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Behaviour of the upper ocean in response to an idealized symmetric and asymmetric Indian Ocean Cyclone in opposite hemisphere

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ABSTRACT
The effect of moving symmetric and asymmetric tropical cyclone in the northern and southern Indian Ocean, on the oceanic upper layer is studied, using a simple reduced gravity ocean model. Different tracks in the northern Indian Ocean and their mirror image in southern hemisphere are considered on the basis of existence of various such systems. The model temperature and mixed layer depth are examined during the passage of cyclone along these tracks. The model fields show the bias to the right (left) of the storm track in the northern (southern) hemisphere for the symmetric cyclone case. The asymmetric winds to the left and right of the each track considered are used to force the model in another experiments. The model output is found to be enhanced with the right asymmetric case as compared to the left asymmetric case.

INTRODUCTION

Tropical cyclones are one of the most violent natural disasters that affect many countries around globe and cause tremendous loss of lives and property. Indian subcontinent is worst affected by tropical cyclones in virtue of it's geographical positioning in the central part of the Indian Ocean and a long coastline spanning over 7500 km. These cyclones produce a vigorous response in the ocean; surface wave height in excess of 20 m and upper ocean current strength of 1m/s. The understanding of significant changes in the oceanic mixed layer is important for dynamical prediction of tropical cyclone.

Efforts in the past, for understanding tropical cyclone, are more or less restricted to the problems of convective parameterization, vortex movement, vortex flow interaction etc. (Demaria 1985; Greatbatch 1983, 1984 and Thu & Krishnamurti 1992). For the dynamical prediction of tropical cyclone, the knowledge about the ocean response to storm forcing is essential. Various observational and numerical studies have shown that tropical cyclone produces significant changes in the underlying ocean thermodynamic structures, which also involves SST changes. In earlier studies the ocean response to moving cyclones in the Indian Ocean has been studied by considering idealized symmetric vortex and tracks similar to the observed ones (Behera, Deo & Salvekar1998; Deo, Ganer & Salvekar 2001). The effect of moving symmetric and asymmetric tropical cyclone in the northern and southern Indian Ocean, on the oceanic upper layer is studied for the present work.

FORMULATION OF THE MODEL

The model used in this study is a simple 1½ layer reduced gravity ocean model (horizontal resolution: ½° x ½° grid) over the Indian Ocean region (35E-115E, 30S-25N) with one active layer overlying a deep motionless inactive layer. The model equations are vertically integrated depth averaged momentum and continuity equations assuming no vertical shear in the horizontal field. Complete description of model equations, numerical methods, boundary conditions etc, is contained in Behera & Salvekar (1995). The entrainment term added to continuity equation is considered as that in Chang & Anthes (1978). In the present study the thermodynamics is included to study the variation in the temperature of the mixed layer during the passage of cyclone. The thermodynamic equation contains the advection term, horizontal diffusion term and the effect of vertical mixing with bottom water. The cooling by evaporation and the effect of sensible heat transfer are neglected as in Chang & Anthes (1978). The effect of vertical mixing terms is incorporated implicitly so that the final temperature equation uses the mixed layer depth before and after entrainment and the temperature difference between the mixed layer and the bottom layer. The initial thermocline is 50 m deep. The reduced gravity parameter g′ is set equal to 0.02 m/s^2. These values give an initial gravity wave speed of 1m/s. The initial temperature in the mixed and bottom layer are 29 °C and 22 °C.

THE MODEL INPUT

The idealized symmetric cyclonic vortex similar to that of a Rankine vortex is considered. The model cyclone has tangential and radial wind components varying with the radial distance, r, as follows.

Tangential wind component:

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

Radial wind component:

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

Where, R_{max} = Radius of the storm = 400 km,
V_m = Maximum tangential wind = 20 m/s, at a radial distance R = 55 km.

The cyclonic wind stress derived from this is used as input to the model. The model is integrated for the period of the storm duration (five days for all the cases considered here) from the state of rest with the time step of 30 min.

RESULTS AND DISCUSSION

Best track data (Source: http://metoc.npmoc.navy.mil/jtwc/best_tracks) of the Indian Ocean cyclones in the northern and southern hemisphere, are used to select

Table 1. Numerical experiments carried out

Expt No	Track Name	Track Direction	Initial Position	Final Position	Wind forcing	Direction of asymmetric winds w.r.t. track
1	Track1	Northward	90E, 6N	90E, 16N	Symmetric	
2					Asymmetric	Left
3						Right
4	Track 2	Westward	92E, 14N	82E, 14N	Symmetric	
5					Asymmetric	Left
6						Right
7	Track 3	Northwestward	96E, 8N	86E, 18N	Symmetric	
8					Asymmetric	Left
9						Right
10	Track 4	Southward	90E, 6S	90E, 16S	Symmetric	
11					Asymmetric	Left
12						Right
13	Track 5	Westward	92E,14S	82E, 14S	Symmetric	
14					Asymmetric	Left
15						Right
16	Track 6	Southwestward	96E, 8S	86E, 18S	Symmetric	
17					Asymmetric	Left
18						Right

