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Oceanic response to cyclone moving in different directions over Indian Seas using IRG model

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सार - भारतीय समुद्रों में विभिन्न दिशाओं में चलने वाले उष्णकटिबंधीय चक्रवातों के प्रभाव की जाँच करने के लिए आई.आई.टी.एम. के लघुकृत गुरूत्व (आई.आर.जी.) महासागर निदर्श का प्रयोग किया गया है। अरब सागर और बंगाल की खाड़ी में देखे गए उत्तराभिमुखी और पश्चिमाभिमुखी तूफानों के मार्गों में से कुछ पर विचार किया गया है। तूफान की आरम्भिक अवस्थिति (90°पू., 10° उ.) और विभिन्न दिशाओं में उसके चलने के संबंध में संवेदनशीलता अध्ययन किया गया। पश्चिमाभिमुखी चक्रवातों के संबंध में निदर्श में ऊपरी स्तर स्थूलता विचलन (यू.एल.टी.डी.) क्षेत्र में राइट बायस लुप्त हो जाता है। विभिन्न अक्षांशों पर बनने वाले पश्चिमाभिमुखी चक्रवातों के एक अन्य प्रयोग में कोरिऑलिस प्राचल (*f*) के प्रति महासागरीय अनुक्रिया संवेदनशील पाई गई। कोरिऑलिस प्राचल (*f*) के बढ़ने पर सतही धाराएँ और यू.एल.टी.डी. दोनों कम हो जाते हैं। चक्रवात के बनने की प्रक्रिया में कोरिऑलिस प्राचल (*f*) में कमी होने पर जडत्व तरंग के आयाम और तरंगदैर्घ्य में वृद्धि हुई है। इस अध्ययन से चक्रवात के आगे बढ़ने के कारण बनने वाले उत्स्रवण क्षेत्रों के निर्धारण में सहायता मिलती है।

ABSTRACT. The IITM Reduced Gravity (IRG) ocean model is employed to investigate the influence of tropical cyclone moving in different directions in Indian Seas. Some of the observed storm tracks in the Arabian Sea and Bay of Bengal are considered which have northward and westward movement. Sensitivity study is carried out for initial position of the storm at (90°E, 10°N) and moving in different directions. For westward moving cyclones the right bias in the model upper-layer thickness deviation (ULTD) field disappears. In an another experiment of westward moving cyclone originating at different latitudes, the ocean response is found to be sensitive to the Coriolis parameter (f) . The surface currents as well as ULTD reduce, as f increases. The amplitude and the wavelength of inertia gravity wave increase with decrease in f, in the wake of the cyclone. This study helps to determine the upwelling region arising due to movement of the cyclone.

Key words – IRG (IITM Reduced Gravity) Model , storm track, upwelling, inertia gravity wave.

1. Introduction

Climate of a region depends upon many factors such as latitudinal position, distribution of continents and ocean, topography, ocean currents, SST etc. Atmospheric motions of various space and time scales are involved in the transfer of energy between the ocean and atmosphere. Therefore, most of the atmospheric phenomena will respond directly or indirectly to sea surface temperature (SST). An increase in SST over a region may change the stability of the overlying air mass which in turn changes the convection in the boundary layer. On the other hand the atmospheric forcing events such as tropical cyclones, monsoon depressions are responsible for the large scale instability of the atmosphere. Further, these synoptic scale weather disturbances and the upper ocean response to them represent one of the extreme examples of mesoscale ocean-atmosphere interaction (Shay *et al.*, 1998).

In an earlier study, Behera *et al.* (1998) have investigated the upper ocean response to an idealised, symmetric cyclone moving over the Bay of Bengal. Different sensitivity experiments were carried out by changing the cyclone parameters *viz.* intensity, size, speed of cyclone, as well as by changing the model parameters such as the initial conditions, grid length etc. The oceanic response was asymmetric in contrast to the symmetric wind forcings. A "right" bias was noticed in the model simulated surface currents and upper layer thickness deviation (ULTD) field. This is in close agreement with earlier studies (Chang and Anthes, 1978; Price, 1981, 1983; Greatbatch, 1983, 1984). All these results show that maximum cooling and

