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Sensitivity of Oceanic Mixed Layer to Different Model Resolutions in Response to Indian Ocean Cyclone

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ABSTRACT
Present work deals with the numerical investigation of the oceanic upper mixed layer response to Indian Ocean cyclones by changing different model parameters such as horizontal resolution, vertical temperature gradient in a simple 1½-layer wind driven reduced gravity ocean model. The sensitivity experiments are performed for a cyclone moving along a northward track, initially. Cyclones in the Arabian Sea and Bay of Bengal during the year 2004 are chosen. The sensitivity of ocean response to model resolution is examined by increasing the model resolution from ½° x ½° to 1/8 x 1/8° and 1/12° x 1/12°. Further, the sensitivity to initial vertical temperature gradient is also studied. The model simulated SSTs are compared with the observed SSTs during cyclone period. It is found that the cooling in model SSTs is in agreement with that in the observed SSTs for each case.

INTRODUCTION

Tropical cyclones are the most destructive of seasonally recurring rapid onset natural hazards. Each year about 80 to 100 tropical cyclones occur around the world. The extensive coastal belt of India spanning over 7500 km, is vulnerable to these storms. India experiences 4 to 6 such storms annually originating over Indian seas. Devastation by strong winds, heavy to very heavy rainfall, storm surges and coastal floods can lead to huge losses in terms of lives, property and agriculture.

The earlier efforts of modeling the tropical cyclone were confined to the problems of convective parameterization, vortex movement, vortex flow interaction, (Thu & Krishnamurti 1992; Shapiro 1992; Rao & Ashok 1999). Several model studies for simulation of tropical cyclone, prediction of storm track and intensity have been performed (Elsberry 1995; Goerss 2000; Ashok 2001). A good knowledge of the ocean response to storm forcings is a key factor in tropical cyclone prediction. The ocean response to moving cyclones in the Indian Ocean has been studied earlier by considering idealized symmetric and asymmetric vortex for tracks similar to the observed ones (Behera, Deo & Salvekar 1998, Deo, Salvekar & Behera 2001, Deo, Ganer & Salvekar 2004). They also studied how the ocean response is affected by storm intensity, storm translation speed, storm size etc. The objective of the present paper is to investigate numerically the upper mixed layer response to Indian Ocean cyclones by varying different model parameters such as horizontal resolution, vertical temperature gradient across thermocline etc. Such experiments are useful as the finer horizontal model resolution can resolve the vortex more precisely, also the movement of the vortex can be accurately provided to the model, which is the model input. The model output in terms of ocean currents, mixed layer depth and temperature is estimated at the finer grid, which gives the detailed idea of the horizontal variation of these parameters. Initially, the idealized cyclonic storm track along the northward direction is considered for the sensitivity study. Further, the oceanic response to the two cases of Indian Ocean cyclones (TC 01A) and (TC 02B) in 2004 is studied for different resolutions. The simple 1½ layer wind driven reduced gravity ocean model is employed for this study. The model derived Sea Surface Temperature change is validated with the observation for both the cases.

THE MODEL AND DATA

The model used in this study for control experiment is the same as used in Deo, Ganer & Salvekar (2004). The simple 1½ layer reduced gravity ocean model (½° x ½°) over the tropical Indian Ocean (35E-115E, 30S-25N) has one active layer overlying a deep motionless inactive layer. The model equations are based on vertically integrated shallow water equations over the active layer assuming no vertical shear in horizontal field. The formulation of the equations and the numerical methods used are fully described in Behera & Salvekar (1996). The entrainment term in the continuity equation and the thermodynamics added, following Chang & Anthers (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 gradient between the mixed layer and the bottom layer. The initial thermocline is assumed to be 50 m deep and the gravity wave speed is 1 m/s. The initial temperature in the mixed and bottom layer are considered as 29°C and 23°C. The sensitivity of ocean response to model resolution is examined by increasing the model horizontal resolution to 1/8° x 1/8° and 1/12° x 1/12°.

The idealized symmetric cyclonic vortex similar to that of a Rankine vortex is considered as the model cyclone, which has tangential and radial wind components same as that considered in Deo, Ganer & Salvekar (2004). The vortex represents the cyclonic winds well. That is maximum winds at the eyeball and wind magnitude reducing to periphery from the eye wall. Many studies have referred such vortex. The model is forced with the wind stress derived from the cyclonic winds and is integrated for the period of the storm duration from the state of rest with a time step of 30 min.

The daily global TMI Sea Surface Temperature data during the period of cyclones is used to compare the model SST during the passage of two cases of cyclone, one in the Arabian Sea and the other in the Bay of Bengal, in the year 2004.

RESULTS AND DISCUSSION

Idealized track

#The model is integrated for 4 days starting from an initial condition of rest. The wind stress fields derived from the prescribed cyclonic vortex are used as input to force the model. The storm center moves northward from an initial position of (90E, 6N) up to (90E, 14N) in 4 days, so that the translation speed of the storm is 2.55 m/s. The track is chosen such that it is close to frequently occurring tracks. It is a smooth track where cyclone is assumed to travel with uniform speed. The analysis of model output with idealized track is necessary to understand the sensitivity of ocean response, so that it can be considered as the base for comparing with that for observed track. The observed or real tracks are not smooth and hence the ocean response changes due to recurvature etc. To understand the effect of these parameters, the study with idealized track is necessary. In the control experiment the horizontal model resolution is ½° x ½°. The sensitivity of ocean response to model