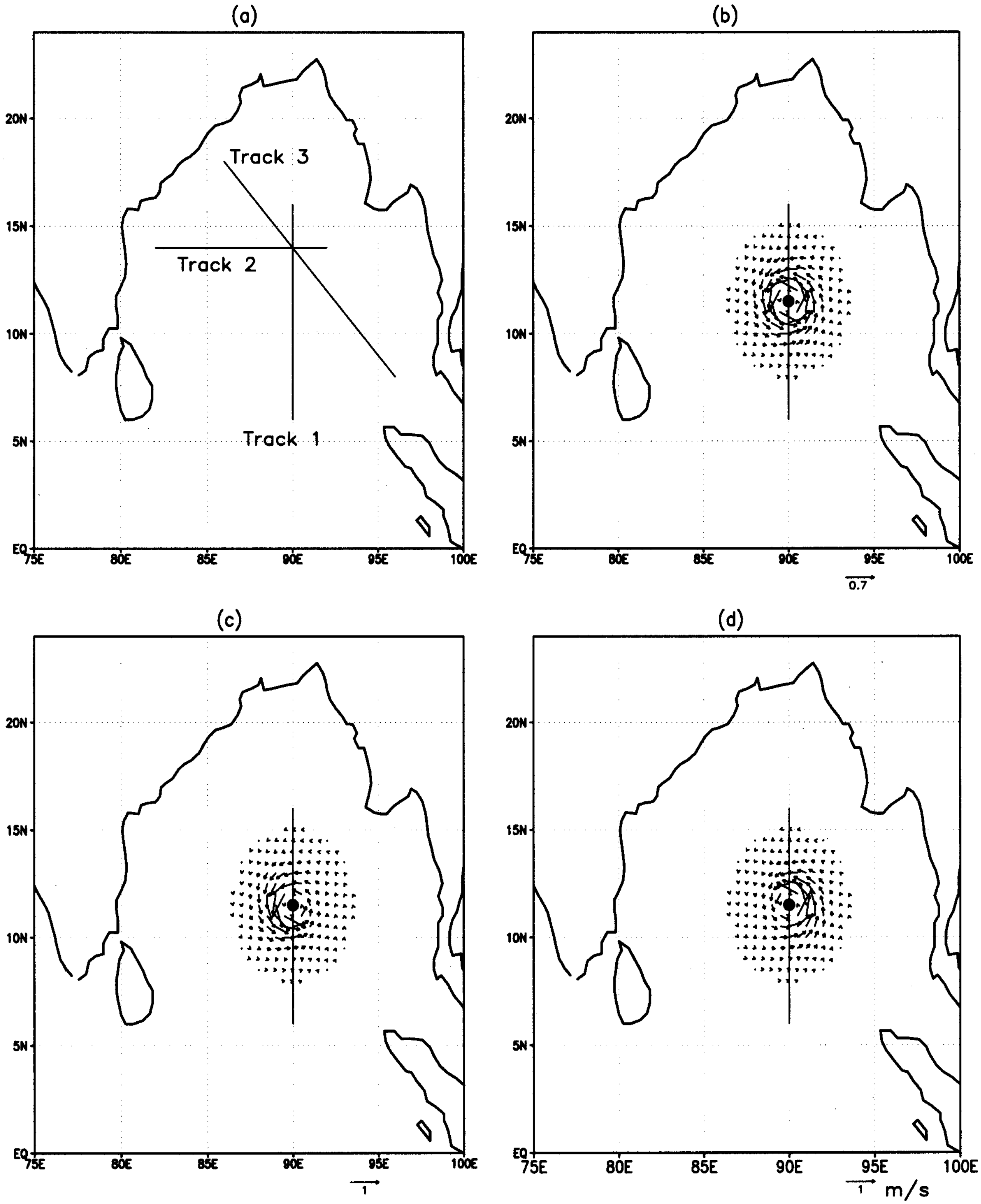

Figure 1. (a) Tracks in NH (b) Symmetric winds (c) Left asymmertric winds (d) Right asymmetric winds, along track 1.