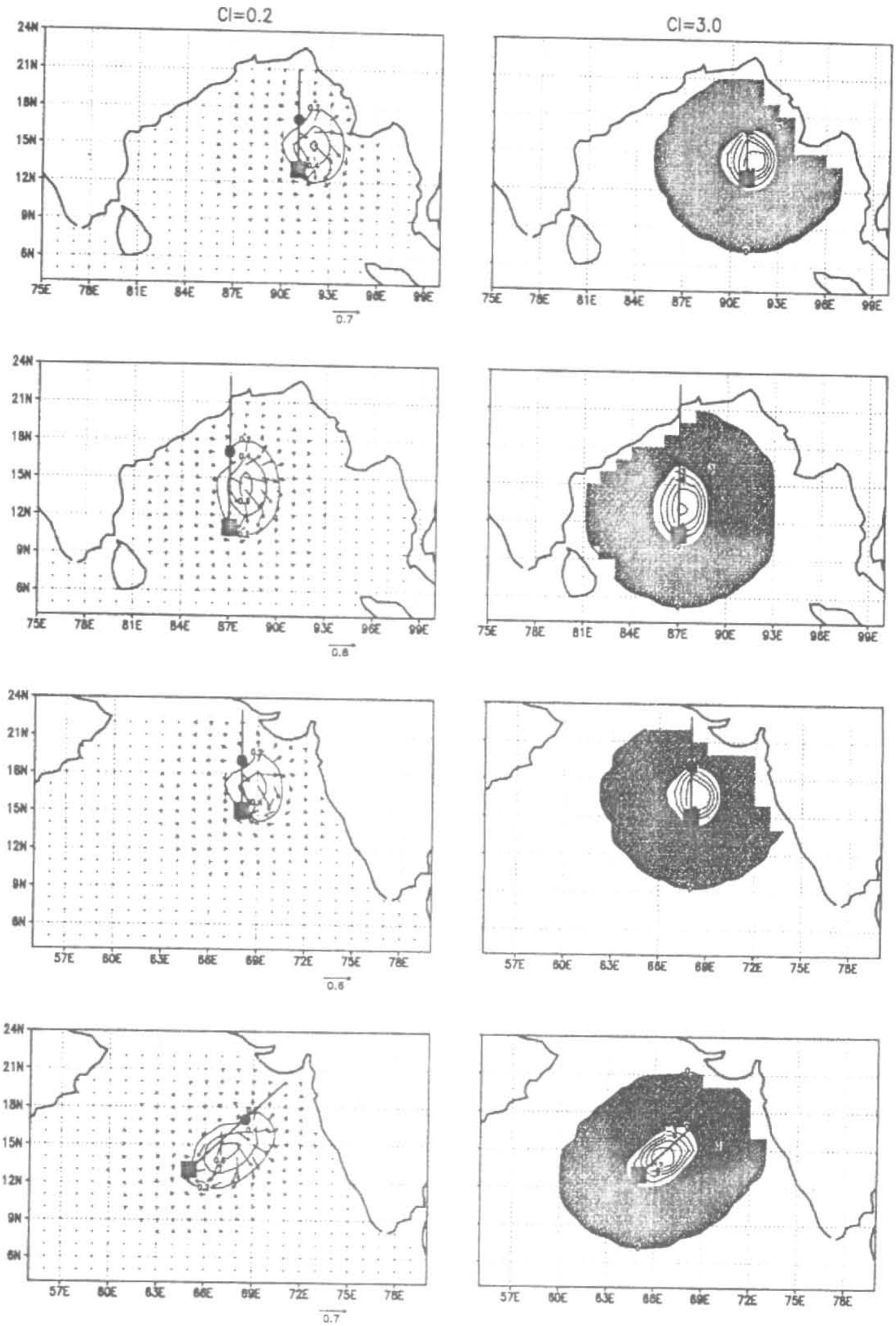

Fig. 1. Model output for eight observed cases of cyclone tracks. The model surface currents in m/s (Left panels) and ULTD in metres (right panels), after 2nd day. In every figure, ■ indicates the initial position and • indicates the present position of the cyclone center. The solid line drawn is the storm track. Positive ULTD values are shaded. Contour intervals are mentioned on the top of the figure

