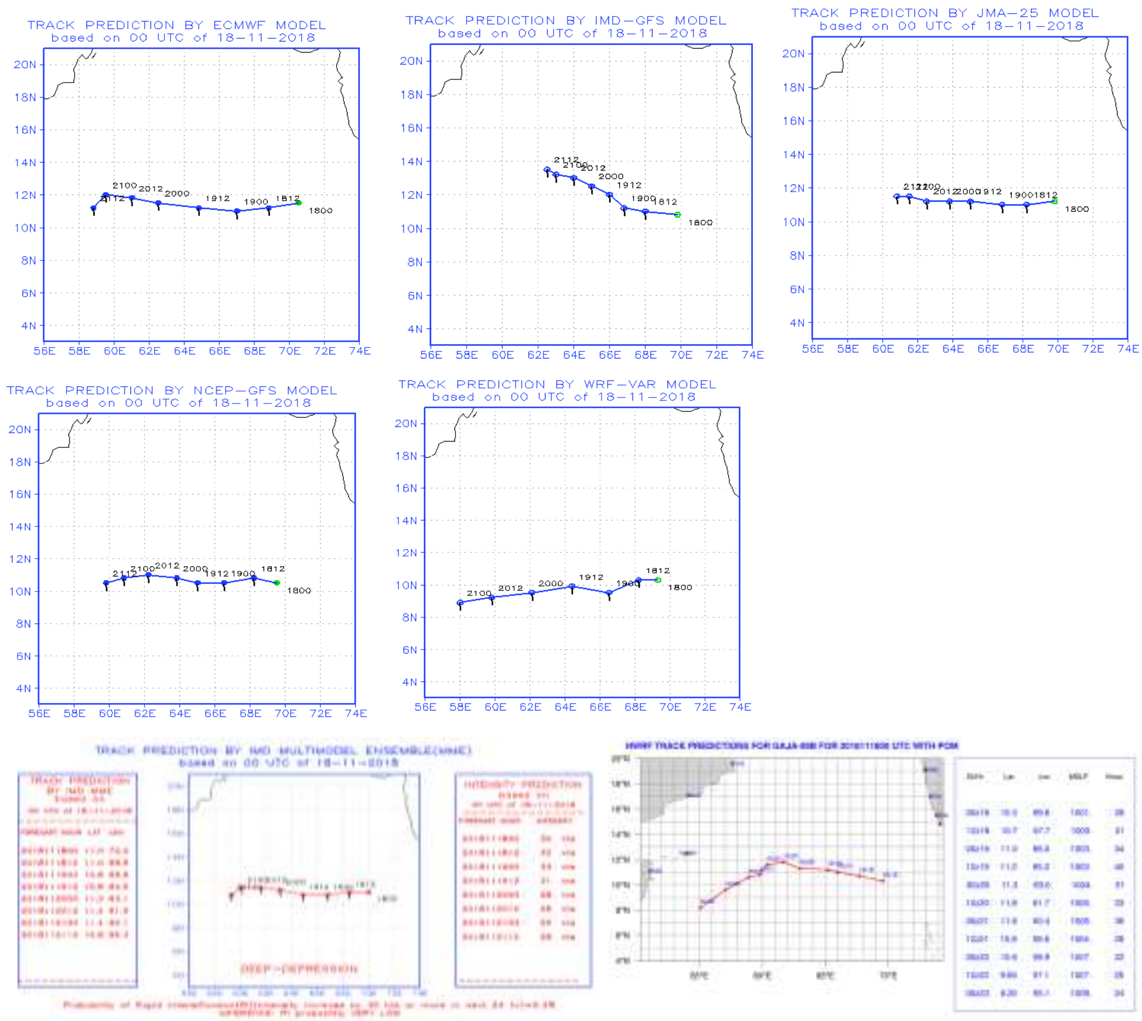


Fig. 11 (h): NWP model track forecast based on 0000 UTC of 18th November

Based on initial conditions of 0000 UTC of 19th November, all the models except HWRF were indicating near westwards movement of the system upto southwest AS and weakening over sea. However, HWRF was predicting initial westwards movement followed by southwestwards movement and landfall over Somalia on 24th.

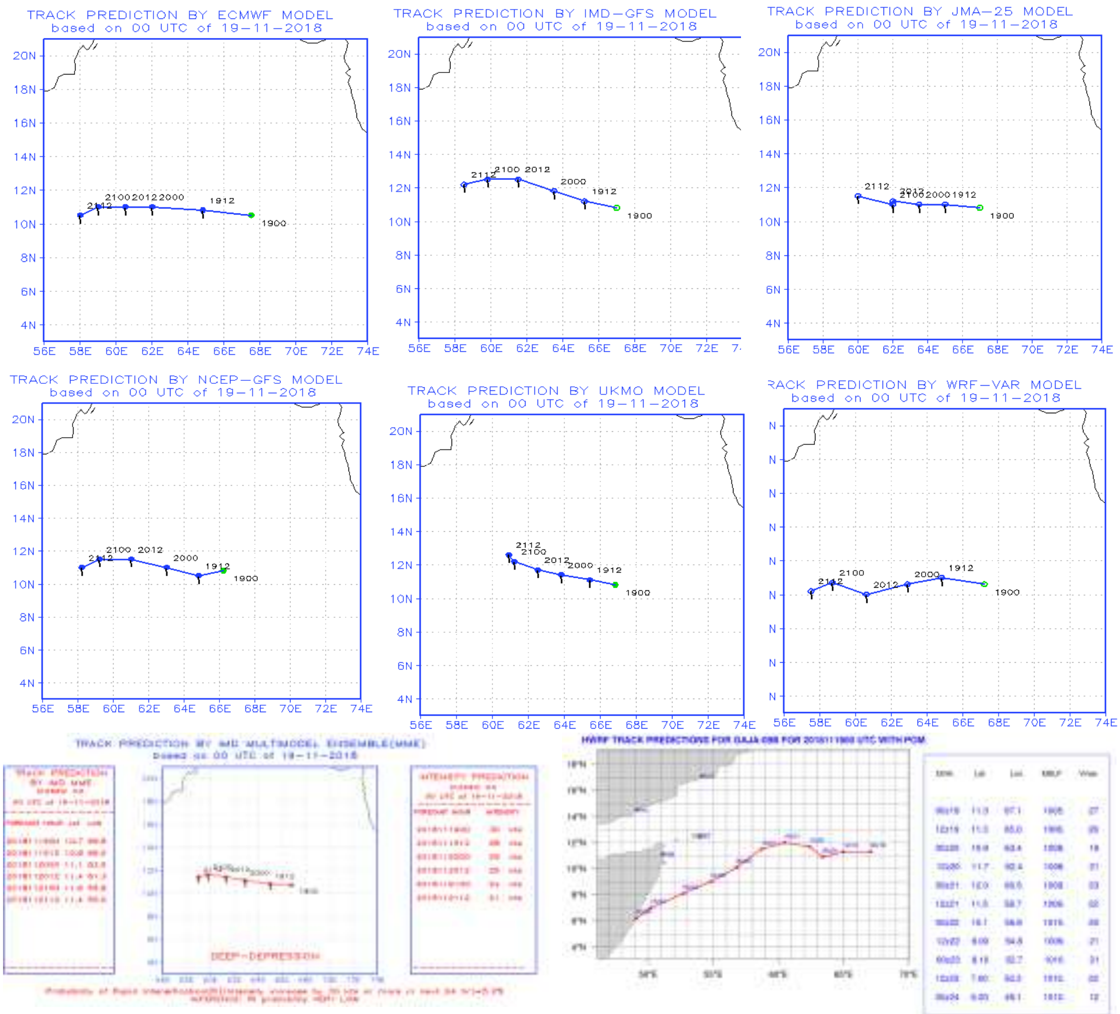


Fig. 11 (i): NWP model track forecast based on 0000 UTC of 19th November

Hence to conclude, to a good extent models could capture the movement, landfall characteristics and emergence of the system into AS. But intensity at the time of landfall and dissipation of the system was not consistently correctly captured. MME underestimated the intensity of the system throughout its life cycle. HWRF could predict the intensity during landfall correctly, but dissipation of system on 24th and landfall over Somalia was not correctly captured.