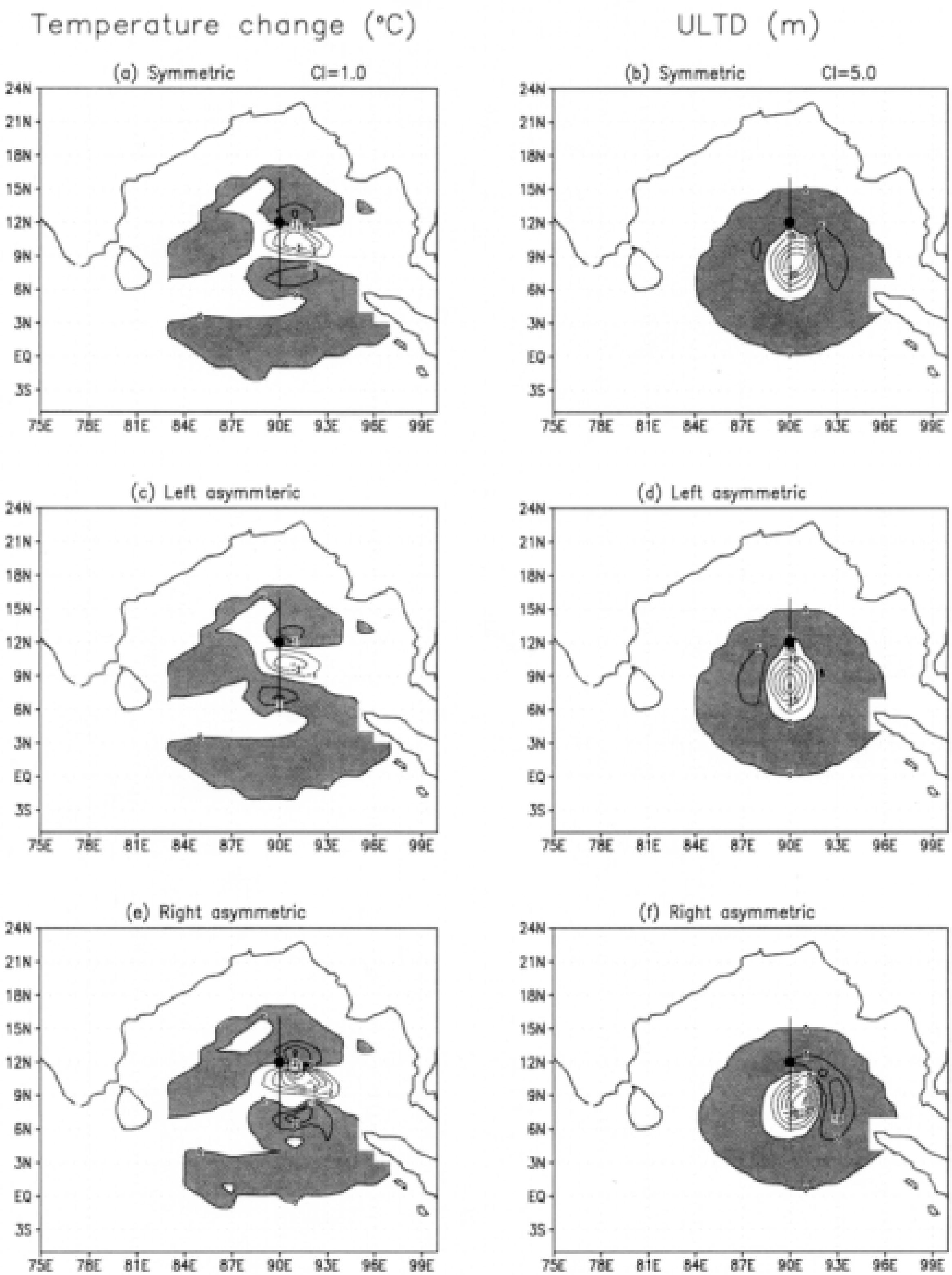

Figure 2. Model temperature change and ULTD for symmetric, left and right asymmetric cyclone moving along track 1 on Day 3, positive values are shaded.

different idealized cyclonic tracks such that the frequency of storms passing along these tracks is quite high. Three tracks in the north Indian Ocean are selected which are towards north (Track 1), west (Track 2) and northwest (Track 3). The mirror image of these tracks in the southern Indian Ocean is considered (Tracks 4, 5 and 6). The idealized symmetric cyclonic vortex as defined above, having radius 400 km is allowed to travel along these tracks for 5 days in the separate numerical experiments. In each experiment the translation speed of the cyclone is about 2.55 m/s for track 1, 2, 4 & 5 and is 3.59 m/s for track 3 & track 6.

However, a real tropical cyclone is seldom symmetric. Stronger winds and stresses are many times found in the right of the storm's direction of movement. When a tropical cyclone changes it's course or it recurves or slows down, the asymmetry in the wind stresses occurs. Hence the asymmetric cyclonic wind forcing is generated artificially, to the right and left of the storm track and it's effect on Upper Ocean is examined in further experiments. The model is then forced with the asymmetric cyclonic winds in the two directions viz. left and right of each track. The asymmetric wind forcing is provided to the model by multiplying the symmetric winds with a factor of $(1 + b \cos \theta)$, where b is the magnitude of asymmetry, $0 \le b \le 1$ (equal to 30 % for the present work) and θ is the angle measured anticlockwise from the axis perpendicular to the storm track. This gives 30 % increase in the wind speed on the left (right) of the track for left (right) asymmetric case (Fig.1). The details of these experiments are described in Table 1.

Fig.2 shows the model results from the experiments 1, 2 and 3. The left panel shows the temperature change on 3rd day for symmetric cyclonic winds, asymmetric cyclonic winds to the left and to the right side of the track 1. Corresponding upper layer thickness deviation (ULTD) for the same cases is shown in the right panel. Solid line drawn is the storm track and the dot represents the position of the storm center. The results indicate for the experiment 1, that the maximum cooling of about 4° C occurs right of the track which suggests that the mixed layer on the right of the track is cooled more than the left and there is right bias in the temperature field (Fig 2a). The ULTD field (Fig 2b) also shows the right bias and the maximum upwelling (24 m) on the right of the storm track. There is lag of 400 km between the storm position and maximum upwelling. This is equivalent to 1.8 days with the prescribed cyclone speed. The region of upwelling (negative ULTD) is surrounded by the region of downwelling (positive ULTD). The surface circulation is also obtained which shows the divergence of the flow near the storm center (figure not shown). Also, the maximum magnitude of the circulation is found to be located right of the storm track. This asymmetric ocean response in contrast to symmetric wind forcing is also observed in the earlier studies of Price 1981, 1983. The bias is explained by the sense of rotation on either side of the track with respect to time. The inertial forces turn the ocean currents in the same (opposite) direction of wind stress in the right (left) side of the track in the northern hemisphere (Price 1981).

This right bias is also supported by observational studies. Because of the scarcity of observational network during the existence of cyclone with the given resolution, there are few observational studies showing this bias. A remarkable asymmetric response of the ocean was illustrated by the surface temperature pattern in the Atlantic after Hurricane Ginger as it slowed down and changed its course (Black 1983). Shay et al. (1992) have reported observational evidence about the hurricane Gilbert in Gulf of Mexico from 14-19 Sep.1988. On 16 Sep during the passage of storm, SST started decreasing with maximum decrease of 3.5 to 4 ° C on the right rear quadrant.