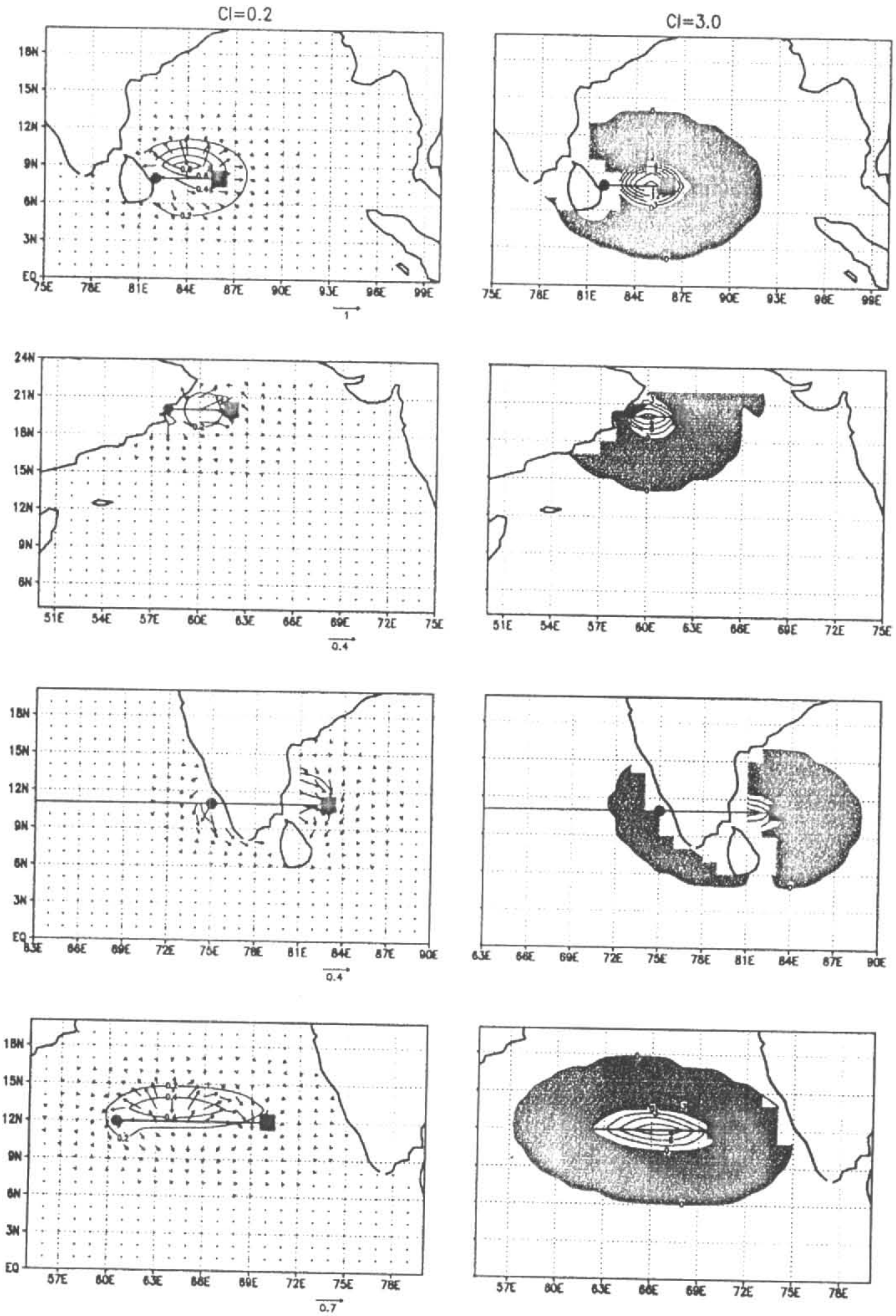

Fig. 1(*Contd*). Model output for eight observed cases of cyclone tracks. The model surface currents in m/s (Left panels) and ULTD in metres (right panels), after 2nd day. In every figure, ■ indicates the initial position and • indicates the present position of the cyclone center. The solid line drawn is the storm track. Positive ULTD values are shaded. Contour intervals are mentioned on the top of the figure

TABLE 1

Observed Tracks

Track direction	Initial Position	Final position	Duration (Days)	Storm speed (m/s)	Observed cyclone
Northward	91° E, 13° N	91° E, 21° N	4	2.55	TC 29-81, 1981
Northward	87 ° E, 11° N	87° E, 23° N	4	3.82	TC 31-81, 1981
Northward	68 ° E, 15° N	68 ° E, 23 ° N	4	2.55	TC 02A, 1985
Northeastward	65° E, 13° N	71° E, 20° N	3.5	3.35	TC 25-82, 1982
Westward	86° E, 9° N	82° E, 9° N	2	2.55	TC 27-80, 1980
Westward	62° E, 20° N	58° E, 20° N	2	2.55	TC 01A, 1983
Westward	83° E, 11° N	63° E, 11° N	5	5.1	TC 04B, 1984
Westward	70° E, 12° N	60.5° E,12° N	2	6.1	TC 03A, 1986

TABLE 2

Sensitivity experiment using idealised tracks

Track direction	Initial Position	Final position	Duration (Days)	Storm speed (m/s)
Northward	90 ° E, 10° N	90° E, 18 ° N	4	2.55
Westward	90° E, 10° N	82° E, 10 ° N	4	2.55
Eastward	90° E, 10 ° N	98° E, 10° N	4	2.55
Northwestward	90° E, 10° N	82° E, 18 ° N	4	3.59
Northeastward	90 ° E, 10° N	98 ° E, 18° N	4	3.59

maximum of ocean currents lie on the right of the storm track, in the wake of the storm. In a recent study by Deo *et al.* (1999), ocean mixed layer response was studied to idealised cyclones moving in westward and northward direction having tracks similar to those of observed Arabian Sea cyclones. The model ULTD field showed no right bias for the westward moving storm. However, the model circulation, in both the cases showed right bias.

The objective of the present paper is to understand, in detail, the oceanic impact of a tropical cyclone moving in different directions over Indian seas. The in-house developed IITM Reduced Gravity model, hereafter referred as IRG model (Behera and Salvekar, 1996) is used to investigate the oceanic response.

2. The Model

The IRG model used in this study is a simple 1.5 layer reduced gravity transport model, with one active layer overlying a deep motionless inactive layer. Therefore pressure gradient is zero in the lower layer which effectively filters out the fast barotropic mode. The model equations are vertically integrated depth averaged momentum and continuity equations, assuming no vertical shear in the horizontal fields. Complete description of model equations, numerical methods, boundary conditions etc is contained in Behera and Salvekar (1996).

The model parameter values used here are (*i*) reduced gravity $g' = 0.02$ m/s^2 and (*ii*) initial upper layer

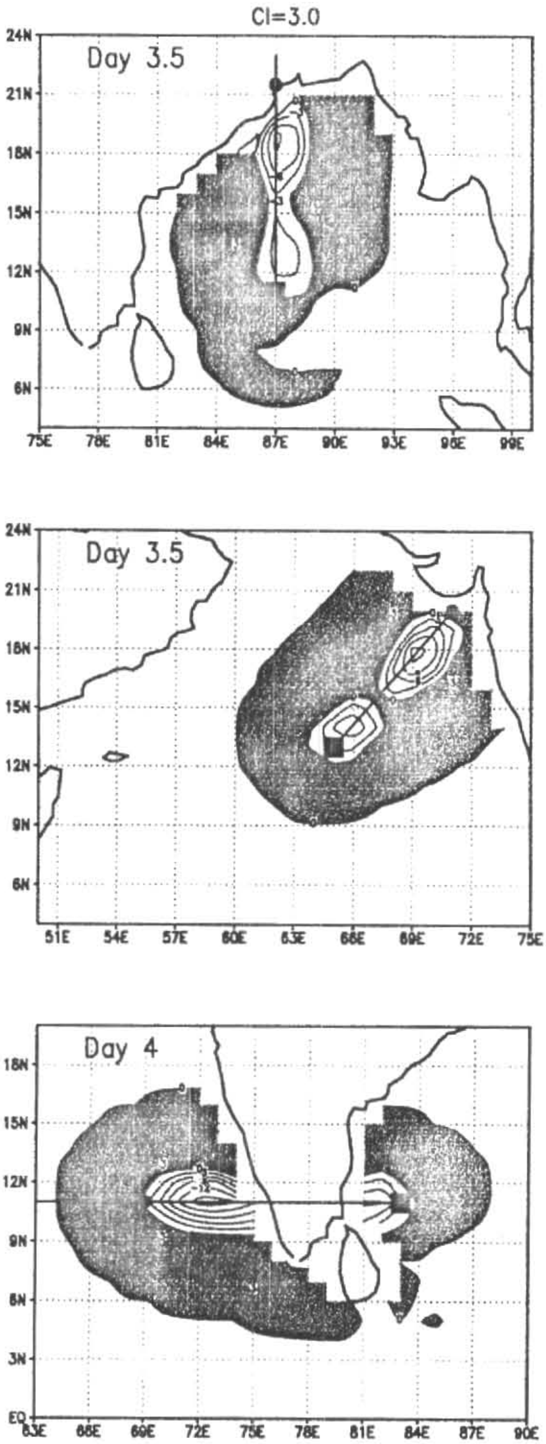

Fig. 2. Model ULTD field for tracks towards north, northeast and west, on days 3.5, 3.5 and 4