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 NCEP-GFS and IMD HWRF were the least followed by IMD-GFS, MME & ECMWF for 24 hours lead period. For 48 hours lead period, the errors were the least by IMD-GFS followed by MME, NCEP GFS, HWRF and ECMWF. For 72 hours lead period, the errors were the least by NCEP GFS followed by HWRF, IMD GFS, MME and ECMWF. Overall the errors were the least by NCEP-GFS, IMD-GFs and HWRF followed by MME & ECMWF for various lead periods.

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

Lead time →	12H	24H	36H	48H	60H	72H	84H	96H	108H	120H
IMD-GFS	89(16)	92(15)	112(14)	99(12)	131(9)	142(7)	151(6)	169(5)	227(3)	442(2)
IMD-WRF	115(16)	182(15)	183(14)	240(12)	326(9)	442(7)	-	-	-	-
JMA	133(16)	134(15)	155(14)	215(12)	303(9)	384(7)	337(6)	-	-	-
NCEP-GFS	70(16)	83(15)	107(14)	113(12)	121(9)	130(7)	126(6)	143(5)	92(3)	123(2)
UKMO	106(16)	144(15)	163(14)	198(12)	262(9)	342(7)	346(6)	316(5)	411(3)	458(2)
ECMWF	83(16)	118(15)	99(14)	126(12)	160(9)	159(7)	233(6)	271(5)	271(3)	245(2)
IMD-HWRF	82(33)	84(31)	89(29)	127(27)	134(25)	141(24)	162(24)	187(23)	207(21)	227(19)
IMD-MME	71(16)	96(15)	98(14)	113(12)	153(9)	182(7)	206(6)	207(5)	218(3)	172(2)

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

Landfall point forecast errors (LPE) are presented in Table 3. The landfall point error was the minimum for IMD-HWRF model 20 and 68 hrs lead period followed by MME, ECMWF and UKMO. For 44 hrs lead period, LPE was the least for JMA followed by UKMO, IMD HWRF and MME. Overall upto 72 hrs lead period, the errors by IMD HWRF were the least and beyond that the errors by MME and ECMWF were the least.

Table 4: Landfall point forecast errors (km) of NWP Models at different lead time

Lead time →	20H	32H	44H	56H	68H	80H	92H	104H	116H	128H
Based on	**15/00z**	**14/ 12z**	**14/00z**	**13/12z**	**13/ 00z**	**12/12z**	**12/00z**	**11/12z**	**11/00z**	**10/12z**
IMD-GFS	91	37	-	168	-	62	106	117	117	-
IMD-WRF	174	101	-	40	106	-	-	62	-	-
JMA	62	62	6	40	139	173	117	174	-	-
NCEP-GFS	83	30	-	-	-	-	333	84	-	-
UKMO	61	30	17	84	62	30	174	62	265	210
ECMWF	30	40	84	40	62	62	12	84	128	139
IMD-MME	40	40	40	40	40	83	79	84	128	150
IMD-HWRF	5	40	28	27	23	230	285	171	192	--

Landfall Point Error = Landfall Forecast Point- Actual Landfall Point, "-" : No forecast

Landfall time forecast errors (LTE) are presented in Table 4. For 20 hr lead period LTE was the least by IMD-HWRF followed by MME, ECMWF and UKMO. For 44 hr lead period, LTE was the least for ECMWF & MME followed by IMD-HWRF. For 68 hr lead period, LTE was the least by IMD-WRF followed by IMD-HWRF and ECMWF. Overall the errors by IMD-HWRF were the least followed by IMD GFS.

Table-5: Landfall time forecast errors (hr) at different lead time (hr)
('+' indicates delay in landfall, '-' indicates early landfall)

Lead time →	20H	32H	44H	56H	68H	80H	92H	104H	116H	128H
Based on	**15/00z**	**14/12z**	**14/00z**	**13/12z**	**13/00z**	**12/12z**	**12/00z**	**11/12z**	**11/00z**	**10/12z**
IMD-GFS	+8	+1	-	+2	-	+3	-2	+4	-9	-
IMD-WRF	+5	+2	-	-4	0	-	-	-32	-	-
JMA	+5	0	-5	-8	-15	-20	-1	-20	-	-
NCEP-GFS	+4	+5	-	-	-	-	+4	-12	-	-
UKMO	+3	-3	-5	+1	-18	+20	+4	-32	-22	-21
ECMWF	+1	-2	-1	-3	-6	-2	-19	-15	-16	-13
IMD-MME	+1	0	-1	-2	-9	-6	-8	-20	-14	-7
IMD-HWRF	0	0	-3	0	-3	-9	-3	-3	-3	--

Landfall Time Error: Landfall Forecast Time- Actual Landfall Time, "-": No forecast

The composite intensity prediction by IMD SCIP model based on initial conditions of 0000 & 1200 UTC during 10th-17th November is presented in Fig. 12. Overall, SCIP underestimated intensity of the system including the peak intensity.

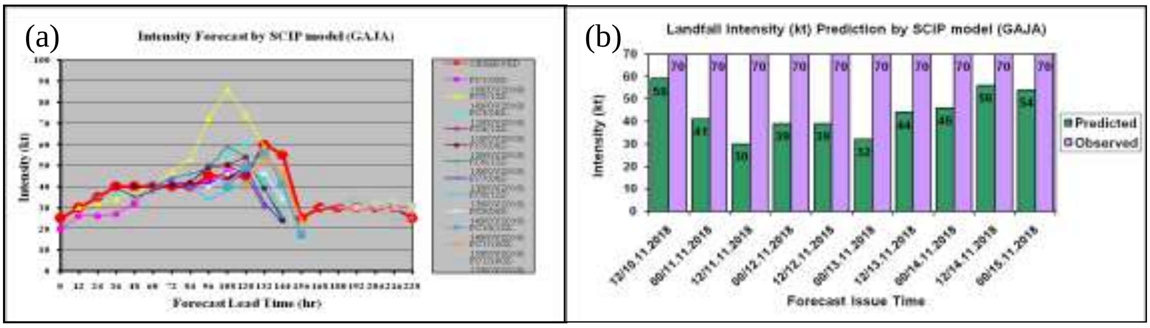


Fig.12 (a): Composite intensity prediction by SCIP Model based on 0000 and 1200 UTC during 10th—14th and 17th November and (b) landfall intensity predicted and observed

The average intensity forecast errors by IMD-SCIP and IMD-HWRF are presented in Table 5. It is seen that the intensity forecast errors by HWRF were significantly higher than IMD SCIP for all lead periods except 84 & 96 hrs.

Table 5: Average absolute errors (AAE) and Root Mean Square (RMSE) errors in knots by SCIP and HWRF models (Number of forecasts verified is given in the parentheses)

Lead time → (hrs)	12	24	36	48	60	72	84	96	108	120
IMD-SCIP (AAE)	3.5 (16)	4.2 (15)	4.6 (14)	7.2 (12)	10.1 (9)	12.6 (7)	14.8 (6)	24.2 (5)	16.7 (3)	3.0 (2)
IMD-HWRF (AAE)	10.6 (33)	13.3 (31)	16.4 (29)	16.1 (27)	13.9 (25)	13.8 (24)	13.4 (24)	13.7 (23)	16.8 (21)	18.4 (19)
IMD-SCIP (RMSE)	4.4	5.0	6.8	9.6	14.3	15.9	19.0	27.6	20.0	3.6
IMD-HWRF (RMSE)	13.6	18.3	21.5	22.2	18.9	20.5	17.6	16.9	22.0	22.5

Comparative analysis of predicted decay after landfall based on initial conditions of 2100 UTC of 15th and 0300 UTC of 16th vis-à-vis actual decay is presented in Fig.13. It can be seen that based on 2100 UTC of 15th initial conditions, the decay predicted was much steeper than actually realized. However, the decay model could better predict the fall in intensity of the system after landfall based on 0300 UTC initial conditions of 16th.

