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Impact of sea surface temperature in modulating movement and intensity of tropical cyclones

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Abstract It is well recognized that sea surface temperature (SST) plays a dominant role in the formation and intensification of tropical cyclones. A number of observational/empirical studies were conducted at different basins to investigate the influence of SST on the intensification of tropical cyclones and in turn, modification in SST by the cyclone itself. Although a few modeling studies confirmed the sensitivity of model simulation/forecast to SST, it is not well quantified, particularly for Bay of Bengal cyclones. The present study is designed to quantify the sensitivity of SST on mesoscale simulation of an explosively deepening storm over the Bay of Bengal, i.e., Orissa super cyclone (1999). Three numerical experiments are conducted with climatological SST, NCEP (National Center for Environmental Prediction) skin temperature as SST, and observed SST (satellite derived) toward 5-day simulation of the storm using mesoscale model MM5. At model initial state, NCEP skin temperature and observed SST over the Bay of Bengal are 1–2°C warmer than climatological SST, but cooler by nearly 1°C along the coastline. Observed SST shows a number of warm patches in the Bay of Bengal compared with NCEP skin temperature. The simulation results indicate that the sea surface temperature has a significant impact on model-simulated track and intensity of the cyclonic storm. The track and intensity of the storm is better simulated with the use of satellite-observed SST.

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Keywords Sea surface temperature (SST) · Tropical cyclone · Intensity · Track · Heat flux

1 Introduction

The Bay of Bengal is a potentially energetic region for the development of cyclonic storms (Gray 1968). At an average 3–4 tropical cyclones, 2–3 of severe intensity hit the east coast of India in a year. These storms, in particular, post-monsoon storms, are devastating (De Angelis 1976). As far as the death toll is concerned, the Indian region is one of the worst affected parts of the world and is mainly due to densely populated coastal regions, shallow bathymetry, and the almost funnel shape of the coastline.

It is well recognized that the ocean provides the necessary energy for the formation (genesis) and intensification (maintenance of deep convection) of tropical cyclones (Palmen 1948; Riehl 1979; Miller 1958; Malkus and Riehl 1960). A number of empirical studies (Brand 1971; Namias 1973; Gray 1975) suggested that tropical cyclones form over relatively warm ocean and tend to follow tracks along areas of warm water and weaken when moved over cooler water (Fisher 1958). A number of observational and modeling studies (Miller 1958; DeMaria and Kaplan 1994; Cione and Uhlhorn 2003; Ooyama 1969; Rosenthal 1971; Shay et al. 2000; Bosart et al. 2000) established the relationship between changes in tropical cyclone intensity and changes in sea surface temperature (SST). Although these findings are significant, it is still difficult to quantify the extent to which changes in SST have an impact on changes in tropical cyclone intensity, and this can be done only through controlled numerical experiments.

In the present study, the authors tried to provide an estimation of the impact of sea surface temperature changes/gradient on mesoscale simulation of the Orissa super cyclone, which was the most intense storm of the century in the Bay of Bengal. The next section provides findings of some important observational and empirical studies. In subsequent sections, the mesoscale model used in the present study is briefly described, the numerical experiments conducted and the data used are discussed, the results obtained, observational facts, and related discussions are presented, and the conclusions drawn from the study are provided.

2 Important observational studies

Merrill (1987) examined the relationship between the intensity of tropical cyclones (hurricanes) in the Atlantic Ocean and climatological sea surface temperature (SST). The study was based on observations from a sample of 12 hurricane seasons. It clearly pointed out that intense storms occur over warm SST regions although it is not a sufficient condition for the intensification of these storms. This finding was later confirmed for tropical cyclones over other basins as well (Evans 1991). DeMaria and Kaplan (1994) investigated the nature of the intensification of Atlantic cyclones occurring over a span of 30 years and established an empirical relationship between storm intensity and climatological SST. The study once again clarified that occurrence of cyclonic storms is much less with SST < 26°C, even if other atmospheric conditions are favorable. The most important finding from this study is that the SST and its gradient have the greatest influence on intensity of the storm when it varies within the range 26–29°C. With SST > 29°C, the SST gradient seems to have relatively less impact on the intensification of cyclonic storms. Orlanski (1998) made an attempt to relate the trajectory followed by the hurricanes with the prevailing SST and concluded that cyclonic storms always have the tendency to reach the warm ocean surface.

3 Model description

The community mesoscale model (fifth generation) MM5 developed at Pennsylvania State University (PSU)/National Center for Atmospheric Research (NCAR) is used in the present study. This is a non-hydrostatic primitive equation mesoscale model with pressure perturbation p', three velocity components (u, v, w), temperature T and specific humidity q as the main prognostic variables. Model equations are written in surface pressure weighted flux form in the terrain following sigma co-ordinates and solved in an Arakawa B grid. The leapfrog time integration scheme together with the time splitting technique is used for integrating the model.