thickness H_o = 50 m. This basic structure produces a baroclinic gravity wave speed of 1.0 m/s. The model upper active layer also entrains mass from the lower motionless layer through a source term as discussed in Chang and Anthes (1978). The source term arises due to horizontal divergence, in the continuity equation. The effect of this entrainment on the upper layer density, momentum and kinetic energy has been neglected. It is assumed that the entrained water engulfed into the upper layer has zero velocity and is instantaneously adjusted to the density of the upper layer. Latitude and longitude limits of the model domain are from 24°S to 23°N and from 35°E to 115°E. The horizontal resolution is 28 km and time step is 30 min.

3. The model input

The model cyclone is assumed to have a symmetric vortex similar to that of a Rankine vortex. It has tangential and radial wind components as a function of radial distance, *r*, *viz.*

$$V_t(r) = V_m\,(r/R_{max}), \quad 0 \le r \le R$$

$$= V_m\,(R_{max} - r)\,(R_{max} - R), \quad R \le r \le R_{max}$$

$$V_r(r) = 0.3\,V_t(r)$$

where

V_t = tangential component of wind

V_r = radial component of wind

R_{max} = radius of the storm = 550 km

V_m = maximum tangential wind = 20 m/s, at a radial distance R = 55 km

The cyclonic wind stress used as input to the model, is derived by using constant drag coefficient, $C_D = 1.25\times10^{-3}$ and air density, (ρ = 1.2 kg/ m^3). The model is integrated for the period of the duration of storm, from the initial condition of rest. The center of the storm moves with a speed depending on the distance between initial and final position and the life time of the cyclone. The center of a storm and wind stress are computed at each time step.

4. Results and Discussion

4.1. *Observed tracks*

Eight observed cases of cyclone tracks in the Arabian Sea and the Bay of Bengal are chosen such that, the direction of movement of the cyclone is more or less northward or westward. Among these, one case in the Arabian Sea is highly unusual, being northeastward

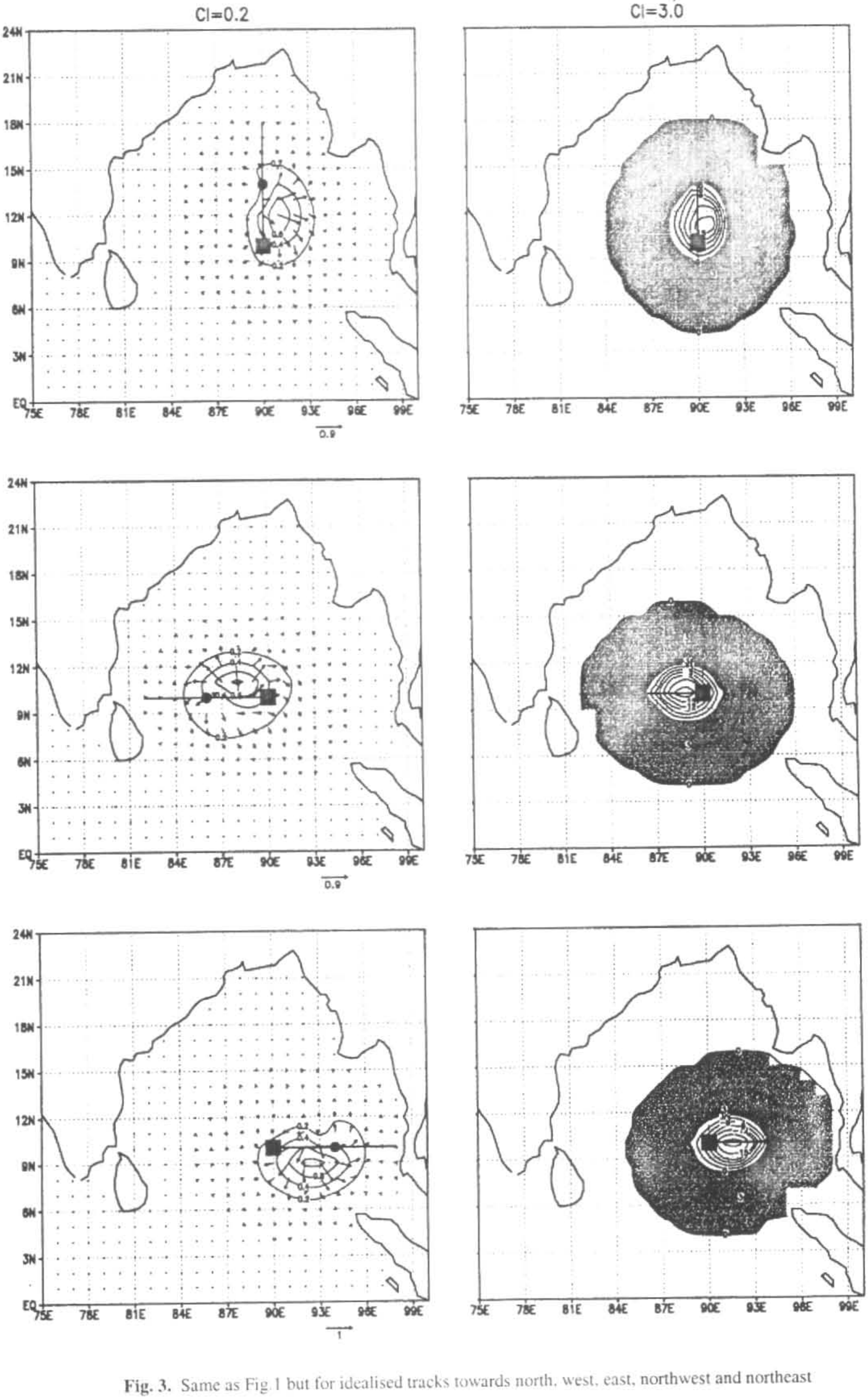

Fig. 3. Same as Fig.1 but for idealised tracks towards north, west, east, northwest and northeast