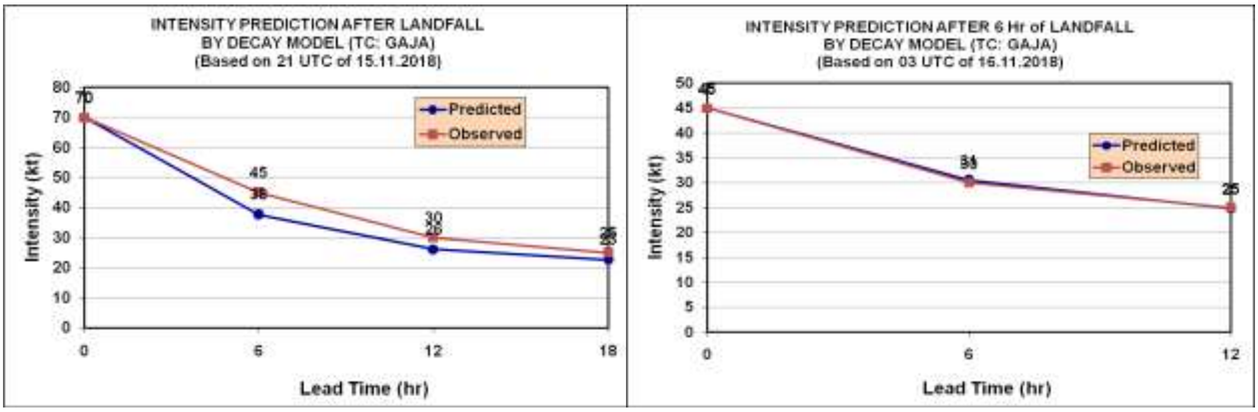


Fig.14. Decay after landfall (i) based on 2100 UTC of 15.11.2018 and (ii) updated forecast based on 0300 UTC of 16.11.2018

9.4. Heavy rainfall forecast by HWRF model

The forecast rainfall swaths by HWRF model based on 0600 UTC during 10th-15th and 17th-18th are presented in **Fig.15**. HWRF could successfully predict occurrence of rainfall along the predicted track even after the landfall of system and during re-emergence into AS over north Kerala coast. Based on 06 UTC of 11th, the expected cumulative rainfall in 126 hrs was about 8-16 inches (20-40cm) over coastal areas of north Tamil Nadu and at isolated places over south Andhra Pradesh. Based on 06 UTC of 12th- 14th, the expected cumulative rainfall in 126 hrs was about 8-16 inches (20-40cm) at few places over north Tamil Nadu and north Kerala. On 15th, cumulative rainfall of about 20-40 cm for next 126 hrs over few places of north Tamil Nadu and isolated places of north Kerala was predicted.

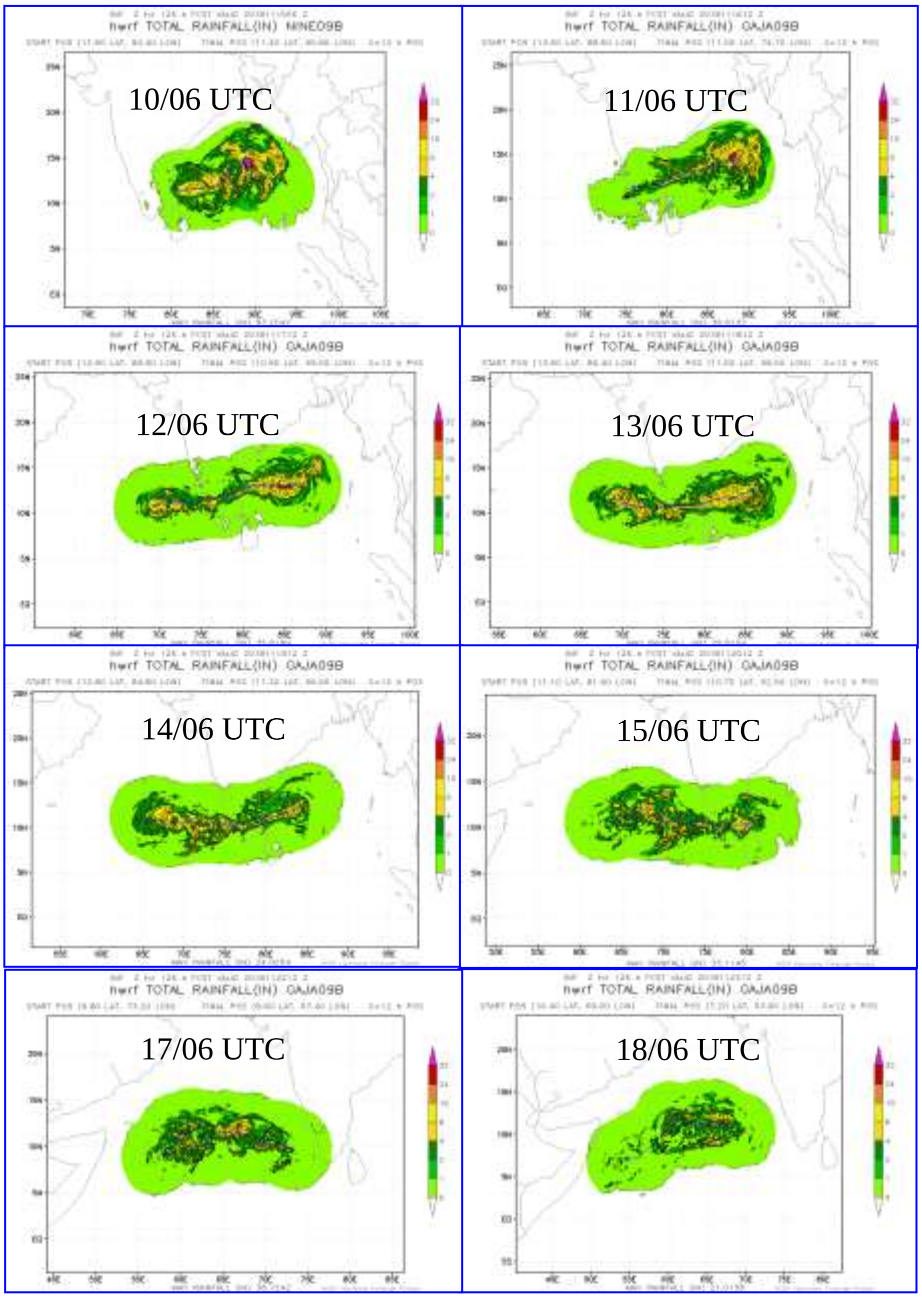


Fig.15: Heavy rainfall forecast by HWRF based on initial conditions of 0000 UTC of 10th-18th November, 2018.

10.5 Storm surge forecast

IMD predicted storm surge forecast based on guidance from Advance Circulation (ADCIRC) model and Indian Institute of Delhi Model. IMD predicted Storm surge of about 1 metre above astronomical tide inundated low lying areas upto about 1 km from the coast near the landfall point. Typical storm surge forecast by ADCIRC Model based on 0300 UTC observations of 12th November is presented in **Fig.16**.

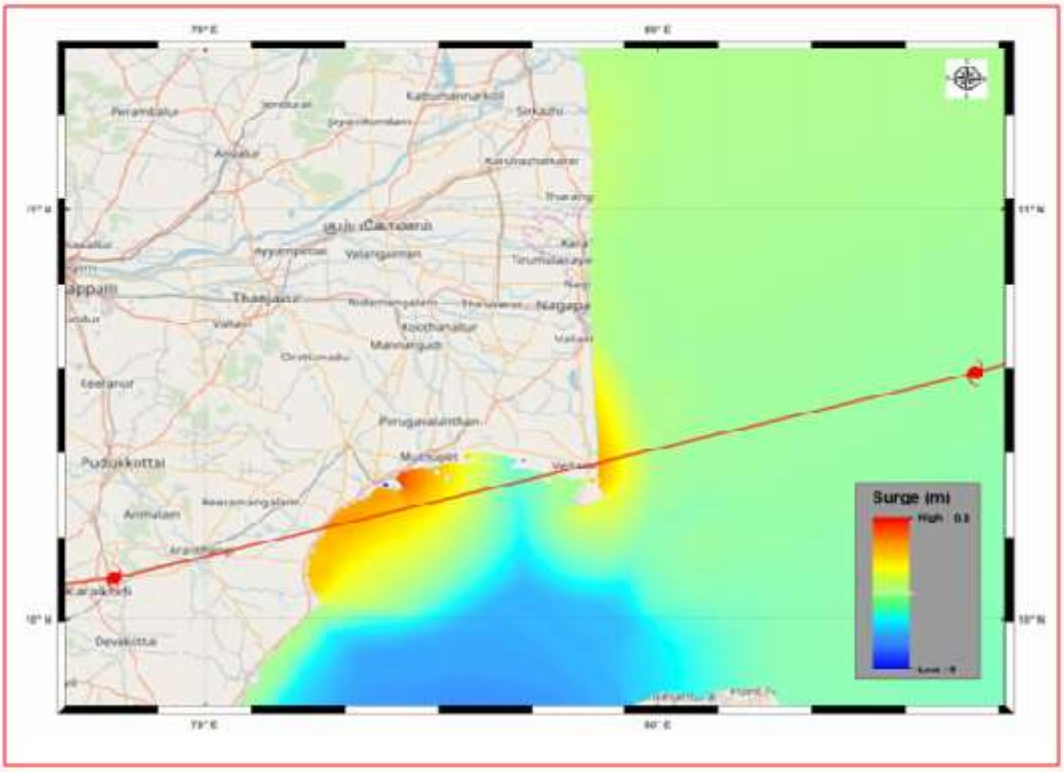


Fig. 16: Storm Surge Forecast issued by ADCIRC Model based on 0300 UTC of 12th November, 2018

10. Operational Forecast Performance

10.1. Genesis Forecast

- ❖ First information about formation of LPA over southeast Bay of Bengal and adjoining Andaman Sea around 9th was issued in the Tropical Weather dated 7th November at 1200 IST (around 48 hours in advance of formation of LPA). LPA from Gulf of Thailand emerged in Andaman Sea in the afternoon of 9th.
- ❖ In the TWO issued at 1200 IST of 8th, it was mentioned that, the LPA will become WML around 9th and will intensify into depression around10th. WML formed in the evening (1730 IST) of 9th and depression formed in the morning of 10th.

