J. Ind. Geophys. Union (October 2004)
Vol.8, No.4, pp.283-291

Investigation of upper ocean temperature in response to cyclonic circulations over tropical Indian Ocean using satellite winds

D.W.Ganer, A.A.Deo and P.S.Salvekar
Indian Institute of Tropical Meteorology, Dr.Homi Bhabha Road, Pashan, Pune - 411 008

ABSTRACT
In the present study a 2½-layer thermodynamic ocean model over the region 35°E -115°E, 30 °S - 25 °N is used to simulate the thermal structure during the passage of cyclonic circulations as revealed from daily SSM/I winds. The simulation of Sea Surface Temperature (SST) over the Tropical Indian Ocean with interannually varying daily SSM/I surface winds is in close agreement with observed SST. The daily surface wind data for the year 1994, 1995 and 1996 is examined for the cyclonic vortex during the period of all the cyclonic storms over tropical Indian Ocean. The wind speed however, is less as compared to the real storms. The simulated SST anomalies show cooling of sea surface of the order of 0.5 to 1 °C within a week after the cyclonic circulation has passed over that region. This magnitude of cooling is much smaller due to less wind speed as compared to the earlier model studies and observations reported for cyclone period. The model results for each case are discussed in detail.

INTRODUCTION

The winds induce dramatic changes in the thermodynamic characteristics of the upper north Indian Ocean. The reversal of monsoon winds, strong southwester lies during summer months and cyclonic circulations, cause cooling due to upwelling near the coast and in the interior ocean. The objective of the present study is to examine the sensitivity of a 2½ layer thermodynamic ocean model, for studying the ocean response to cyclonic circulations in the reanalyzed / analyzed surface winds. The daily surface data provides the opportunity to study the effect of such small-scale systems. The daily reanalyzed NCEP surface winds are examined during the period of cyclones in the Indian Ocean. These winds rarely show cyclonic circulations during the existence of cyclones. Hence, the model simulation of SST using these winds does not show the proper thermal response during the existence of cyclone. However, some cyclonic circulations are noticed in daily-analyzed SSM/I winds during the cyclone period. Therefore, model simulated SSTs during the existence of cyclonic storm could be investigated. In this study eight cases of cyclonic storms in the northern and southern Indian Ocean are considered. The evolution of temperature and mixed layer depth during the passage of these storms is studied.

THE MODEL

The model used in this study is a 2½-layer thermodynamic ocean model (McCreary, Kundu & Molinari 1993) hereafter referred as MKM. In short, the model has two active layers overlaying a deep motionless layer of infinite depth. The upper two active layers interact with each other through entrainment and detrainment while conserving mass and heat of the total system. In simpler form the surface uppermost layer is a single layer with a thickness of h_1 and temperature T_1 that separates into two sub-layers i.e. well-mixed upper turbulent layer of thickness h_m and temperature T_m and a non-turbulent fossil layer of thickness h_f and temperature T_f (Fig.1).

The uppermost sub-layer of the surface layer that can be termed as upper mixed layer entrains or detrains water in a process in which the mixing is maintained by turbulence generated by both wind stirring and cooling at the surface. The non-turbulent fossil layer i.e. the lower sub-layer of the surface layer being formed by the detrainment of water from the upper mixed layer is kept isolated from the surface turbulence. There is also provision for detrainment of water from the upper surface layer to the model second layer to conserve mass of the layer, as entrainment through the base of the surface layer takes