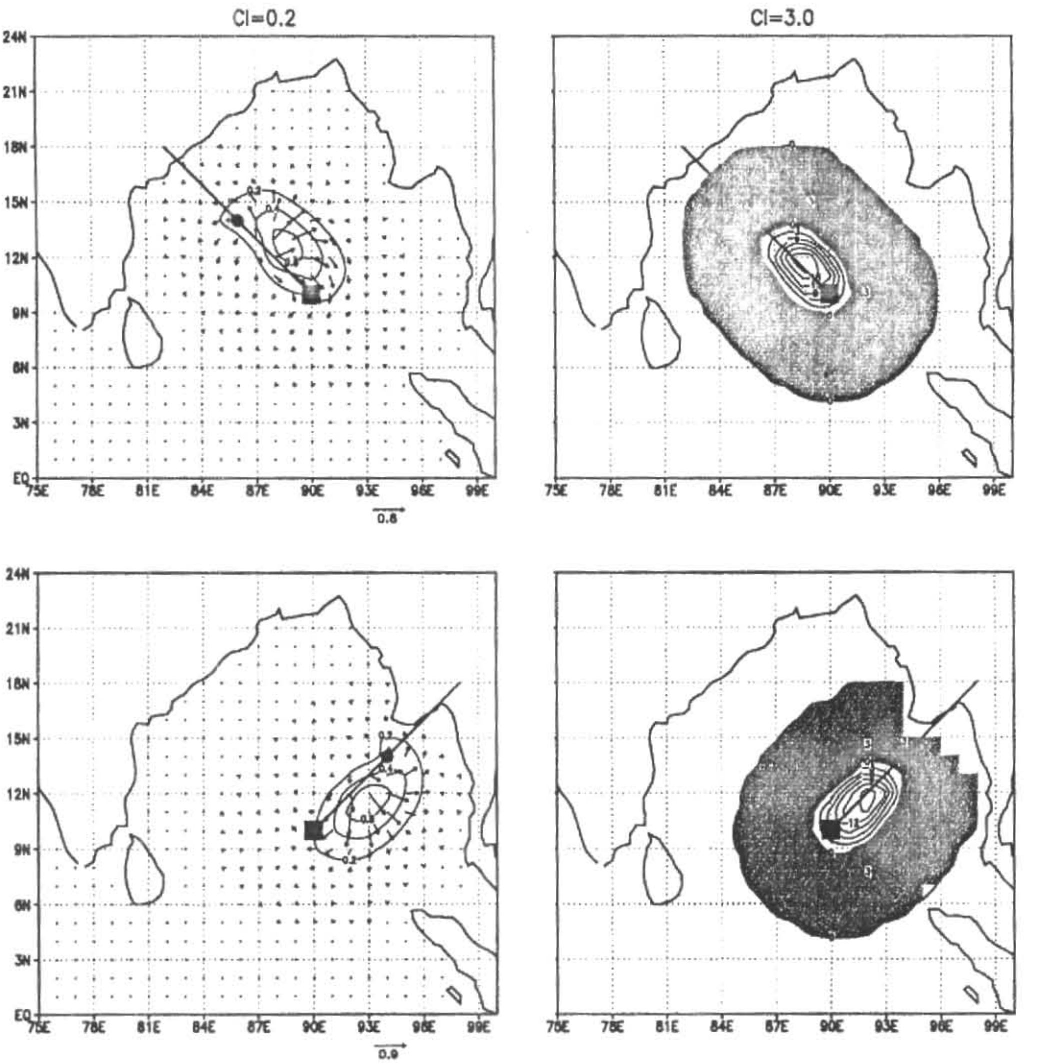

Fig. 3 (*Contd.*) Same as Fig.1 but for idealised tracks towards north, west, east, northwest and northeast

translating cyclone. To understand the oceanic response of these cyclones, a vortex, (see section 3) is allowed to move along these tracks for the period 2 to 5 days as per the observed life cycle given in the Table 1. The storm speed in each case depends on the initial and final position as well as the duration of the storm.

Though the model is integrated for 2 to 5 days, in these eight cases (Table 1), the model output, only after 48 hrs integration, are shown for all the cases (Fig. 1) as the minimum duration of the storm is two days. The left side panels show the isotachs and streamline analyses of the storm-induced surface currents. For clear representation of surface currents, arrow length is set as indicated in each case.The right side panels show the corresponding ULTD (Upper Layer Thickness Deviation from H_o) field. The positive ULTD values are shaded. The negative values of ULTD field indicate upwelling, which means cooling of sea surface. The storm track is also drawn for easy reference, with a solid square as the initial position. The solid circle denotes the position of the storm center at 48^{th} hr. For the first three cases of northward storm track, both the model circulation and ULTD fields are asymmetric to the storm track in spite of symmetric wind forcing as reported by Behera *et al.* (1998). The flow is divergent near the storm center. The maximum magnitude (of about 0.7 m/s) is located to the rear of the storm center and about 100 km to the right of the storm track. The maximum speed lags the storm center by about 220 km. For translation speed of 2.55 m/s, this lag can be considered as equivalent to 23 hrs. The bias in the current field toward the right of the storm track mainly arises due