The most useful feature about this modeling system is its flexibility in terms of many options that are user-specified. Setting these parameters to appropriate values, the model can be used for a wide range of weather and climate applications. The model has already shown its skill in the simulation of severe Bay of Bengal cyclones (Mandal et al. 2004; Mohanty et al. 2004) and also those in other basins (Karyampudi et al. 1998; Liu et al. 1997, 1999; Braun and Tao 2000).

A detailed description of the model is available in Dudhia (1993) and Grell et al. (1995). The overview of the model used in this study is shown in Table 1.

Table 1 Overview of the mesoscale model fifth generation (MM5) model used in the present study. *PBL* planetary boundary layer, *NCAR* National Center for Atmospheric Research, *NCEP* National Centre for Environmental Prediction, *MRF* medium range forecast

Dynamics	Non-hydrostatic
Model domain	10°S–30°N, 60°E–110°E
Horizontal grid distance	30 km
Integration time step	45 s
Map projection	Mercator
Horizontal grid system	Arakawa B-grid
Vertical co-ordinates	Terrain-following sigma co-ordinates, 23 sigma levels (seven within boundary layer)
Time integration scheme	Leapfrog scheme (with time split technique)
Spatial differencing scheme	Second order centered
Lateral boundary condition	Relaxation
Top boundary condition	Rigid lid
Radiation parameterization	NCAR CCM2 radiation scheme
Surface layer parameterization	Multi-layer soil model
Cumulus parameterization	Grell
PBL parameterization	NCEP MRF
Microphysics	Hsie's warm rain scheme

4 Experimental design and data used

The super cyclone that crossed the Orissa coast on 29 October 1999 was the most intense storm of the century in the Bay of Bengal. The initial vortex of the storm was observed over the gulf of Thailand at 00:00 UTC (Universal Coordinated Time) on 24 October 1999 and is believed to be a remnant of the tropical cyclone "TS992EVE" over the South China Sea. Moving westward across the Malaysian Peninsula, it emerged in the north Andaman Sea as a well-marked low-pressure area at 00:00 UTC on 25 October. Moving in a west of northwesterly direction it had intensified into a cyclonic storm by 03:00 UTC on 26 October and into a severe cyclonic storm by 03:00 UTC on 27 October. Moving in the same direction, it further intensified into a super cyclonic storm by 18:00 UTC on 28 October. The storm crossed the Orissa coast close to the south of Paradip around 05:30 UTC on 29 October. Figure 1 shows the satellite picture of the storm at the time of landfall as obtained from METEOSAT-5. After landfall, the storm was found to lay centered around 20.5°N/86.0°E by 06:00 UTC on 29 October (close to Bhubaneswar). It remained almost stationary at this location for nearly 42 hours and caused exceptionally heavy rainfall over Orissa during 29–31 October 1999.

The mesoscale model MM5 described in the previous section was used to simulate the Orissa super cyclone to investigate the influence of SST in modulating the intensity and track of the storm. The NCEP/NCAR reanalysis dataset (2.5° × 2.5°) horizontal resolution) interpolated to model grids was used as initial and boundary conditions for model integration. The model was initialized with 12 hours' analysis

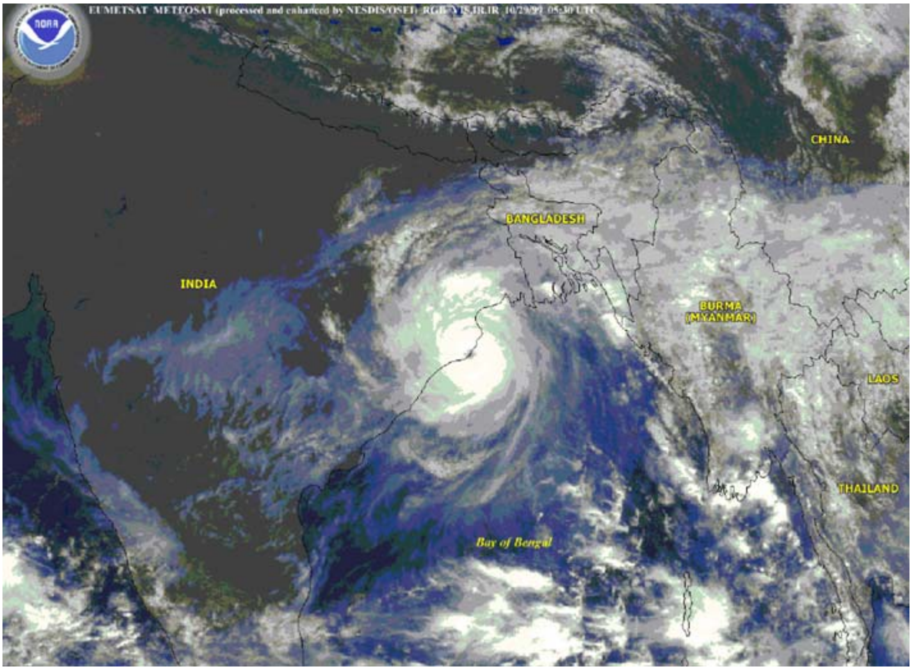

Fig. 1 Satellite picture of the storm as obtained from EUMETSAT METEOSAT at 05:30 UTC (Universal Coordinated Time) on 29 October 1999, i.e., at the time of landfall

nudging before the start of the actual forecast period at 00:00 UTC on 26 October 1999 and was integrated for 123 hours to produce a 5-day simulation of the storm. To investigate the impact of SST and its gradient, three numerical experiments were conducted with three types of SST data. All other meteorological and geophysical parameters were kept unchanged in all these experiments and the SST was also kept constant throughout the model integration period.

