MAUSAM, **59**, 1 (January 2008), 51-68

551.515.5

Intensification and movement of cyclonic storm in the Bay of Bengal during post monsoon season

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(*Received 4 December 2006, Modified 10 April 2007*)

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सार – एन. सी. ई. पी. / एन. सी. ए. आर. पुनः विश्लेषण आँकड़ों और 1981–2005 तक की अवधि के भारत मौसम विज्ञान विभाग से प्राप्त किए गए तूफानों के मार्ग के उपलब्ध आँकड़ों का उपयोग करके मानसून पश्चात् ऋतु के दौरान बंगाल की खाड़ी में तूफानों के तीव्र होने और उनके आगे बढ़ने की प्रक्रिया को समझने का इस शोध पत्र में प्रयास किया गया है। यह देखा गया है कि अक्तूबर के माह में केवल 12 प्रतिषत चक्रवातीय तूफान कमजोर पड़े जबकि नवम्बर और दिसम्बर में क्रमष : 28 प्रतिषत और 41 प्रतिषत कमजोर पड़े। मानसून पश्चात् ऋतु के सभी महीनों में उत्तर पूर्वी दिषा की तरफ बढ़ने वाले चक्रवातीय तूफान कमजोर पड़ जाते है। बंगाल की खाडी में पष्चिम की ओर बढने वाले अधिकांष तूफान कमजोर नहीं पड़ते हैं। दिसम्बर को छोडकर समुद्र सतह तापमान और सापेक्ष आर्द्रता तूफानों के कमजोर पडने के लिए उत्तरदायी नही है बल्कि इसके लिए पवन अपरूपण उत्तरदायी है। बंगाल की खाड़ी के समुद्र सतह तापमान में समतापी रेखाओं की अवस्थिति तूफानों की दिषा को प्रभावित करती है। जिन वर्षों में तूफान प्रबल रूप से उत्तर उत्तर पूर्वी दिषा की ओर बढ़ते है उनकी तूलना में जब तूफान प्रबल रूप से पष्चिम / उत्तर पष्चिम दिषा की ओर बढ़ते है तब बंगाल की खाडी में समुद्र सतह तापमान लगभग एक डिग्री उष्ण होता है। यदि समुद्र सतह तापमान की समतापी रेखाएँ दक्षिण पष्चिम उत्तरपूर्वी दिषा में उच्च मानों के साथ पूर्व में अवस्थिति होती है तब यह प्रणाली उत्तर अथवा उत्तर पूर्वी दिषा की ओर आगे बढ़ेगी और ऐसे अवसरों पर पूर्वी बंगाल की खाडी पष्चिमी बंगाल की खाड़ी से उष्ण होती है।

ABSTRACT. Using NCEP/NCAR reanalysis data and from the available data on tracks of the storms from India Meteorological Department for the period 1981-2005 an attempt is made to understand the intensification of storms and their movements in the Bay of Bengal during post-monsoon season. It is noticed that in the month of October only 12 % of the cyclonic storms weakened whereas in November and December it is 28 % and 41 % respectively. Cyclonic storms moving in a northeast direction weaken in all the months of post-monsoon season. Most of the westward moving storms do not undergo weakening. In the Bay of Bengal, SST and relative humidity are not responsible for weakening of the storms except in December but wind shear is responsible for weakening. The orientation of isotherms of SST of Bay of Bengal influences the direction of motion. During the years when the storms are predominantly moving west/northwest the SST over the Bay of Bengal is about 1.0° C warmer than the years when the storms are predominantly moving in north/northeastward. If the isotherms of SST are oriented southwest-northeast with higher value in the east then system may move in north or northeastward and on such occasions east Bay of Bengal is warmer than west Bay of Bengal.

Key words – Cyclonic storm, Sea Surface Temperature (SST), Wind shear, Convective precipitation, Vorticity and β - effect.

1. Introduction

Cyclonic storms are intense atmospheric vortices, which develop over warm tropical oceans causing enormous damage to life and property at the time of crossing the coast and subsequent movement over the land. The systems are maintained by the release of latent heat extracted from the under-lying sea. Most of these systems (87%) occur between 20° N and 20° S. Though only 7% of them form over north Indian Ocean, they are the most severe. Srinivasan and Ramamurthy (1973) concluded that although the development from tropical depression into a tropical cyclonic storm usually occurs in about 12-24 hours, 15% require more than 48 hours and others less than 12 hours. Bansal and Datta (1972) studied the various aspects of intensification of storms in the Bay of Bengal. Libermann *et al.* (1994) remarked that in north west Pacific and Indian Ocean cyclones predominantly occur during the convective phase of the Madden-Julian oscillation. They cluster around the low-level cyclonic vorticity and divergence anomalies (negative). These anomalies lie generally poleward and westward of the large-scale convective anomaly over the northwest Pacific and Indian Ocean.

Gray (1968, 1975, 1979) demonstrated that the distribution of genesis may be related to environmental factors such as large value of low level relative vorticity, location of at least few degrees of poleward of equator giving a significant value of planetary vorticity, weak vertical shear of horizontal winds, Sea Surface Temperature (SST) exceeding 26° C and a deep thermocline, conditional instability through deep atmospheric layer and large values of relative humidity in the lower and middle troposphere. Mathur (1997) concluded in his model that the transfer of moisture and heat from low levels to the higher troposphere in cumulonimbus clouds takes place in several minutes. The surface low then tends to deepen resulting in fall of pressure. Convection encouraged by large scale lifting increases the associated low-level convergence. Sridharan and Muthuchami (1998) while studying the behaviour of northeast monsoon of 1997 attributed wind shear as a reason for weakening of November 1997 storm of Bay of Bengal. Krishna Rao (1997) remarked that during the formative stage when the low level convergence zone is superimposed by upper level divergence it gets intensified. Sridharan and Muthuchami (2002) studied the structural features of October 1999 super cyclone. Muthuchami (2000) concluded that during post monsoon season in the Bay of Bengal cyclonic storms have a particular annual behavior in direction of motion in each year, *i.e.*, the storms in a year tend to move in a particular direction.

Schade (2000) concluded that the effect of SST on the intensity of tropical cyclones can be separated into two distinct contributions: one from the large-scale SST field that is in equilibrium with the atmosphere and another one from a local reduction of the SST under the eye of the cyclone due to surface winds of the cyclone. Cione and Uhlhorn (2003) while studying the SST variability in hurricane intensity change found that the energy available to a cyclonic storm is at least an order of magnitude higher than the energy extracted by the storm. WISHE (Wind–Induced Surface Heat Exchange) proposed by Emmanuel (1993), Yano and Emmanuel (1991) and Emmanuel *et al.* (1994) indicates that the latent heat release in the free troposphere is governed by the evaporation of moisture from the sea, which is primarily determined by the magnitude of surface winds. But this alone will not explain large-scale convection and warm core structure of the storm. The correlation–coefficient indicate weak correlations among vertical wind shear and the intensity change and slightly higher correlations are shown with Infra-Red (IR) cloud asymmetry measurements *versus* numerical model derived vertical shear as shown by Zehr (2003). In WMO report of 1995 it is mentioned that "as a result of storm forcing, the Sea Surface temperature (SST) decreased by 3.5 to 4.0° C surrounding the eye in some of the strong cyclones. The temperature of the sea surface has both positive and negative feedback. Due to positive feedback the system intensifies as the storm moves over a warm sea surface. In case of negative feed-back when the storm moves over a cold area or stagnates for longer period in the same place, the resulting reduction in total heat flux leads to decrease in storm intensity". Sea current in the Bay of Bengal is not so strong to replenish the energy as in the case of Atlantic and Pacific. Sharma and Vatal (1992) suggest that north of the equator over Indian ocean, the waters are completely influenced by the changing nature of the monsoon wind system and no particular current is found throughout the year.

In this paper the climatology of intensification of cyclonic storms and the role of physical parameters in intensification of storms such as SST, relative humidity, convective precipitation and vertical wind shear in the Bay of Bengal during post monsoon season (October, November and December) is studied and the results are presented. The possible reason for storms moving north/northeast from SST distribution and convective precipitation over Bay of Bengal is also presented.

2. Data and methodology

The data for this study has been collected from various sources like 1979 and 1996 IMD publications of Tracks of storms and depressions in the Bay of Bengal and Arabian Sea, Annual cyclone report, Regional Specialized Meteorological Centre (RSMC) report on cyclonic disturbances in the North Indian Ocean, Indian Daily Weather Report, Indian Weekly Weather reports for the period 1971-2003. In order to find out the seasonal and monthly character in intensification of the system, the weakening rate which is a ratio between number of cyclonic storms/severe cyclonic storms weakened into depressions in the sea itself to the total number of cyclonic storms formed was computed on the basis of direction of movement in different months of Post monsoon season. Generally SST, humidity and vertical wind shear influence the intensification of tropical storm. In order to study the influence of these factors in weakening of the systems in the Bay of Bengal during post monsoon season about 20 cyclonic storms were selected during the period 1981-2005 of which 10 storms weakened into low pressure area in the sea itself and other 10 storms did not weaken till they crossed the coast. The SST distribution, relative humidity, convective precipitation and wind distribution at different levels over north Indian ocean during above storms period were collected from the NCEP/NCAR Reanalysis website of NOAA. Using *in situ* and satellite SST plus SSTs simulated by sea-ice cover the data on SST was derived. Before it is computed satellite SST is adjusted for bias.

