A STUDY ON THE UNCONVENTIONAL TRACKS OF TROPICAL CYCLONES IN THE NORTH INDIAN OCEAN

1. **Preface**. Tropical cyclones occur as seasonal weather systems over North Indian Oceans, with a higher frequency during the months of October and November. Normally, they form as a low pressure system in the lower latitudes of Arabian Sea/ Bay of Bengal, followed by intensification into Depression, Deep Depression and thereafter Cyclonic Storm (of varying intensity). In the Northern Hemisphere, as per classical theory, they initially track a NWward path subsequently re-curving to Northward and then NEward after reaching about 15º to 18ºN (Fig 1). Depending on their area of formation, track and state of intensification, they have landfall over the coastal region.

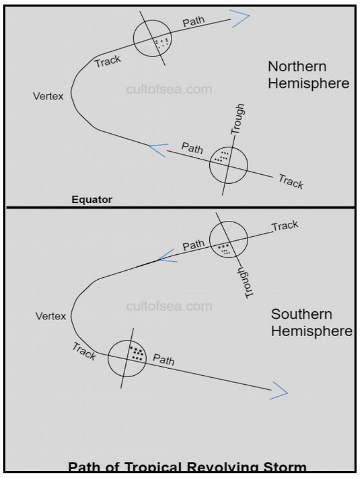


Fig - 1: Classical path of a Tropical Storm in Northern and Southern Hemisphere

2. **Reason for the Study**. During the period 24 October to 09 November of 2019 over the North Indian Ocean, it was observed that the tracks of three cyclones (Kyaar, Maha, and Bulbul) that formed over North Indian Ocean followed 'unconventional' tracks. The paths (and related features) of these cyclones are depicted in **Figs 2 (a) – (e), 3 (a) – (e)** and **4 (a) – (e)** respectively. A need was felt to study/ analyse the tracks of these cyclones over the North Indian Ocean, to discern a **conclusive pattern/ trend change** in the cyclone tracks and if **the Standard Operating Procedures of avoiding and navigating through a cyclone** (based on the navigable and dangerous semi-circle theory) **needed to be reviewed**.

3. **Methodology and Data Used**. The study was undertaken using the data on tracks of cyclones that occurred during the month of Nov during the last 30 years (being a conventional data sample period for any climatology). The data of **cyclone tracks** (from 1990 to 2019) has been taken from the '*best track data*' published in **Cyclone eAtlas by IMD**. The SST, wind vectors, atmospheric temperature and moisture data, available at a resolution of 1ºx1º, have been extracted from the data archives of National Centre for Environmental Prediction(NCEP) and National Centre for Atmospheric Research (NCAR) of NOAA. The plotting is done using GrADS based programming.

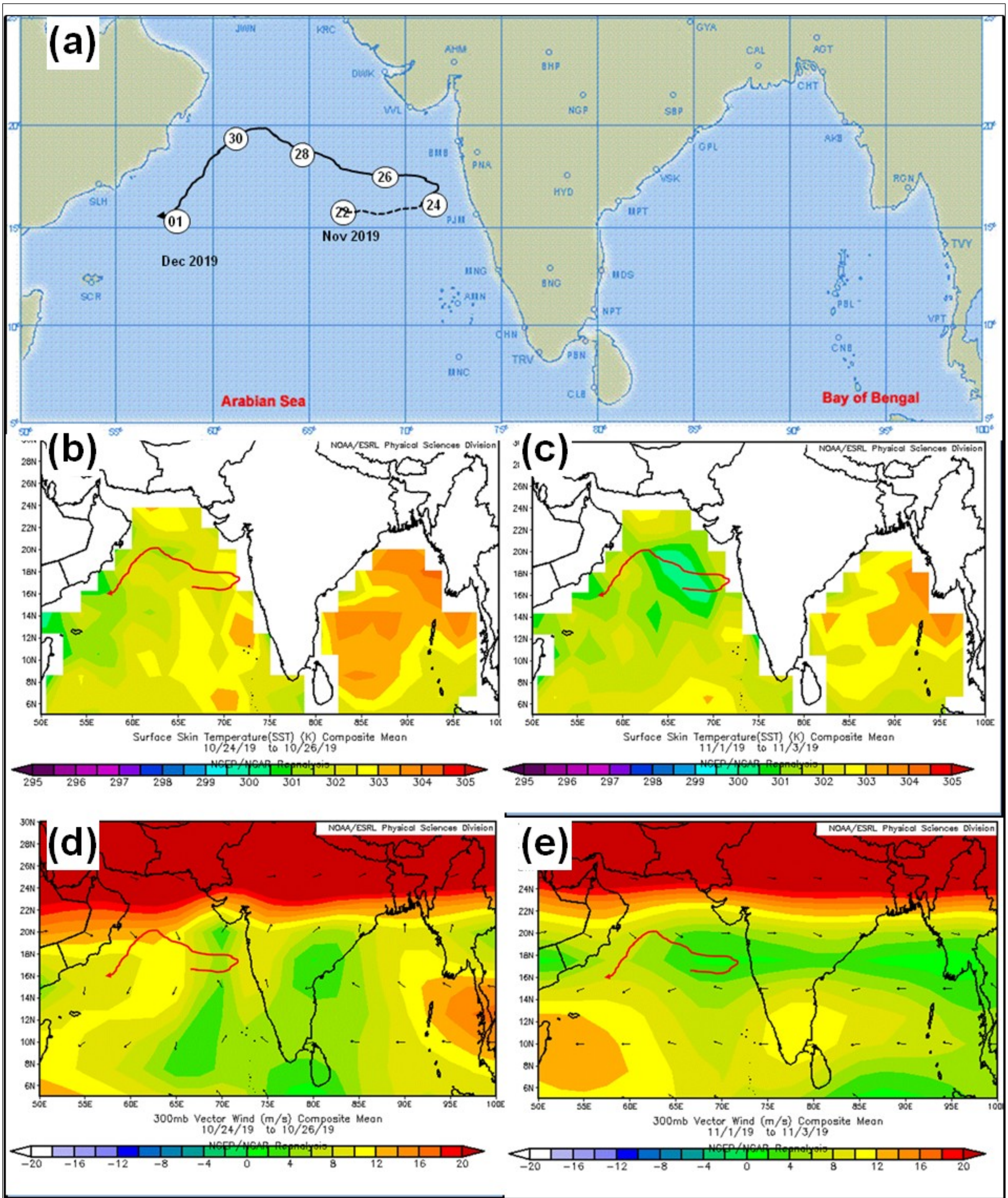


Fig 2:

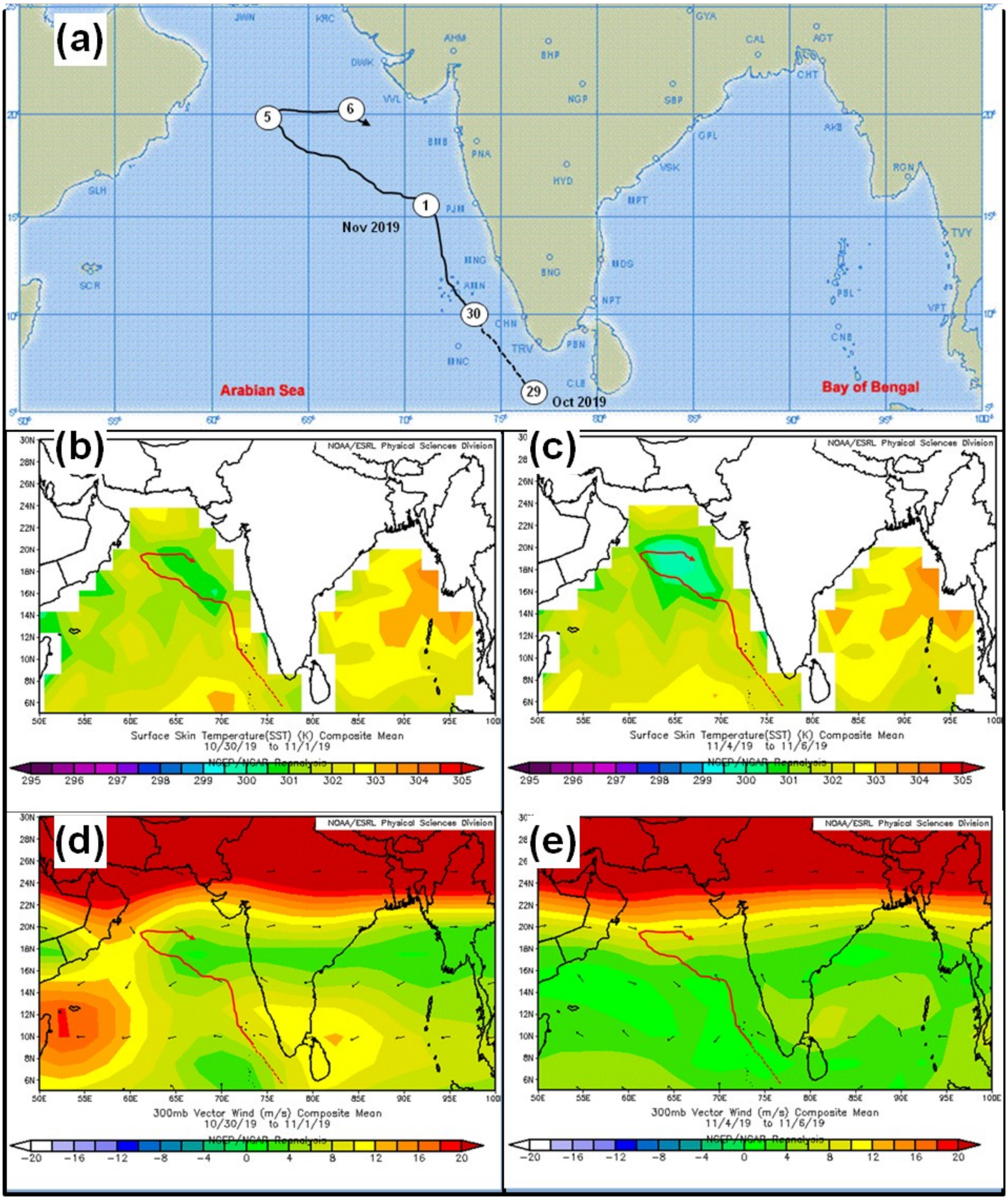
(a) The track of cyclone "*Kyaar*" in AS from 24 Oct to 03 Nov 2019