For the case of asymmetric winds to the left of the track (Expt. 2) temperature anomalies show reduced magnitude (cooling ~ 3 °C) and region of cooling has less extension to the right as compared to the symmetric case, still the maximum cooling lies on the right of the track (Fig 2c). In the ULTD field, the right bias is not seen and the region of upwelling has shifted to the left as compared to the symmetric case. The downwelling on the left of the storm is increased (Fig 2d).

For the case of asymmetric winds to the right of the track (Expt. 3) temperature anomalies become strong; the maximum cooling reaches to 6 °C. The existing right bias in the symmetric case is increased and the cooler region lies almost to the right of the track (Fig. 2e) The ULTD field also shows more right bias, stronger values and increase in the downwelling on the right of the track. It is seen that the center of the storm lies ahead on the downwelling region as compared to the symmetric case where as it is little behind in the left symmetric case (Fig. 2f). Comparing the results with those of experiment 2, it is seen that more cooling, more upwelling and currents are found for the right asymmetric case than those for the left asymmetric case. The reason is that existing right side bias in the case of symmetric cyclonic winds enhances with more winds on right side where as the left asymmetric case tries to nullify the right bias and consequently magnitudes are reduced.

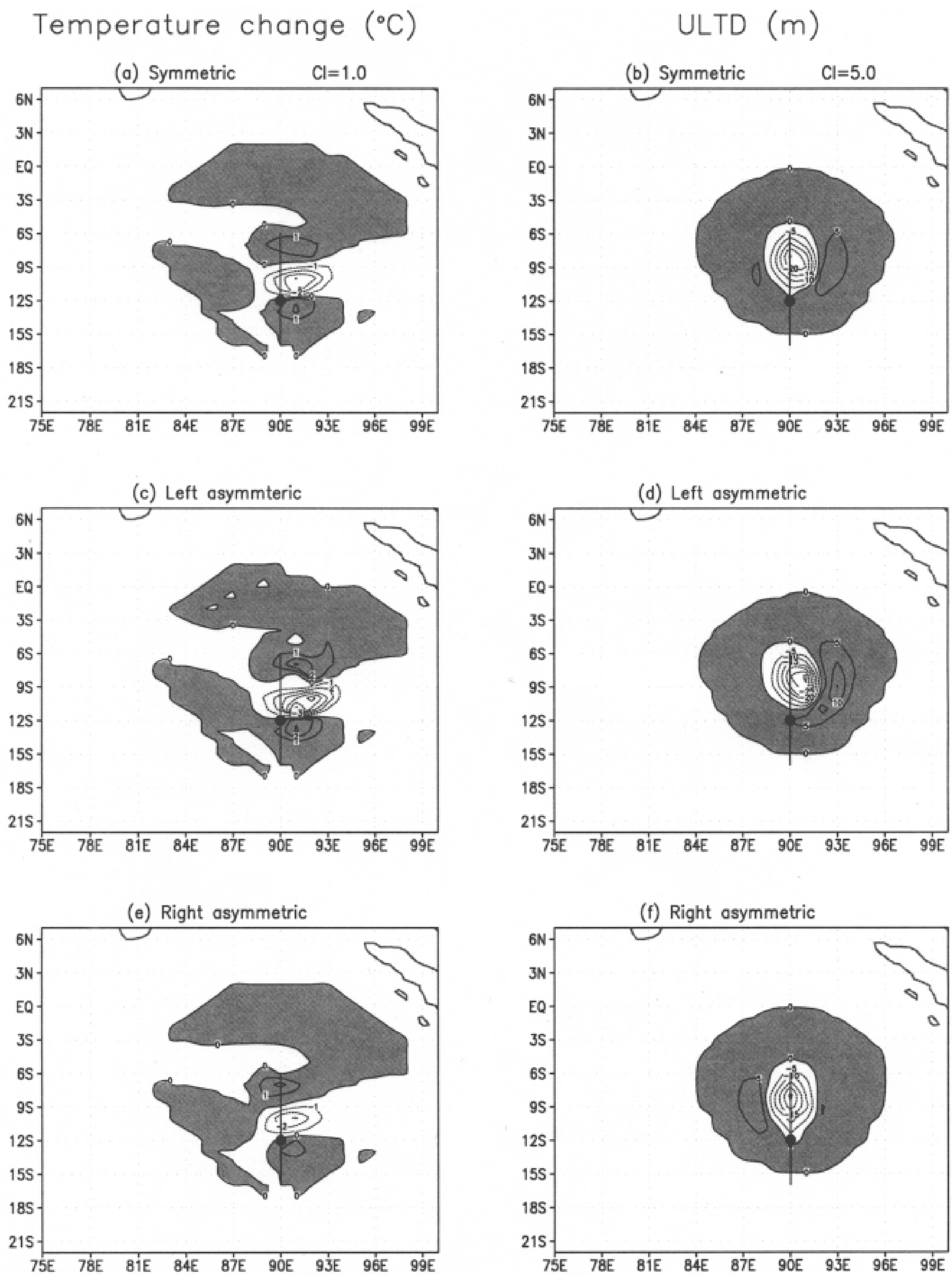

Figure 3. Model temperature change and ULTD for symmetric, left and right asymmetric cyclone moving along track 4 on Day 3, positive values are shaded.