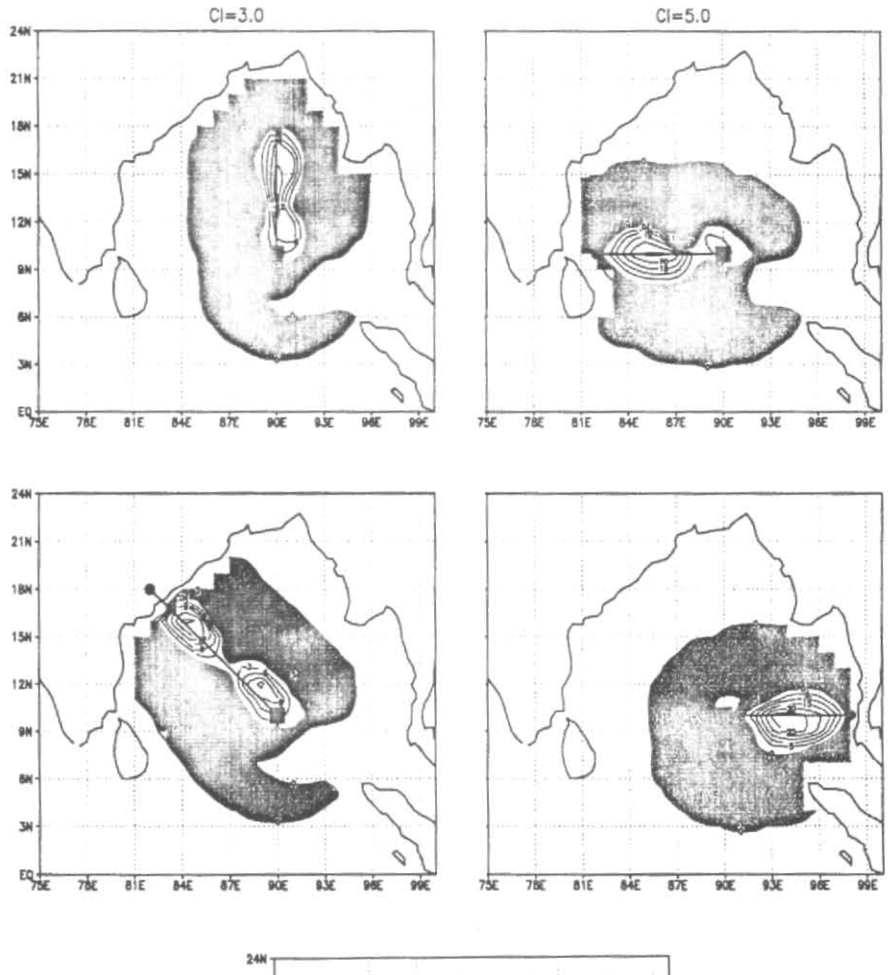

Fig. 4. Model ULTD field for the idealised tracks as in Fig.3, but for 4th day

to the inertial forces. The right bias is also seen in the ULTD field, but is weak as compared to that in the circulation field. The region of upwelling is surrounded by the region of positive ULTD. In most of the cases the translated storm center lies on the boundary of the positive and negative ULTD values.

For the 4th case of abnormal northeastward moving cyclone, right bias in the model currents and ULTD field is also seen. The maximum flow intensity and the maximum upwelling lag the storm center by about 300 km and 350 km respectively. This is equivalent to the lag of 24 hrs and 29 hrs approximately, since the translation,