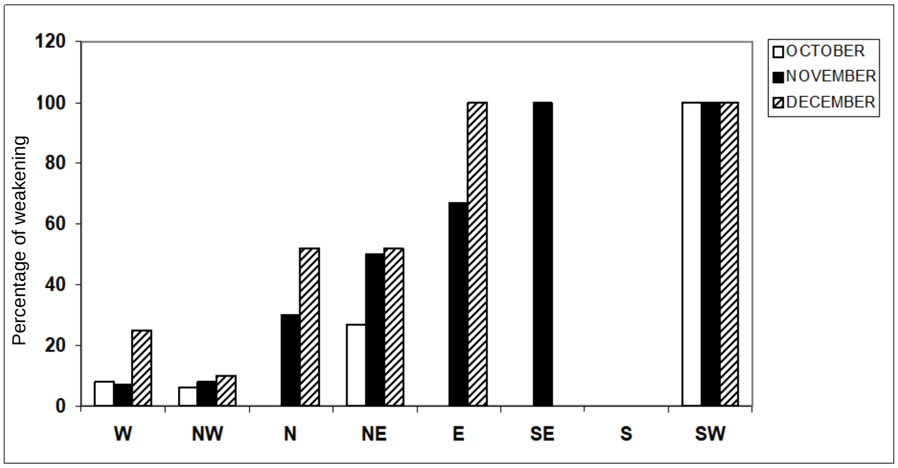


Fig. 1. Percentage of cyclonic storms weakening in sea while traveling in different direction in Post monsoon season. (W-West, NW- Northwest, N-North, NE –Northeast, E- East, SE- Southeast, S-South, SW- Southwest)

The mean relative humidity, mean SST and mean vertical wind shear were computed separately for the storms which weakened in the sea and those did not weaken till they crossed the coast. *t* – test also applied to test the existence of any significant difference between these two category of storms and the results are discussed. The Gray parameter for humidity also computed using the relation G_{rh} = (RH-40)/30, where G_{rh} is the Gray parameter for relative humidity, RH is the mean relative humidity between the levels 700-500 hPa and discussed four cyclonic storms are taken as case study to explain role of above parameters in weakening the system. The two storms which attained the intensity of $\geq T$ - 6.0 and other two storms which were unable to intensify beyond the cyclone stage are considered.

In order to find out the relationship between the direction of motion of cyclonic storms with the SST distribution over Bay of Bengal. SST was collected from NCEP/NCAR Reanalysis website during storm period of about 16 storms during 1981-2005.

3. Results and discussions

3.1. *Climatological aspect of weakening of systems in the Bay of Bengal*

Fig. 1 gives the percentage of the cyclonic storms, which weakened into depressions in the Bay of Bengal before they crossed the coast. It is found that in the month of October only 12 % of the cyclonic storms weakened where as in the month of November and December it is 28 % and 41 % respectively. In the month of October northward moving storms have not weakened. But when they moved northeastward about 27% of them weakened. In all the months when the storms moved southwestward they were definitely subjected to weakening. In November all the storms, which moved with a southerly component, have weakened. However when they move in a westerly direction only 8% of them weakened into depression or low-pressure area. In December when the movement is either northwest or north the percentage of weakening is less than 50 %. Less percentage of weakening in the month of October may be attributed to higher SST over entire Bay of Bengal. By December SST over North Bay of Bengal becomes cool and upper level subtropical westerly jet shifts southward and so the storms moving into this area have a tendency to weaken.

The 24-hour change in intensity of the storms over the Bay of Bengal moving north and northeastward was computed for each storm till it crossed the coast or weakened into a depression. Mean intensity change in 24 hours is calculated separately for the storms, which moved northward and northeastwards. It is seen that in post monsoon months of October and November the storms which move northward generally intensify with mean rate of intensification of about 17.7 hPa fall in pressure per day but storms moving northeastward generally tend to weaken with the rate of rise in pressure of 31.7 hPa per day. The percentage number of storms weakened in the sea itself when they travel in different directions (in the order of west, northwest, north …south and southwest) is computed. It is seen that the weakening of a system with respect to direction of movement of the system increases in all the months if we go from west to

TABLE 1

Date, time, intensity and position of storms

Date	Time (UTC)	T. No	Position Lat/Long
		1-8 November 1989	
1	0300	1.5	8.0° N/103.0° E
	1200	2.0	8.0° N/103.0° E
2	0300	2.0	8.5° N/102.5° E
	1200	2.5	9.0° N/102° E
3	0300	3.0	9.5° N/101.5° E
	1200	4.0	10° N/101° E
4	0300	5.0	11° N/99.5° E
	1200	5.0	11.5° N/98.0° N
5	0300	5.5	11.7° N/96.5° E
	1200	4.5	12.4° N/94.8° E
6	0300	4.0	13.1° N/91.8° E
	1200	5.0	13.5° N/90,0° E
7	0300	5.5	14.2° N/88.0° E
	1200	5.5	14.5° N/86.0° E
8	0300	6.0	14.5° N/83.4° E
	1200	6.0	14.7° N/81.3° E
		4-9 November 1997	
4	0300	2.0	12.5° N/98.5° E
	1200	2.0	13.5° N/96.5° E
5	0300	2.5	14.0° N/95.0° E
	1200	2.5	14.5° N/94.0° E
6	0300	2.5	15.0° N/93.5° E
	1200	2.0	15.0° N/92.0° E
7	0300	2.5	15.5° N/91.5° E
	1200	2.5	15.5° N/91.0° E
8	0300	2.5	15.5° N/91.0° E
	1200	2.0	15.0° N/90.5° E
9	0300	1.5	15.0° N/90.0° E
	1200	Weakened into low pressure area	

Date	Time (UTC)	T. No	Position Lat/Long
		25-31 October 1999	
25	0600	1.5	12.0° N/98.5° E
	1200	1.5	12.5° N/98.0° E
26	0300	2.0	13.5° N/95.5° E
	1200	3.0	14.5° N/94.0° E
27	0300	3.5	16.0° N/92° E
	1200	3.5	17.0° N/90.5° E
28	0300	4.5	18.0° N/89.0° E
	1200	6.0	18.5° N/88.0° E
29	0300	7.0	19.9° N/86.7° E
		Crossed the coast: 0430-0630	
		The system was over Orissa upto 31st	
		23-28 November 2002	
23	0300	1.5	10.0° N/87.0° E
	1200	1.5	12.0° N/87.0° E
24	0300	2.5	13.0° N/87.5° E
	1200	2.5	15.0° N/88.0° E
25	0300	2.5	15.5° N/88.0° E
	1200	2.5	15.5° N/88.0° E
26	0300	2.5	16.0° N/88.0° E
	1200	2.5	16.5° N/88.5° E
27	0300	2.5	17.0° N/90.0° E
	1200	2.0	17.2° N/91.0° E
28	0300	1.5	17.5° N/91.5° E
		Weakened into low pressure area in the night	

southwest in clockwise direction through north. The correlation coefficient between direction of movement of these systems and the percentage of weakening is significant in all the months and is as high as 0.96 in November and least (0.80) in October. The weakening of these storms while they move southward is obvious on account of low planetary vorticity. The higher rate of weakening when they move towards northeastward is due to shear associated with westerlies which will be discussed in detail in section 3.2 and also due to cooling over north Bay of Bengal in December.

3.2. *Intensification of storms in the Bay of Bengal*

3.2.1. *History of the cyclonic storms considered for case study*

Table 1 gives the date, time, intensity in terms of INSAT T- number and position of the four storms considered for case study of intensification/weakening of cyclonic storms in the Bay of Bengal and the corresponding tracks are given in Fig. 2(a). The first system which reached the maximum intensity with T number 6.0 initially formed as depression in the Gulf of Thailand on 1 November 1989. It intensified into cyclonic storm on 2 November 0300 UTC and it further intensified into severe cyclonic storm on 3 November at 0300 UTC. After 24 hours, on 4th it intensified into very severe cyclonic storm in Gulf of Thailand itself. It crossed Thailand Coast on 4th 1200 UTC and emerged into Andaman sea with same intensity of T 5.0. After emerging into the Andaman sea it further intensified and passed over Andaman Island on 6th night. After crossing over Island its intensity decreased from T number 5.5 to 4.0 on account of land friction. Then it further intensified to its maximum intensity of T number 6.0 on 8th 0300 UTC, crossed the Andhra coast with same intensity at 1900 UTC on the same day and rapidly weakened over the land.