The model was first integrated with $1° \times 1°$ resolution monthly mean climatological SST from NCEP and this will be referred to as ''CONTROL'' simulation hereafter. In the next experiment, the model was forced with SST derived from skin temperature in an NCEP reanalysis dataset and will be referred to as ''EXPERIMENT 1'' in the subsequent discussion. In the last experiment, the SST provided to the model was the reanalysis prepared with NCEP skin temperature as background field and satellite-derived (TRMM) SST observations (at $0.25° \times 0.25°$ resolution). This methodology has been employed as the observed SST data was missing in some areas and could not be used directly. This final experiment will hereafter be referred to as ''EXPERIMENT 2''. The monthly mean climatological SST data used in the CONTROL simulation was from NCEP and was prepared by combining measurements from satellite-borne instruments and in situ ship and buoy platforms using the Optimum Interpolation technique (Reynolds and Smith 1994). The climatological SST was prepared for the period 1981–1997 (Reynolds and Smith 1995).

5 Results and discussions

The results obtained from the numerical experiments are presented with related observational facts. The focus is on the intensity (in terms of sea level pressure, wind strength, and precipitation) and track of the storm.

5.1 Influence on intensity

Figure 2 represents the SST field used in three model simulations CONTROL, EXPERIMENT 1, and EXPERIMENT 2 along with the track of the storm obtained from respective model simulations. This shows that in all three simulations, the storm was initially over the same SST zone ($301.5 < \mathrm{SST} < 302$). Figure 3 illustrates the model simulated mean sea level pressure. In the first two experiments (CONTROL and EXPERIMENT 1), the storm moved over the same SST zone in the first 24 hours and intensified in a steady rate. In EXPERIMENT 2, the storm moved over a positive SST gradient in the first 18 hours and over a negative SST gradient in the next 6 hours. The model-simulated central pressure drop shows that the increase in the rate of intensification of the storm was higher in the first 18 hours than in the next 6 hours, although the pressure drop in the first 24 hours was the same in all three simulations. Close examination of latent and net heat fluxes (Figs. 4, 5; Table 3) also reflects a similar trend. The model-simulated PBL height (shown in Fig. 6) was marginally more in EXPERIMENT 2 indicating a tendency toward higher intensification in the coming hours. It can be mentioned here that the model-simulated (in all three experiments) central sea level pressure (SLP) on day 1 (27 October 1999) was the same as the observed central SLP (998 hPa, Table 2), although the initial strength of the storm (central SLP of 1,002 hPa) was not well represented in the model's initial condition derived from NCEP reanalysis.