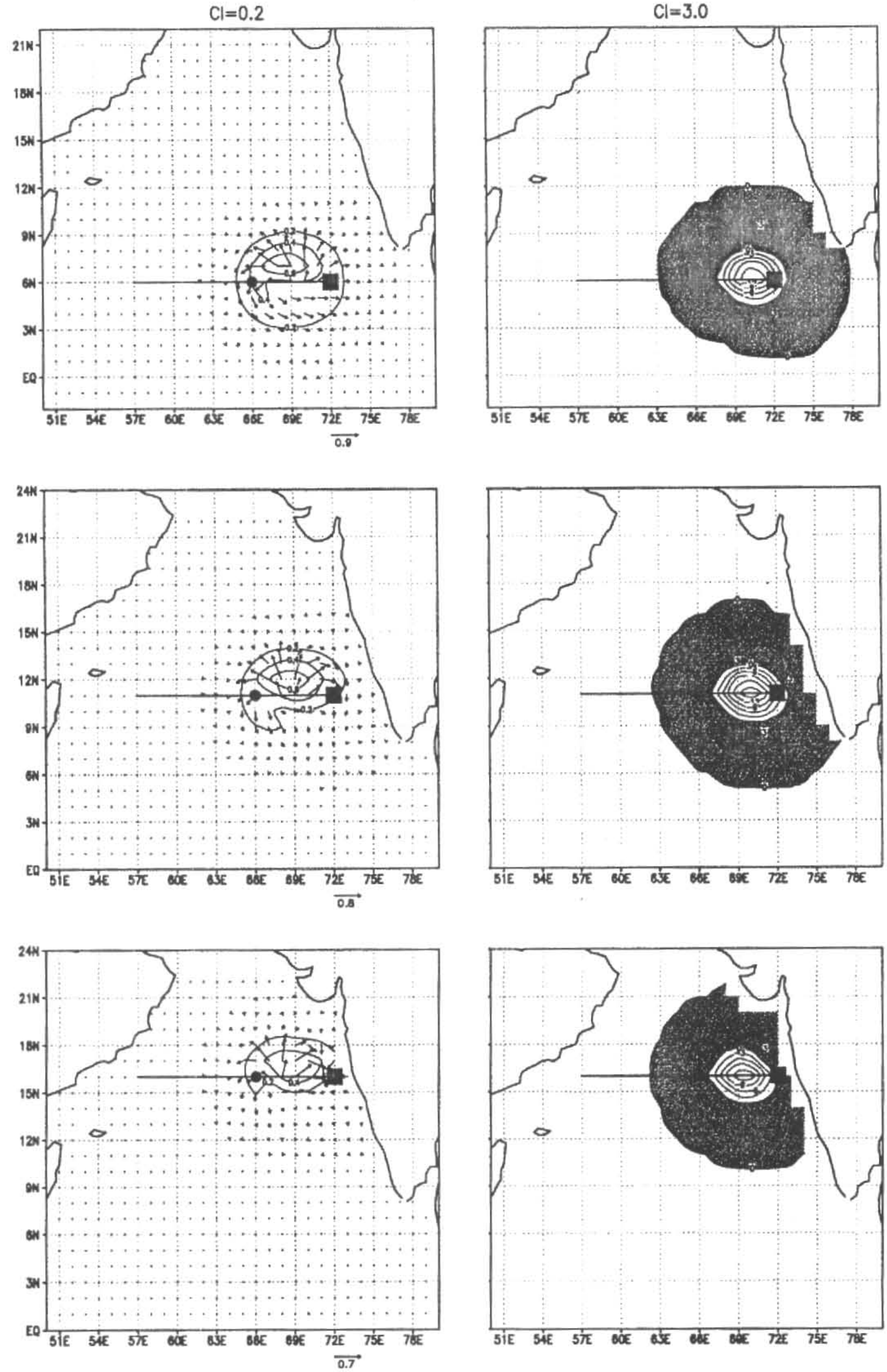

Fig. 5(a). Same as in Fig. 1 but for the tracks along latitudes 6° N, 11° N, 16° N

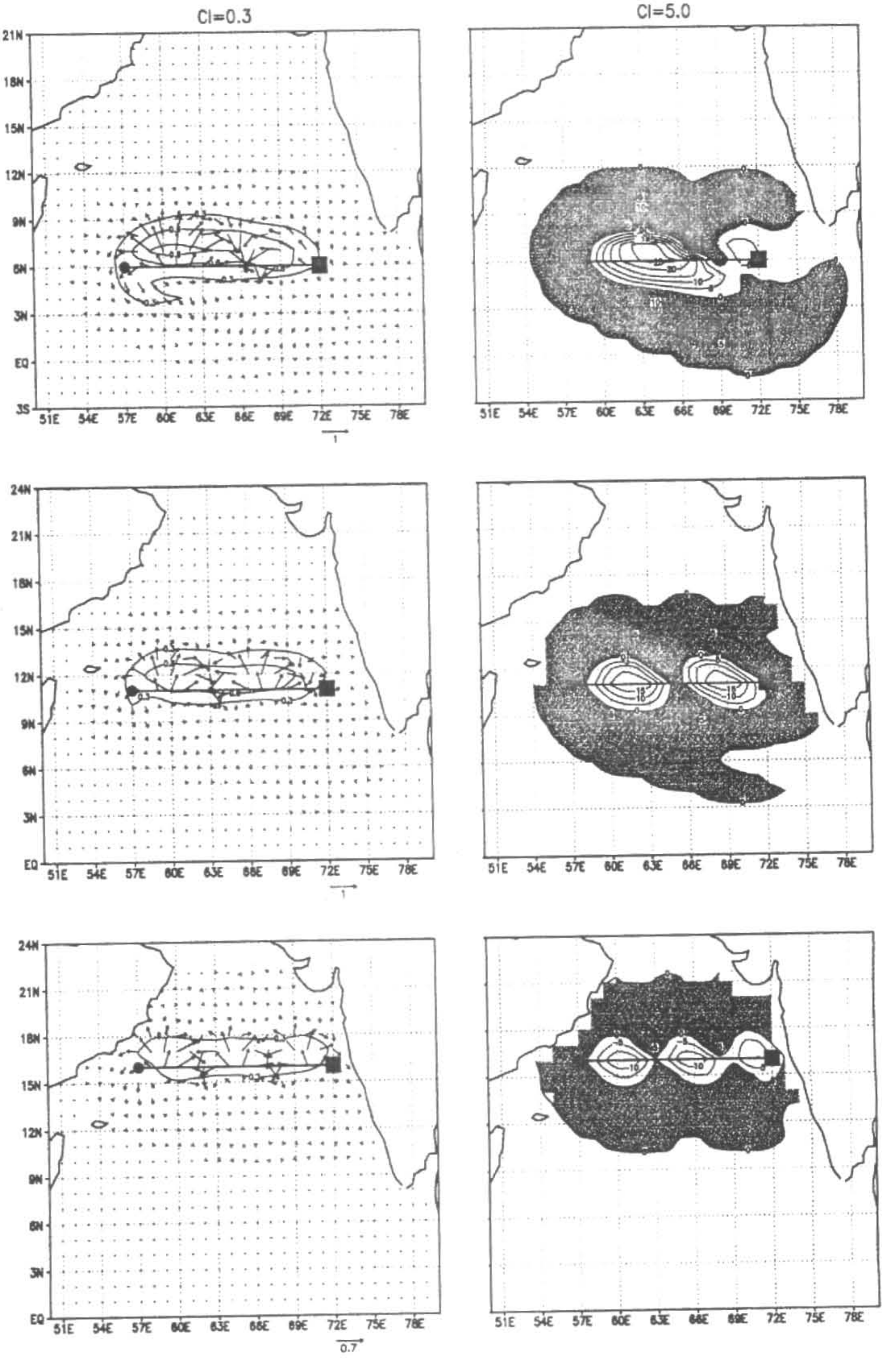

Fig. 5(b). Same as in Fig. 5(a) but for 5th day speed of the cyclone is 3.35 m/s. Again near the storm center the flow is divergent.