10.2. Landfall Forecast

- ❖ In the first bulletin issued on 10th (issued at 1230 IST), it was mentioned that, the system would move west-northwestwards during next 48 hours and then west-southwestwards towards north Tamil Nadu – south Andhra Pradesh coasts. (about 5 days in advance of actual landfall).
- ❖ The landfall over Tamil Nadu coast during evening hours of 15th (around 1330 IST) was predicted on 11th early morning (0930 IST) more than 4 days in advance. At 1430 IST of 12th November (around 81 hours in advance of actual landfall), it further indicated the landfall of the cyclonic storm over Tamil Nadu

coast between Cuddalore and Pamban, around Nagapattinam. Typical observed and forecast track is presented in **Fig. 17**.

- ❖ The landfall point forecast errors were about 31, 43 and 70 km for 24, 48 and 72 hrs lead period respectively against past five year (2013-17) average errors of 42.3, 94.8 and 122 km respectively. The landfall time forecast errors were about 3.0, 8.5 and 14.5 hours for 24, 48 and 72 hrs lead period against past five year (2013-17) average errors of 3.6, 5.4 and 3.8 hours respectively. The higher landfall time error for 48 and 72 hrs lead period were mainly due to the fact that the system followed a looping track during 11th night to 13th morning leading to delay in landfall time. (**Fig.18 and Table 6**)

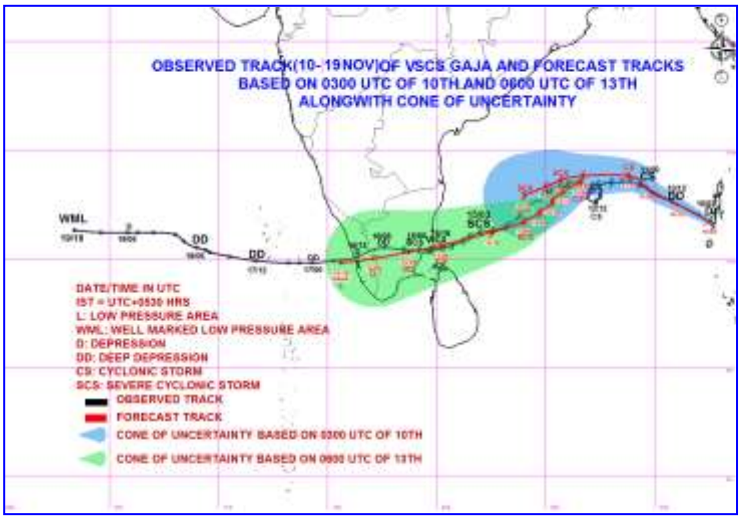


Fig.17: Typical forecast and observed tracks of VSCS, Gaja demonstrating accurate track and landfall point forecast

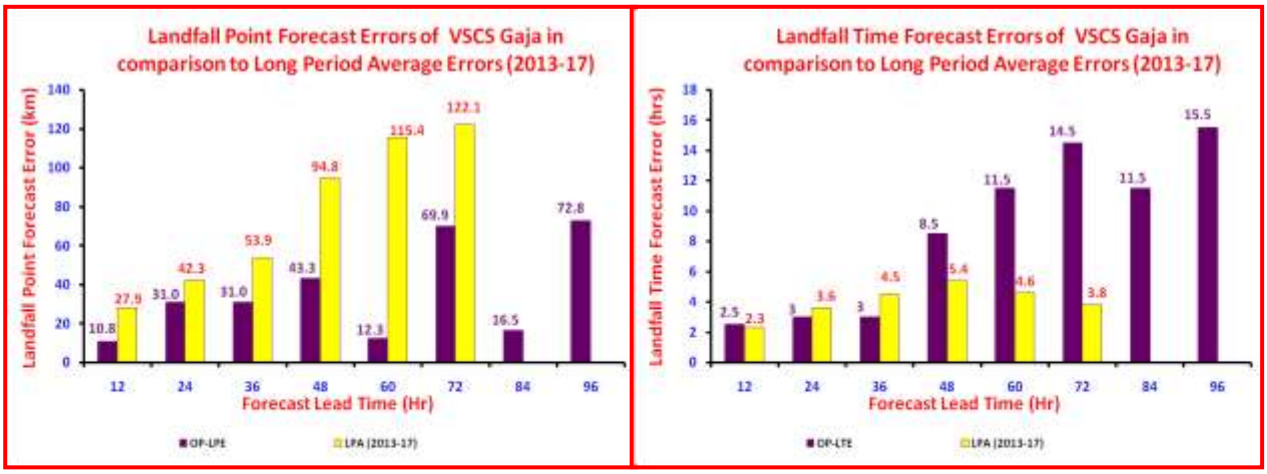


Fig.18: Landfall Point (km) and Time (hrs) Errors for VSCS Gaja

Table6: Landfall Point and Time Error in association with VSCS Gaja

Lead Period (hrs)	Base Time	Landfall Point (^{0}N/^{0}E)		Landfall Time (hours)		Operational Error		LPA error (2013-17)	
		Forecast	Actual	Forecast	Actual	LPE (km)	LTE (hours)	LPE (km)	LTE (hours)
12	15/12	10.54/79.84	10.45/79.8	15/1800	15/2030	10.8	2.5	27.9	2.3
24	14/18	10.73/79.83	10.45/79.8	15/1730	15/2030	31.0	3	42.3	3.6
36	14/06	10.73/79.83	10.45/79.8	15/1730	15/2030	31.0	3	53.9	4.5
48	13/18	10.84/79.85	10.45/79.8	15/1200	15/2030	43.3	8.5	94.8	5.4
60	13/06	10.55/79.85	10.45/79.8	15/0900	15/2030	12.3	11.5	115.4	4.6
72	12/18	10.15/79.24	10.45/79.8	15/0600	15/2030	69.9	14.5	122.1	3.8
84	12/06	10.30/79.80	10.45/79.8	15/0900	15/2030	16.5	11.5	-	-
96	12/00	11.11/79.86	10.45/79.8	15/0500	15/2030	72.8	15.5	-	-

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. Track Forecast

- In the first Bulletin issued a 1230 IST of 10th, it was mentioned that the system would move west-northwestwards for next 48 hours and then west-southwestwards during subsequent 72 hours towards north Tamilnadu-south Andhra Pradesh coasts. The system crossed Tamilnadu & Puducherry coast between Nagapattinam and Vedaranniyam near latitude 10.45˚N and longitude 79.8°E during 0030 to 0230 hours IST of 16th November.
- The track forecast errors were about 121, 185 and 195 km for 24, 48 and 72 hrs lead period against past five year (2013-17) average errors of 93, 144 and 201 km respectively. The track forecast skills were about 49, 68 and 82 % for 24, 48 and 72 hrs lead period against past five year (2013-17) average skills of 55, 68 and 72% respectively. The track error was higher due to recurving and looping nature of the track. However, comparing with long period average error of the recurving tracks, the errors in case of Gaja were less (**Fig.19 and Table 7**).