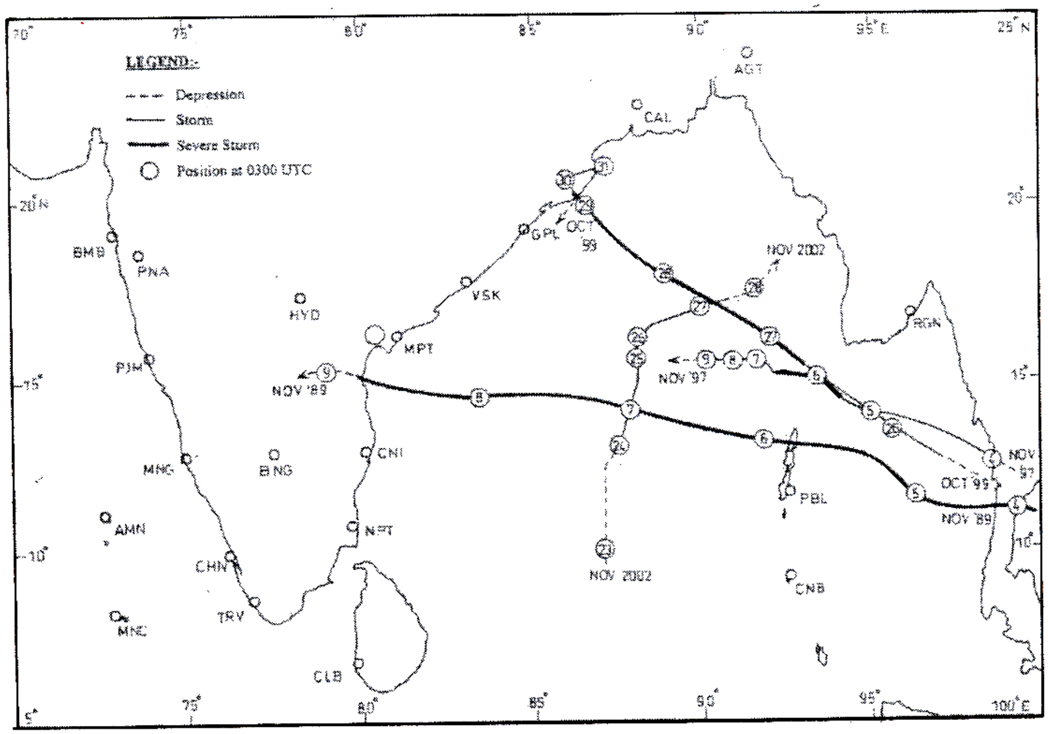


Fig. 2 (a). Tracks of storms in the Bay of Bengal considered for intensification/weakening

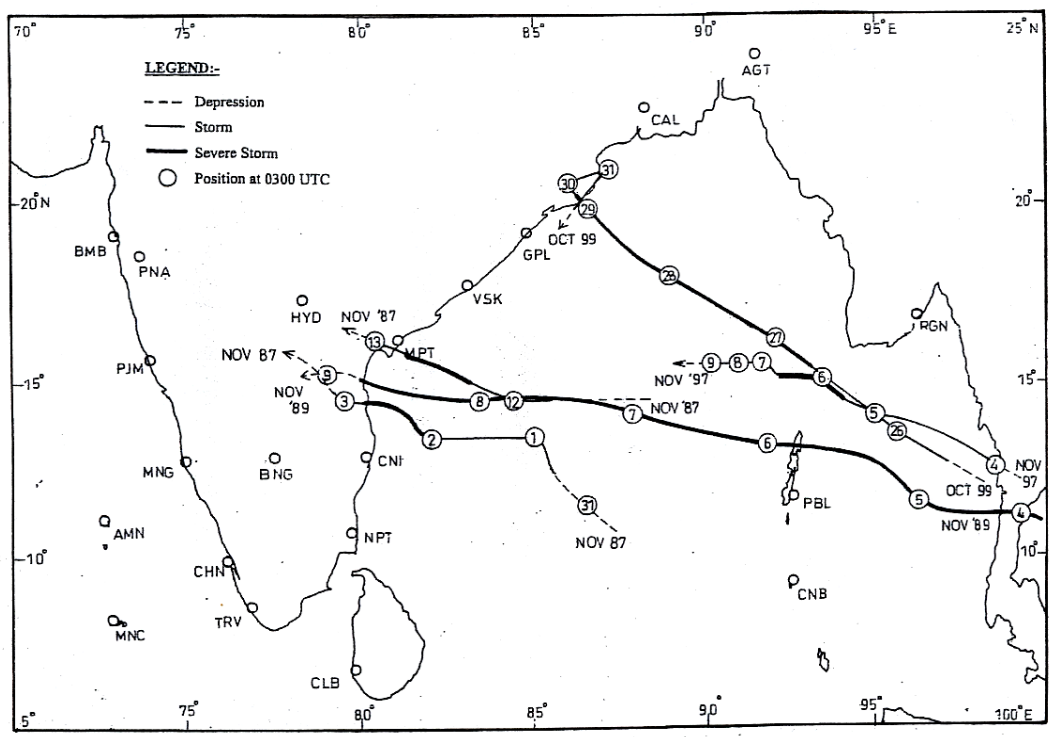


Fig. 2(b). Tracks of West/Northwest moving storms in the Bay of Bengal

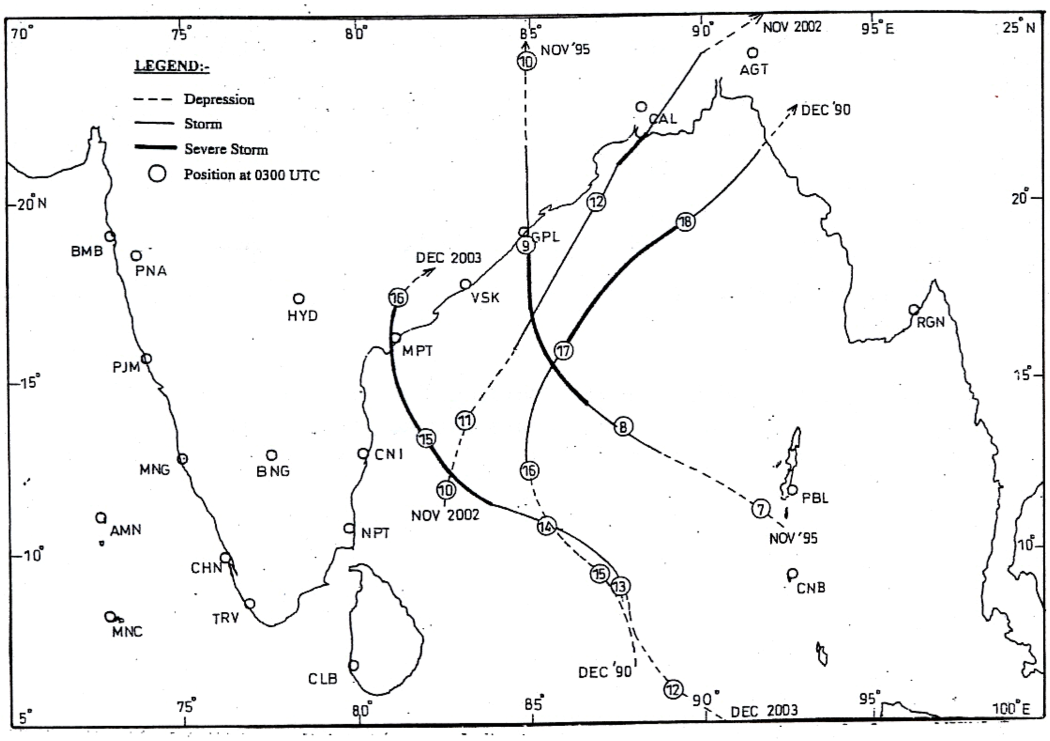


Fig. 2(c). Tracks of North/Northeast moving storms in the Bay of Bengal

The second system also entered into Andaman sea as cyclonic storm from the Gulf of Thailand on 4 November 1997. It maintained its intensity as a cyclonic storm up to 9/0300 UTC and gradually weakened into depression then into low-pressure area over the sea.