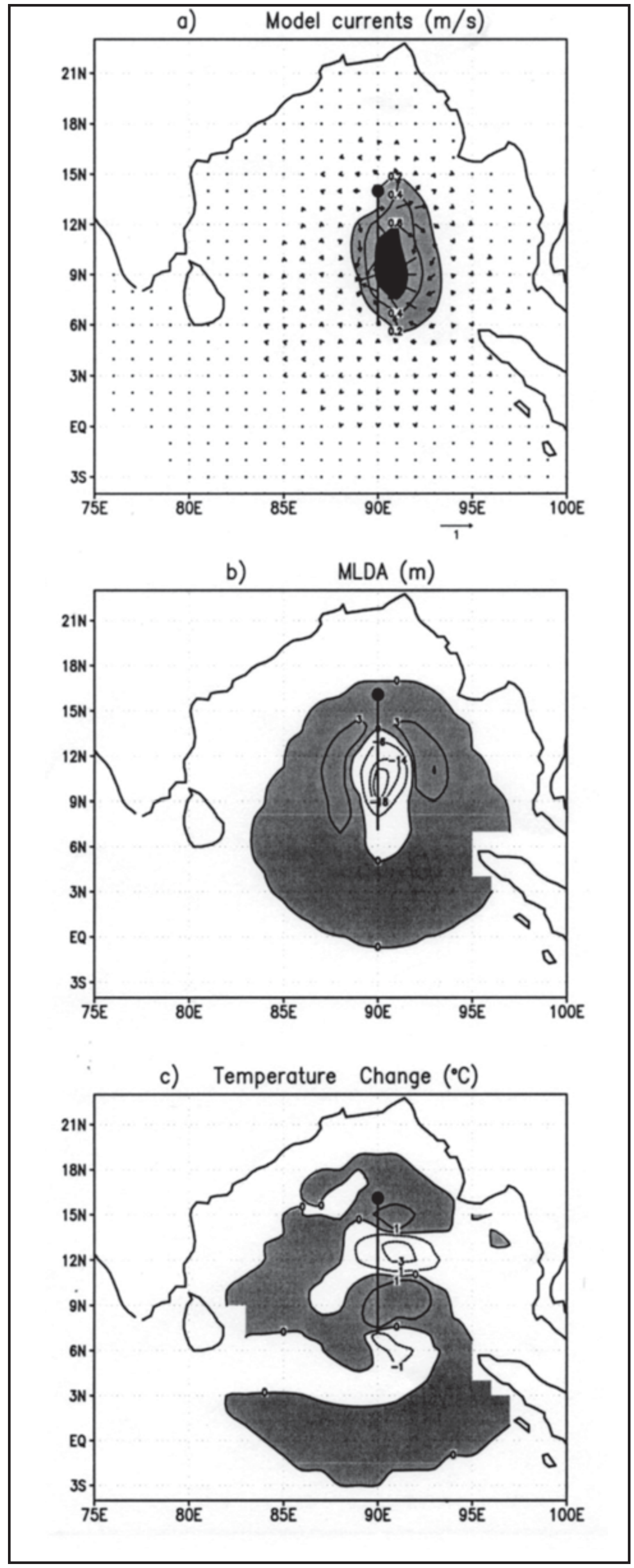

Figure 1. Model Currents, Mixed Layer Depth Anomaly and Temperature Change on the fourth day in the control experiment. Positive values are shaded in b) and c)

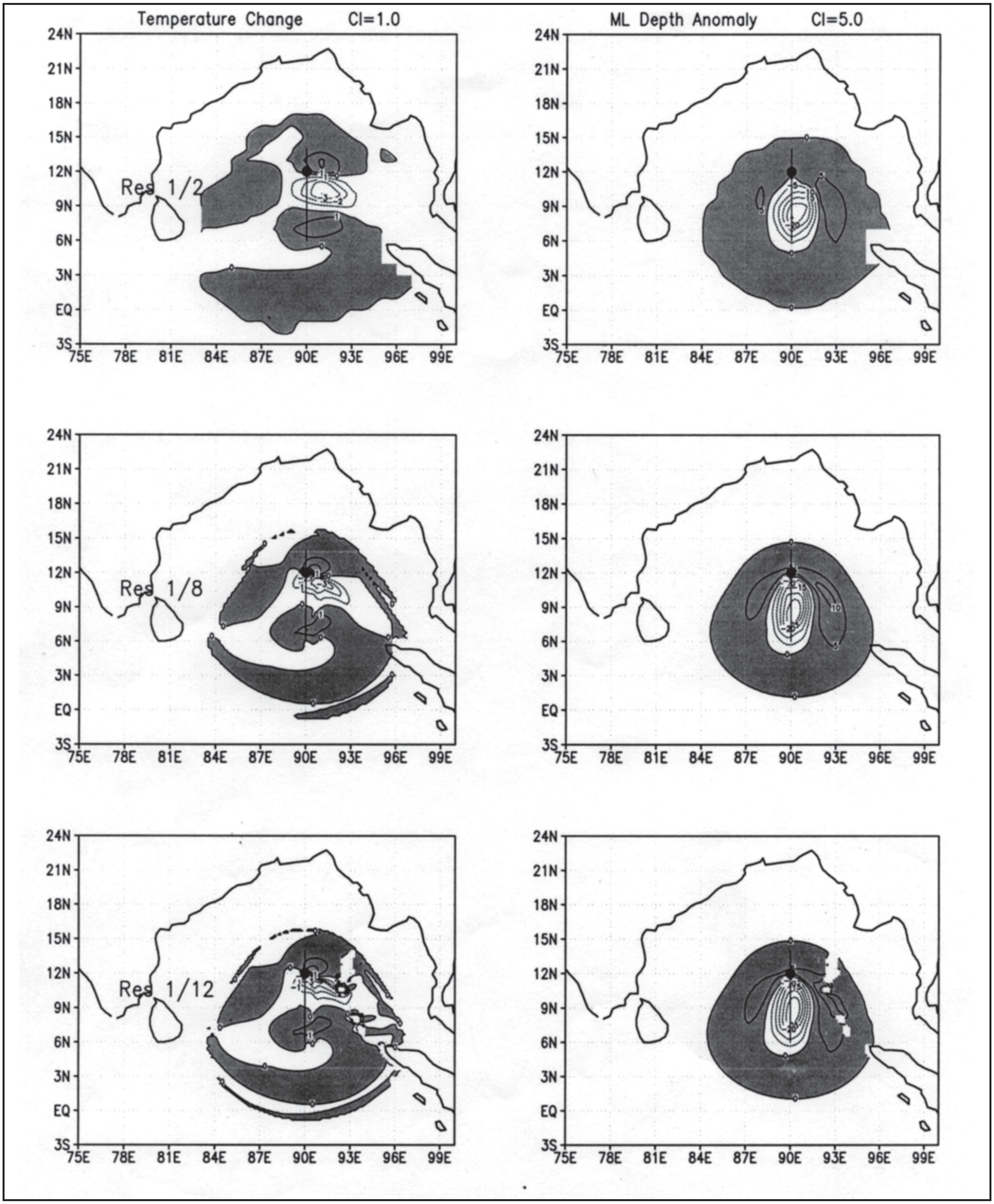

Figure 2. Model Temperature Change (ºC) and Mixed Layer Depth Anomaly (m) on third day for different resoluations. Solid line and dot represents the storm track and position of the storm center. Positive values are shaded.