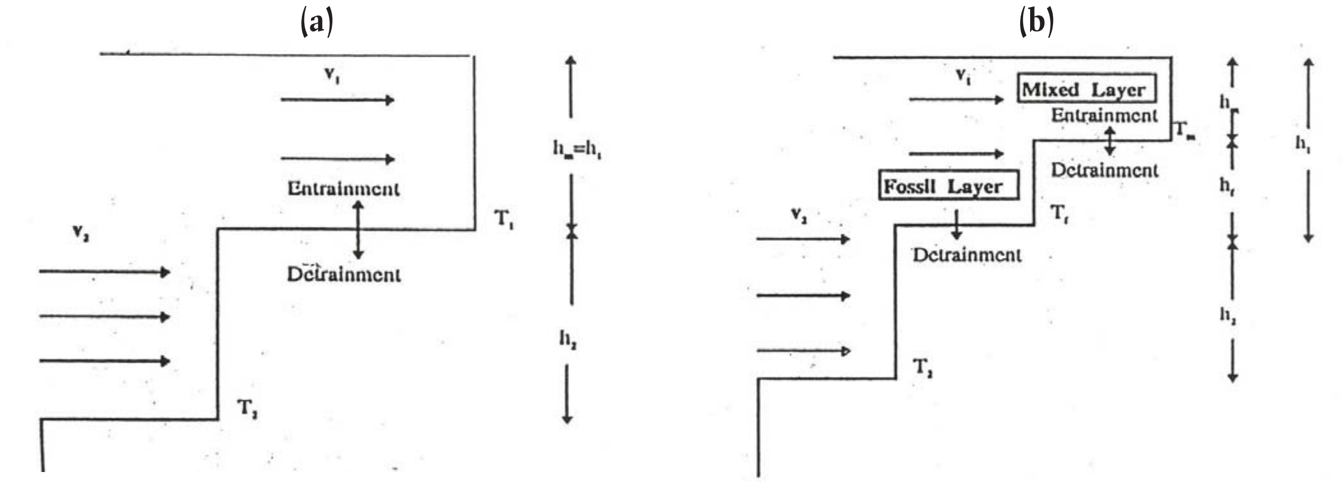

Figure 1. Model structure in (a) simple and (b) complex form

mass from the second layer. In this study the temperature of the uppermost turbulent sub-layer is considered as representative of SST.

MODEL INPUT

Six hourly SSM/I wind data available at 2.5° x 2.0° resolution is averaged over daily scale and linearly interpolated to the model grid (½° x ½°). The interpolated winds show the cyclonic circulations during the considered cyclonic storms. The wind stress was derived from daily SSM/I winds with drag coefficient $C_D = 1.25 \times 10^{-3}$ and air density $\rho = 1.2$ Kg m^{-3}. The surface heat flux used as a thermal forcing in the model is derived from the daily net solar radiation (incoming - outgoing), air temperature, specific humidity and scalar wind magnitudes. These fields were derived from the daily NCEP data set. Linear interpolation is then used in both space and time to get the data at model grid points and at model time steps. The drag coefficient used for computation of sensible heat flux and latent heat flux is same as given in MKM.

RESULTS AND DISCUSSION

Initially the model is spun up with climatological winds obtained by 3-year average of daily SSM/I winds and NCEP heat fluxes for the period 1994 to 1996. The numerical solution reached a quasi-equilibrium state after 6th year. Therefore the model solutions from 7th year are considered as steady state solutions for the inter-annual runs in which the model equations are integrated for further 3 years with inter-annually varying daily winds and heat flux during the considered years. The simulation of north Indian Ocean SST and circulation during the onset phases of SW monsoon was studied (Salvekar et al, 2002). This daily SSM/I surface wind data for the year 1994, 1995 and 1996 is examined for the cyclonic vortex during the period of all the cyclonic storms over tropical Indian Ocean. The cyclonic circulation of about 400 km radius is clearly visible in many cases of cyclonic storms in all the three years. The wind speed however, is less as compared to the real storms. The eight cases of tropical cyclones (Table 1) are chosen during this period of which 5 are in northern hemisphere and 3 are in southern hemisphere.

Earlier, the model simulation studies of tropical cyclones have shown cooling in the wake of cyclone (Chang & Anthes 1978; Behera, Deo & Salvekar 1998, Deo, Salvekar & Behera 2001a). This cooling is found on the right of the track for symmetric vortex. Chang & Anthes (1978) have also shown that this right bias increases for the asymmetric vortex with more winds on the right side. Deo, Salvekar & Behera (2001b) have studied the ocean response with asymmetric vortex with stronger winds on right (left) side and obtained more upwelling on the right (left) side in the northern hemisphere. In the southern hemisphere, (Deo, Ganer & Salvekar 2001c) have shown that the maximum upwelling, or cooling of sea surface due to symmetric cyclonic vortex has left bias. In the light of these studies, the model SST anomalies in response to cyclonic circulations considered for the present study are examined and results are discussed below.