(b) SST (K) average during the period from 24 to 26 Oct 2019

(c) SST (K) average during the period from 01 to 03 Nov 2019

(d) Wind Vector (m/s) average at 300hpa during period from 24 to 26 Oct 2019

(e) Wind Vector (m/s) average at 300hpa during period from 01 to 03 Nov 2019



<u>**Fig 3**</u>:

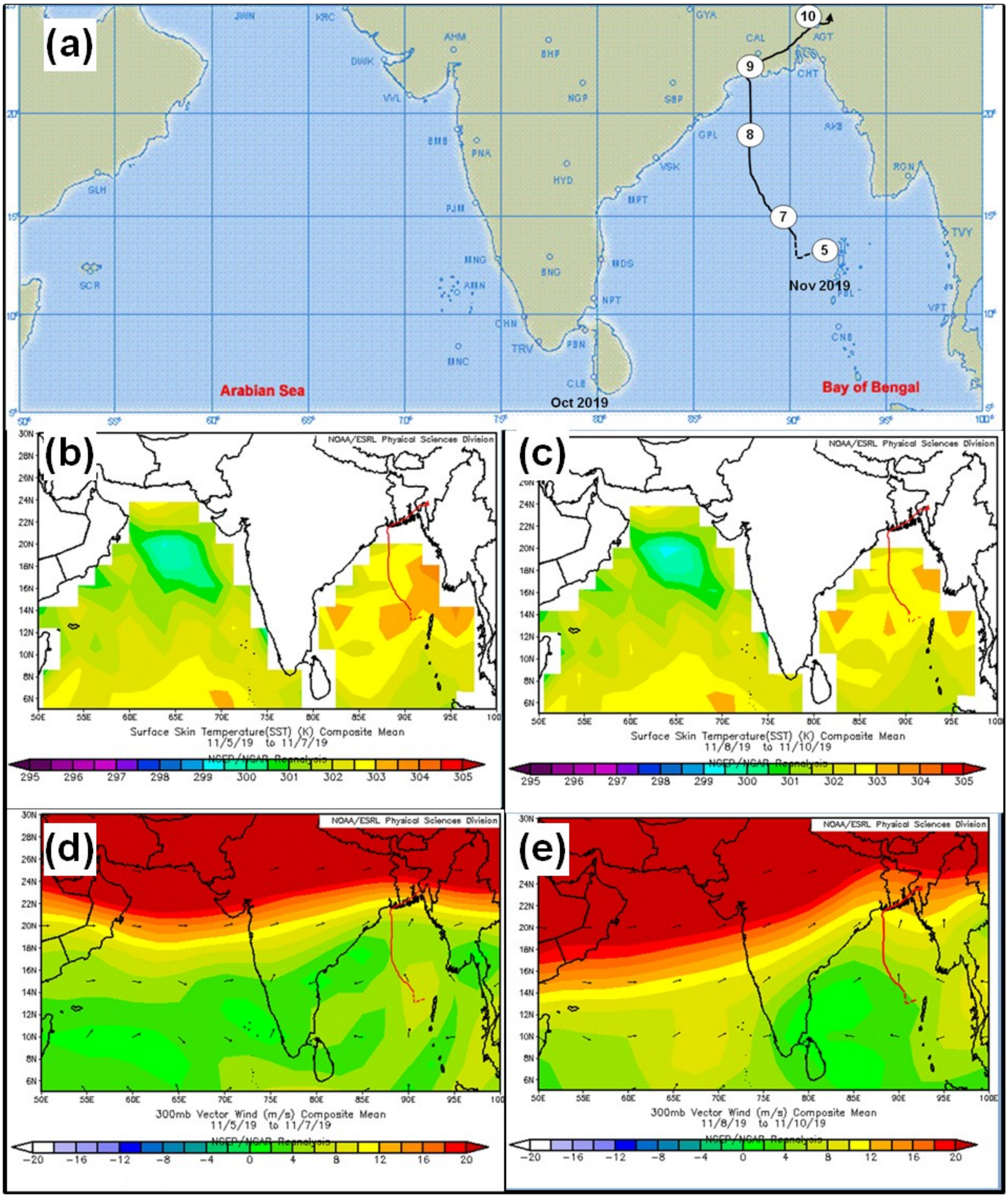
(a) The track of cyclone "***Maha***" in AS from 30 Oct to 06 Nov 2019

(b) SST (K) average during the period from 30 Oct to 01 Nov 2019

(c) SST (K) average during the period from 04 Oct to 06 Nov 2019

(d) Wind Vector (m/s) average at 300hpa during period from 30 Oct to 01 Nov 2019

(e) Wind Vector (m/s) average at 300hpa during period from 04 Oct to 06 Nov 2019



<u>**Fig 4**</u>:

(a) The track of cyclone "***Bulbul***" in BoB from 05 Nov to 09 Nov 2019
(b) SST (K) average during the period from 05 Nov to 07 Nov 2019
(c) SST (K) average during the period from 08 Nov to 11 Nov 2019
(d) Wind Vector (m/s) average at 300hpa during period from 05 Nov to 07 Nov 2019
(e) Wind Vector (m/s) average at 300hpa during period from 08 Nov to 11 Nov 2019

4. The broad features of the observed tracks of the three cyclones are enumerated below:-

Ser	Cyclone Name	Region	Period	Remarks
(a)	Kyaar	Ar Sea	24 Oct - 03 Nov	(i) Formed over Central Arabian Sea, it **initially tracked NEwards**. (ii) Subsequently after crossing about 16ºN latitude it tracked NWwards. (iii) It intensified into an **Extremely severe Cyclonic Storm** and after reaching about 19ºN latitude, it started tracking SWwards (**Fig. 2**)
(b)	Maha	Ar Sea	30 Oct – 04 Nov	(i) The Cyclone formed over SE Arabian Sea. Initially Tracked NNWwards. (ii) Subsequently it tracked NWward and intensified into a Severe Cyclonic Storm. (iii) After Reaching about 20ºN latitude, it tracked completely Eastwards and subsequently again SEwards before weakening over East Central Arabian Sea **(Fig. 3**)
(c)	Bulbul	Bo B	05 Nov - 11 Nov	(i) It formed as a Depression over NW Andaman Sea and started tracking Westwards. (ii) After 24 hrs it intensified into a DD and started tracking Northwards and intensified into a Cyclonic Storm. (iii) Subsequently, it intensified into a severe cyclonic storm and moved NWwards and further intensified into a Very Severe Cyclonic Storm and tracked Northwards until about 21ºN and then recurved NEwards NE wards to have landfall over Bangladesh (**Fig. 4**).

5. **Causes of Cyclogenesis**. Classically, a cyclone forms over an ocean based on the following favourable conditions:-

(a) Sea Temperature upto an integrated depth of 60m should be more than 26ºC.

(b) There should be a pre-existing low pressure area over the region.

(c) The region of formation should have a deep unstable moist atmosphere.

(d) The region of formation should be away from Jet Stream or region of strong vertical wind shear.