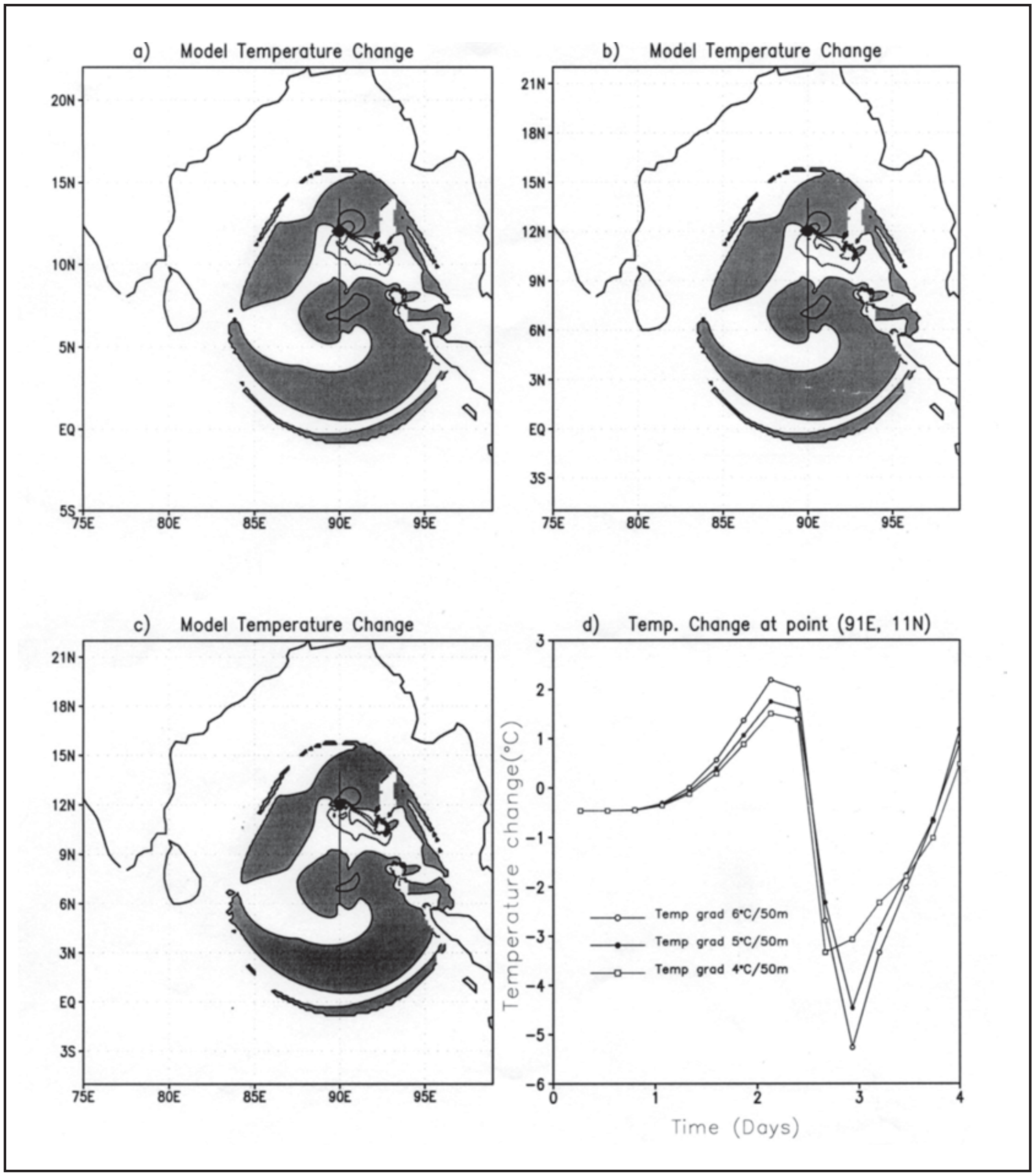

Figure 3. Model Temperature Change on the third day for different values of vertical temperature gradient over 50m, a) 6°C, b) 5°C c) 4°C Positive values are shaded and d) time series at the point (91E, 11N).

resolution is examined by increasing the resolution to 1/8° x 1/8° and 1/12° x 1/12°.

Fig.1 shows the model derived upper layer currents, anomalies in the mixed layer depth and temperature change on the fourth day for control experiment. Solid line drawn is the storm track and the dot represents the position of the storm center. The surface circulation shows the divergence of the flow near the storm center and the maximum magnitude of the circulation (0.7 m/s) is located to the right of the storm track. The right bias is about 100 km and the maximum current lags the storm center by 400 km. The mixed Layer Depth Anomaly (MLDA) field also shows the right bias and the maximum upwelling (22 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 MLDA) is surrounded by the region of downwelling (positive MLDA). 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. 1c). The bias in the temperature field is more than that in the currents or MLD. This asymmetric ocean response in contrast to symmetric wind forcing is also observed in the earlier studies of Price (1981, 1983), Greatbatch (1983, 1984). 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). The model mixed layer depth anomaly and temperature change for the third day for different resolution is displayed in Fig.2. The model fields became stronger for the finer resolution. The upwelling increases from 24 to 29 m and downwelling increases from 9 to 12 m as the resolution is increased from ½° to 1/12 °. The cooling is increased up to 6°C for higher resolution. It is also seen that the areal extent of the region affected is reduced for the higher resolution.

The model temperature change in the case of high resolution (1/12° x 1/12°) was unrealistically high (about 10°C cooling on 4th day). In order to get the realistic model temperature change the initial temperature gradient across the thermocline is reduced. The previous value of 6°C/50 m is changed to 5°C/50m and 4°C/50m in the case of high resolution model. Fig.3 (a, b, c) shows the model temperature change for these three values of initial temperature gradient during the passage of cyclone. The cooling of 6°C is reduced to 3°C as the initial vertical temperature gradient is reduced from 6°C/50 m to 4°C/50 m. Fig. 3d shows the time series of temperature change at a point (91E, 11N) off the track during the passage of the storm. It is clearly seen that warming and cooling of sea surface is decreased for reduced value of temperature gradient. The MLDA field remains constant during this experiment. Hence it should be noted that while using high resolution model, parameterisation of temperature needs to be changed and initial temperature difference across the thermocline should be less, for getting realistic temperature change.