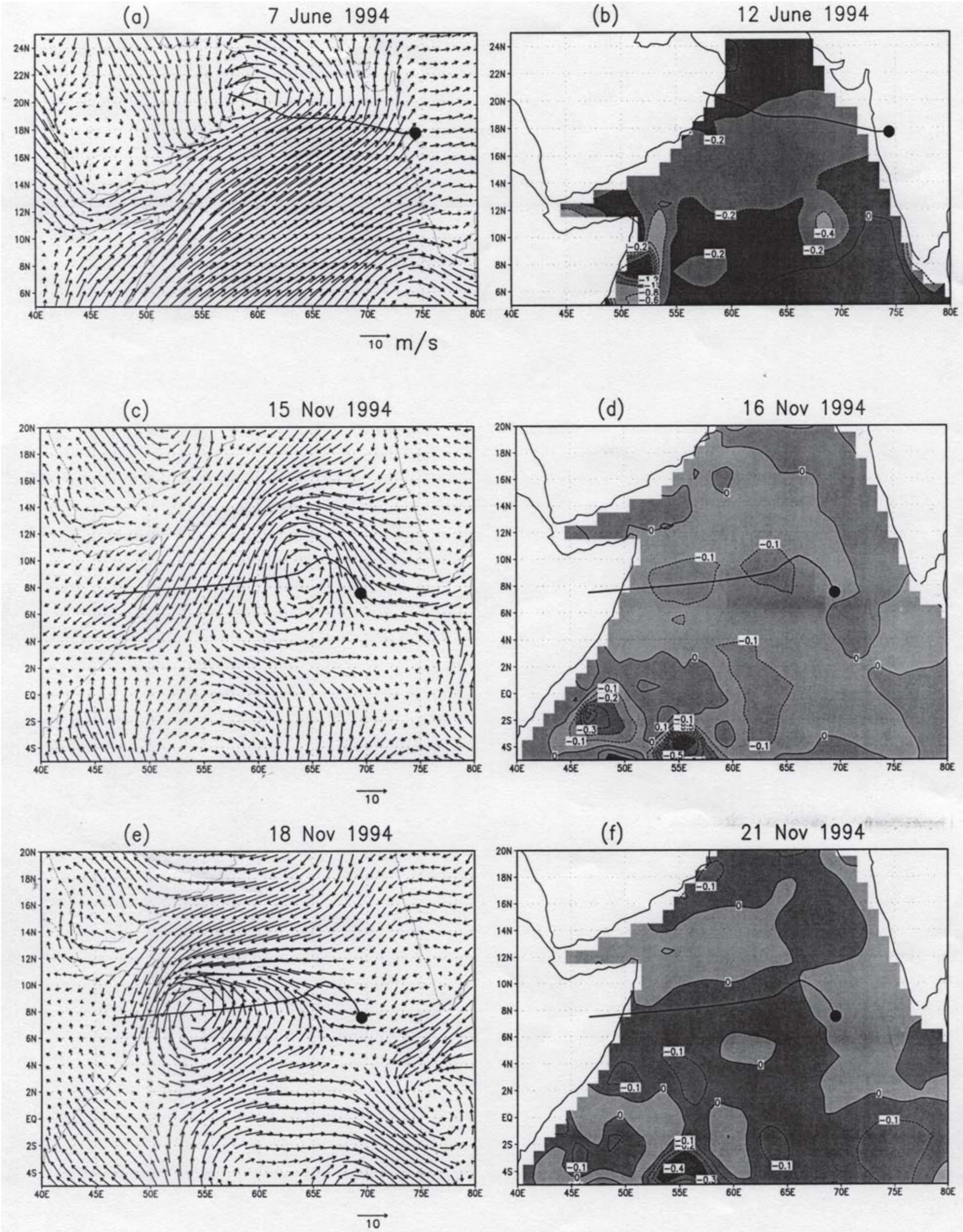

Figure 2. Surface circulation from SSM/I winds and model simulated SST anomalies.