(e) The value of Coriolis Force over the region must be less, however but not zero. It is especially favoured near the seasonal location of equatorial trough.

6. **Movement of Cyclones**. The movement of a cyclone in respect of direction and speed is dependent on the following and the resultant of their interaction:-

(a) The individual momentum of the Cyclone system (**β-effect**).

(b) The force exerted on the Cyclone System by the strong persisting winds in the environment between 5 to 9 km above the sea level (where the maximum mass of the cyclone is concentrated), generally considered to be the **steering current**.

7. **β-Effect**. Post formation, the cyclonic system tends to move towards region of more **positive vorticity** {the ability for an air parcel to spiral/ spin in an anticlockwise direction in northern hemisphere measured in number of rotations per second (i.e S^{-1})}. As shown in Fig 5, there are two regions of higher vorticity with respect to the region of formation of Cyclones, in the northern hemisphere. They are:-

(a) The poleward region due to higher Coriolis force. (The Corriolis force is zero at equator and maximum at poles).

(b) The region towards west of the cyclone, where due to the West to East rotation of the earth, the individual air parcel relatively moves towards the west and generates more spiral due to relative east to west advection of the air mass.

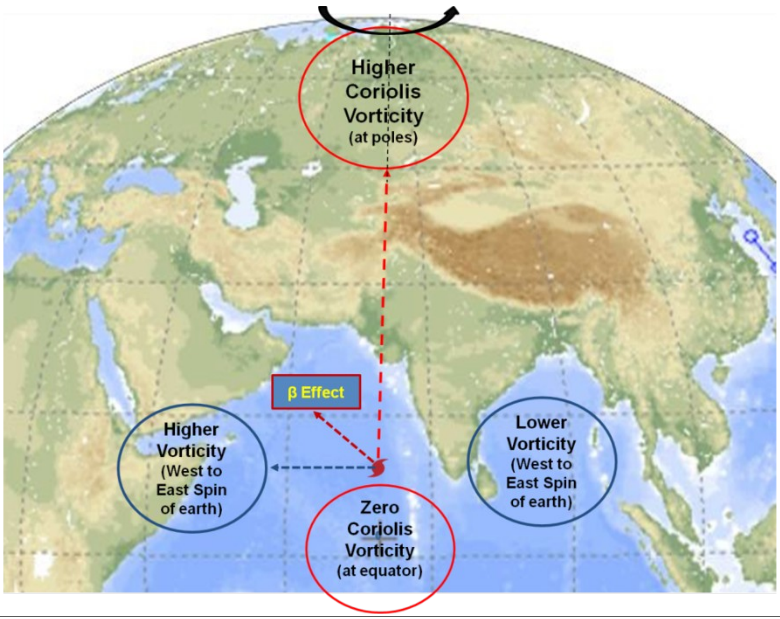


Fig - 5: Zones of varying vorticity with respect to a cyclone system

8. The two regions of higher vorticity tend to pull the cyclone towards north and west respectively. As a resultant of these two forces, the cyclones which form over the equatorial region in the northern hemisphere, have a natural tendency to move Northwestwards. **This is called β-effect**.

9. **Steering Current**. Another important factor which drives a cyclone's movement, is the persisting strong wind field from 500hpa to 300hpa level (about 5 to 9km above mean sea level). At the subtropical high region i.e 30ºN, a strong Sub Tropical Westerly Jetstream (STWJ) with wind speed 60 to 100 kts persists at about 10km above the sea level throughout the year. The STWJ seasonally oscillates in the north-south direction, following the movement of the sun and during northern hemispheric winters they normally oscillate south reaching even upto 20ºN. This creates a strong wind field upto 5 kms and above, till about 15ºN latitude. Any tropical cyclone system which forms or moves over the region, comes under the strong influence of these strong wind fields and gets steered along its path as depicted in Fig 6.

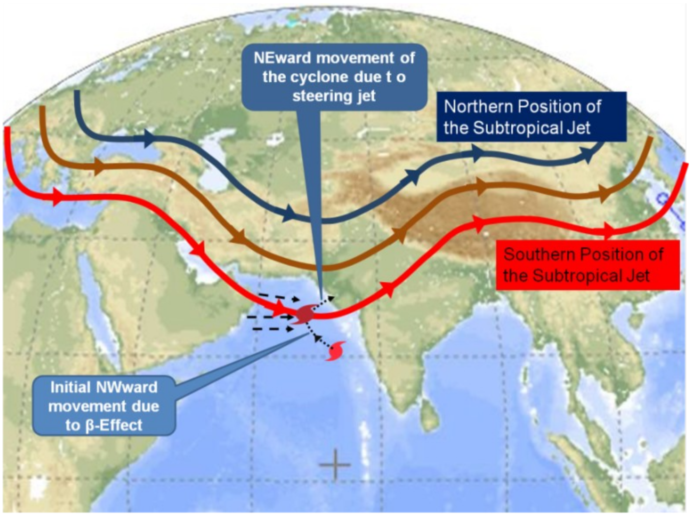


Fig - 6: When the jet stream is in the southernmost position, it influences the cyclone in the path to move NEwards against its normal flow

10. **Analysis of Paths Tracked by Cyclones in North Indian Ocean (1990 -2018)**. A total of **30** cyclones formed in the North Indian Ocean during the month of November during the period 1990 - 2018 (Fig-7).

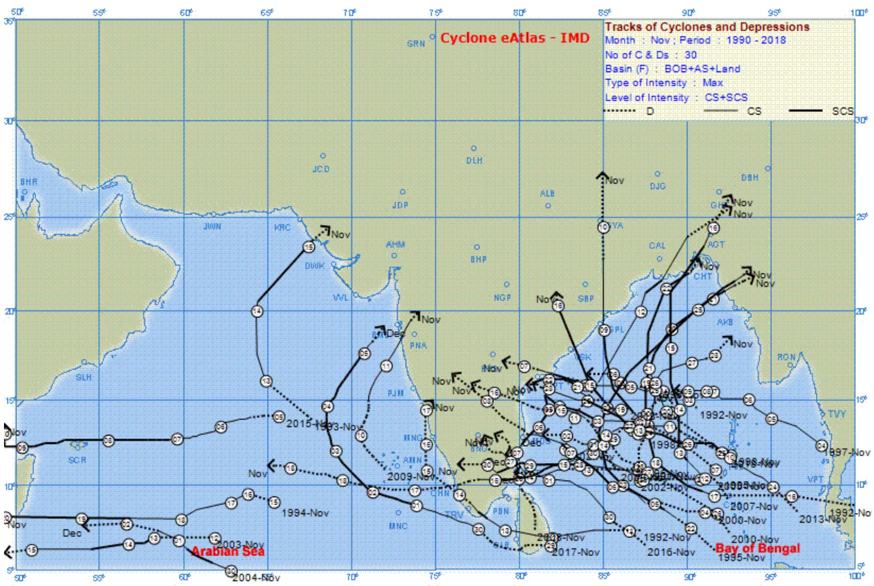


Fig - 7: Cyclone tracks from 1990- 2018

11. **The basic statistics** of the **33 cyclones** that occurred during the month of November (including 2019) are summarised as follows:-

Ser	Condition	Statistic (1990 -2019)
(a)	No. of years without any cyclone	7
(b)	No of cyclones which followed complete classical path	7
(c)	No of cyclones which followed **unconventional path**	**12**
(d)	No of cyclones which had incomplete path(Premature land fall/ dissipated at sea while following a classical track)	12
(e)	No of cyclones which crossed over from one Sea to Another	2
	Total : (b)+(c)+(d)+(e)	**33**

(a) Cyclones which move completely Westwards or SWwards after formation.

(b) Systems which follow erratic path and loop upto Deep Depression Stage and rapidly intensify into a cyclone.