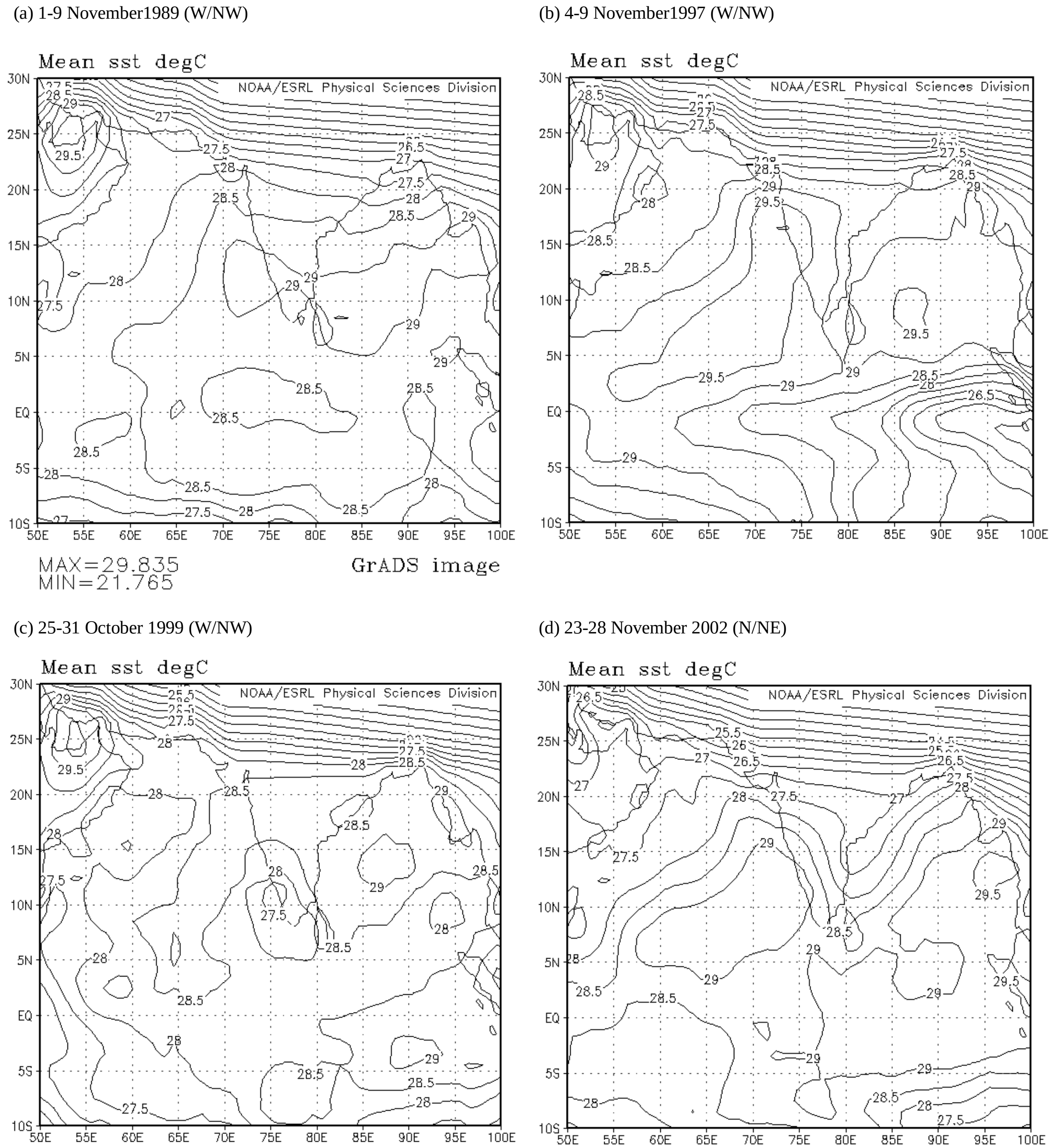
Third system was spotted as a vortex on 24 October 1999 over Gulf of Thailand, moved westward across Malaysian peninsula, emerged into Andaman sea as a well marked low pressure area and concentrated into depression on 25/1200 UTC. It moved in a westnorthwesterly direction and intensified into cyclonic storm at 26/0300 UTC, further intensified as a severe cyclonic storm at 27/0300 UTC and as very severe cyclonic storm at 27/1500 UTC. It became as super cyclonic storm after 24 hours at 28/1500 UTC. It crossed the coast on 29/1200 UTC and it was stationary for a long time over Orissa and weakened as a low-pressure area on 1 November.

Initially a low pressure system developed over southeast Bay of Bengal on 22 November 2002 and it concentrated into a depression at 23/0300 UTC. After 24 hours it intensified into a cyclonic storm. Then it moved nothnortheasterly direction, thereafter it weakened into a deep depression on 27/1200 UTC. Moving northeasterly direction the system weakened as depression at 1800 UTC on the same day and by 28/1200 UTC further weakened as low pressure area in the sea.

3.2.2. *SST distribution during storm period*

The SST distribution is the main source of energy for the tropical cyclone intensification. The SST distribution for all the storm periods of 20 storms were collected separately for intensifying and weakening systems. It is noticed that in all the cases irrespective of whether the system weakened in the sea or not the SST was above 27.5° C except in the case of one system which reached the intensity of severe cyclonic storm (14-18 December 1990) moved initially north, then moved northeastward and crossed Bangladesh coast as depression. During the period of the system the SST was below 25.5° C in the north Bay of Bengal. *t* - test also suggests no variation in SST distribution between weakening system and intensifying system.

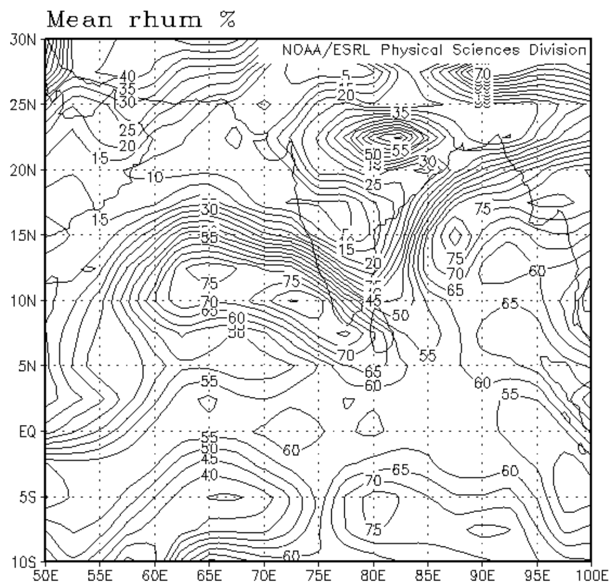
Figs. 3 (a-d) give the mean SST during life periods of cyclonic storms. It can be seen that in all the cases SST was above 26º C, which is lower limit for the formation of the storm. It can be seen from the Fig. 3(a) that during the life period of 1-9 November 1989 system the SST was



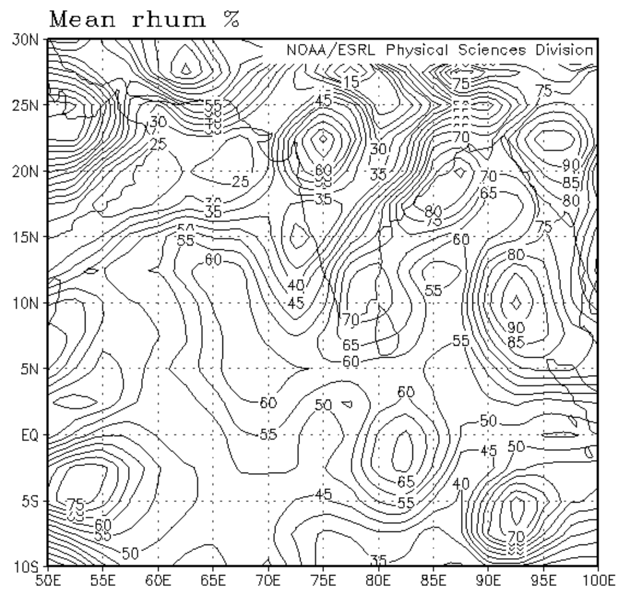
Figs. 3(a-d). SST distribution during storms period in the north Indian ocean (W/NW – moved west/northwest, N/NE-moved north/northeast)

above 29º C south of 15° N and in rest of Bay the SST was between 28.5° C and 29° C. It can be noticed from Fig. 3(c) that the SST in the region of storm track was between 28.5° C to 29° C during the life period of Super cyclonic storm of October 1999. In the case of 4-9 November 1997 system the SST was above 29° C over most parts of the Bay. In the case of 23-28 November 2002 system also the SST was between 28.5° C and 29.5° C in the region of storm track during its life period as seen from the Fig. 3(d). There is no difference in SST