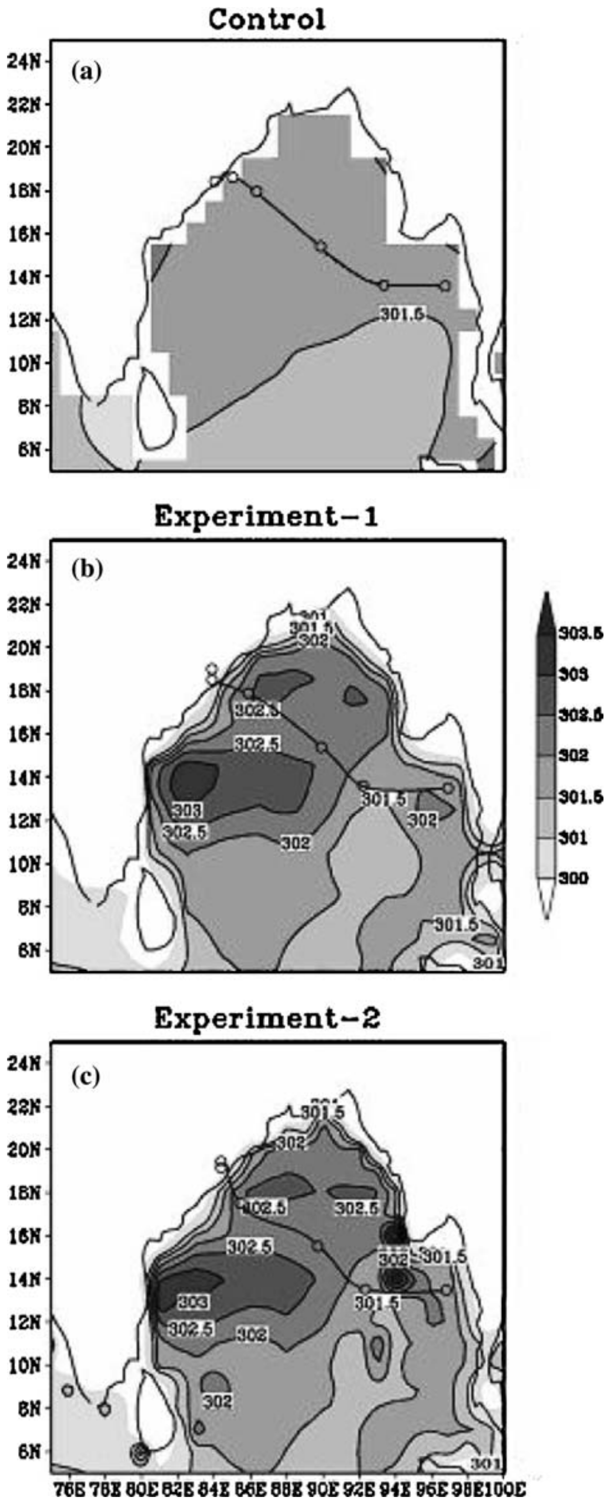

Fig. 2 Sea surface temperature used in model simulation valid at 00:00 UTC on 26 October 1999 with the model-simulated storm track for **a** CONTROL, **b** EXPERIMENT 1, and **c** EXPERIMENT 2

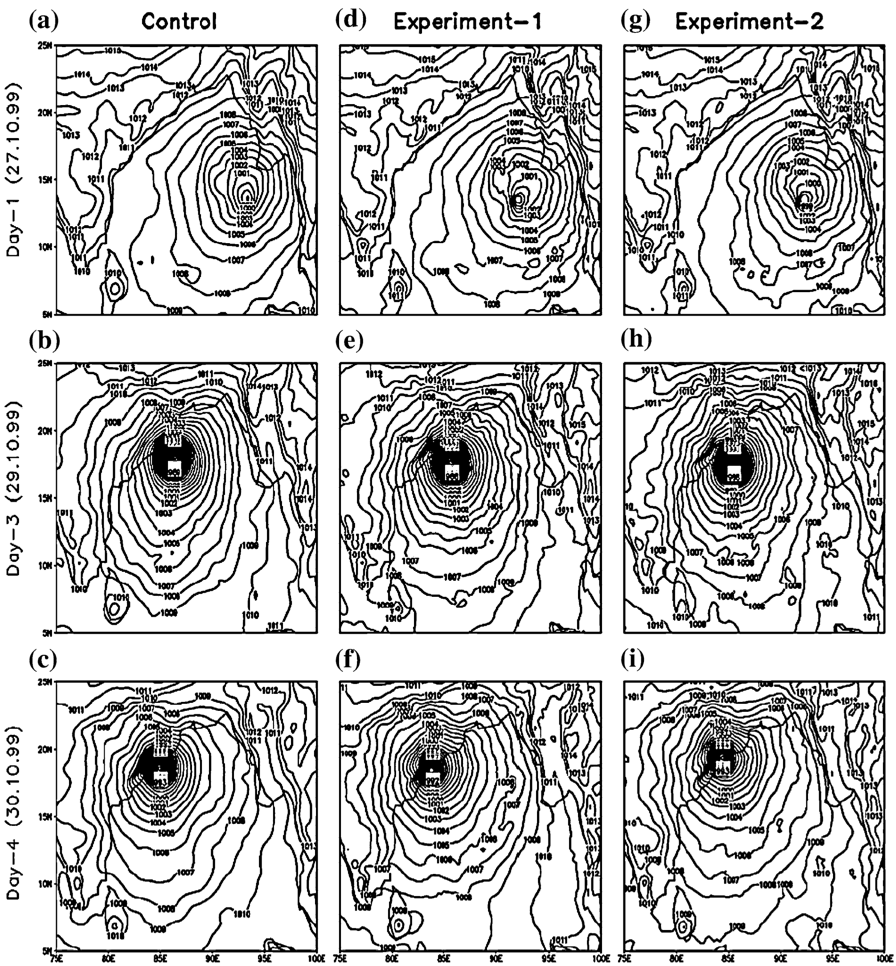

Fig. 3 Model-simulated mean sea level pressure (MSLP, in hPa; all at 00:00 UTC) with contour interval one valid on day 1, day 3, and day 4 for **a**–**c** CONTROL, **d**–**f** EXPERIMENT 1, and **g**–**i** EXPERIMENT 2

In the next 24 hours (between day 1 and day 2), the storm moved over a positive SST gradient in all the three experiments, although the gradient (the figure does not show this weak SST gradient as for the sake of uniformity the three SST fields were plotted with the same contour interval) was weak in the climatological SST (CONTROL simulation). This led to slightly more intensification of the storm during this period in last two experiments (1 hPa in EXPERIMENT 1 and 2 hPa in EXPERIMENT 2). This higher intensification of the storm is shown in the model-simulated PBL height and heat fluxes as well (Table 3).