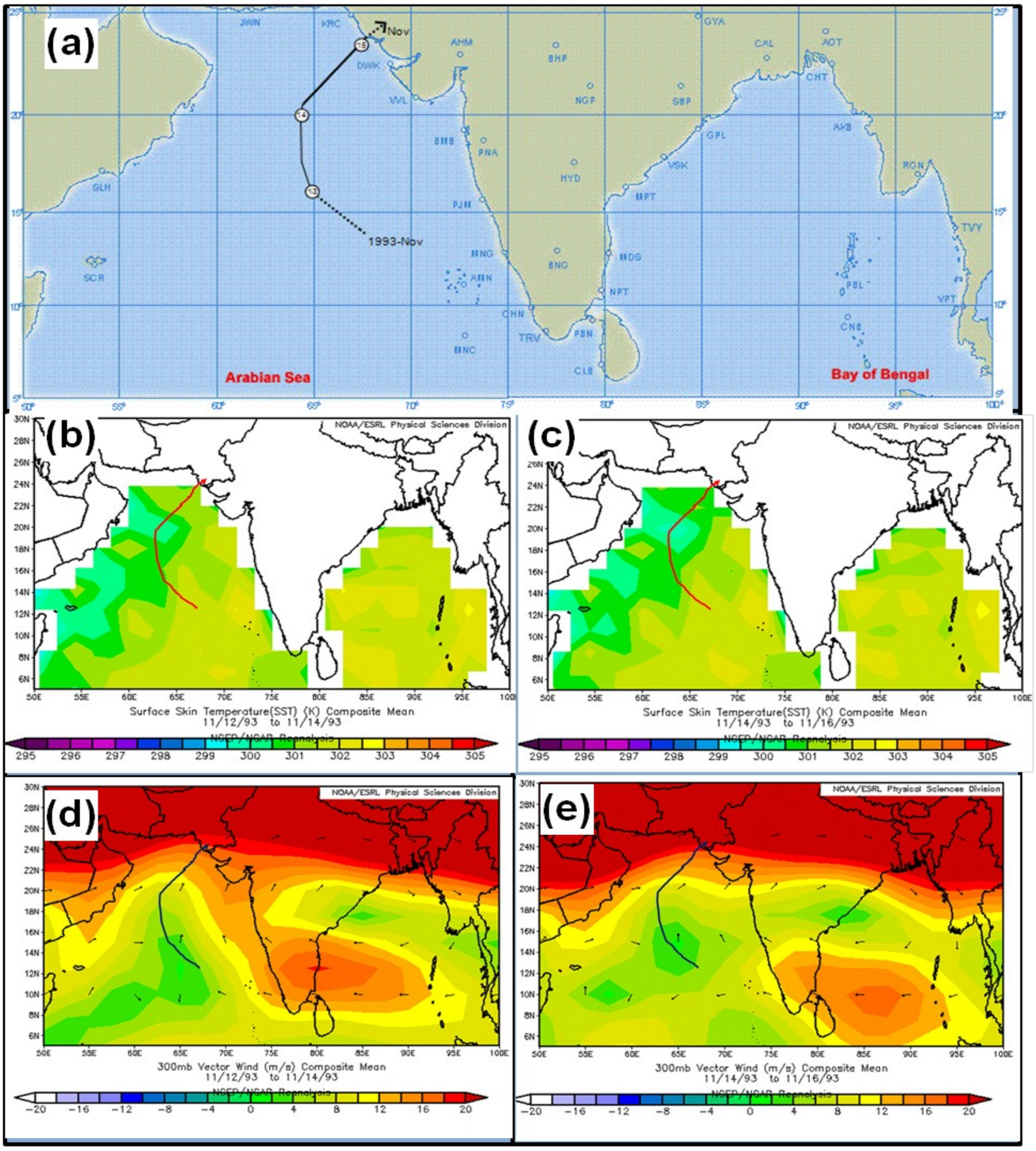
(c) Cyclones which form in the lower latitudes but track a NEly path right from the formation stage.

Ser	Cyclone	Region	Period	Remark
(a)	VSCS	AS	12 - 16 Nov 93	Classical Path
(b)	ESCS	BoB	22 - 27 Nov 95	Classical Path
(c)	VSCS	BoB	28 Nov - 05 Dec 96	Unconventional Path in Bay of Bengal
(d)	Megh	AS	05 - 10 Nov 15	Unconventional path Similar to Kyaar in Arabian Sea
(e)	Kyaar	AS	24 Oct - 03 Nov 19	Unconventional path noted in 2019
(f)	Maha	AS	30 Oct - 04 Nov 19	Unconventional path noted in 2019
(g)	Bulbul	BoB	05 - 11 Nov 19	DD's unconventional path and sudden intensification noted in 2019
(h)	SIDR	BoB	12 - 16 Nov 07	Cyclone very similar to BulBul which also became ESCS

13. Since the track statistics were not confirmative, an analysis of the physical structure (SST, Vector winds, moisture etc.,) of the cyclone environment was carried out by superimposing them over the unconventional cyclone tracks. An analyses of the following selected cyclones was carried using track superimposition on the SST average and 300hpa Wind Vector average plot for the first three days and last three days of the Cyclone period:-

14. **<u>Benchmarking of the Environment of Classical Track Cyclone</u>**. It is pertinent to mention that naming of cyclones over North Indian Ocean region started only from 2004. Before analysing the unconventional tracks, the environment of classical tracks were benchmarked for reference. Two classical paths viz. 12 - 16 Nov 1993 over Arabian Sea and 22-27 Nov 95 over Bay of Bengal are shown in Fig 8 and Fig 9 along with its super imposition on other parameters.

15. **<u>12 to 16 Nov 93 Cyclone (AS) – Fig 8</u>**. A low pressure system had intensified into a Depression in the Central Arabian Sea on 12 Nov 93 where the SST was about 28ºC. Subsequently on 13 Nov it had formed into a Cyclone tracked NWward followed by NNWward path. On 14 Nov it had intensified into a Very Severe Cyclonic Storm and under the influence of the Sub Tropical Westerly Jet (STWJ) (Fig.5d) and curved NEwards. It had land fall over Karachi (about 25nm NW of Gujarat Coastline).



<u>Fig 8</u>:

(a) The track of cyclone in AS from 12 to 16 Nov 1993

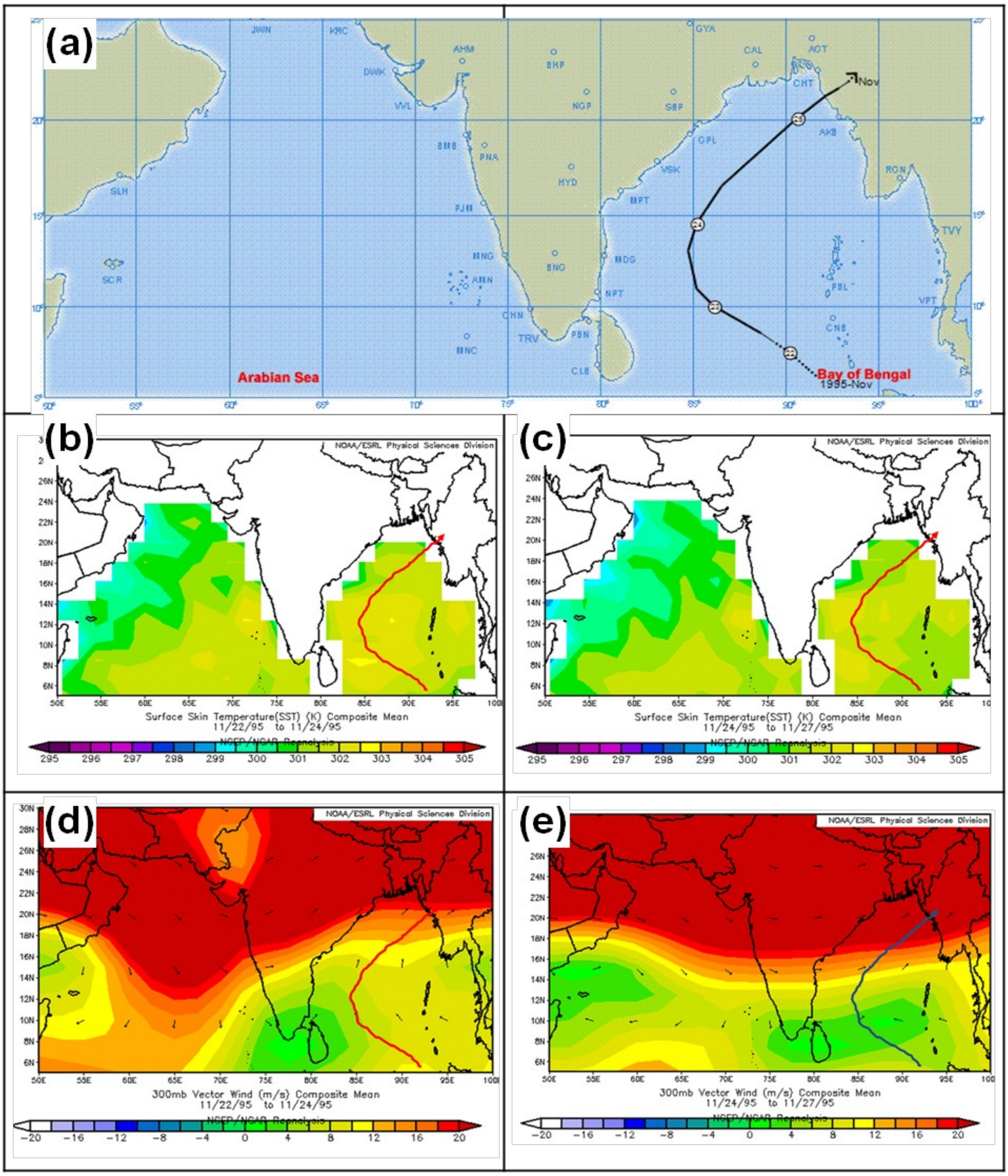
(b) SST (K) average during the period from 12 to 14 Nov 1993

(c) SST (K) average during the period from 14 to 16 Nov 1993

(d) Wind Vector (m/s) average at 300hpa during period from 12 to 14 Nov 1993

(e) Wind Vector (m/s) average at 300hpa during period from 14 to 16 Nov 1993

16. **<u>22 to 26 Nov 95 Cyclone (BoB) - Fig 9</u>**. A Depression had formed on 21 Nov 95 in the South Andaman Sea and had tracked NWward from the beginning. It had intensified into a Cyclonic Storm on 22 Nov and further into an Extremely Severe Cyclone on 24 Nov 95. **It is notable that the STWJ is well south of its normal position** (similar to the case discussed at Para 15 above) and the re-curvature of the Cyclone commenced when it reached about 13ºN and had land fall over the Myanmar Coast on 27 Nov 95.