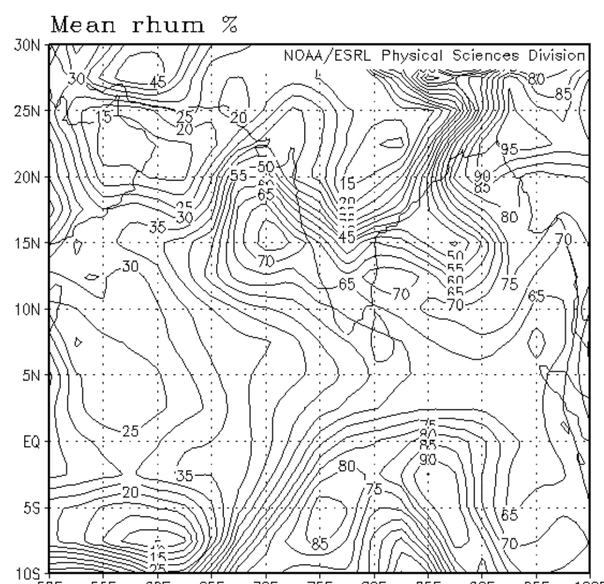
(a) 7 November 1989



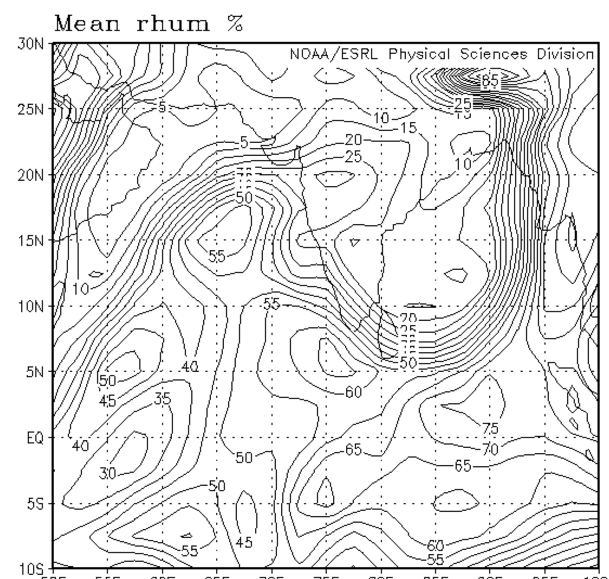
(b) 7 November 1997



(c) 27 October 1999



(d) 26 November 2002

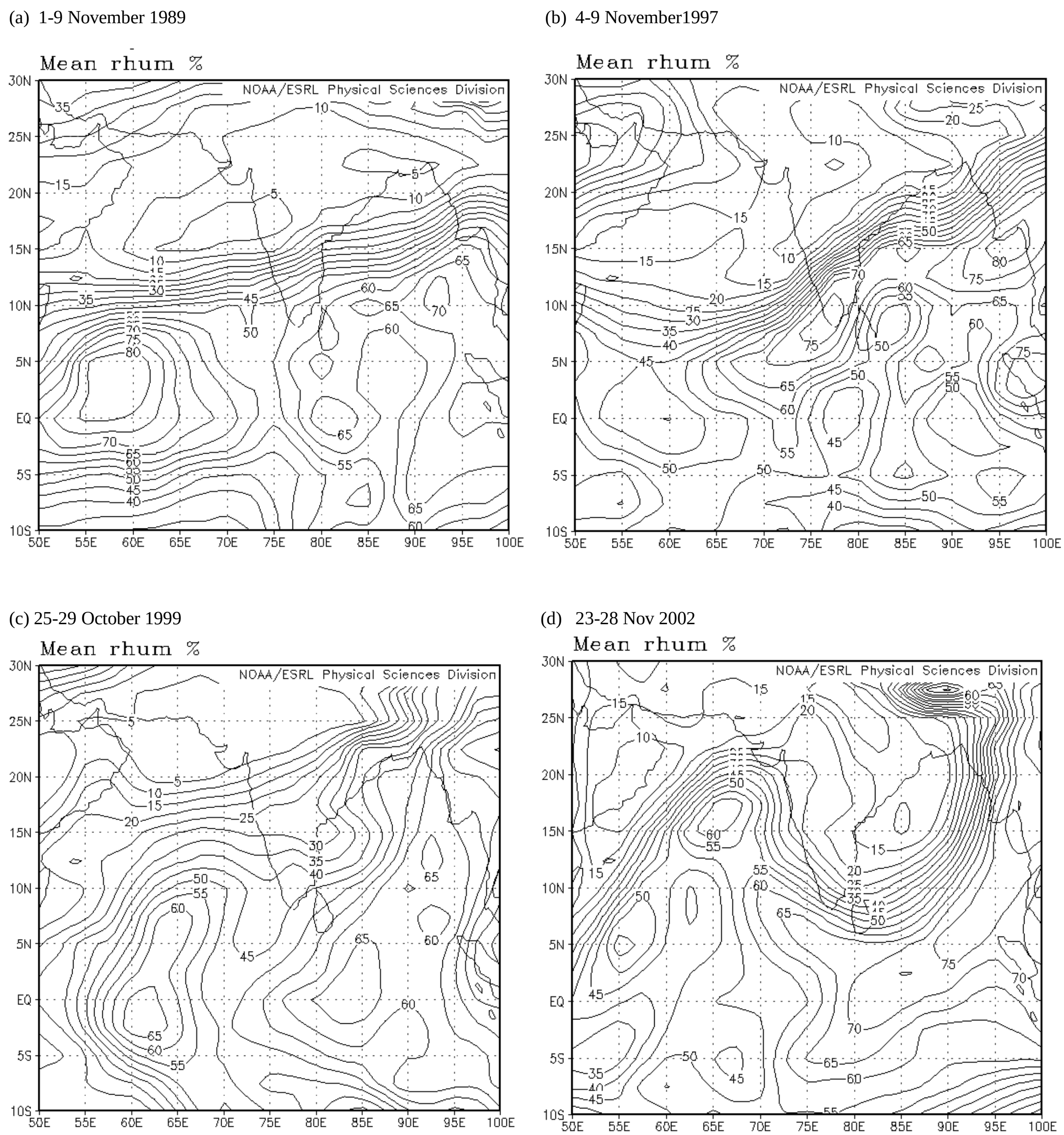


Figs. 4(a-d). Relative humidity at 700 hPa level during intensification and weakening phase of storms

distribution over Bay of Bengal during intensification and weakening phase of systems. Therefore the weakening of the November 1997 and 2002 systems is not due to SST. This suggests that though SST is controlling factor for intensification of the system it is not responsible for weakening of the systems.

3.2.3. *Humidity distribution*

The mean relative humidity between 700 and 500 hPa levels were computed for the storms that weakened in the sea itself and for those storms which intensified in the sea. It is seen that the mean relative humidity is 71%



Figs. 5(a-d). Mean relative humidity at 500 hPa level during life period of intensifying and weakening storms

for the first set of storms and 74% for the second kind of storms and these values are statistically not different. Further Gray genesis parameter for relative humidity is same for both kind of storms and it is 0.81. As in the case SST distribution during 14-18 December 1990 the relative humidity and Gray genesis parameter are also responsible for weakening of the 14-18 December 1990 system since the relative humidity was below 25% in the middle troposphere over the north Bay of Bengal and Gray parameter was 0 in the same area.

Figs. 4(a-d) give the humidity distribution at 700 hPa level during rapid intensification phase in the case of intensifying storms and during weakening phase of the storm for decaying storms. If we compare the Fig. 4(a) and Fig.4(b), in the 1997 storm the overall humidity in the

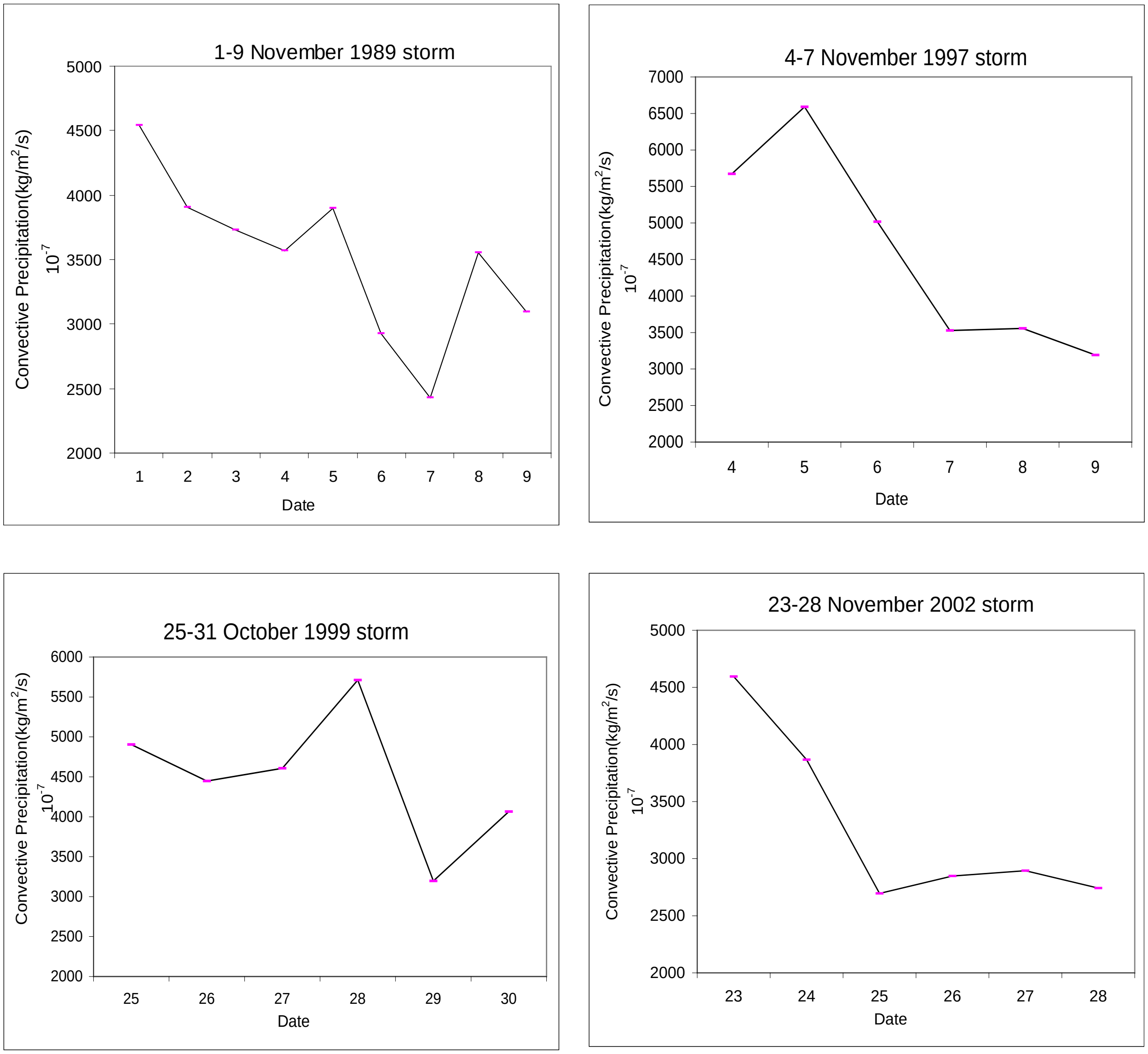


Fig. 6. Maximum convective precipitation during life periods of intensifying and weakening storms

Bay of Bengal at 700 hPa level during weakening phase is more than that of 1989 system during intensifying phase and it is very much above the level of minimum humidity required for storm intensification in both the cases. In spite of this, 1997 system weakened in the sea itself. If we compare Fig. 4(c) and Fig. 4(d) the humidity distribution at 700 hPa level is similar in both 1999 and 2002 storms in the vicinity of the storm field but 2002 storm weakened after moving towards northeast. Figs. 5 (a-d) present the mean humidity during storms life period at 500 hPa level. It can be seen from the figures that the humidity in all the cases are similar in the storm field over Bay of Bengal during their life period. In fact the humidity in intensifying storms is less than that of weakening storm close to the tracks of the storms. Therefore it is clear that the humidity is also not responsible for weakening of the system in sea in the case of 1997 and 2002 systems.