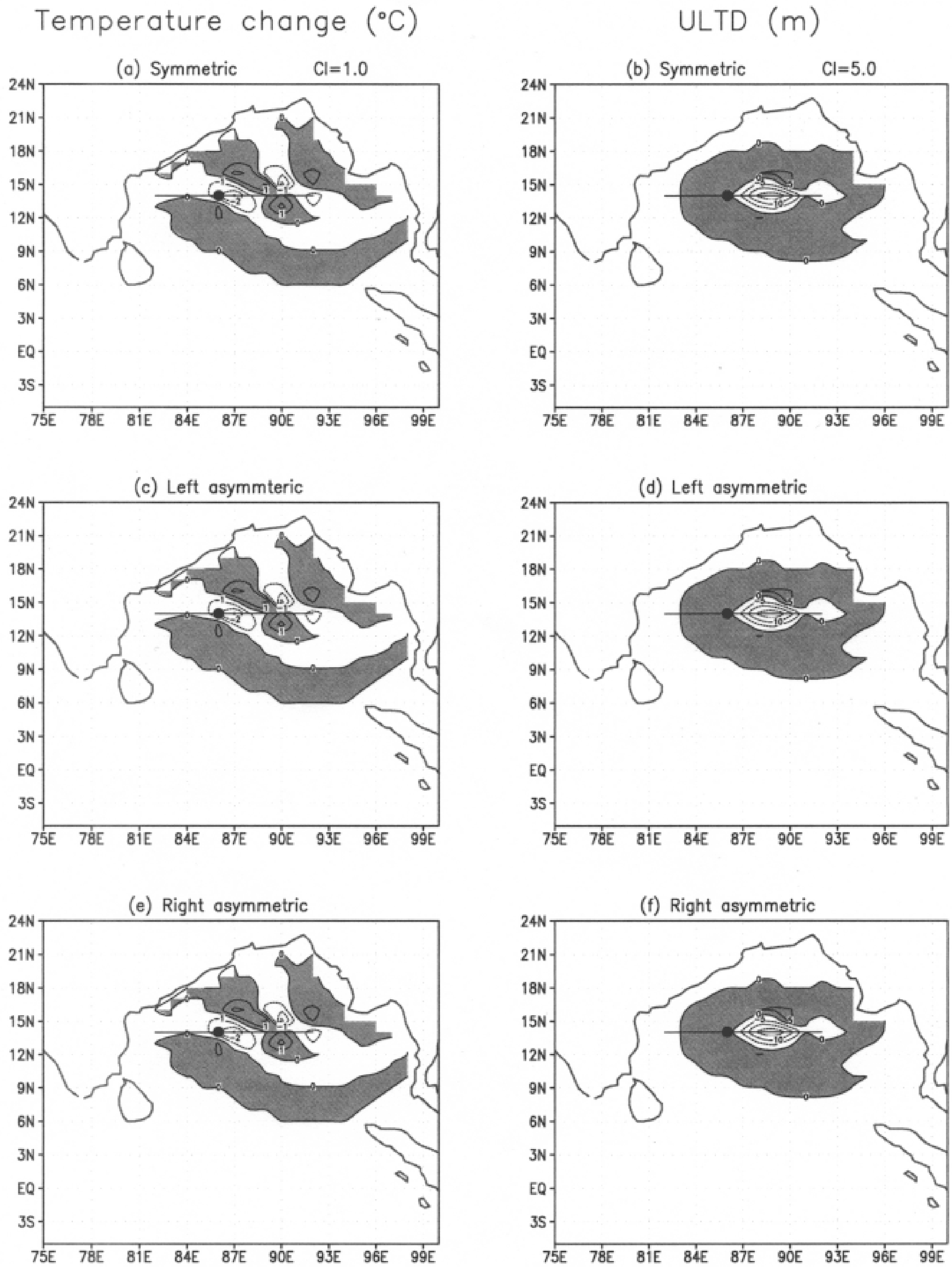

Figure 4. Model temperature change and ULTD for symmetric, left and right asymmetric cyclone moving along track 2 on Day 3, positive values are shaded.

The model results for the track 4 (mirror image of track 1) are depicted in the Fig.3. The symmetric cyclonic vortex along southward track (Expt. 10) produces left bias in the model temperature and ULTD field (Fig 3a & b). The upper layer is more cooled on the left of the track. The left bias is basically due to the change in sign of Coriolis parameter *f*, in the southern hemisphere. The inertial forces turn the ocean currents in the same (opposite) direction of wind stress in the left (right) side of the track in the southern hemisphere. The magnitude of temperature and ULT field remain same as that for experiment 1.

In the experiment 11 of the asymmetric winds to the left of the track 4, the temperature anomaly and ULTD field show increase in the magnitude (Fig. 3c & d) as compared to that in experiment 10 and also increase in the existing left bias. This case of asymmetry to the left of the track 1 is identical to the case of right asymmetric winds in the experiment 3. Hence the model results are similar to that for experiment 3. The magnitudes are same only the directions are opposite. On the same lines the model results for the experiment 12 (Fig. 3e & f) are equal to that for experiment 2. In these cases the asymmetric wind is on the opposite side of already existing bias. So the bias and the magnitudes of model field reduce.

Comparing the results of the experiments 11 and 12, it is found that more cooling, more upwelling and currents are found for the left asymmetric case than those for the right asymmetric case. In the southern hemisphere this is opposite to what is seen in northern hemisphere. The existing left side bias enhances with more winds on left side where as the right asymmetric case tries to nullify the left bias and consequently magnitudes are reduced.