<u>Fig 9</u>:

(a) The track of cyclone in BoB from 22 to 26 Nov 1995

(b) SST (K) average during the period from 22 to 24 Nov 1995

(c) SST (K) average during the period from 24 to 26 Nov 1995

(d) Wind Vector (m/s) average at 300hpa during period from 22 to 24 Nov 1995

(e) Wind Vector (m/s) average at 300hpa during period from 24 to 26 Nov 1995

Study of Unconventional Tracks

17. **28 Nov to 07 Dec 96 Cyclone (BoB) – Fig.10**. The system intensified into a Depression on 28 Nov 07 over Central Bay of Bengal. The SST was approximately 29ºC. The system further intensified into a Deep Depression (DD) on 29 Nov, weakened briefly to a Depression and subsequently re-intensified into a DD on PM 01 Nov. This phase saw random looping movement of the system. ***The directional influence of the overall steering flow on TC trajectory may vary with intensity(Velden and Leslie 1991)[1].*** The system here in the DD phase was not influenced by any particular steering flow and was moving due to the *β*-effect factors explained at Para 7. However, the NWward movement was not followed. This may be attributable to the influence of SST in the initial stage of formation. The higher SST and the associated thermal energy generates more instability in the atmosphere especially when the environmental temperature is relatively lower. The instability in the atmosphere leads to upward movement of air from the surface which further increases the vorticity in the upper atmosphere. As mentioned at Para 7 above, the *β*-effect is the resultant NWward movement of the system between the two forces viz. northward pull due to Coriolis generated Vorticity and Westward pull of the east to west advection generated vorticity. The northward pull remaining relatively constant (Coriolis parameter due to rotation of the earth) the increased vorticity towards west is affected by the instability generated vorticity in addition to the advection generated vorticity. Hence, influence of instability generated vorticity provided more randomness to the path of the System. The VSCS hardly came under the influence of strong westerly jet which was also well north of the system. The steering current in the region between 500 to 200 hpa level also influences the movement, and the overall resultant movement of the system did not conform to the classical path.

18. ***'Megh'*****(AS) - 05 Nov to 10 Nov 15 – Fig.11**. System *Megh* intensified into a Depression over Central Arabian Sea on 04 Nov 15 and further intensified into a Cyclonic Storm within about six hours. The system further intensified into an Extremely Severe Cyclonic Storm by 08 Nov 19 and had landfall over Yemen coast as a Cyclonic Storm. During the entire duration of the system, it tracked Westward/ SWward completely different from the classical path. It is relevant that the initial conditions during the formation were similar to the previously discussed ones viz. high SST up to 30ºC and the region was well south of the influence of the westerly jet.

19. '***Kyaar'*****(AS) - 24 Oct to 03 Nov 19 – Fig.2**. *Kyaar* is a 2019 system which intensified even into an Extremely Severe Cyclonic Storm. Formed into a Depression over Central Arabian Sea on 22 Oct 19 and started tracking Eastwards. It is relevant to mention that during the Depression stage the effect of steering current is relatively lesser and the strong winds at lower level affects the movement of the system. This system formed over a region surrounded with high SST of 29-30ºC when the surrounding atmospheric temperature at two meters above the sea level was about 26-27ºC. (Fig 13. shows the average 2m atmospheric temperatures corresponding to first three days of formation of Depression in all the systems discussed). In addition there is indication in the Fig 2(b), that the SST over East of region of formation of the Depression is more than that in the west. This may be correlated to the instability induced vorticity and the system tending to move towards the region. Post formation into a Cyclonic Storm, *Kyaar* tracked a NWward path though the region was about

17ºN latitude. The STWJ is evidently above 20ºN latitude and by the time cyclone reached 61ºE longitude it came under the influence of strong Northerly and NEly winds at 300hpa level. The system subsequently moved SWwards and dissipated at sea in the region of relatively lower SST.

20. **<u>'Maha'(AS) - 30 Oct to 06 Nov 19 - Fig.3</u>**. 'Maha' formed into a depression on 29 Oct 19 over South East Arabian Sea and tracked NNWward path. The region of formation influences the track to a extent by affecting the advection vorticty. Though the SST at the region of formation was about 27 to 28ºC, towards SW of the region there were region with 31ºC SST. The higher SST in the vicinity will increase the moisture inflow into the system there by providing the system with more energy and consequently affect its resultant β-effect movement. 'Maha' also intensified into an ESCS on 04 Nov while tracking NWwards and subsequently came under the influence of the STWJ at about 20ºLat and started moving eastwards. Though the path may not look completely classical, it did follow the conventional trend of initial NWward trend and following under the influence of steering current after 20ºN latitude. It is also pertinent to mention that vicinity of another system ***Kyaar*** which had formed over the region did possibly influence each other and further made them deviate from the convention, in terms of track as well as intensification.

21. **<u>'Bulbul'(BoB) - 06 to 09 Nov 19 – Fig.4</u>**. 'Bulbul' appeared over the North Andaman sea, as a residual low of the SW Pacific Cyclone *Matamo*. The persisting high SST upto 31ºC over the region helpedintensify the residual low into a Depression on 05 Nov 19 and further intensified into a Deep Depression within another six hours. The system was tracking a random path initially due to effect of associated surrounding vortices as discussed above. After intensification into a Cyclonic Storm, it tracked Northward initially and thereafterNEward under the influence of STWJ and had a landfall over Sundarban region on 09 Nov as a Very Severe Cyclonic Storm (VSCS). Bulbul too did not conform completely to a conventional path during the initial stages uptoDD, but thereafter the movement was following the conventional path. It is relevant to mention that when the system forms over the Central Bay of Bengal, there is a greater likelihood of a Northward movement. It is conjectured that the vicinity of landmass and the frictional drag could be damping the east to west advection of air mass {Para 7(b) refers}. A closely resembling path was tracked by a cyclone 'Sidr' in 2007 between 12 and 16 Nov 07 (Fig. 12), which had formed over SW Andaman Sea and had intensified into an ESCS. However, the SST over the region was relatively lesser compared to the 2019 system.