3.2.4. *Convective precipitation*

Convective precipitation is a measure of both humidity and convection in the system. It plays an important role in the vortex intensification of the cyclonic systems. A study on this will be helpful in understanding the role of this in intensification of the system. The

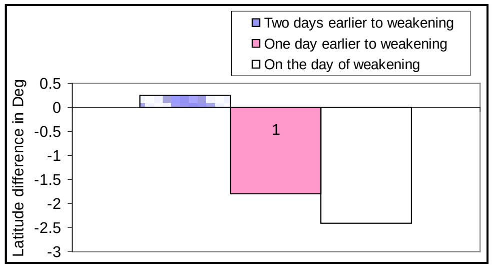
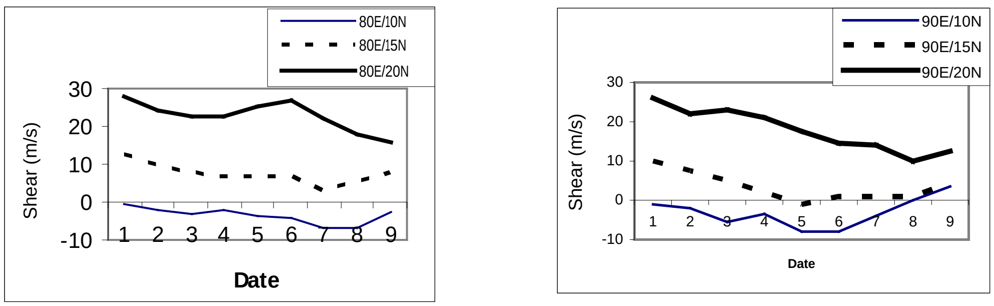
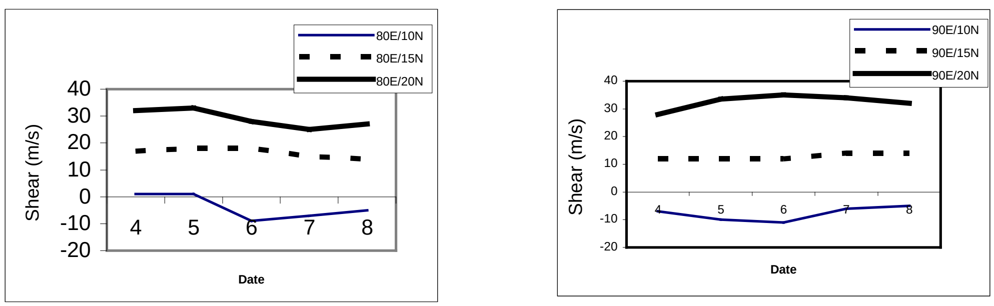


Fig. 7(a). Latitudinal difference between ridge position and storm centre in the case of weakening systems

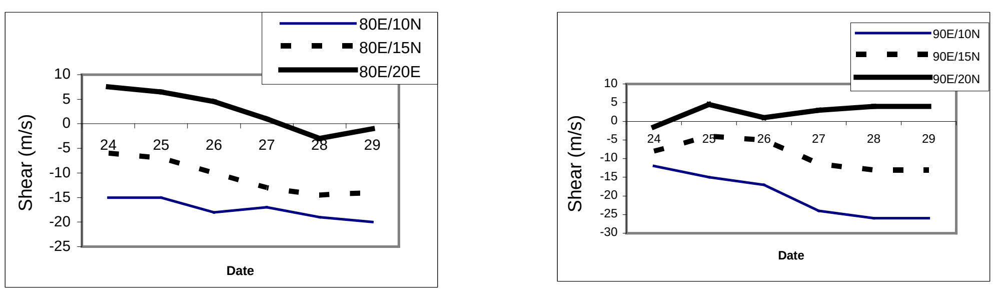
(b) 1-9 November 1989



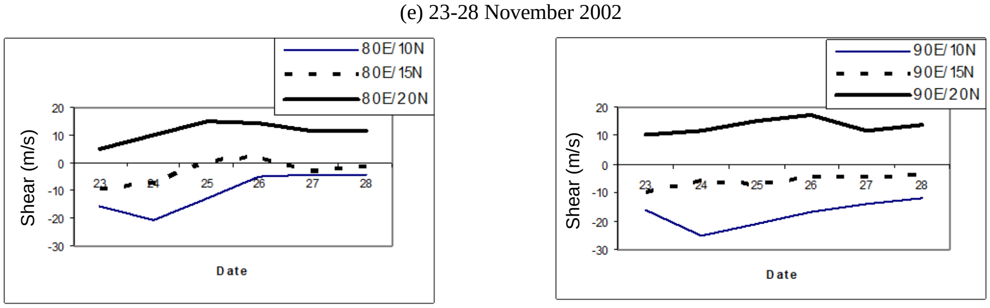
(c) 4-9 November 1997



(d) 24-29 October 1999



(e) 23-28 November 2002



Figs. 7(b-e). Vertical wind shear (between 850 and 200 hPa level) during storms period at different locations in the Bay of Bengal (longitude and latitude of locations are given in label) convective precipitation P_t can be computed by the relation

$$P_t = \frac{1}{g}\int_{P_T}^{P_B} \frac{a C_P (T_S - T)}{L\Delta\tau} dp \tag{1}$$

where

$$a = \frac{-\int_{P_T}^{P_B} \left[\nabla . q\bar{V} + \frac{\partial}{\partial p} q\omega \right] dp}{\int_{P_T}^{P_B} \left[\frac{C_P (T_S - T)}{L\Delta\tau} + \frac{q_S - q}{\Delta\tau} \right] dp} \tag{2}$$

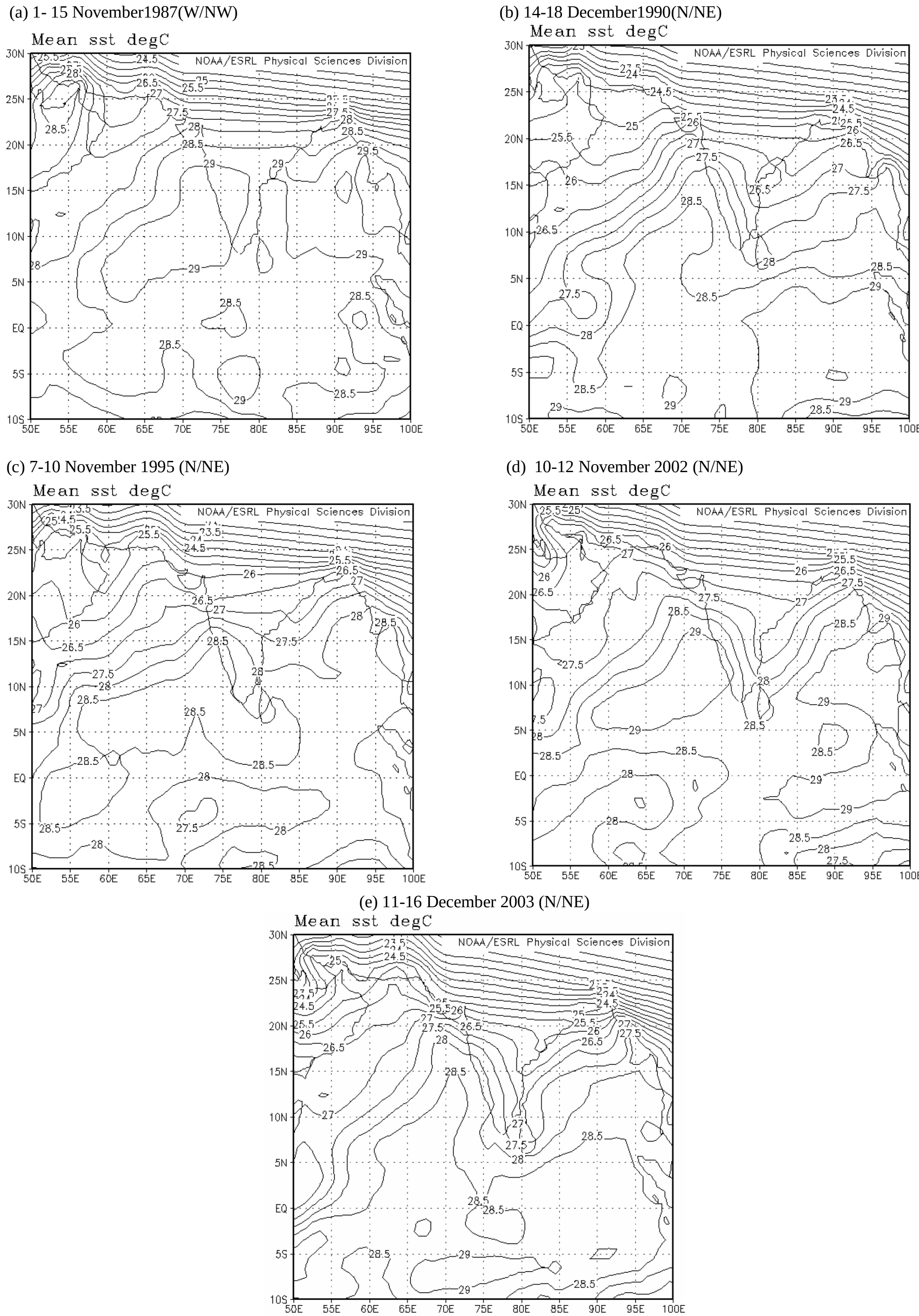
where P_T and P_B are the pressure at top and bottom of the cloud, $\bar{V}$ - velocity of air parcel ω - vertical velocity in pressure coordinate system, C_P - specific heat constant at constant pressure, T_s - temperature at surface, q_s - saturation specific humidity, q - specific humidity, L- latent heat of condensation, g - acceleration due to gravity and Δτ is the cloud time scale and this denote the frictional area that would be covered by newly generated convective cells. The Figs. 6(a-d) present the maximum convective precipitation in the storm field during the life period of the storms. It can be seen that the convective precipitation is decreasing in general in all the cases. But in the case of 1999 the convective precipitation increased up to 28 October, and then decreased rapidly, again it increased slightly. In the weakening system of 1997, the convective precipitation is of higher order than any other system in spite of its decrease. In comparing rapidly intensified system of 1999 with weakening system of 2002 the convective precipitation is of same order at the time of maximum intensity in the case of 1999 system and during weakening phase of 2002 system. Therefore convective precipitation also has not induced the weakening of the storms.