From day 2 to day 3, in all (three) model simulations, the storm moved over the constant SST surface (no SST gradient), although the SST was marginally higher in EXPERIMENT 1 and EXPERIMENT 2 compared with the climatological SST. On day 3, the storm reached its peak intense stage with peak values of heat flux, wind strength, and PBL height in all three experiments. This result corroborates the

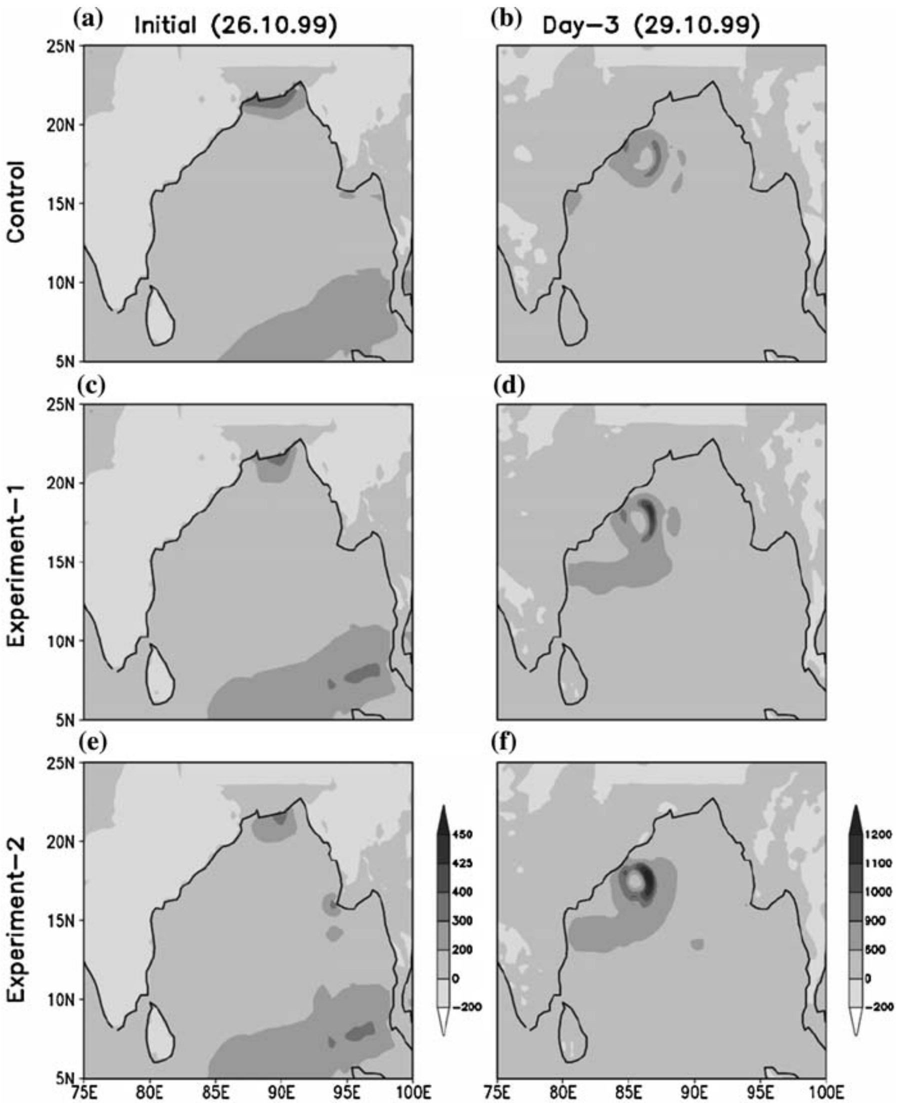

Fig. 4 Model-simulated latent heat flux (in W m^{-2}; all at 00:00 UTC) valid on the initial day (26 October) and day 3 (29 October) for **a**, **b** CONTROL, **c**, **d** EXPERIMENT 1, and **e**, **f** EXPERIMENT 2

findings of Joly et al. (1999), whoi concluded that a tropical cyclone reaches its peak intensity over the warmest SST. The storm was found to be most intense in the EXPERIMENT 2 simulation with central SLP 967 hPa compared with 974 hPa in EXPERIMENT 1 and 975 hPa in CONTROL simulations respectively. The high intensification on day 3 is indicated by the higher PBL height and heat fluxes.

In the next 24 hours (i.e., between day 3 and day 4), the storm crossed the coastline and hence started to dissipate in EXPERIMENT 1 and EXPERIMENT 2 simulations, whereas the CONTROL simulation showed dissipation of the storm even before the landfall. This was due to its movement over a cooler SST region.