Observed Tracks

Further, the model is integrated for the two observed tracks of tropical cyclones over the Indian Seas, in the year 2004. The first one is the TC 01A (designated ARB0401 by IMD) which formed early in the month of May just off the southwestern Indian coast. TC-01A (5 -10 May) moved erratically for several days, and then began to move on a north- westerly trajectory paralleling the Indian coastline (Fig.4). Based on JTWC's analysis, the system peaked at 23 m/s, but both IMD and the Pakistani Meteorological Department classified ARB0401 as a severe cyclonic storm, implying a Mean Sustained Wind (MSW) exceeding 25 m/s. The second cyclone TC 02B (designated BOB0401 by IMD), during the period 17-19 May, formed south of Calcutta and then moved east-northeastward, (Fig. 4) reaching hurricane intensity and smacking into the northwestern coast of Myanmar where it was quite destructive. The Indian Meteorological Department classified TC 02B as a Very Severe Cyclonic Storm, which implies winds in excess of 33 m/s. The details of the origination, tracking and the synoptic features for both the cyclones are given below:

a) TC 01A

An area of convection developed in the Arabian Sea, roughly 277 km northwest of Cochin, India on 4th May. After 8 hrs the center of the Low Level Cloud Cover (LLCC) was located at approximately 425 km west-northwest of Cochin and the MSW was estimated at 13-15 m/s. On 5th May the center of the system was placed approximately 370 km west-northwest of Cochin, or about 832 km south of Bombay with the MSW of 15 m/s, which was increased to 18 m/s six hours later. Initial motion of the system was very slow towards the west or west-northwest as TC 01A was trapped in a very weak steering environment. The system spent most of the time of the next three days wandering aimlessly around just off the southwest Indian coast. The track during this period looks like a tangled strand of cooked spaghetti. Deep convection continued to consolidate over the LLCC, very slowly, at times being cyclic in nature. Thus, TC 01A was very slow to intensify. The MSW reached 20.4 m/s by 06/0600 UTC, and the winds climbed to their peak of 23m/s at 0000 UTC on the 7th. At this time TC 01A was located approximately 740 km due south of Bombay, and had begun to move a little faster towards the north-northwest. For about 18 hours the cyclone moved slowly and erratically, then began to track at an increased pace toward the northwest due to the influence of a low to mid-level steering ridge building in from India. As late as the 08/1800, TC 01A reached hurricane intensity. However, drier air flowing from the northwest plus moderate vertical shear inhibited further intensification of the cyclone. At 09/1200 UTC, TC01A was centered roughly 370 km southwest of Bombay, and the LLCC became weaker and more elongated. Convection continued to decrease and by

1800 UTC the mid-level circulation got decoupled from the weak LLCC. On 10 May, the system was located approximately 407 km west of Bombay but no LLCC was identified.

b) TC 02B

Late on 14th May an area of convection developed approximately 879 km south of Calcutta, India. The upper-levels were marginal for development with good poleward outflow but with moderate vertical shear. By 1800 UTC on the 15th the system was located about 823 km south-southeast of Calcutta. The convection became better organized over the LLCC and the peak winds were 10-13 m/s. Twenty-four hours later the disturbance was centered about 527 km south-southeast of Calcutta. On 16th May at 2200 UTC, the center of the system was located about 462 km south-southeast of Calcutta. Convection was getting organized over the LLCC and vertical shear continued to weaken. The maximum winds were 13-15 m/s. On 17 May, at 1200 UTC, the center was placed approximately 425 km south of Calcutta with the MSW 18m/s. Twelve hours later the cyclone drifted southwestward to a position almost 555 km south-southwest of Calcutta. However, at 1200 UTC on the 18th, TC 02B reversed direction and was moving northeast- ward at 4.6 m/s. Based on satellite estimates, JTWC upped the MSW slightly to 20.4 m/s. By early on the 19th the cyclone underwent a significant intensification. The MSW increased to 30.6 m/s, and the system was moving east - northeastward at 5 m/s towards the coastline of Myanmar. At 19/0000 UTC the center of TC 02B was located approximately 509 km east-southeast of Calcutta, or about 111 km west-southwest of Sittwe, Myanmar. The center of TC 02B made landfall near Sittwe around 19/0600 UTC. The 1200 UTC warning estimated the MSW at 30.6 m/s which means that the cyclone was of hurricane intensity when it made landfall in Myanmar. At 19/1800 UTC, TC 02B reduced the MSW to 15.3 m/s and placed the weakening center inland near the city of Taurggyi, Myanmar.

The reduced gravity model (½° x ½°) is integrated for the entire life span of these two tropical storms separately, from the initial condition of rest as the control experiments. The idealized cyclonic vortices suitable for these storms are used to force the model in separate numerical experiments. Fig.5 shows the model currents, MLDA and temperature change for the tropical storm TC 01A on the fifth day in the left panel and for TC 02B on the third day in the right panel. The maximum currents of 0.6 m/s are on the right of the track for TC 01A. But the MLDA and Temperature field has left bias giving maximum upwelling (30 m) and maximum cooling (3 °C) on the left of the track. This is due to the erratic nature of the storm track in the first three days. The storm travels southeastward for sometimes when there is looping of the track. This causes the left bias in the MLD and temperature anomalies. For the track of TC 02B the model currents, MLDA and temperature change, have right bias. The maximum currents of 0.2 m/s, maximum upwelling (7 m) and maximum