3.2.5. *Wind shear*

Vertical wind shear is one of the important parameters for intensification of systems. To study the role of vertical wind shear, the zonal vertical wind shear between 850 and 200 hPa level was computed for each day of the storm for all the 20 storms considered. It is found that the system weakened rapidly when it entered into strong vertical wind shear region particularly when they entered into upper level westerly regime. It is found that when the wind shear exceed 10 m/s the system starts weakening. Fig. 7(a) gives the latitudinal difference between the ridge position and the system centre two days earlier to weakening, one day earlier to weakening and on the day of weakening. It can be seen from the figure that immediately after the system entered into westerly wind regime the system started weakening and the system continues to move further north from the ridge position.

Figs. 7 (b-e) present the zonal vertical wind shear computed between 850 and 200 hPa levels during the storm period. It can be seen that in the case of two intensifying systems the wind shear was below 10m/s in storm field through out their life period. In the case of 1989 system, it intensified rapidly from low pressure area to very severe cyclonic storm up to 5th, then as it passed over Andaman Islands the intensity decreased on account of land friction and thereafter it intensified further. The wind shear gradually decreased and became less than 5m/s after 5 November in the region between 10° N to 15° N where the storm traveled. As a consequence of low wind shear the system was able to intensify upto the stage of very severe cyclonic storm (upto T = 6.0). In the case of 1999 storm the easterly wind shear with greater than 10m/s is noticed far to the south of the track. Near the storm track the vertical wind shear was less than 5m/s and on the approach of the storm the vertical wind shear decreased at 80° E. The rapid intensification is noticed after 27 October 1200 UTC. As seen from the Fig. 7(d) during this period the vertical wind shear decreased to as low as 3m/s in the storm region. This low vertical wind shear in the storm region rapidly enhanced the intensity of the storm.

In the case of 1997 storm, which emerged into the Bay of Bengal as a cyclonic storm initially intensified slightly but was unable to intensify further after 6 November as it entered the region where the wind shear was above 10m/s. Because though at 10º N the wind shear was below 10m/s but towards north the wind shear increased rapidly and it exceeded 10m/s at 15° N and reached even upto 35m/s at 20° N. Therefore the system was unable to survive due to the strong vertical wind shear in its field. In 2002, the system intensified from low pressure into cyclonic storm when it is in the low latitudes below 15° N where the vertical wind shear was low. As it traveled towards north beyond 15° N, where the westerly vertical wind shear was above 10m/s due to ventilation of dry continental air from the west into the system it did not allow further intensification. Thereafter it weakened into depression and then into low-pressure area even though other parameters were favourable for intensification. Therefore wind shear is the main factor for weakening of the systems in the Bay of Bengal even though other parameters were favourable for intensification.



Figs. 8(a-e). SST distribution during storms moved west/northwest and north/northeast (W/NW – moved west/northwest, N/NE-moved north/northeast)

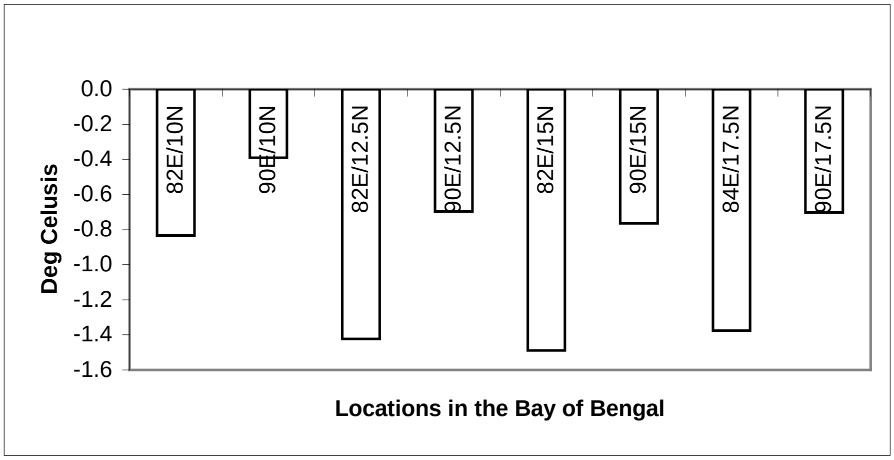


Fig. 9. Mean difference between SST during west/northwest moving storm and during north/northeast moving storms at different location of the Bay of Bengal (The latitudes and longitudes of the location are given inside the bar)

3.3. *Direction of the storm motion*

3.3.1. *SST and storm motion*

Though SST is not responsible for weakening of the system it is seen that in most of the cases it controls the direction of motion of the system in the Bay of Bengal. Figs. 2(b&c) give tracks of some of the storms that moved west/northwest ward and north/northeastward. Figs. 8(a-e) give the SST distribution during the life period of the systems shown in Figs. 2(b&c). It can be seen from the Figs. 8 (a-d) and Figs. 3 (a-d) that when the systems traveled west or northwest ward the gradient of SST is weak with isotherms mostly zonal but in the case of storms that moved north or northeastward the isotherms of SST are more meridional and apart from this the higher values are seen in the east. Further in the years when storms initially travel west/northwest and then moved north/northeast the SST gradient in lower latitudes is very small but it increases in higher latitudes.

Table 2 gives the mean difference in SST between west and east Bay of Bengal during the periods of west/northwest moving and north/northeast moving storms. It can be noticed that the difference in SST between west Bay of Bengal and east Bay of Bengal during the north/northeast moving storms is ranging from –0.9° to –0.5° C and the difference is higher towards north. In the case of west/northwest moving storms the difference almost nil. This longitudinal SST difference in the Bay of Bengal determines the direction of motion because SST over Bay of Bengal is not influenced by any ocean current which is noticed in other ocean basins. Fig. 9 gives the mean difference in SST between periods of north/northeast moving and west/northwest moving storms at different location of the Bay of Bengal. It is seen that during the years when the storms are moving predominantly west/northwest entire Bay is warmer by about 1.0° C on an average compared to the years when the storms are moving north/northeastward. During such occasions west central Bay of Bengal is warmer by about 1.4° C.

TABLE 2

Mean difference in SST between east and west Bay of Bengal during west/northwest moving and north/northeast moving storm

Direction of movement of storm	Difference in SST between longitudes at 82ºE and 92ºE in latitudes (ºC)			
	10.0° N	12.5° N	15.0° N	17.5° N
West/Northwest	-0.1	0.0	-0.1	-0.1
North/Northeast	-0.5	-0.7	-0.9	-0.8

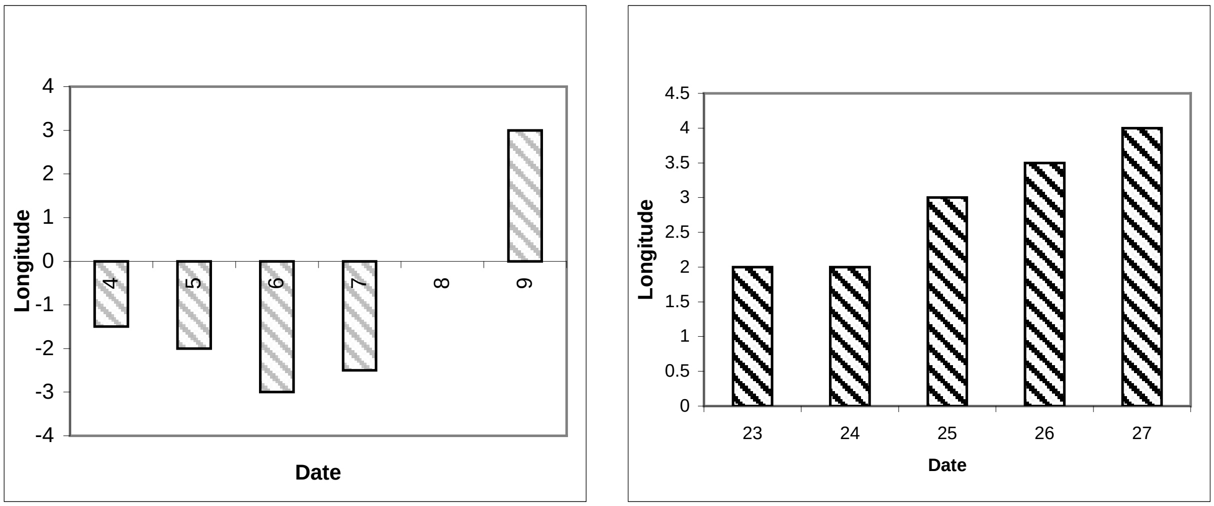
Note:- At 17.5º N the SST difference is between 84° E and 92º E

Therefore over Bay of Bengal during October and November when the SST are above 27.5° C it has no role in weakening of the system but it is able to determine the direction of motion of the cyclonic storms.