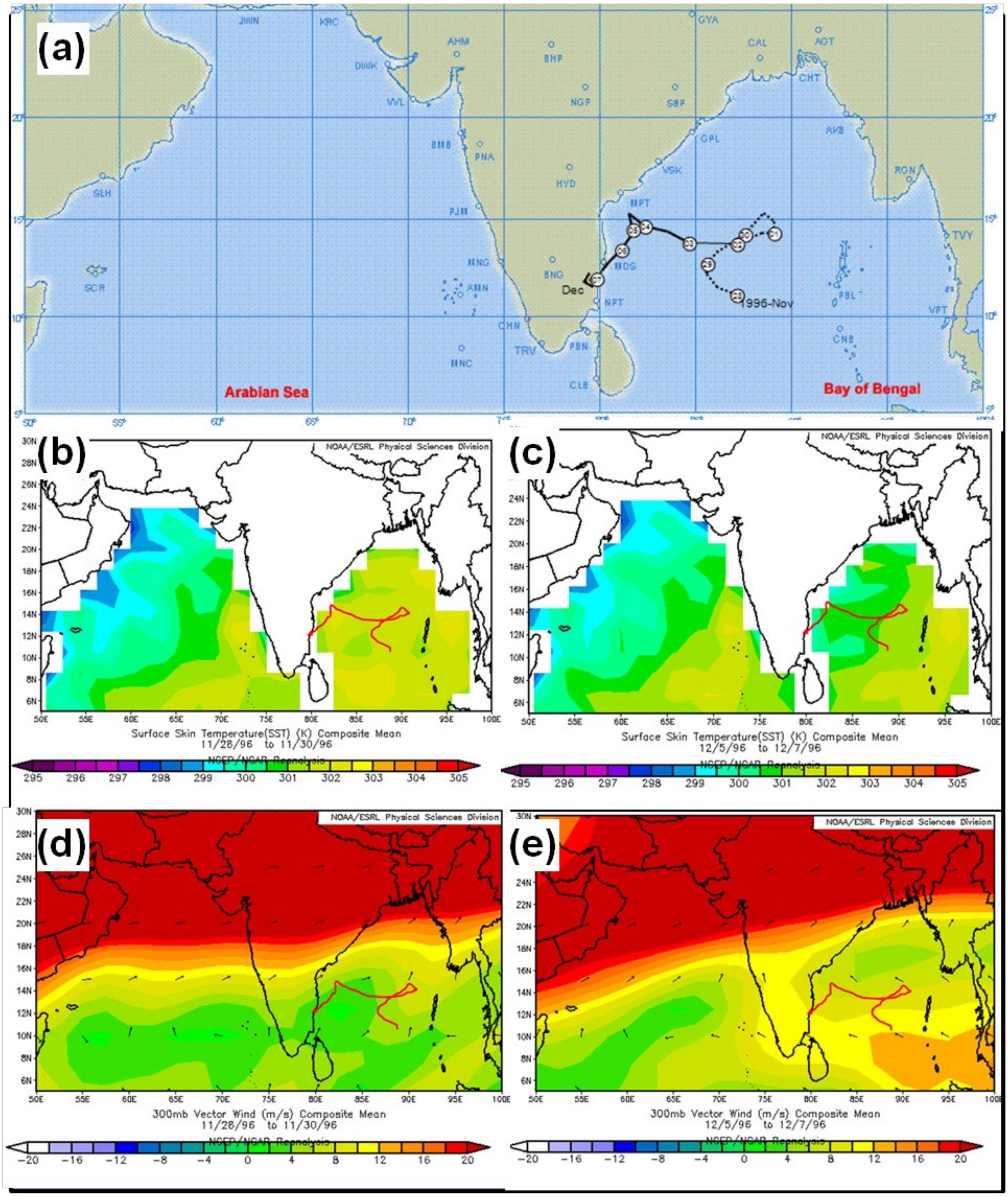
22. **<u>Analysis</u>**. The salient points of the analysis are as follows:-

(a) 'Unconventional' tracks of cyclones have not been very uncommon in the last 30 years.

(b) The SST over the region and its vicinity, **during the formation stages** of the Depression/ Cyclone influences the resultant *β*-effect of the system. There is no however, direct correlation between SST data and Unconventional Tracks.

(c) SST does not directly affect the day-to-day movement of the cyclone.

(d) Position of STWJ, if it happens to be in the path of a cyclone, has a major influence in steering the path of the cyclone.



<u>Fig 10</u>:

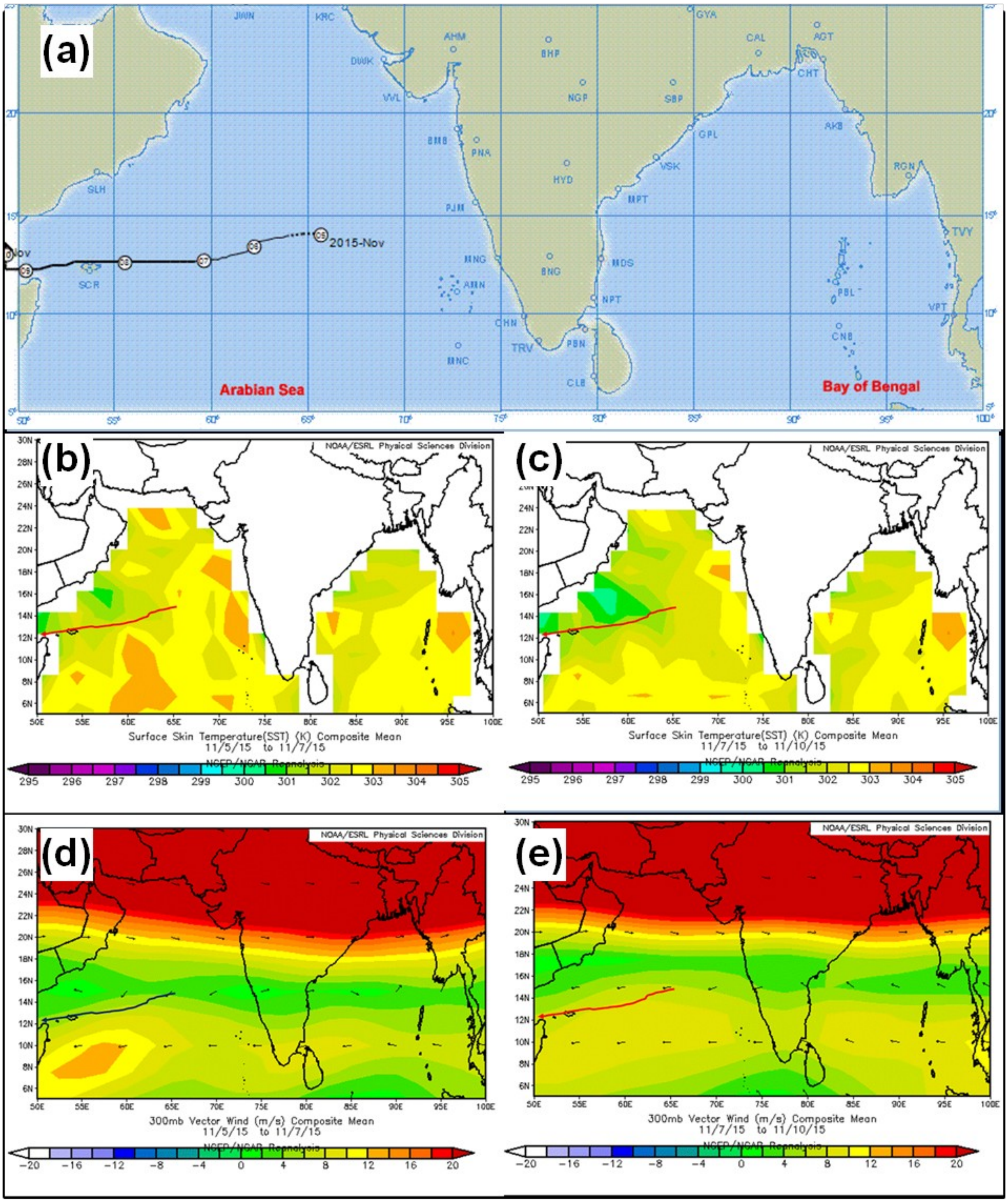
(a) The track of cyclone in BoB from 28 Nov to 07 Dec1996

(b) SST (K) average during the period from 28 to 30 Nov 1996

(c) SST (K) average during the period from 05 to 07 Dec 1996

(d) Wind Vector (m/s) average at 300hpa during period from 28 to 30 Nov 1996

(e) Wind Vector (m/s) average at 300hpa during period from 05 to 07 Dec 1996



<u>Fig 11</u>:

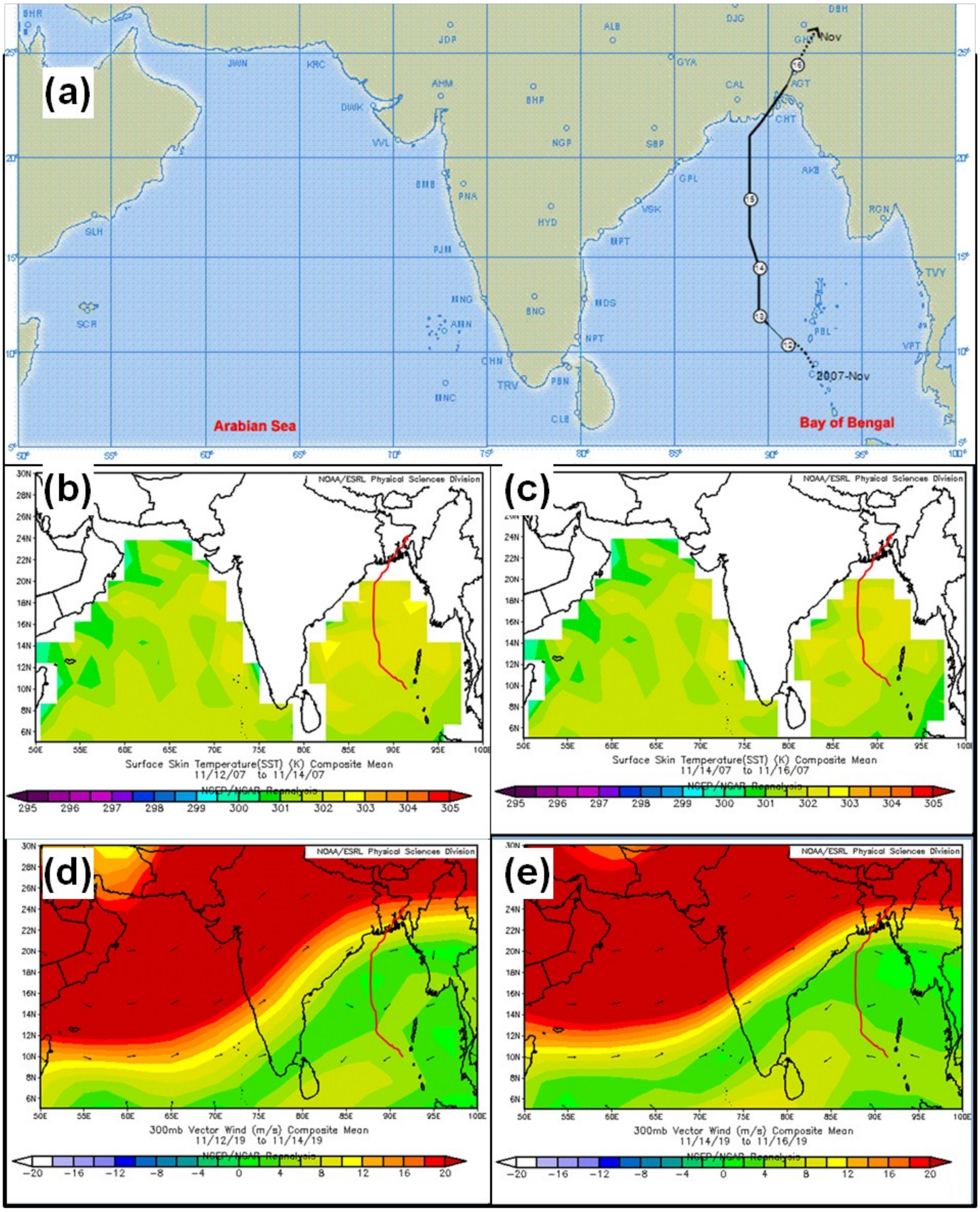
(a) The track of cyclone "***Megh***" in AS from 05 Nov to 09 Nov 2015

(b) SST (K) average during the period from 05 to 07 Nov 2015

(c) SST (K) average during the period from 07 to 09 Nov 2015

(d) Wind Vector (m/s) average at 300hpa during period from 05 to 07 Nov 2015

(e) Wind Vector (m/s) average at 300hpa during period from 07 to 09 Nov 2015



<u>**Fig 12**</u>:

(a) The track of cyclone "***Sidr***" in BoB from 12 Nov to 16 Nov 2007

(b) SST (K) average during the period from 12 Nov to 14 Nov 2007

(c) SST (K) average during the period from 14 Nov to 16 Nov 2007

(d) Wind Vector (m/s) average at 300hpa during period from 12 Nov to 14 Nov 2007

(e) Wind Vector (m/s) average at 300hpa during period from 14 Nov to 16 Nov 2007

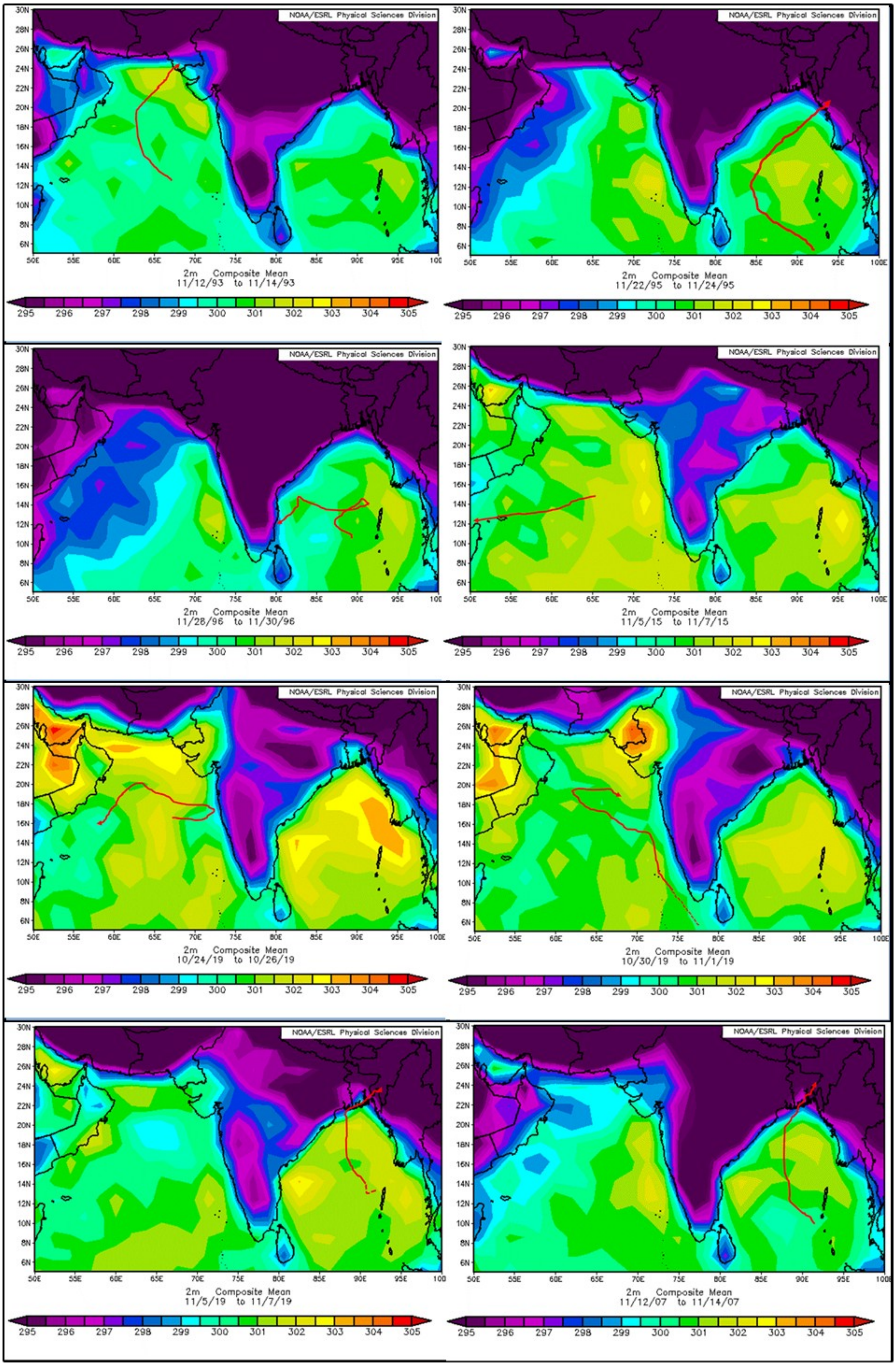


Fig 13: Indicates atmospheric temperature at 2 m above sea level corresponding to first three days of the cyclone systems discussed in Fig 5 to 12.

23. **Global Warming Effect**. As mentioned in the summary of analyses, SST does play an important role in determining both the intensity and track of the cyclone. The NCEP/ NCAR satellite data for SST over the Indian Ocean region was specifically plotted for the month of November. As indicated in the **Fig. 14** below there is an increasing trend though minimal (**Avg SST: 301.4K, Slope of increase: 0.14 and standard deviation: 0.26**). However, it has been cited in literature that even 0.5ºC increase in SST may significantly increase the intensification of Cyclones (as discussed in Para 17).