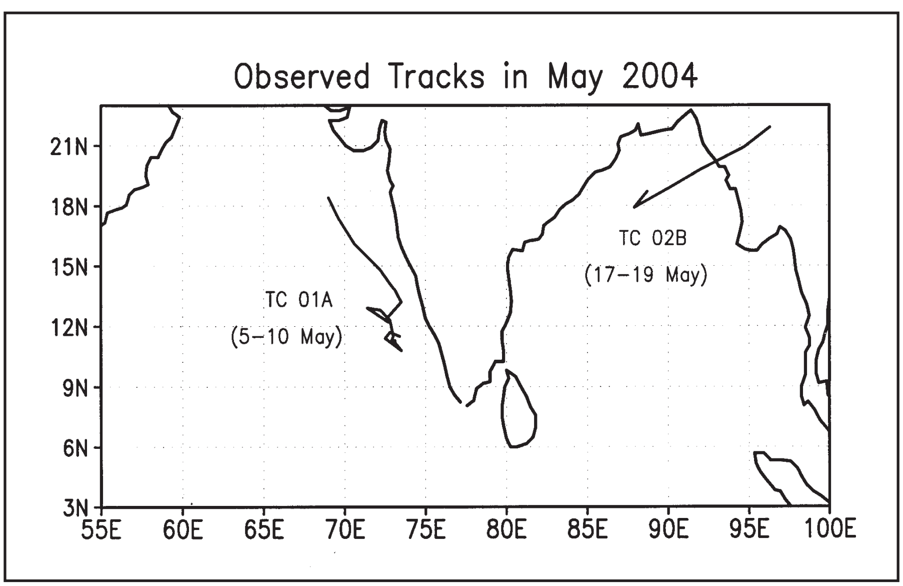

Figure 4. Tracks of Tropical Cyclones TC 01A in the Arabian Sea and TC 02 B in the Bay of Bengal.

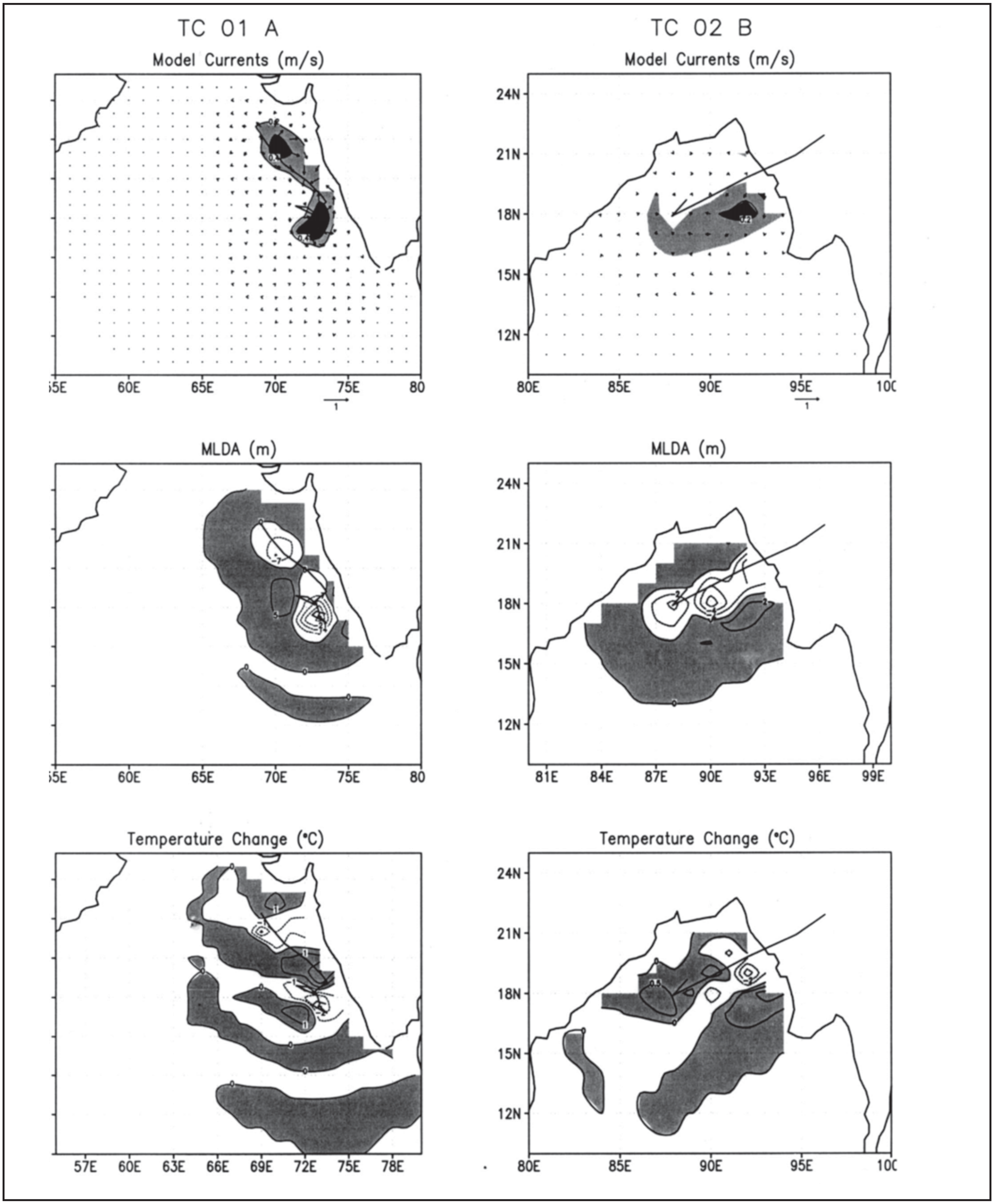

Figure 5. Model Currents, Mixed Layer Depth Anomaly and Temperature Change on the last day of the observed tracks (solid line) in the control experiments. Positive values are shaded.