Fig.4 gives the model results from the experiments 4, 5 and 6. The temperature anomalies show maximum cooling on the storm track for symmetric winds case, but the second maximum occurs on the right of the track, hence, on the whole the mixed layer is cooled more on the right side (Fig. 4a). The ULTD field shows upwelled region lying symmetrically about the track and no bias in the field is seen (Fig 4b). In the cases of left and right asymmetric winds (Fig 4c, d, e & f) the magnitudes of maximum cooling and upwelling do not differ from each other and are same as symmetric case, but warming and downwelling increase for the left and right asymmetric case. This increase is more for right asymmetric case than the left asymmetric case. The values of maximum warming are 2°C, 3°C and 5°C for the symmetric and left and right asymmetric cases (Fig 4a, c & e) and that for downwelling are 5m, 8m and 11m (Fig 4b, d & f). The downwelling is more to the left (right) for the asymmetric winds cases to the left (right). For the left (right) asymmetric case the temperature anomalies show shift on the left (right) of the track (Fig 4c &e). Also a little shift to the left (right) of the track is seen in the ULTD field correspondingly (Fig 4d & f). In the southern hemisphere, the numerical experiments 13, 14 &15 for the track 5, resulted into the cooling on the left of the track and symmetrically placed upwelled region along the track, in the symmetric cyclonic winds case (Fig. 5a & b). The warming and downwelling increase for the left (Fig. 5c & d) and right (Fig 5e & f) asymmetric case. This increase is more for left asymmetric case than the right asymmetric case. Again the model field magnitudes are same for northern and southern hemispheric cases.

Fig.6 show the results from the experiments 7, 8, 9 on 4th day. Temperature anomaly field reveals that for symmetric cyclone case (Expt. 7) maximum cooling of about 5^{o}C occurs right of the track on day 4 (fig 6a), which suggests that the mixed layer on the right of the track is cooled more than the left and there is right bias in the temperature field. The isotherms exhibit an oscillation with wavelength of ~ 650 km. ULTD field shows the maximum upwelling of 15 m on the right of the track 3 at a distance of about 50m in the symmetric wind case (Fig. 6b). It has a lag of about 300 km The inertial wave in the wake of the cyclone is seen which has a wavelength of about 500 km. For the experiment 8 of left asymmetric case the maximum cooling decreases to 2.5 ^{o}C. Warming is of the same magnitude as for symmetric case. More warming occurs on the left side of the track for left asymmetry case as against on the right side for the symmetric case. The right bias in the temperature field is reduced (Fig. 6c). ULTD field shows increase in warming on the left of the track. The maximum cooling of the same magnitude occurs on the track itself and the bias is zero (Fig. 6d). For experiment 9 of the right asymmetric case, the temperature field shows increase in the cooling and warming (Fig 6e). The ULTD field shows increase in the upwelling and downwelling magnitude. The right bias is increased (Fig. 6f).

Fig.7 shows the results from the experiments 16, 17, 18 for track 6 in the southern hemisphere, on 4th day. The temperature and ULTD field shows the left bias for symmetric case (Fig. 7a & b). The magnitudes are same as that for northern hemispheric track 3. The left asymmetric cyclonic winds increase the cooling and warming of upper layer (Fig 7c). Also more upwelling and downwelling occurs on the left of the track (Fig. 7d). For the right asymmetric case cooling and warming is reduced as compared to symmetric