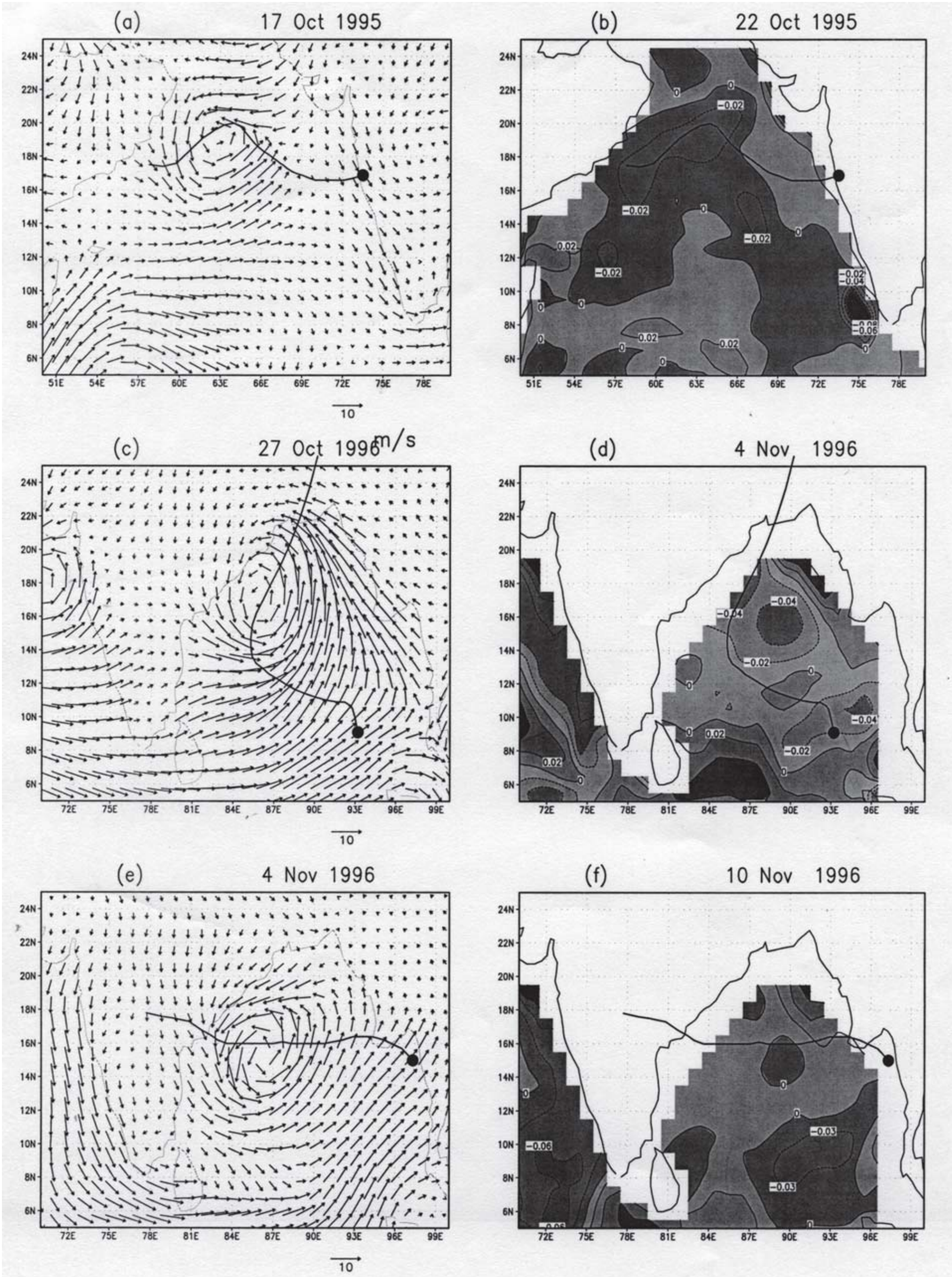

Figure 3. Surface circulation from SSM/I winds and model simulated SST anomalies.

Table 1. Cyclonic storms considered in the present study.