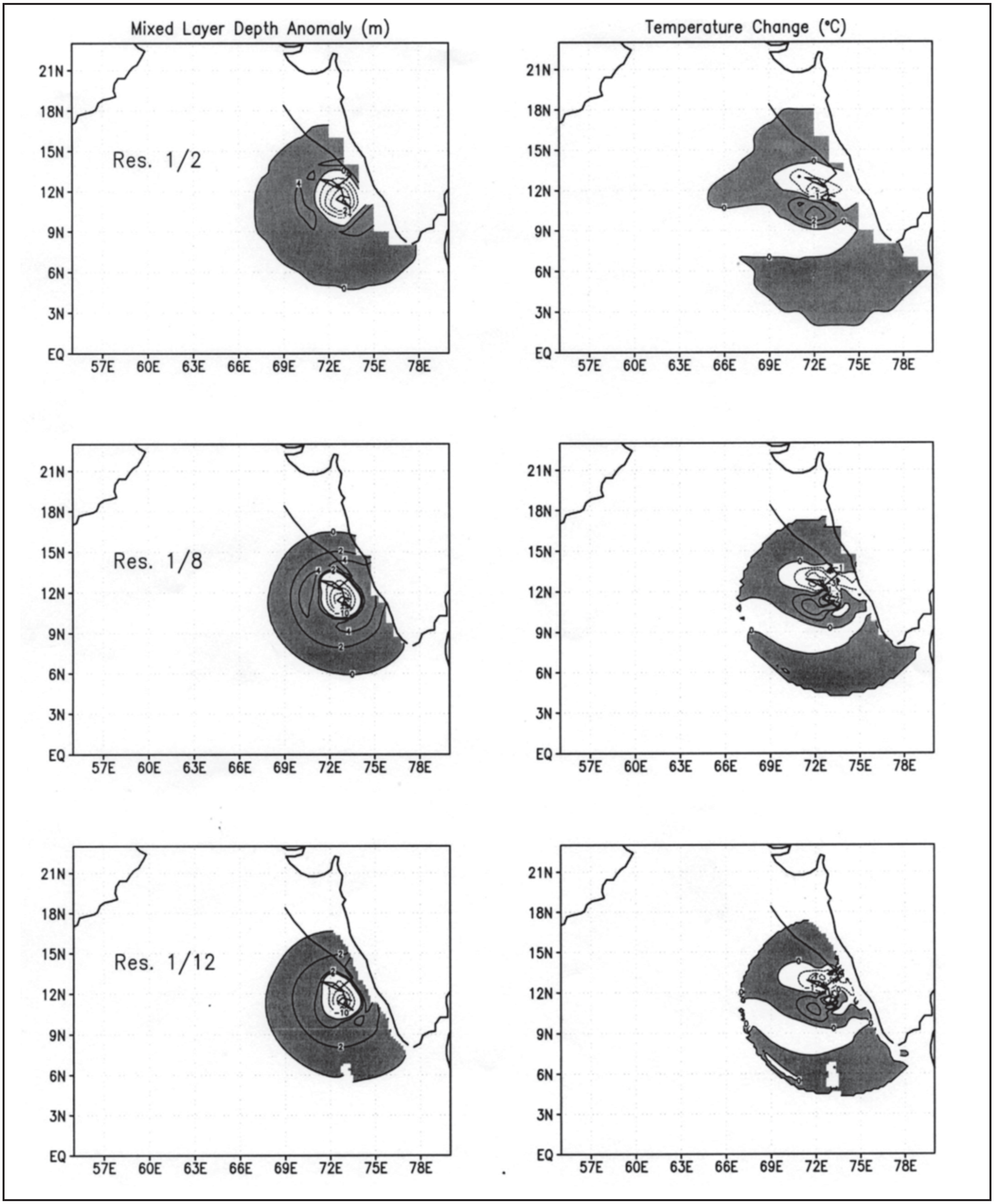

Figure 6. Model Mixed Layer Depth Anomaly and Temperature Change on the third day of TC 01 A, for different resolutions. Positive values are shaded.

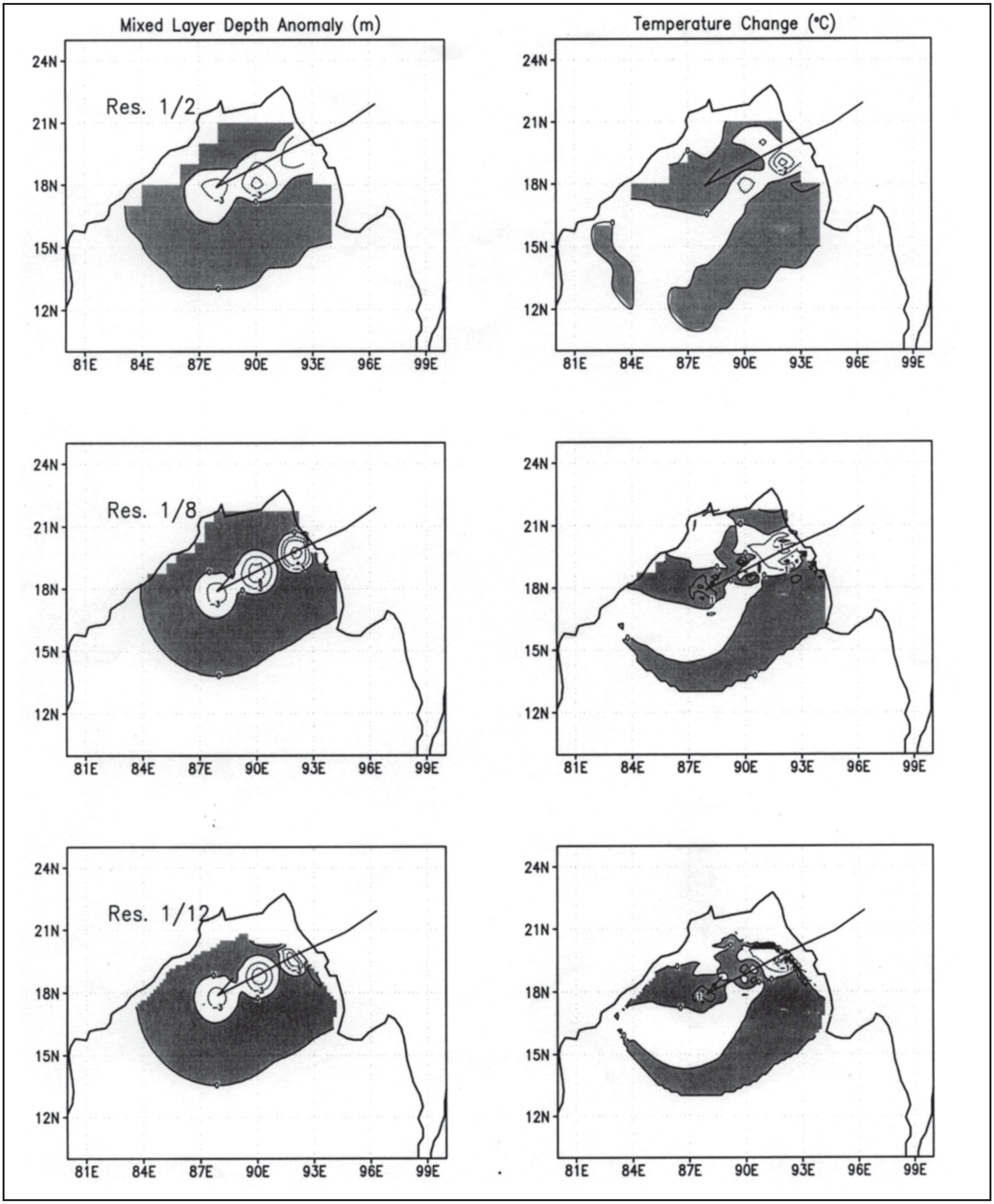

Figure 7. Model Mixed Layer Depth Anomaly and Temperature Change on the third day of TC 02 B, for different resolutions. Positive values are shaded.

cooling (3.5 °C) are on the right of the track (Fig. 5). For both the tracks the surface circulation shows the divergence of the flow near the storm center. Also the region of upwelling (cooling) is surrounded by the region of downwelling (warming).