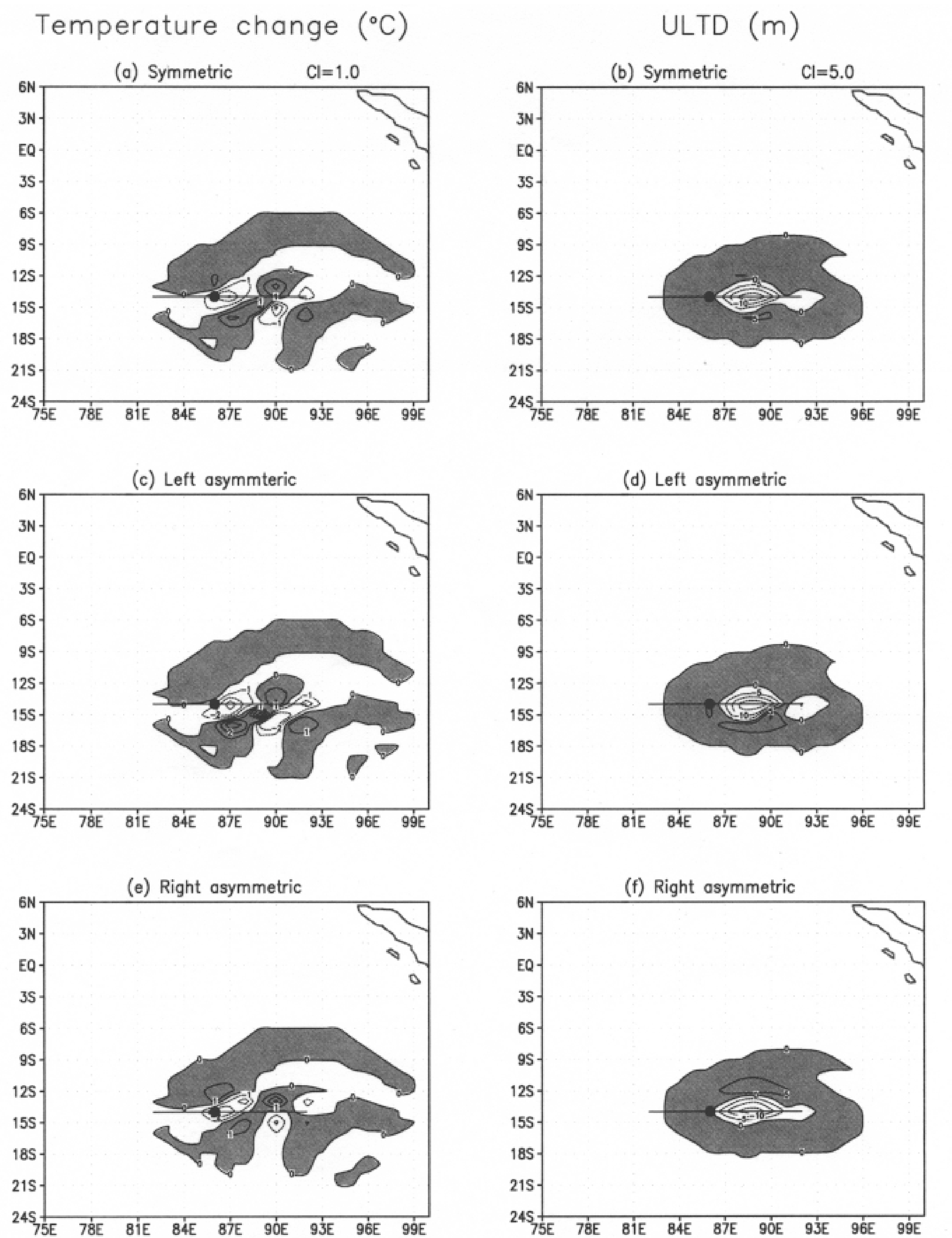

Figure 5. Model temperature change and ULTD for symmetric, left and right asymmetric cyclone moving along track 5 on Day 3, positive values are shaded.

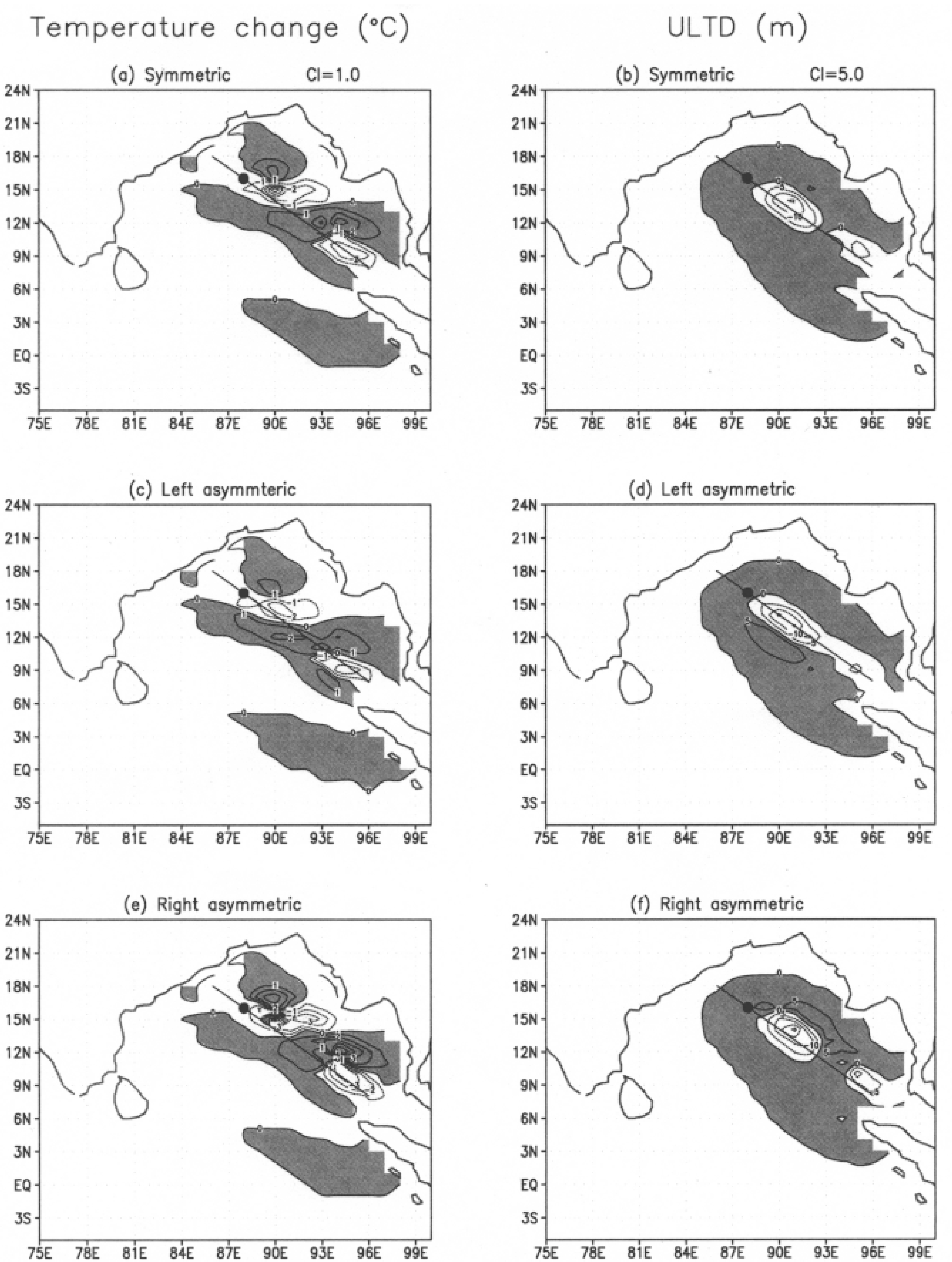

Figure 6. Model temperature change and ULTD for symmetric, left and right asymmetric cyclone moving along track 3 on Day 3, positive values are shaded.