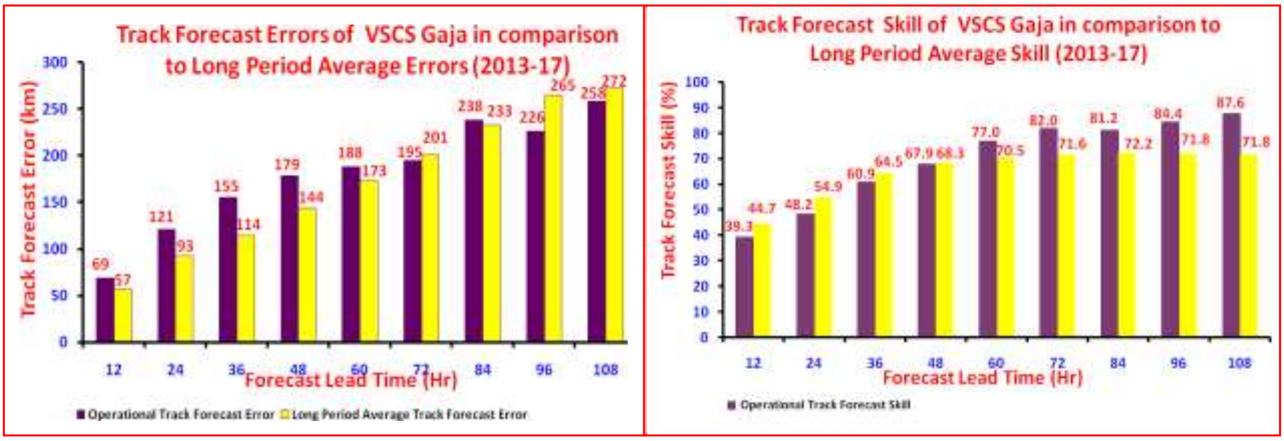


Fig.19: Track Forecast Errors and Skill for VSCS Gaja

Table 7:Operational & long period average track forecast errors(km) & Skill(%)

Lead Period (hrs)	No. of obs. verified	Operational Track Forecast		Long Period Average (2013-17) Track Forecast	
		Error (km)	Skill (%)	Error (km)	Skill (%)
12	35	69	39.3	57	44.7
24	30	121	48.2	93	54.9
36	25	155	60.9	114	64.5
48	22	179	67.9	144	68.3
60	17	188	77.0	173	70.5
72	13	195	82.0	201	71.6
84	8	238	81.2	233	72.2
96	6	226	84.4	265	71.8
108	2	258	87.6	272	71.8

10.4. Intensity Forecast

- In the first bulletin issued by IMD at 1230 hrs IST of 10th with the formation of depression, it was indicated that the system would intensify into a deep depression during next 12 hours and into a cyclonic storm during subsequent 24 hours. The depression intensified into a deep depression in the evening (1730 IST) of 10th and into a CS in the early morning (0530 IST) of 11th.
- The absolute error (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 9.1, 11.0 and 14.6 knots against the LPA of 10.4, 15.5 and 15.7 knots respectively. The skill in intensity forecast based on AE for 24, 48 and 72 hrs lead period was 22.0, 37.5 and 22.0% respectively (**Fig.20 and Table 8**).
- The root mean square error (RMSE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 10.9, 14.8 and 19.5 knots against the LPA of 14.0, 20.6 and 20.6 knots respectively. The skill in intensity (wind) forecast based on RMSE for 24, 48 and 72 hrs lead period was 50.5, 31.7 and 14.5% against the LPA of 40.1, 60.0 and 73.0% respectively (**Fig.21 and Table 8**). For all lead periods, the errors in intensity forecast were significantly less.

Table 8: Mean Intensity forecast errors (kt) and Skill(%) in association with VSCS Gaja

Lead Period (hrs)	N	Average Intensity Error (kts)		LPA (2013-17) Intensity forecast Error (kts)		Skill (%) in intensity forecast	
		AE	RMSE	AE	RMSE	AE	RMSE
12	33	5.6	7.9	6.3	8.7	16.7	36.2
24	29	9.1	10.9	10.4	14.0	22.0	50.5
36	24	9.1	11.5	13.8	18.4	4.7	5.3
48	21	11.0	14.8	15.5	20.6	37.5	31.7
60	16	10.7	13.6	15.8	20.9	41.8	39.9
72	12	14.6	19.5	15.7	20.6	22.0	14.5
84	8	16.9	22.3	24.6	22.1	46.0	36.9
96	6	20.1	24.3	16.9	20.7	29.1	27.7
108	2	35.3	35.7	14.2	17.1	11.8	20.3

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

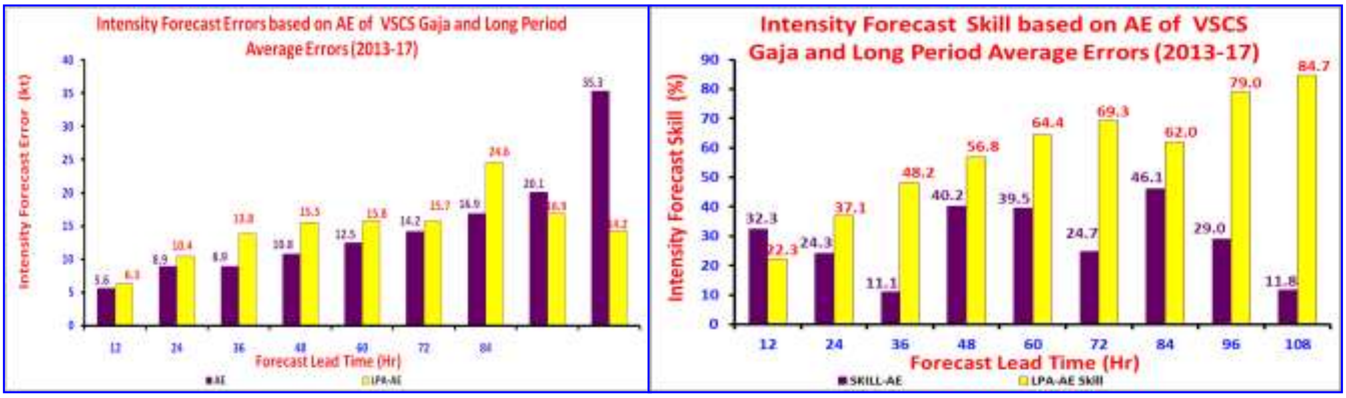


Fig.20: Absolute errors (AE) of intensity forecast and skill for VSCS Gaja

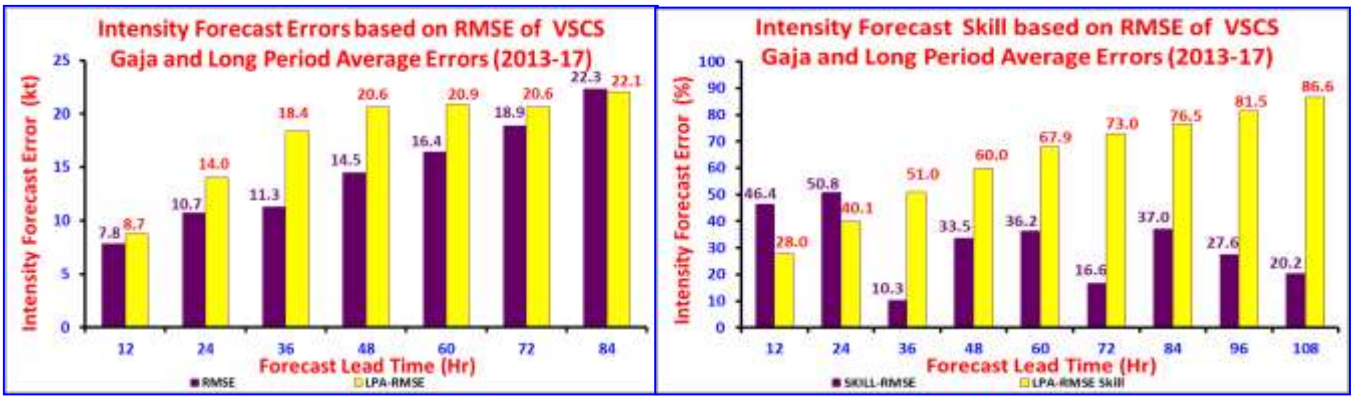


Fig.21: Root Mean Square Errors (RMSE) of intensity forecast and skill for VSCS Gaja

10.5 Verification of Adverse Weather associated with the system:

The verifications of adverse weather like heavy rainfall, gale wind and storm surge forecast issued by IMD are presented in Table 9-11. It is found that all the three types of adverse weather were predicted accurately and well in advance.