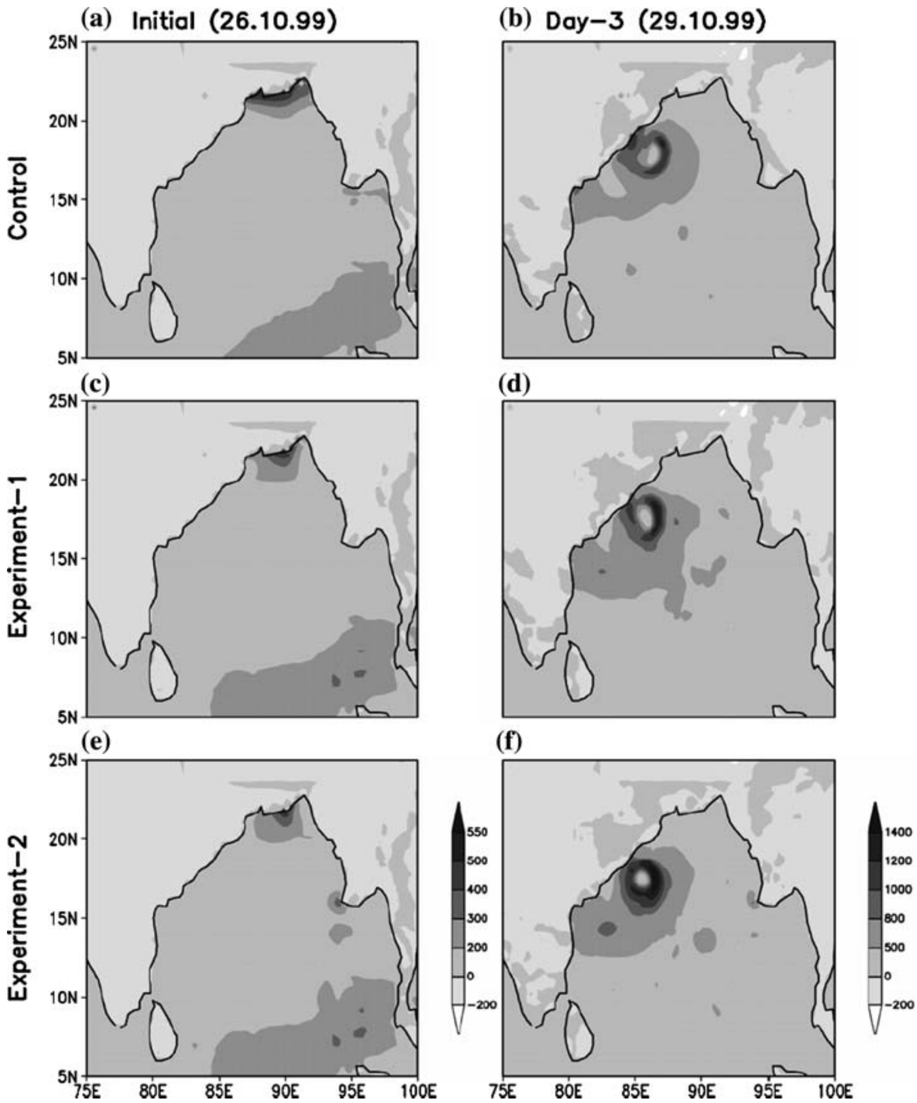

Fig. 5 Model-simulated net heat flux (in W m^{-2}; all at 00:00 UTC) valid on the initial day (26 October) and day 3 (29 October) for **a**, **b** CONTROL, **c**, **d** EXPERIMENT 1, and **e**, **f** EXPERIMENT 2

The pressure drop and strength of surface wind shown in Table 2 clearly indicate that the intensity of the storm in three simulations varied in the range of 10–25% of the intensity in the CONTROL simulation (in terms of pressure drop). This infers that SST had a significant influence on modulating the intensity of the storm, particularly at the severely intense stage, and the intensification and dissipation of the storm was better simulated with the observed SST (i.e., in EXPERIMENT 2). The model simulations show higher variations (as much as 75%) in storm intensity on day 4 and day 5, but this is probably due to a complex land–ocean–air interaction.