Further, the sensitivity of the ocean response to horizontal model resolution is studied for both the tracks. The model MLDA and temperature change on the third day of TC 01A for different horizontal resolutions are shown in Fig.6 and those of TC 02B are shown in Fig.7. It is seen that the model fields become strong as the resolution increases. The cooling increases from 3 °C to 7 °C for the TC 01A (Fig. 6) and increases from 3.5 °C to 5°C for the TC 02 B (Fig.7), as the resolution is increased from ½° to 1/12°. The MLDA field shows more increase in downwelling than in the upwelling for the higher resolution for both the cyclones. Qualitatively no significant change is found in the model output for different resolutions.

As was done in the case of the idealized track, the initial vertical temperature gradient across the thermo cline for higher resolution models is reduced accordingly so as to reduce the drastic increase in the model temperature change for both the tracks. The model simulated temperature change thus obtained, is then compared with the observed temperature change from TMI SST during the passage of the cyclones. The observed temperature change and model

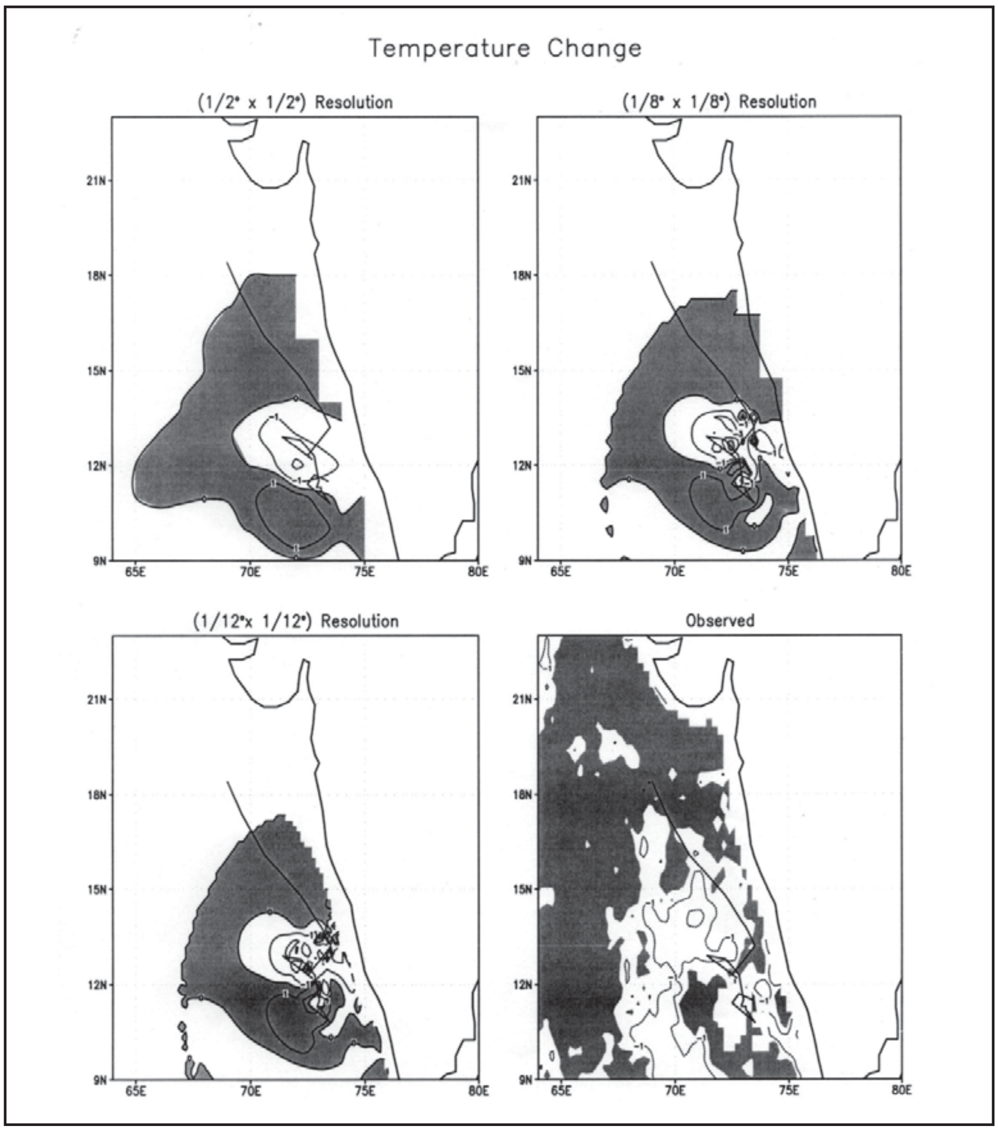

Figure 8. Temperature Change (°C) on the third day of TC 01A, for the different resolutions compared with the observed one. Positive values are shaded.