Table – 9: Verification of Heavy Rainfall Forecast

Date/Base Time of observation (UTC)	24 hr Heavy rainfall warning ending at 0830 hrs IST of next day	Realised 24-hour heavy rainfall ending at 0300 UTC of date
10/11/2018 0300 UTC	• Heavy falls at isolated places very likely to commence over coastal Tamil Nadu and adjoining south coastal Andhra Pradesh from 14th November. • Heavy to very heavy rainfall at isolated places is very likely over Andaman and Nicobar Islands on 10th and isolated heavy rainfall over Andaman Islands on 11th November 2018.	**10 November 2018** **Andaman & Nicobar Islands:** Long Island-14, Maya Bandar-10, Port Blair-9 **11 November 2018** **Andaman & Nicobar Islands:** Maya Bandar-7,
11/11/2018 0300 UTC	• Heavy falls at isolated places very likely to commence over north coastal Tamil Nadu and adjoining south coastal Andhra Pradesh from evening of 14th November. Rainfall intensity is very likely to increase gradually thereafter with rainfall at most places and heavy to very heavy at a few places and **extremely heavy falls (≥ 20 cm)** at isolated places very likely over north Tamil Nadu and at most places with heavy to very heavy falls at	**16 November:** **Tamilnadu & Puducherry:** Thiruthuraipoondi & Muthupet-17 each,

<table>
<tr>
<td></td>
<td>isolated places very likely over south Tamil Nadu, south Coastal Andhra Pradesh and Rayalaseema on 15th November.
• Heavy rainfall at isolated places likely over Andaman Islands on 11th November 2018 and decrease thereafter.</td>
<td rowspan="3">Adirampatnam-16, Peravurani, Pattukottai & Neyveli-14 each, Virudachalam-12, Chengalpattu-11, Cuddalore-9, Madukkur, Arantangi & Vandavasi-8 each, and Srimushnam, Valinokkam, Nagercoil, Uthiramerur, Orthanad, Needamangalam, Thuckalay, Sethiathope, Pondicherry & Tozhudur-7 each

17 November:
Coastal Andhra Pradesh: Kandukur and Gudivada-7 each,
Telangana: Aswaraopeta-7,
Tamilnadu & Puducherry: Sivaganga-17, Kodaikanal-14, Thammampatty-10, Nilakottai, Illuppur, Periyakulam & Bodinaickanur-9 each, Tirupathur-8 and Chinnakalar, Vadipatti-7 each
Kerala: Kozha-28, Piravam-19, Thodupuzha-15, Cherthala & Munnar Kseb-12 each, Kumarakam-11, Idukki-10, Vaikom, & Myladumpara-9 each, Kottayam-8, Peermade To-7.</td>
</tr>
<tr>
<td>12/11/2018
0300 UTC</td>
<td><u>Tamilnadu</u>
14 November 2018
Heavy falls at isolated places very likely to commence over north coastal Tamil Nadu from 14th November evening
15 November 2018
Heavy to very heavy at a few places and extremely heavy falls (≥ 20 cm) at isolated places very likely over north Tamil Nadu and rainfall at most places with heavy to very heavy falls at isolated places very likely over south Tamil Nadu.
16 November 2018
Heavy falls at a few places and very heavy at isolated places very likely over interior Tamil Nadu.
<u>South Coastal Andhra Pradesh</u>
14 November 2018
Heavy falls at isolated places very likely to commence from 14th November evening.
15 November 2018
Heavy falls at isolated places
16 November 2018
Heavy falls at isolated places.
<u>Rayalaseema</u>
15 November 2018
Heavy falls at isolated places
<u>Kerala</u>
15 November 2018
Heavy at isolated places
16 November 2018
Heavy to very heavy falls at isolated places</td>
</tr>
<tr>
<td>13/11/2018
0300 UTC</td>
<td><u>Tamilnadu</u>
14 November 2018
Heavy falls at isolated places very likely to commence over north coastal Tamil Nadu & adjoining districts of south coastal Tamil Nadu from 14th Nov. evening
15 November 2018
Heavy to very heavy at a few places over Tamilnadu. Extremely heavy falls (≥ 20 cm) at isolated places is also likely over Cuddalore, Nagappattinam, Tiruvarur, Thanjavur, Pudukkottai, Tuticorin and Ramanathapuram districts.
16 November 2018
Heavy falls at a few places and very heavy at isolated places very likely over interior Tamil Nadu.
<u>South Coastal Andhra Pradesh</u>
14 November 2018
Heavy falls at isolated places very likely to commence from 14th November evening.</td>
</tr>
</table>

	15 November 2018 Heavy falls at isolated places **<u>Rayalaseema</u>** **15 November 2018** Heavy falls at isolated places **<u>Kerala</u>** **15 November 2018** Heavy to very heavy falls at isolated places **16 November 2018** Heavy to very heavy falls at isolated places.	
14/11/2018 0300 UTC	**<u>15 November 2018</u>** **Tamilnadu & Puducherry** Heavy to very heavy at a few places over Tamilnadu & Puducherry. **Extremely heavy falls** (≥ 20 cm) at isolated places is also likely over Cuddalore, Nagappattinam, Tiruvarur, Thanjavur, Pudukkottai, Tuticorin and Ramanathapuram districts. **South Coastal Andhra Pradesh** Heavy falls at isolated places **Rayalaseema** Heavy falls at isolated places **Kerala** Heavy falls at isolated places **<u>16 November 2018</u>** **Tamilnadu & Puducherry** Heavy falls at a few places and very heavy at isolated places very likely over interior Tamil Nadu. **South Coastal Andhra Pradesh** Heavy falls at isolated places **Kerala** Heavy to very heavy falls at isolated places	
15/11/2018 0300 UTC	**<u>15 November 2018</u>** **Tamilnadu & Puducherry** Heavy to very heavy at a few places over Tamilnadu & Puducherry. **Extremely heavy falls** (≥ 20 cm) at isolated places is also likely over Cuddalore, Nagappattinam, Karaikal, Tiruvarur, Thanjavur, Pudukkottai, Tuticorin and Ramanathapuram districts. **South Coastal Andhra Pradesh** Heavy falls at isolated places in Nellore and Prakasam districts. **Rayalaseema** Heavy falls at isolated places Chittoor district **Kerala** Heavy falls at isolated places over south Kerala **<u>16 November 2018</u>** **Tamilnadu & Puducherry** Heavy falls at a few places and very heavy at isolated places very likely over south interior Tamil	

	Nadu. Rainfall at most places with heavy falls at isolated places very likely over north interior Tamil Nadu. **Kerala** Heavy to very heavy falls at isolated places	
16/11/2018 0300 UTC	• Heavy falls at a few places and very heavy at isolated places over south interior Tamil Nadu and with heavy falls at isolated places over north interior Tamil Nadu during next 24 hours. Rainfall at most places with heavy to very heavy falls at isolated places very likely over Kerala during next 24 hours. • Heavy falls at isolated places very likely over Lakshadweep on 17th November, 2018.	
17/11/2018 0300 UTC	Heavy to very heavy falls with extremely heavy falls at isolated places very likely over Lakshadweep during next 24 hours and heavy falls at isolated places during subsequent 24 hours.	