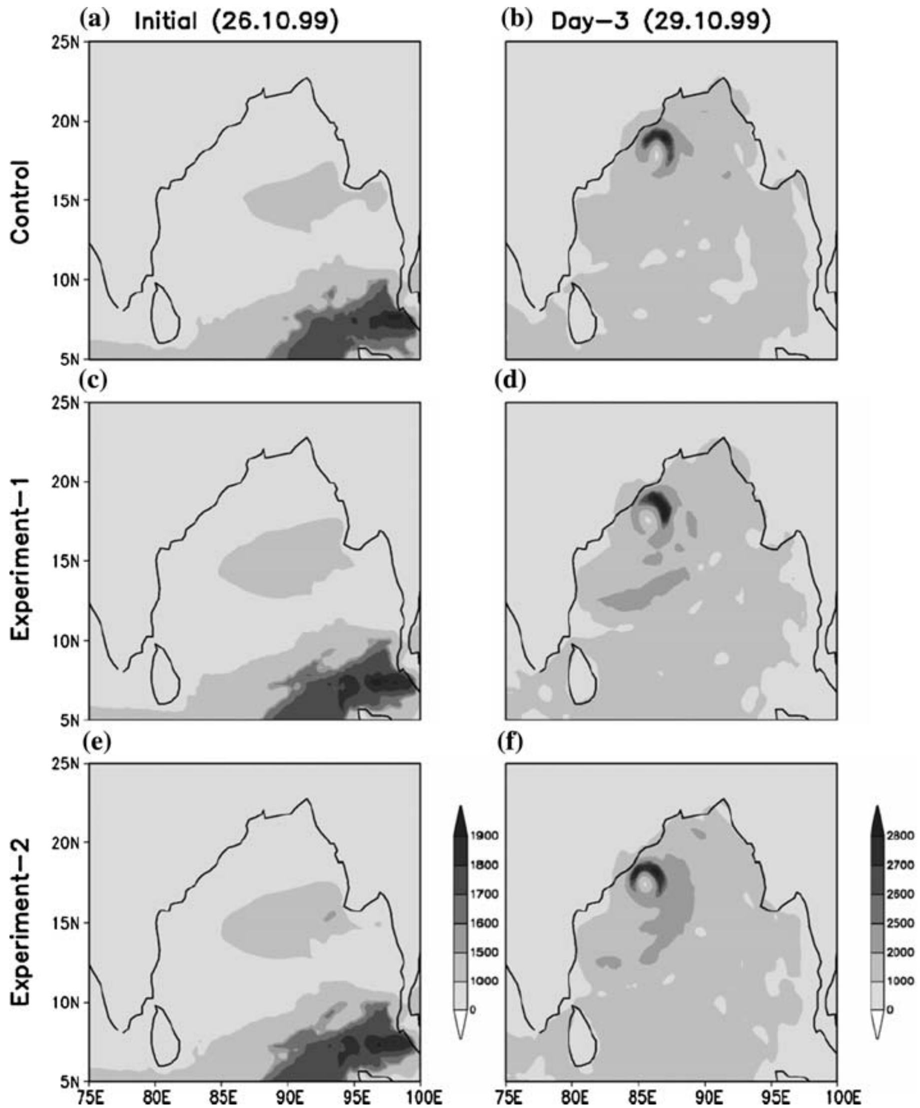

Fig. 6 Model-simulated PBL height (in meters; all at 00:00 UTC) valid on the initial day (26 October) and day 3 (29 October) for **a**, **b** CONTROL, **c**, **d** EXPERIMENT 1, and **e**, **f** EXPERIMENT 2

As mentioned earlier, the storm caused heavy rainfall over Orissa during 29–31 October 1999. The isohyets drawn from the India Meteorological Department (IMD) recorded station rainfall during these 3 days (day 3 to day 5) are shown in Fig. 7. Model simulated 24 hours accumulated precipitation valid for these days from CONTROL, EXPERIMENT 1, and EXPERIMENT 2 simulations is shown in Fig. 8. The maximum rainfall over Orissa from model simulations and observations are also provided in Table 4. For all 3 days, the model under-predicted 24 hours accumulated precipitations. On day 3 and day 4, 24 hours accumulated precipitation

Table 2 Model-simulated and observed central pressure drop (hPa) and surface wind (10 m above from surface) strength (m s^{-1}) of the Orissa super cyclone

Time (00:00 UTC)	Pressure drop				Surface wind			
	Control	Experiment 1	Experiment 2	Observed	Control	Experiment 1	Experiment 2	Observed
Day 1	11	11	11	10	18	18	18	45
Day 2	21	22	23	20	22	23	23	65
Day 3	35	36	42	98	31	32	33	140
Day 4	31	24	25	14	25	22	20	65
Day 5	19	14	11	12	18	15	14	18

UTC Universal Coordinated Time

Table 3 Model-simulated latent heat flux (W m^{-2}), net heat flux (W m^{-2}), and PBL height (m) of the Orissa super cyclone

Time (00:00 UTC)	Latent heat flux			Net heat flux			PBL height		
	Control	Experiment 1	Experiment 2	Control	Experiment 1	Experiment 2	Control	Experiment 1	Experiment 2
Day 1	500	500	500	600	600	600	1,400	1,450	1,500
Day 2	600	650	700	700	750	800	2,000	2,100	2,200
Day 3	1,000	1,100	1,300	1,200	1,300	1,500	2,800	2,900	3,000
Day 4	900	800	700	1,200	900	700	2,300	1,900	1,900
Day 5	600	500	400	800	700	600	1,800	1,500	1,400