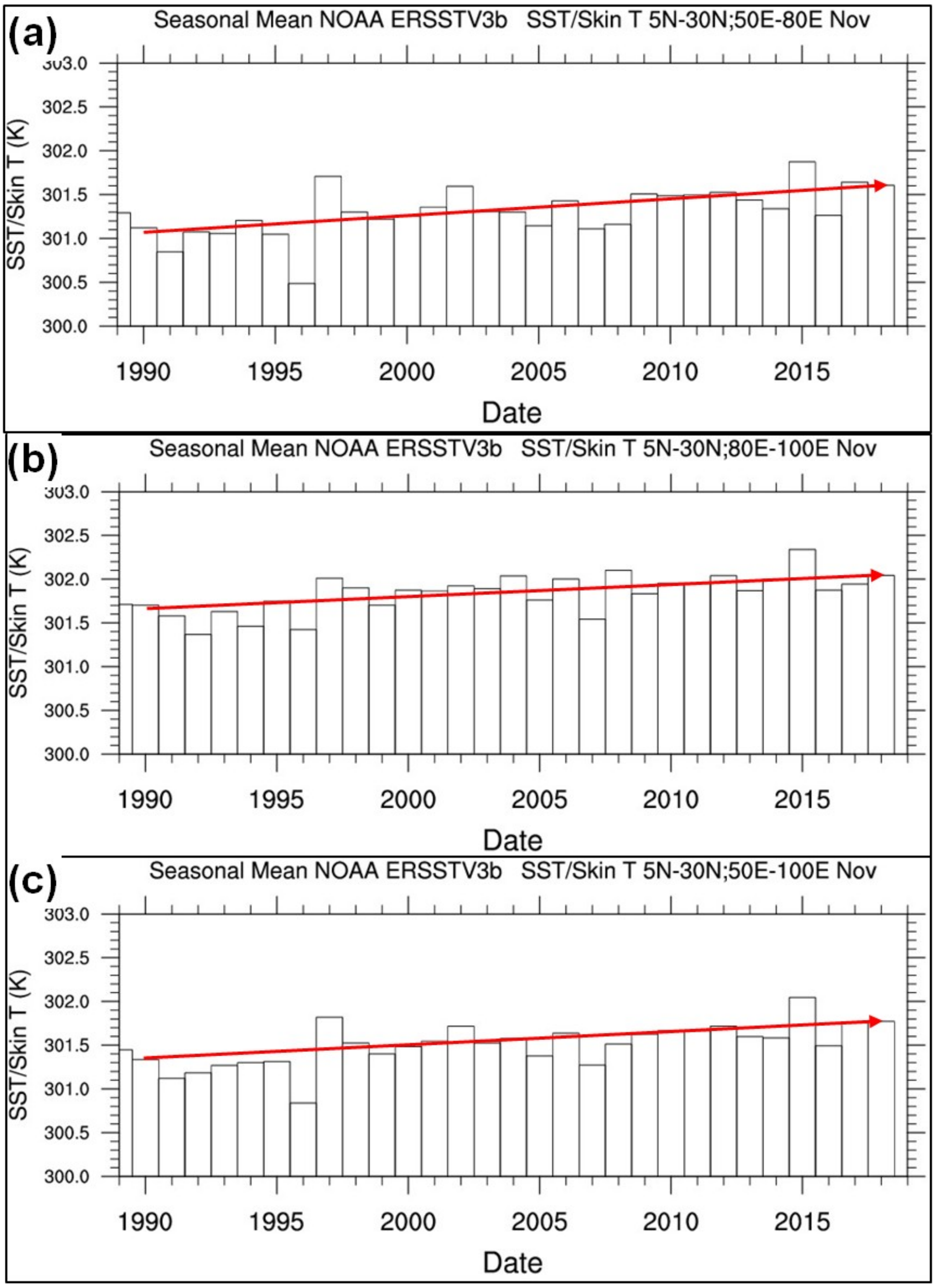


Fig 14:

(a) Bar plot of time-series of Nov SST over Arabian Sea

(b) Bar plot of time-series of Nov SST over Bay of Bengal

(c) Bar plot of time-series of Nov SST over North Indian Ocean

SOP for Navigation - Dangerous and Navigable Semi Circles

24. The Navigable and Dangerous Semi Circles of a Cyclone with respect to both the hemispheres are defined with respect to the direction of movement of the cyclone as shown in **Fig.** 15 below:-

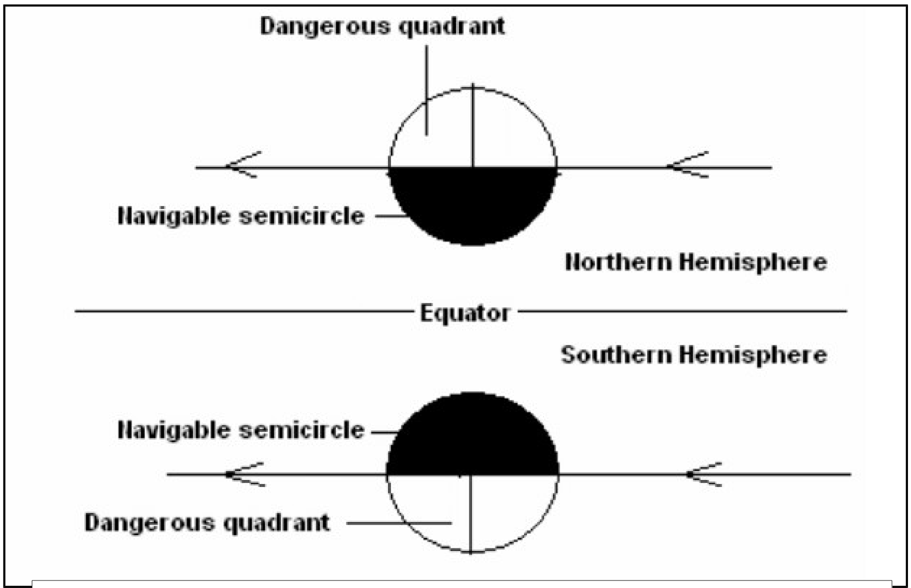


Fig - 15: Cyclone tracks from 1990- 2018

25. The anti-clockwise spiral of winds towards the centre of a low pressure in the northern hemisphere leads to right hand side half of the cyclone with respect to its direction of movement, being called the **dangerous Semi Circle**. The winds are stronger because the cyclone's translation speed and rotational wind field are additive. The opposite side is termed the **navigable semicircle**. Since the navigation philosophy remains the same, as long as the track of the cyclone can be correctly predicted, no changes in SoP are required, even though the rapid intensification of storms are going to pose a challenge in the foreseeable future.

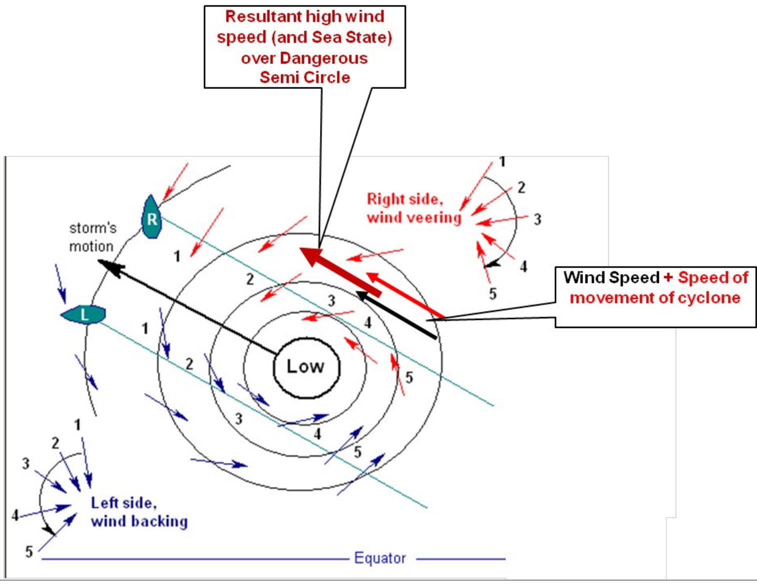


Fig - 16: Indication of Backing and Veering of winds in the Navigable and Dangerous Semi-Circle respectively, and additive resultant wind speed in the Dangerous Semi-Circle.

Conclusion

26. The study on the cyclones in the month of November from 1999 to 2019 has revealed an important fact that in majority of the cases, the 'Classical Track' of the cyclone was not followed strictly. Various factors play a role in determining the path of a cyclone. Though the impact factor of the steering jet current is more in defining the final movement of the cyclone, the SST in the region of cyclogenesis provides the initial feed to define the movement and intensification before coming under the influence of the jet. The generated instability in the atmosphere due to higher SST, affects the β-effect of the cyclone influencing the initial randomness in the movement of a system.

27. Navigation of ships and aircraft through a storm is based on the Navigable and Dangerous Semi Circle defined in a Cyclone which is based on the anticlockwise spiral and clockwise spiral of the winds in the north and southern hemisphere (as an effect of Coriolis force). The perceived 'unconventional' paths of the cyclone do not warrant any change in the SOPs for navigation as long as the tracks of cyclone can be predicted with a fair degree of accuracy. However, it is to be noted that rapid intensification of storms may leave little reaction times even if the paths are accurately predicted.

28. With the advancement in the satellite imageries and products, the forecast accuracy of cyclone intensity and its tracks has increased. The issuance of timely warnings shall be of crucial importance. Increase in computational power for running cyclone track models is the key to improvement in the prediction capability in respect of cyclones in the future.

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