Table 10: Verification of Gale/Squally Wind Forecast issued by IMD

Date/ Time of observation (UTC)	Gale/ Squally wind Forecast	Realised wind speed
10/11/2018 0300 UTC	• Squally wind speed reaching 45-55 kmph gusting to 65 kmph very likely over and around Andaman Islands and north Andaman Sea on 10th and 11th. • Squally wind speed reaching 45-55 kmph gusting to 65 kmph very likely over southeast & adjoining eastcentral Bay of Bengal on 10th. The wind speed will gradually increase becoming 50-60 kmph gusting to 70 kmph on 11th, • Gale wind speed reaching 65-75 kmph gusting to 85 kmph is very likely over central parts of south & adjoining west central and eastcentral Bay of Bengal from 11th November 2018 evening. It would gradually increase becoming 90-100 kmph gusting to 110 kmph over west central and adjoining southwest Bay of Bengal from 12th November 2018 evening • Squally wind speed reaching 45-55 kmph gusting 65 kmph likely to commence along and off north Tamil Nadu – south Andhra Pradesh coasts from 13th November evening.	Atiramapattinam reported maximum wind speed of 117 kmph at 0330 hrs IST, Nagapattinam reported 100 kmph during 0230-0330 IST and Karaikal reported 92 kmph at 0130 IST of 16th. Estimated maximum wind speed at the time of landfall was 130 kmph gusting to 145 kmph.
11/11/2018 0300 UTC	• Squally wind speed reaching 45-55 kmph gusting to 65 kmph very likely over and around Andaman Islands and north Andaman Sea during next 12 hours. • Gale wind speed reaching 65-75 kmph gusting to 85 kmph prevails over Eastcentral and adjoining Westcentral & Southeast Bay of Bengal. It is very likely to increase gradually becoming 90-100 kmph gusting to 110 kmph over west central & adjoining southwest Bay of Bengal from morning of 12th November 2018. • Squally wind speed reaching 45-55 kmph gusting to 65 kmph likely to commence along & off north Tamil Nadu – south Andhra Pradesh coasts from 14th November morning. It is very	

	likely to increase gradually becoming Gale wind speed 80-90 kmph gusting to 100 kmph along & off north Tamil Nadu – south Andhra Pradesh coasts over west central & adjoining southwest Bay of Bengal from 14th November mid-night onwards.	
12/11/2018 0300 UTC	• Gale wind speed reaching 70-80 kmph gusting to 85 kmph prevails over Eastcentral and adjoining Westcentral & Southeast Bay of Bengal. It is very likely to increase gradually becoming 90-100 kmph gusting to 110 kmph over southwest & adjoining westcentral and southeast Bay of Bengal from morning of 13th November 2018. • Squally wind speed reaching 45-55 kmph gusting to 65 kmph likely to commence along & off north Tamil Nadu & Puducherry – south Andhra Pradesh coasts from 14th November morning. It is very likely to increase gradually becoming Gale wind speed 80-90 kmph gusting to 100 kmph along & off north Tamil Nadu & Puducherry coasts from 14th November night onwards.	
13/11/2018 0300 UTC	• Gale wind speed reaching 70-80 kmph gusting to 90 kmph prevails over Westcentral and adjoining Eastcentral & South Bay of Bengal. It is very likely to increase gradually becoming 90-100 kmph gusting to 110 kmph over southwest & adjoining westcentral and southeast Bay of Bengal from 14th November 2018. • Squally wind speed reaching 45-55 kmph gusting to 65 kmph very likely to commence along & off north Tamil Nadu & Puducherry and adjoining south Andhra Pradesh coasts from 14th November morning. It is very likely to increase gradually becoming Gale wind speed 80-90 kmph gusting to 100 kmph along & off Tamil Nadu & Puducherry coasts from 15th November morning onwards. • Strong wind speed reaching 30-40 kmph gusting to 50 kmph very likely over interior Tamilnadu, south Kerala, southeast Arabian Sea along & off Kerala coast, Comorian area, Gulf of Mannar and Palk Strait on 16th November. Strong wind speed reaching 30-40 kmph gusting to 50 kmph very likely to prevail over southeast Arabian Sea and along & off Kerala coast on 17th November.	
14/11/2018 0300 UTC	• Gale wind speed reaching 70-80 kmph gusting to 90 kmph prevails over Southwest and adjoining southeast & westcentral Bay of Bengal. It is very likely to increase gradually becoming 90-100 kmph gusting to 110 kmph over these areas from today, the 14th November 2018 evening. • Squally wind speed reaching 45-55 kmph gusting to 65 kmph very likely to commence along & off Tamil Nadu & Puducherry and adjoining south Andhra Pradesh coasts from today, the 14th November 2018 evening. It is very likely to increase gradually becoming Gale wind speed 80-90 kmph gusting to 100 kmph along & off central parts of Tamil Nadu & Puducherry coasts from 15th November morning onwards. • Strong wind speed reaching 30-40 kmph gusting to 50 kmph very likely over interior Tamilnadu, Kerala, southeast Arabian Sea along & off Kerala coast, Comorian area, Gulf of Mannar and Palk Strait on 16th November. Strong wind speed reaching 30-40 kmph gusting to 50 kmph very likely to prevail over southeast Arabian Sea and along & off Kerala coast on 17th	

	November.	
15/11/2018 0300 UTC	• Squally wind speed reaching 45-55 kmph gusting to 65 kmph very likely to prevail along & off Tamil Nadu & Puducherry and adjoining south Andhra Pradesh coasts. It is very likely to increase gradually becoming Gale wind speed 80-90 kmph gusting to 100 kmph along & off central parts of Tamil Nadu & Puducherry coasts from today, the 15th November evening onwards. • Strong wind speed reaching 30-40 kmph gusting to 50 kmph very likely over interior Tamilnadu, Kerala, southeast Arabian Sea along & off Kerala coast, Comorian area, Gulf of Mannar and Palk Strait on 16th November. Strong wind speed reaching 30-40 kmph gusting to 50 kmph very likely to prevail over southeast Arabian Sea and along & off Kerala coast on 17th November.	
15/11/2018 1500 UTC	• Gale wind speed reaching 60-70 kmph gusting to 80 kmph is prevailing along & off Tamil Nadu & Puducherry coasts. It is very likely to increase gradually becoming Gale wind speed 100-110 kmph gusting to 120 kmph along & off central parts of Tamil Nadu & Puducherry coasts during next 09 hours. • Strong wind speed reaching 30-40 kmph gusting to 50 kmph very likely over interior Tamilnadu, Kerala, southeast Arabian Sea along & off Kerala coast, Comorian area, Gulf of Mannar and Palk Strait on 16th November. Strong wind speed reaching 30-40 kmph gusting to 50 kmph very likely to prevail over southeast Arabian Sea and along & off Kerala coast on 17th November.	
16/11/2018 0300 UTC	• Gale wind speed reaching 65-75 kmph gusting to 85 kmph very likely over central parts of Tamil Nadu during next 03 hours. It would gradually decrease becoming squally wind speed reaching 50-60 kmph gusting to 70 kmph over these areas during subsequent six hours. • Strong wind speed reaching 30-40 kmph gusting to 50 kmph very likely over remaining parts of Tamilnadu, Kerala, southeast Arabian Sea along & off Kerala coast, Comorian area, Gulf of Mannar on 16th November. Strong wind speed reaching 30-40 kmph gusting to 50 kmph very likely to prevail over southeast	

	Arabian Sea and along & off Kerala coast on 17th November. • Squally wind speed reaching 40-50 kmph gusting 50 kmph is likely to prevail along and off Tamil Nadu coast during next 6 hours.	
17/11/2018 0300 UTC	• **Squally wind speed reaching 55-65 kmph gusting to 75 kmph** is prevailing over Southeast Arabian Sea and Lakshadweep Area. It is very likely to gradually increase becoming gale wind speed reaching 70-80 kmph gusting to 90 kmph during next 24 hours. • **Squally wind speed reaching 40-50 kmph gusting to 60 kmph** very likely along & off Kerala coast during next 24 hours.	
18/11/2018 0300 UTC	• **Squally wind speed reaching 40-50 kmph gusting to 60 kmph** is very likely to prevail over Lakshadweep Area during next 12 hours and decrease thereafter. • **Squally wind speed reaching 55-65 kmph gusting to 75 kmph** is likely to prevail over Southeast Arabian Sea to the west of Lakshadweep area on today, the 18th November, 2018. • **Squally wind speed reaching 45-55 kmph gusting to 65 kmph** is very likely to prevail over central parts of south Arabian Sea on 19th November and southwest Arabian Sea on 20th November, 2018.	
19/11/2018 0300 UTC	• **Squally wind speed reaching 45-55 kmph gusting to 65 kmph** is likely to prevail over Southeast Arabian Sea to the west of Lakshadweep area during next 12 hours and decrease thereafter. • **Squally wind speed reaching 45-55 kmph gusting to 65 kmph** is very likely to prevail over central parts of south Arabian Sea on today, the 19th November and 40-50 kmph gusting to 60 kmph over southwest Arabian Sea on 20th November, 2018.	