Case No	Year Track Name	Initial Position	Final Position	Duration of the storm
1	1994 TC03A	17.7N, 74.4E	20.6N, 57.5E	5 Jun - 9 Jun
2	1994 TC05A	9.1N, 93.2E	25.6N, 90.2E	13 Nov -20 Nov
3	1995 TC02A	16.9N, 73.5E	17.5N, 57.8E	11 Oct – 18 Oct
4	1996 TC06B	9.1N, 93.2E	25.6N, 90.2E	21 Oct – 29 Oct
5	1996 TC07B	15N, 97.3E	17.8N, 77.7E	1 Nov – 7 Nov
6	1994 12S Quneton	11.7S,112.6E	21.7S, 95.2E	25 Jan -28 Jan
7	1994 15S Hollanda	8.6S, 75E	30.2S, 56.1E	7 Feb – 14 Feb
8	1994 20S Litanne	12.8S, 98.6E	24.6S, 48.8E	8 Mar – 17 Mar

Case 1

The cyclone TC03A in 1994 is in the Arabian Sea and travelled to the northwest direction approximately. Fig.2 shows the SSM/I surface winds in the left panel and the model SST anomalies on the corresponding dates of respective cyclones in the right panel. The track is drawn for easy reference in each case. The dot represents the starting point of the track. The surface winds on 7th June show cyclonic circulation (Fig.2a) and corresponding model SST anomalies show cooling of the order of 0.2° C on 12th June (Fig. 2b). In the present case the cooling is extended on the left of the track, which is possible due to the asymmetric cyclonic vortex with strong winds on the left side of the track.

Case 2

The cyclone TC 05A in 1994 is again in the Arabian Sea and travelled approximately westward. The daily SSM/I surface winds show cyclonic vortex clearly on 15th Nov. 1994 (Fig. 2c). The surface temperature on 16th November shows cooling of sea surface of the order of 0.1 °C along the track (Fig. 2d). The maximum cooling is extended little to the right side of the track. Next again on the 18th Nov the cyclonic circulation has produced the sea surface cooling along the whole track. The cooling is extended more on the right of the track, which is due to asymmetry in the vortex on the left of the track (Fig. 2e & f).

Case 3

The cyclone TC 02A in 1995 in the Arabian Sea has travelled totally to the west direction, initially to the northwest and then southwest direction. The surface winds on 16th October show cyclonic circulation centered at 63E, 19N (Fig 3a). The model SST anomalies displayed in the right panel (Fig.3b) show cooling of the order 0.02 °C. The cold region is extended to the northern side, which is right of the track. The right bias reported earlier (Chang & Anthes 1978; Price 1981), is clearly seen in the temperature field in effect of the symmetric cyclonic circulation.

Case 4

The cyclone TC 06B in 1996 is in the Bay of Bengal. This has travelled initially in the northwest and then