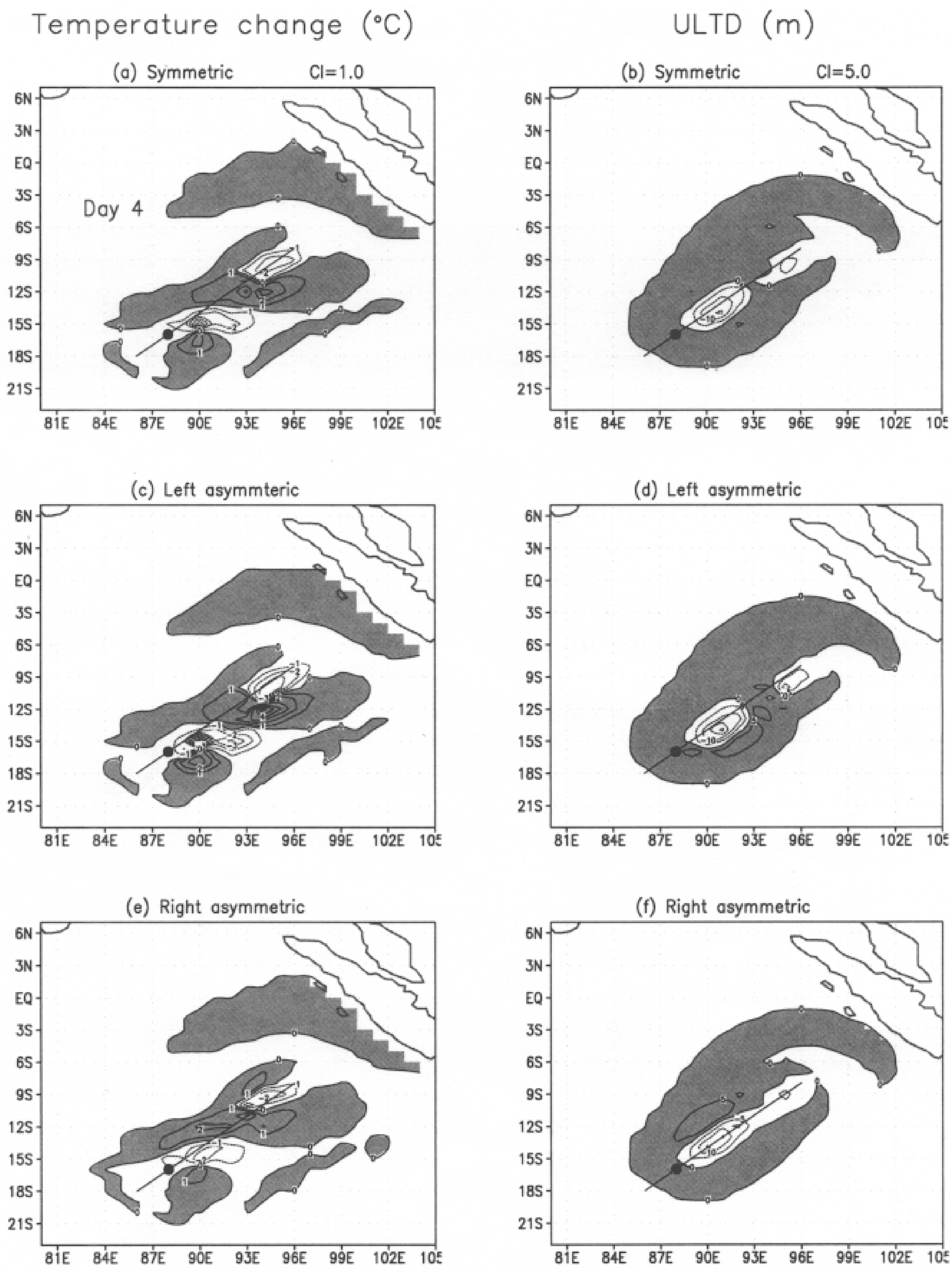

Figure 7. Model temperature change and ULTD for symmetric, left and right asymmetric cyclone moving along track 6 on Day 4, positive values are shaded.

case. The left bias is still present in the temperature field; however warming is more on the right of the track (fig. 7e). The bias is absent in the ULTD field and more warming as compared to symmetric case is seen on the right of the track (Fig. 7f).

CONCLUSIONS

The 1½ layer reduced gravity model used to understand the ocean response to symmetrically moving idealized tropical storm in the northern and southern hemisphere. The oceanic response to a symmetric idealized moving cyclone has right (left) bias in the northern and southern hemisphere. The reason for this is that the wind stresses veer with time to the right of the track and they back to the left of the track in northern hemisphere (Price 1978). Whereas, due to change in sign of Coriolis parameter *f*, the wind stresses veer with time to the left of the track while to the right they back, in southern hemisphere.

There is no difference in the magnitude of model fields for the tracks symmetric along the equator. The oceanic response to the right (left) asymmetric cyclonic winds in the northern hemisphere is same as that for the left (right) asymmetric winds in southern hemisphere quantitatively since they are symmetric about equator. That is, symmetric ocean response is found to the symmetrically moving identical tropical storms in opposite hemisphere.

Ocean response is stronger in the case of right (left) asymmetric cyclonic winds than that in the case of left (right) asymmetric winds in northern (southern) hemisphere. There is increase in the warming and downwelling on the same side of the storm track where the asymmetric wind stress is more.

For all the tracks it is seen that the area of temperature change is widely spread as compared to that of ULTD. Consequently, the lag between the storm position and maximum cooling is less than that for maximum upwelling. The region of influence under the cyclonic storm is more in the southern hemisphere as compared to that in the northern hemisphere due to wide-open ocean.

In this study the influence of ocean response on the cyclone (two way interaction) is not considered. The coupled ocean - atmosphere model for such study would be useful for better prediction of intensity and track of the tropical cyclones. This is proposed to be done in future.

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