3.3.2. *Convective precipitation and storm motion*

The influence of SST in changing the normal direction of motion of storms in the Bay of Bengal can be explained with the help of convective precipitation. For this the centers of maximum convective precipitation in the storm field are noted for each day of the storms and

(a) 4-9 November 1997 (b) 23-27 November 2002



Figs. 10(a&b). Longitudinal difference between centre of maximum convective precipitation and the centre of storms

the difference between the centre of maximum convective precipitation and the centre of the storm is computed. It is seen that in the case of storms moving north/northeast, centre of maximum convective precipitation is found to be in the right of the storm motion in most of the cases but in the case of intense system like very severe cyclonic storms the longitudinal difference between these two are very small. In the case of west/northwest moving storms centre of convective precipitation is in the western side of the storm centre. Figs. 10 (a&b) give the difference between centre of maximum convective precipitation and centre of the storm. It can be seen from the figure that in the case of 2002 storm which moved north/northeastward the differences are positive which suggest that the more convection is taking place in the eastern side of the storm centre where the SST is higher. This difference increased as the storm moved north probably due to the westerly vertical wind shear which induced more shift towards east. This is well established in the 1997 system which moved northwest/westward. In this system the difference between centre of maximum convective precipitation and the centre of storm is negative but it gradually increased and became zero on 8 November and then it became positive. As the westerly vertical wind shear increased the centre of maximum convection gradually shifted eastward and the difference between the centers became positive only on 9th when the storm weakened into low-pressure area and therefore eastward movement was not observed in this case.

3.3.3. *Basic flow of upper levels and storm motion*

Basic flow generally advect the cyclonic system towards its upstream in the absence of any other controlling factor. But when other factors dominate the effect of basic current will not be felt. In order to find out the effect of basic current in determining the direction of motion about 20 storms were taken with 10 storms moving west/northwest and remaining north/northeastwards. The zonal wind speed at 200 hPa level on each day of the storm is noted around the storm area (5° square around the centre). The mean value of this zonal wind is computed for the storms that moved west/northwest and north/northeast. It is seen that the mean zonal wind speed is about -5.6 m/s (easterly) for the storms moving west/northwest and it is about -1.9 m/s (easterly) when they move north. It is interesting to note that when the storm is moving with easterly component of motion the wind direction at 200 hPa level is westerly only.

To substantiate this, latitudinal ridge position over the storm area is estimated for each day of the storm and the latitudinal difference between the ridge and the storm positions were computed. The mean value of the storms that moved west/northwest and north/northeast was computed separately. It is found that the mean difference is about 2.67° latitude for the storms moving west/northwestward and 3.57° latitude for the storms moving north/northeastward. When *t*-test was applied to test the statistical significance of the difference between these two values it is seen that they are not significant. It is further noted that when ever the difference is negative the storm tends to weaken irrespective of the direction of motion of the storm. Therefore the direction of the zonal wind is not determining the movement of the storm but its strength only determines the direction of motion. When compared, the northward movement of storm with the north ward movement of ridge line at 200 hPa level it is seen that the ridge moved along with the storm as the storm moved north but at the time of rapid weakening of the system in the sea itself the ridge position shifted towards south of the system centre which supported the earlier argument that the storms in the Bay of Bengal weaken mostly due to strong vertical wind shear.

3.3.4. *Physical explanation for north/northeast ward movement of storm*

Tropical cyclone tends to move in the direction where the vorticity is maximum. Vorticity asymmetry can arise due to the following factors.

(*i*) Environmental flow in the storm field.

(*ii*) Advection of planetary vorticity from higher latitudes. (β- effect)

(*iii*) Secondary circulation.

Observed asymmetry is arising from the superposition of vortex and the environmental wind field in which it is embedded. In the northern hemisphere storm, cyclonic flow will oppose environmental flow on the left side (looking in the direction of motion of the environmental flow) and strengthening it on the right. However, a residual asymmetry remains when the azimuthal mean flow is removed from the composite wind field. Shapiro (1983) found that the mechanisms that could contribute to this residual asymmetry include: a response to vertical and horizontal shears in the environmental wind field, an internal readjustment because of the cyclone motion and interaction of the moving cyclone with boundary layer.

MacDonald (1968) concluded that in addition to squall line or gravity wave spirals some asymmetry might be due to Rossby waves that depend upon the outward decrease in relative vorticity from the tropical cyclone centre. Rossby wave is the β gyre asymmetry that is responsible for poleward and westward movement of the storm. Chan and Williams (1987) have shown that β – effect will contribute to the vorticity tendency, with positive (negative) tendencies in the northern hemisphere to the west (east) of the centre *i.e.*, the southward flow to the west advects higher values of earth vorticity into this region, and the cyclone will tend to move westward into the region of increasing vorticity. Holland (1983) has shown that the inclusion of vortex scale convergence changes the vorticity tendency propagation to a direction slightly poleward and westward. Secondary circulation is another important parameter responsible for creating asymmetry in cyclone field. It is forced by an intense frictional destruction of angular momentum at the surface, weaker heating in the outer eyewall, extensive but weak cooling caused by frozen precipitation melting along the radar bright band, and similar extensive and weak heating due to condensation and freezing in the anvil above the bright band (Willoughby *et al*. 1982, Marks and Houze 1984). Muthuchami and Dhanavanthan (2005) noted that pressure would fall rapidly in the region where the low density air is near RMW and high density air away from it and these factors are mostly controlled by heat-induced secondary circulations. Holland and Merrill (1984) showed that a convective heat source forces essentially vertical motion that extends through the depth of the troposphere The low level inflow in the heating – induced thermally direct gyres is distinct from the frictional flow (Frank 1977).

As discussed above in the Bay of Bengal during post monsoon season the environmental flow is northeasterly and due to β - effect under uniform SST distribution (secondary circulation is symmetric on account of uniform SST and hence it will not create asymmetry in vorticity) the cyclonic storms will move towards northwest. But when SST is higher in the eastern side of the system the secondary circulation in the eastern side will be increased compared to other sides due to increased evaporation from underlying higher SST sea surface. The rate of evaporation is governed by the relation

$$E = \mu\,(\partial e/\partial z + e/T\,\partial T/\partial z) \qquad (3)$$

Where μ is a constant and is equal to $-0.622 l^2 k / RT \,|\partial U/\partial z|$, T, the mean temperature of air and sea surface, R, the gas constant l, mixing length, U wind velocity, $\partial T/\partial z$, vertical gradient of temperature above the sea surface, $e = q/P$, q - mixing ratio, P - pressure and k a numerical constant. Therefore by the above relation since higher SST is prevailing in the eastern side of the system more vertical transport of moisture is taking place and as other things are symmetric with respect to centre active secondary circulation is taking place in the eastern side of the storm. This creates higher vorticity on the eastern side of the storm and hence storm moves in the north/northeastward as the β- effect and environmental flow continue to act. Since in the Bay of Bengal no ocean current exists the SST distribution is not manifested by external forces.

4. Conclusions

(*i*) In the month of October only 12 % of the cyclonic storms weakened where as in the month of November and December it is 28 % and 41 % respectively.

(*ii*) Cyclonic storms moving in a northeast direction weaken in all the months of post-monsoon season. Most of the westward moving storms do not undergo weakening. There is significant correlation between the direction of movement and the rate of weakening of cyclonic storms over Bay of Bengal.

(*iii*) SST and relative humidity are not responsible for weakening of the storms in the Bay of Bengal during post monsoon season except in December.

(*iv*) Wind shear is responsible for weakening of the systems in the Bay of Bengal.

(*v*) The orientation of isotherms of SST of Bay of Bengal influences the direction of motion in post monsoon season. If the isotherms of SST are oriented southwest-northeast and higher value in the east then system moves north or northeastward.

(*vi*) Bay of Bengal is warmer by 1.0º C during the period when the storms move in west/northwest direction compared to when they move in north/northeastward.

Acknowledgements

Authors are thankful to S/Shri M. Bharathiar and N.Selvam for their assistance in the project.

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