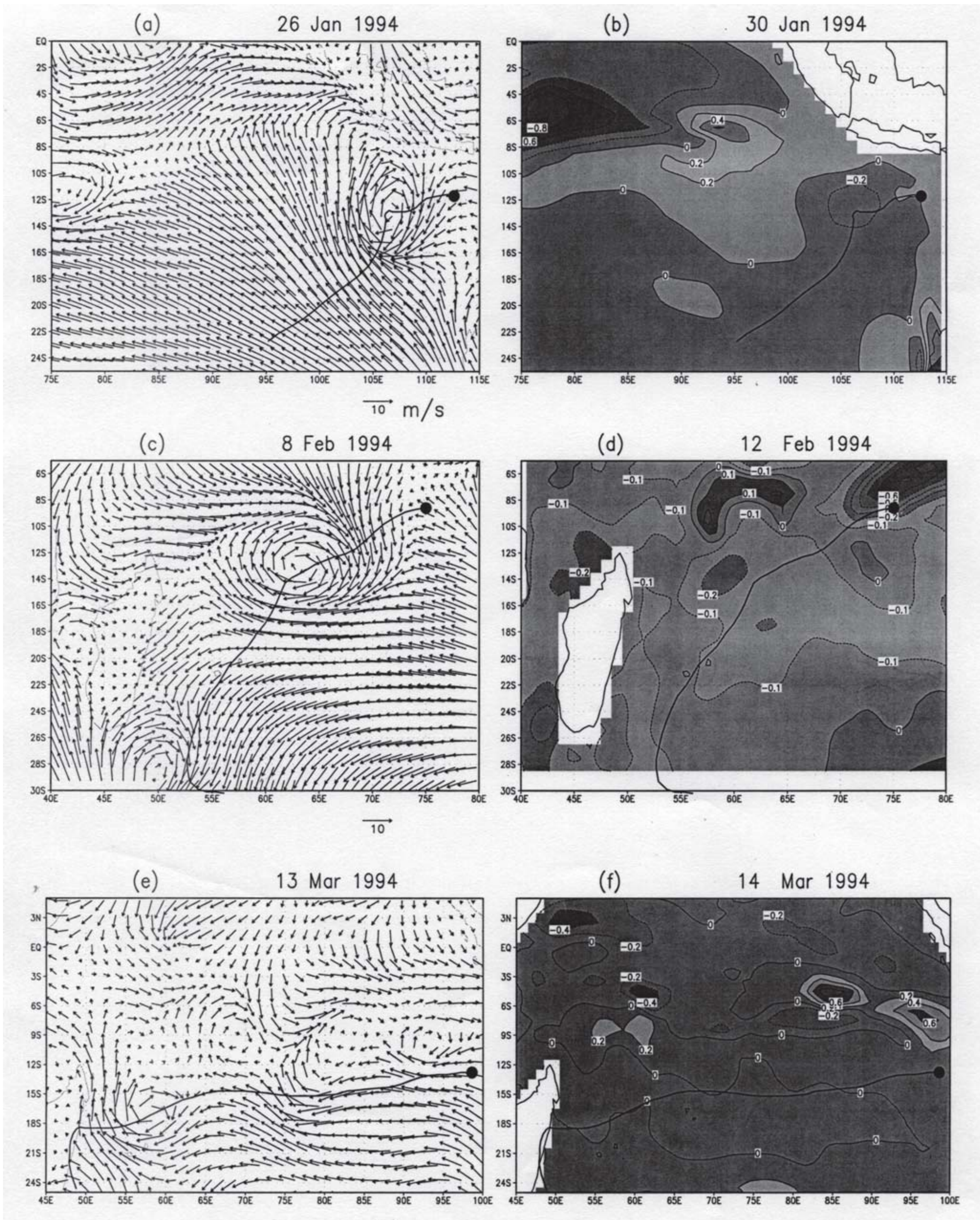

Figure 4. Surface circulation from SSM/I winds and model simulated SST anomalies.