For the remaining cases of westward translating cyclones, right bias in the model current field is clearly depicted but is absent in the model ULTD field. The maximum upwelling lies on the storm track and the negative ULTD field is symmetric about the storm track.

It is also observed for all the cases that, whenever the cyclone has duration, more than three days, irrespective of its direction of movement, the second maximum in the ULTD field exists from 3.5th day, which is associated with the inertia gravity wave in its wake (Fig. 2). Along the track, the wavelength of inertia gravity waves, is about 550 km as obtained from the distance over oceanic region between two centers of upwelling.

4.2. *Idealised Experiment*

It will be interesting to see the behaviour of current and ULTD field for different directions of storm movement but having the same initial position. For this purpose, an idealised experiment is performed such that the prescribed cyclone is translated from the initial position of (90°E, 10°N) in the Bay of Bengal, towards five possible different directions, in four days, *viz.* north, west, east, northwest and northeast so as to reach the final positions as (90°E, 18°N), (82°E, 10°N), (98°E, 10°N), (82°E, 18°N) and (98°E, 18°N) respectively. Therefore, the translation speed of the cyclone is about 2.55 m/s in north, east and west directions; and 3.59 m/s in northwest and northeast direction (Table 2).

Figure 3 shows the results obtained from this idealised experiment after 2nd day. The left panels show, contours of ocean currents and current vectors and the right panels show the ULTD field. For all the tracks, model currents show the maximum flow intensity on the right side of the track. The bias is about 100 km for north, west and east tracks and about 150 km for northwest and northeast tracks. The maximum current lags the storm center by about 200 km for north, east and west tracks whereas for northeast and northwest tracks the lag increases to about 300 km. The maximum value of current in all the five cases, is more or less same. In the case of ULTD field the role of coriolis parameter is found to be important. The ULTD field shows maximum upwelling on the right side of the track with magnitudes of about 16 - 17 m, for north, northwest and northeast track. However, for the case of either east or west track, the negative ULTD field is highly symmetric with reference to the axis of the storm track, with an increase in the maximum upwelling to about 20 m. The ULTD field, for all the cases, after day 4, is shown in the Fig. 4. Qualitative change in the ULTD field is not significant beyond second day integration, except for the case of eastward moving storm. However, quantitative increase in the ULTD fields (both positive and negative) is noticed, only for the cases of east and west tracks, having maximum upwelling on the track itself.

4.3. *The effect of latitude on oceanic response*

From the above results and the study reported by Deo *et al.* (1999), it is seen that the right bias is absent in the model ULTD field, for westward moving cyclone. But it is interesting to see the impact of initial position of the storm at different latitudes for westward moving cases. Hence, the last experiment is designed to reveal the response of ocean to an idealised westward moving tropical storm in the Arabian Sea between longitudes 72°E to 57°E, in five days, along different latitudes from 6°N to 20°N, so that the translation speed (3.82 m/s approximately) remains same in all the cases. Results for three different latitudes, *viz.* 6°N, 11°N and 16°N after 2nd day and 5th day, are shown in Figs. 5(a &b) respectively, in which the surface currents contours are on the left panels, and ULTD field is on the right panels. As the initial position of the storm is away from the equator, reduction in the surface currents, as well as in the ULTD field is noticed. Negative ULTD field is symmetric upto 2 days irrespective of the latitude position but, beyond two days of integration, the effect of latitude position is visible. For the tracks northward (southward) of 9°N negative ULTD field is symmetric (asymmetric) about the axis of movement. The maximum upwelling has values of 27 m, 20 m and 14 m and maximum downwelling of 14 m, 10 m and 7 m occurs for tracks along 6°N, 11°N and 16°N respectively, on 5th day Fig. 5(b). This shows that amplitude of ULTD field reduces with increase in Coriolis parameter.

The effect of latitude is also seen in the region of upwelling. As the initial position of the storm is away from the equator the storm center is found to be close to the upwelled region. The upwelled region lags the storm center by about 220 km, 150 km and 100 km for tracks along 6°N, 11°N and 16°N respectively for the 5th day Fig. 5(b). Further, the wavelength of inertia gravity wave in the wake of the cyclone is found to be sensitive to f (Fig. 5b). The reduction in the wavelength from about 700 km to 500 km is noticed, as f increases. In other words, the number of minima in the ULTD field increases with the latitude. Similar results are also reported by Chang and Anthes (1978). Theoretical investigation by

Geisler (1970) indicated that the displacement of the thermocline in the wake should be inversely proportional to f^3 while the wavelength is inversely proportional to f alone, which supports the behaviour of ULTD field obtained in the present study.

5. Conclusion

The IRG model is applied to understand the oceanic response to the cyclones moving in different directions in Indian seas. The ocean currents and ULTD field show right bias for all the observed cases of storm tracks except for the westward tracks. Second upwelling maximum occurs after 84 hours, associated with inertia gravity wave in the wake of the cyclone, having wavelength on the oceanic region as 550 km approximately.

In the idealised experiment of storm movement in different directions, from a fixed point, no bias in model ULTD fields, is seen for the west and east track, but right bias exists in the model current field for all the cases. The right bias as well as the lag between the storm center and maximum current, are about 1.5 times in the cases of tracks where both latitude and longitude are simultaneously changing during storm movement, than that for the tracks where only latitude or longitude is changing during storm movement. Magnitude of upwelling is significantly less for the tracks having northward component in it's direction, than for the tracks along east/west direction.

Finally, as the initial position of the westward moving cyclone is away from the equator, the amplitude of the current and ULTD reduces. The storm center is found to be close to the upwelled region, as f increases. The inertia gravity waves of greater amplitude and the wavelength are found for smaller values of the coriolis parameter, in the wake of the cyclone.

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