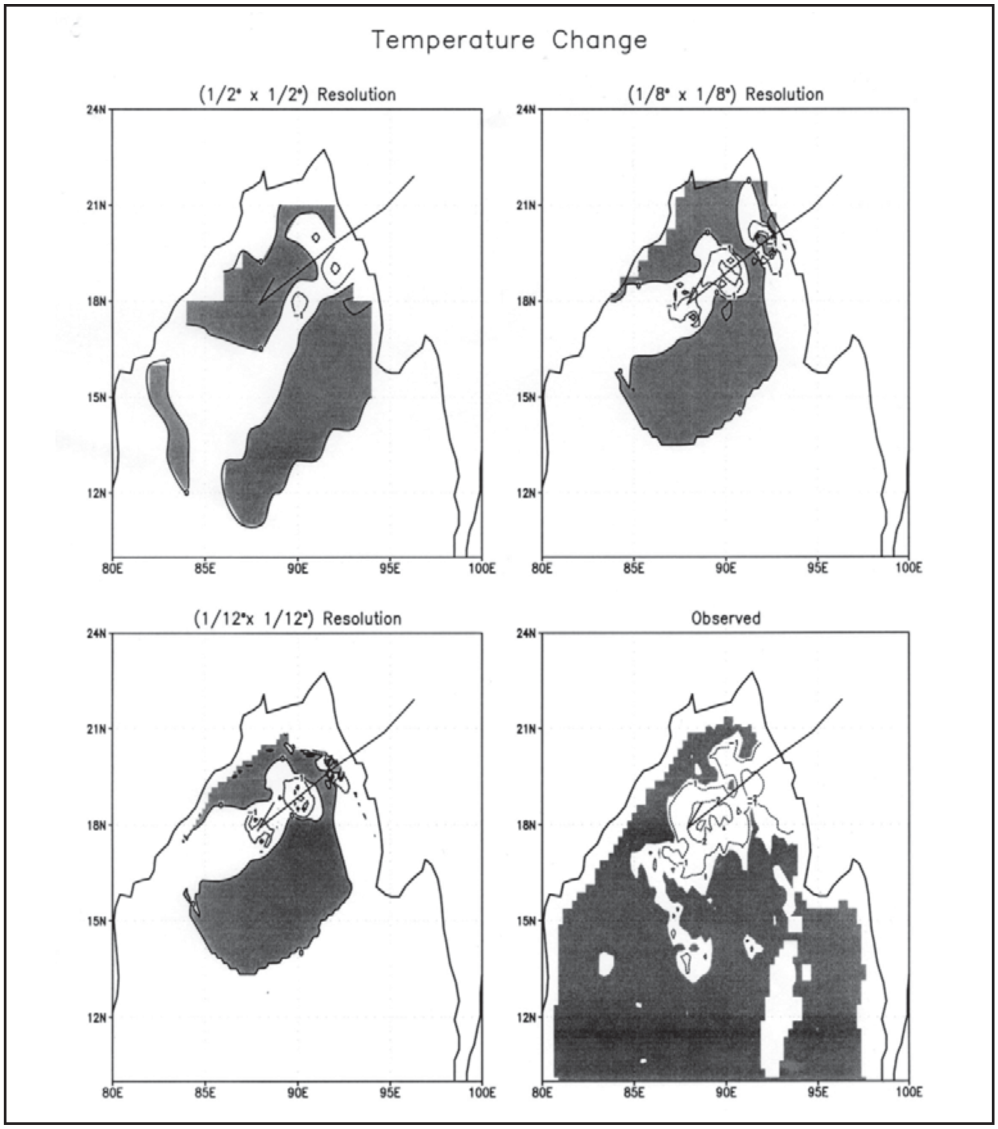

Figure 9. Temperature Change (°C) on the third day of TC 02B, for the different resolutions compared with the observed one. Positive values are shaded.

temperature change for different resolutions on third day of TC- 01A, is shown in Fig.8 and that for TC 02B is shown in Fig.9. It is seen that the observed cooling of 2.5 °C for TC 01A and 3.5 °C for TC 02B is well simulated by the models of different horizontal resolutions. Hence, it is understood that for finer resolution, model parameterization of temperature needs to be changed and initial temperature difference across the thermocline should be less, for getting realistic temperature change.

In the numerical experiment carried out in this study the mixed layer depth and temperature is found to decrease (negative anomalies) to the right of the storm tracks. This cooling in association with upwelling in the wake of the cyclone occurs due to turbulent mixing of the cooler thermocline water into the mixed layer, caused by increased wind stress on the upper layer of the ocean. This leads to a decrease in the SST. The cooling in different models varies from 1°C to about 5°C under the storm depending upon the model parameters such as storm intensity, translation speed of storm and vertical temperature gradient. The cooling causes a reduction of moisture supply to the storm and therefore a possible weakening of the storm. This ocean feedback factor is important to forecasters, especially in the event where the storm is heading towards land or is going to make landfall.

CONCLUSIONS

The 1½ layer reduced gravity model is applied to examine the sensitivity of the upper ocean parameters to different model resolution in response to moving cyclones. In the control experiment for idealized track it is seen that the model fields have right bias, which is well reported in earlier studies. In the sensitivity experiments with different model resolution the model simulated fields are found to become stronger. The cooling in the model becomes 6°C for 1/12° x 1/12° resolution, which is unrealistic. Hence the initial temperature gradient across the thermo-cline is reduced in this model in different numerical experiments. It is seen that when the gradient is reduced the cooling is reduced to the realistic value of 3°C.

The control experiments for the observed tracks of TC 01A and TC 02B are performed with ½ x ½° resolution model. The model upwelling and cooling has left bias for the TC 01A which is unusual. This left bias can be attributed to the erratic motion of TC 01A in first few days. In the case of TC 02B the model fields show right bias. The model cooling is 3 °C and 3.5°C during the passage of TC 01A and TC 02B. The TC 02B being the stronger cyclone than TC 01A, the cooling is more in the former. The sensitivity study with finer model resolutions, resulted in the stronger model output for both the cyclones. Again the numerical experiments with changing vertical temperature gradient have been done, so as to get the reasonable value for model temperature change. The model cooling thus obtained for different resolutions is compared with the observed cooling during the passage of both the cyclones. The model temperature change for different resolutions is in agreement with the observed SST change for both the cyclone cases. Observed cooling of 2.5 °C on the left of the TC 01A track and that of 3.5 °C on the right of the TC 02B track is well in agreement with the model simulated cooling.

The model derived SSTs thus obtained can be used as input to cyclone model, which can forecast the storm intensity and track. The correct way to address this issue is to couple atmospheric and ocean models. By including atmospheric coupling, intensity predictions are likely to improve. In addition, a high-resolution SST analysis and finer resolution cyclone models are needed to obtain accurate intensity forecasts. Moreover, high resolution model output for ocean currents, SST and mixed layer depth are useful near coastal regions when the storm is approaching the coast.

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