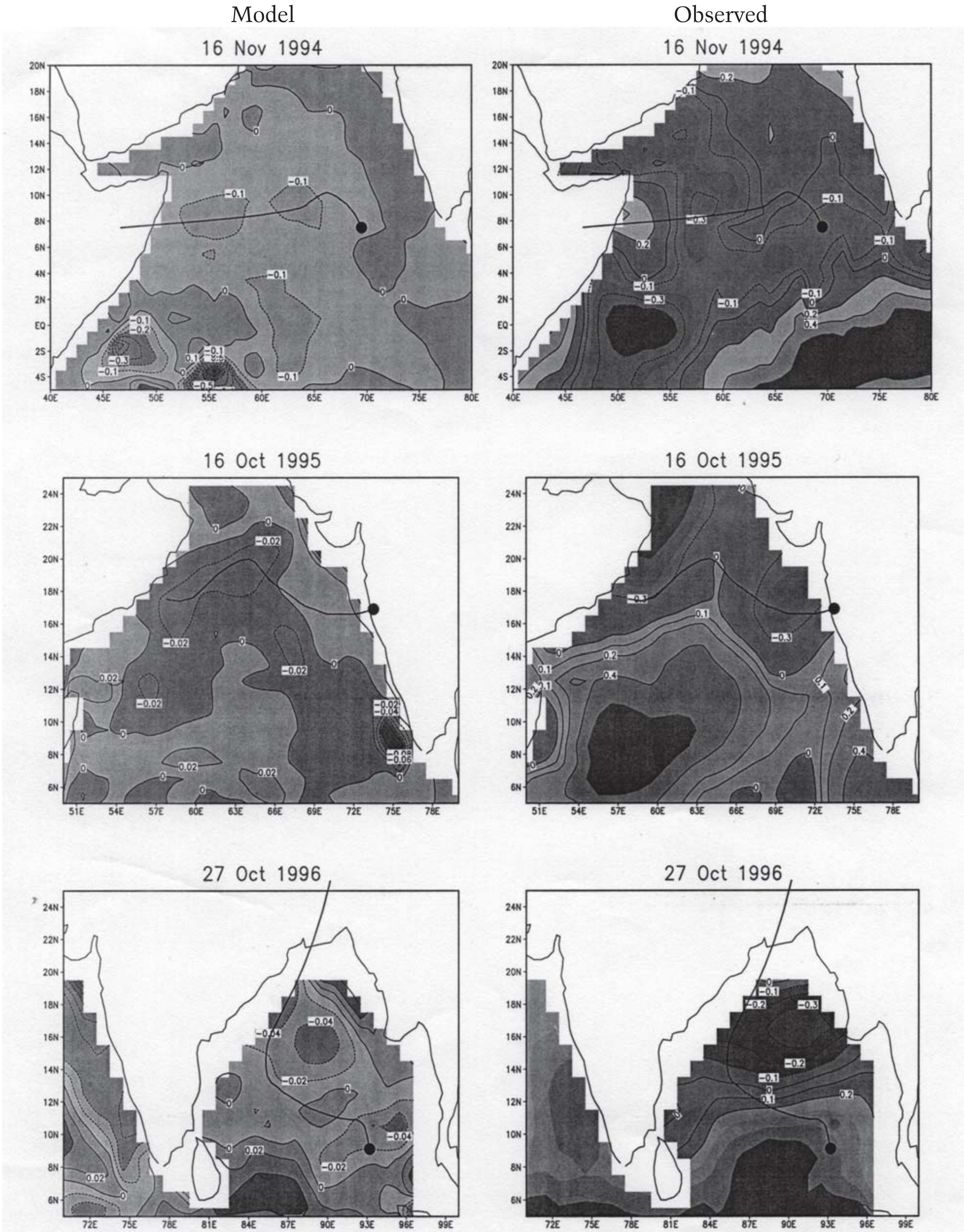

Figure 5. Model and observed SST anomalies for three tracks in each year.

in the northeast direction. Effectively it has a northward track. The winds on 27 October 1996 show cyclonic circulation centered at 87E, 17N (Fig. 3c). The winds are stronger to the right of the track. Therefore, this is the case of asymmetric winds on right side. The corresponding SST anomalies show cooling of sea surface to the right of track and maximum cooling of 0.04°C is seen much to the right of the track (Fig. 3d). The right bias in SST field is increased due to the right asymmetric winds.

Case 5

The cyclone TC 07B is again in the Bay of Bengal. It has travelled in westward direction. The cyclonic circulation on 4th November 1996 (Fig. 3e) shows shifting to the left of the track giving stronger winds to the left of the track. The model SST anomalies (Fig. 3f) show weak cooling on the next day, which has more extent to left of the track.

Case 6

The cyclone 12S Quneton in 1994 is in the southern Indian Ocean. It has travelled in the southwest direction, which is the frequently occurring direction in the southern hemisphere (Fig 4a). In the southern hemisphere, symmetric cyclonic vortex produce cooling of SST more on the left of the track (Deo, Ganer & Salvekar 2001c) but in this case, stronger winds on right of track has shifted the left bias in the winds to the right and cooling of the order 0.2°C is seen in the simulated SST anomalies on 30th Jan (Fig. 4b).

Case 7

The cyclone 15S Hollanda of the year 1994, in south Indian Ocean has moved again in the southwest direction. The vortex is almost symmetric (Fig. 4c) The SST anomalies show cooling of maximum 0.2 °C located to the right of the track but the second cooling maximum of 0.1 °C is located to the left of the track (Fig. 4d). In this case the cooler region oscillates in the wake of the cyclone.

Case 8

The cyclone 20S Litanne in 1994 has translation in the westward direction near to the Madagascar coast and then to the southward direction. The wind field (Fig. 4e) shows cyclonic vortex of smaller size on 13th March approaching near the Madagascar coast. The corresponding SST anomalies (Fig. 4f) show weak cooling of sea surface along the track. The colder region is extended to the left of the track. The weaker cooling is due to the weak and smaller size cyclonic vortex.

All the above-simulated results are in agreement with the earlier studies. However, the magnitude of cooling is less, which is due to the absence of cyclone intensity in the wind forcing.