Table 11: Verification of Storm Surge Forecast issued by IMD

Date/ Time(UTC)	Storm Surge Forecast	Recorded storm surge
12/11/2018 0300 UTC	Storm surge of height of about 1.0 meter above astronomical tide is very likely inundate low lying areas of **Nagappattinam & Cuddalore districts of Tamil Nadu and Karaikal district of Puducherry** at the time of landfall.	Storm surge of about 1 metre above astronomical tide inundated low lying areas upto about 1 km from the coast near the landfall point.
13/11/2018 0300 UTC	Storm surge of height of about 1.0 meter above astronomical tide is very likely to inundate low lying areas of **Nagappattinam, Thanjavur, Pudukkottai and Ramanathapuram districts of Tamil Nadu and Karaikal district of Puducherry** at the time of landfall.	
14/11/2018 0300 UTC	-DO-	
15/11/2018 0300 UTC	-DO-	
17/11/2018 0300 UTC	Storm surge of height of about 0.5 meter above astronomical tide is very likely to inundate low lying areas of Lakshadweep Islands (Androth, Amini, Agatti, Cherium, Kalpeni, Kavaratti, Bangaram, Suheli Islands) at the time of landfall.	

11. Warning Services

Bulletins issued by Cyclone Warning Division, New Delhi

- **Track, intensity and landfall forecast:** IMD continuously monitored, predicted and issued bulletins containing track, intensity, and landfall forecast for +06, +12, +18, +24, +36 and +48… +108 hrs lead period till the system weakened into a low pressure area. The above forecasts were issued from the stage of depression onwards along with the cone of uncertainty in the track forecast five times a day and every three hours during the cyclone period. The hourly update was also provided prior to and during the landfall of the cyclone.
- **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 ….. +108 hrs lead period.
- **Four stage Warning:** The Cyclone Alert for north Tamilnadu, Puducherry and adjoining south Andhra Pradesh coast was issued with the formation of cyclonic storm in the bulletin issued by IMD at 1200 hrs IST of 11th Nov. It was upgraded to cyclone warning for Tamilnadu and Puducherry coasts in the bulletin issued at 1145 hrs IST of 14th Nov. when system was having the intensity of cyclonic storm.
- **Adverse weather warning bulletins:** The tropical cyclone forecasts alongwith expected adverse weather like heavy rain, gale wind and storm surge was issued with every three hourly update during cyclone period to the central, state and district level disaster management agencies including MHA NDRF, NDMA for all concerned states along the east coast of India including Tamil Nadu, Andhra Pradesh, Puducherry, Odisha, West Bengal, Andaman & Nicobar Islands, Kerala and Lakshadweep Islands. 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. The adverse weather warnings related to heavy rain, gale/squally wind & storm surge were also presented in graphics alongwith colour codes in the website.
- **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, Thiruvananthapuram and Visakhapatnam to ports, fishermen, coastal and high sea shipping community.

- **Fishermen Warning:** First warning for fishermen of the states of West Bengal, Odisha, Andhra Pradesh, Tamil Nadu and Andaman & Nicobar Islands, Kerala and Lakshadweep Islands were issued during the life cycle of system.
- **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 and Area Cyclone Warning Centre (ACWC) Chennai and Cyclone Warning Centre (CWC) Thiruvananthapuram in association with the VSCS Gaja are given in **Table 12 (a) and (b)** respectively.

Table 12 (a): Bulletins issued by RSMC New Delhi

S.N	Bulletin	No. of Bulletins	Issued to
1	National Bulletin	65	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- Tamil Nadu, Andhra Pradesh, Puducherry, Odisha, West Bengal, Andaman & Nicobar Islands, Kerala and Lakshadweep Islands
2	Hourly Bulletins	18	• Email to Cabinet Secretary, Principal Secretary to Prime Minister, Secretary Ministry of Home Affairs, Defence, Agriculture, Information & Broadcasting, Department of Sc. & Technology, NDMA, and Shipping & Surface Transport, Control Room Home Affairs, Director Indian Railways, Director General Doordarshan & All India Radio, Director General National Disaster Response Force and Chief Secretary- Tamil Nadu, Andhra Pradesh, Puducherry, Odisha, West Bengal, Andaman & Nicobar Islands, Kerala and Lakshadweep Islands. • Put up on RSMC New Delhi website
3	Bulletin from DGM	8	FAX and email to Cabinet Secretary, Principal Secretary to Prime Minister, Secretary Ministry of Home Affairs, Defence, Agriculture, Information & Broadcasting, Department of Sc. & Technology, NDMA, and Shipping & Surface Transport, Control Room Home Affairs, Director Indian Railways, Director General Doordarshan & All India Radio, Director General National Disaster Response Force and Chief Secretary- Tamil

			Nadu, Andhra Pradesh, Puducherry, Odisha, West Bengal, Andaman & Nicobar Islands, Kerala and Lakshadweep Islands.
4	RSMC Bulletin	61	1. IMD's website 2. WMO/ESCAP member countries and WMO through GTS and E-mail.
5	GMDSS Bulletins	36	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)
6	Tropical Cyclone Advisory Centre Bulletin (Text & Graphics)	34	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
7	Warnings through SMS	Daily	SMS to disaster managers at national level and concerned states (every time when there was change in intensity) To general public to users registered with RSMC website from the states of Odisha, Andhra Pradesh, West Bengal, Tamil Nadu, Andaman & Nicobar Islands, Kerala and Lakshadweep and National level disaster managers.
8	Warnings through Social Media	Daily (4 times)	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).
9	Message through Whatsapp	Daily	Everyday based on observation of 00, 03, 06, 12, 18 UTC observations to central level disaster managers and hourly on the day of landfall
10	Press Release	10	Disaster Managers, Media persons by email and uploaded on website
11	Press Briefings	Daily	Regular briefing daily

Table 12 (b): Statistics of Bulletins issued by ACWC Chennai and CWC Thiruvananthapuram (TRV)

S.No.	Type of Bulletin	No. of Bulletins issued	
		ACWC Chennai	MC TRV
1.	Sea Area Bulletins	13	NIL
2.	Coastal Weather Bulletins	13	NIL
3.	Fishermen Warnings issued	26	72
4.	Port Warnings	8	17
5.	Heavy Rainfall Warning	16	7
6.	Gale Wind Warning	35	NIL
7.	Information & Warning issued to State Government and other Agencies	35	52
8	Special Weather Bulletins	35	
9.	SMS	1200	15 times

12. Summary

An LPA formed over over Gulf of Thailand and adjoining Malay Peninsula in the morning of 8th November. It concentrated into a D over southeast BoB in the morning of 10th November and into a DD in the same evening. It intensified into CS "Gaja" over eastcentral and adjoining westcentral & southeast BoB in the early morning of 11th November, 2018. It moved nearly westwards till early morning of 12th. Thereafter it recurved south-southwestwards and followed an anticlockwise looping track till 13th morning. It intensified, into an SCS in the morning of 15th November and into a VSCS in the same night (2030 IST). It crossed Tamilnadu & Puducherry coast between Nagapattinam and Vedaranniyam near latitude 10.45˚N and longitude 79.8°E with wind speed of 130 kmph gusting to 145 kmph during 0030 to 0230 hours IST of 16th November. Thereafter, it weakened rapidly into an SCS in the early morning, a CS in the morning and into a DD over interior Tamil Nadu in the forenoon of 16th November. It further weakened into a D in the same evening over central Kerala. Moving nearly westwards, it emerged into southeast Arabian Sea (AS) in the same midnight (2330 IST) and into a DD over southeast AS in the early morning of 17th. Thereafter, it moved nearly west-northwestwards and crossed Lakshadweep Islands in the 17th afternoon (1400-1700 hrs IST) as a DD. It weakened into a D over southeast AS around noon (1130 IST) of 19th & into a WML over southwest & adjoining southeast AS in the same midnight (2330 IST).

The system was monitored & predicted continuously by IMD prior to it's genesis as low pressure area over BoB from 7th November onwards till it's dissipation on 19th. It's genesis, movement, landfall, recurvature, intensity and associated adverse weather were well predicted by IMD. The landfall point forecast errors were about 31, 43 and 70 km for 24, 48 and 72 hrs lead period respectively against past five year (2013-17) average errors of 42.3, 94.8 and 122 km respectively. The track forecast errors were about 121, 185 and 195 km for 24, 48 and 72 hrs lead period against past five year (2013-17) average errors of 93, 144 and 201 km respectively. The absolute error (AE) of intensity (wind) forecast for 24, 48 and 72 hrs lead period were 9.1, 11.0 and 14.6 knots against the LPA of 10.4, 15.5 and 15.7 knots respectively.

13. Acknowledgement:

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 VSCS Gaja. 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, Cyclone Warning Centre (CWC) Visakhapatnam, Thiruvananthapuram, Doppler Weather Radar Stations at Chennai, Karaikal Thiruvananthapuram, Kochi, 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.