Further, the model SST anomalies are compared to the observed (Reynolds) SST anomalies for the three cases of cyclones in each year 1994, 1995 and 1996 (Fig. 5). The region of cooling in association with the cyclonic circulation during the above three cases is well simulated and is in agreement with the observed cooling. The model simulated SST anomalies are weaker than the observed. The heat flux used as one of the forcings plays an important role in simulating the SST (Behera et al. 1999). Moreover the winds used are not of cyclone intensity being analyzed winds (~10 m/s), hence simulating weaker than observed cooling. The model mixed layer also shows shallowing in the cooling region during the cyclone period (figure not shown).

CONCLUSIONS

The thermal structure of Upper Ocean is examined during the period of existence of cyclonic circulation as seen in SSM/I winds. The 2½-layer thermodynamic ocean model is used for this study. The cyclonic circulations found in the SSM/I wind data are well organized and are either symmetric (uniform wind circularly) or show stronger winds to the left or right of the track sometimes. The SST anomaly field shows negative values (cooling) in the wake of the cyclone after 2 to 6 days. More cooling to the right (left) of the track is found for northern (southern) hemispheric cyclone, which is in agreement with earlier studies. The stronger winds on either side of the track shift the cooler region to the respective side, more. The model SST anomalies are weak as compared to the observed SST anomalies, however, the region of cooling and warming matches well. The weak model SST anomalies owe to the fact of weak winds as compared to the real cyclonic winds. The heat flux also plays an important role in determining the magnitude of SST. The mixed layer depth examined for these cases show shallowing, which is consistent with the cooling of sea surface in the wake of the cyclone. The sea surface cooling is more for southern hemispheric cyclones compared to northern hemispheric cyclones. This is due to the fact that in southern hemisphere the cyclones have more intensity due to wide-open ocean.

ACKNOWLEDGEMENTS

Authors are thankful to the director of I.I.T.M., for his interest in the work. They are grateful to Dr. Brian Doty for the GrADs software, which is used for preparation of the diagram. This work is carried out on SUN Ultra 60 workstation, which is acquired under DOD project. The daily SSM/I data for the required period is obtained from SAC under the IITM-SAC collaborative project.

REFERENCES

Behera, S.K., Deo A.A.& Salvekar,P.S.,1998. Investigation of mixed layer response to Bay of Bengal cyclone using a simple ocean model, Meteo. Atmos. Phys.,65, 77-91.

Behera,S.K., Salvekar,P.S. & Ganer,D.W.,1999. Numerical Investigation on wind Induced Interannual variability in the north Indian Ocean SST', I.I.T.M. Res. Rep. No. RR-085, pp 31.

Chang,S.W. & Anthes,R.A.,1978.Numerical simulation of the ocean's nonlinear baroclinic response to translating hurricanes, J. Phys. Oceano., 8, 468-480

Deo,A.A., Salvekar,P.S. & Behera, S.K., 2001a. Oceanic response to cyclone moving in different directions over Indian Seas using IRG model, *Mausam*, 52, 163-174.

Deo, A.A., Salvekar, P.S. & Behera, S.K., 2001b. Response of oceanic upper layer to an idealised, asymmetric tropical cyclone in the Indian Ocean, Proc.of National Symposium, TROPMET 2000, 202-265.

Deo,A.A, Ganer,D.W. & Salvekar,P.S., 2001c.Upper ocean response to a moving cyclone in south Indian Ocean. WGNE Report on Research Activities in Atmospheric and Ocean Modelling., pp 8.3-8.4

McCreary,J.P., Kundu,P.K. & Molinari, R.L.,1993. A numerical investigation of dynamics, thermodynamics, and mixed layer processes in the Indian Ocean; *Prog. Ocean*. 31, 181-244

Price,J.F., 1981. Upper ocean response to a hurricane. J. Phys. Oceano., 11,153-175.

Salvekar, P.S., Ganer, D.W., Deo,A.A., Rahul Reddy P., Sujit Basu and Raj Kumar, 2002. Numerical Simulation of North Indian Ocean State Prior to the Onset of SW Monsoon using SSM/I Winds, J. Mar. Geo., 25, 115-131.

(Accepted 2004 April 30. Received 2004 April 21; in original form 2003 November 22)