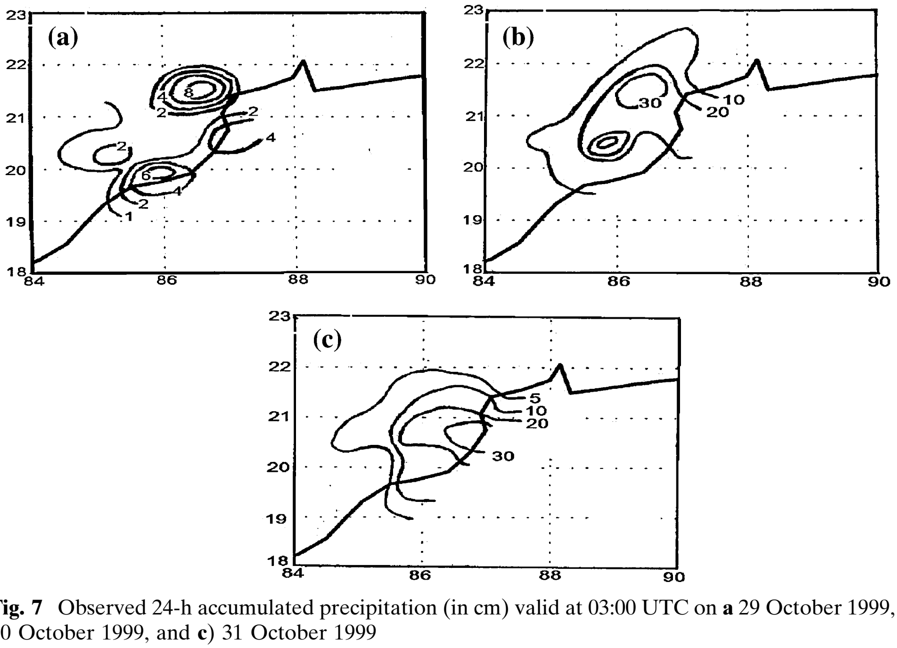

Fig. 7 Observed 24-h accumulated precipitation (in cm) valid at 03:00 UTC on **a** 29 October 1999, **b** 30 October 1999, and **c**) 31 October 1999

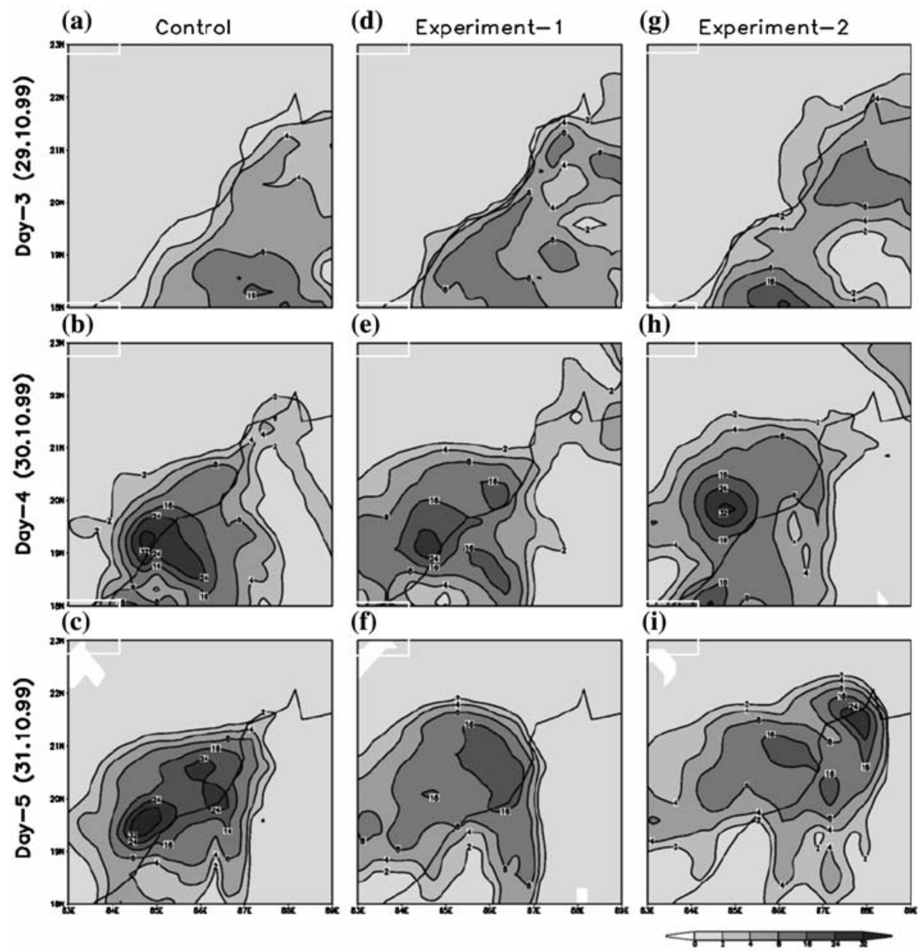

Fig. 8 Model-simulated 24-h accumulated precipitation (in cm) valid at 03:00 UTC on day 3 (29 October), day 4 (30 October), and day 5 (31 October) for **a–c** CONTROL, **d–f** EXPERIMENT 1, and **g–i** EXPERIMENT 2

over Orissa was better simulated in EXPERIMENT 2. On day 4, the model simulation showed a maximum of 36 cm compared with 42.6 cm in the observation. On day 5, the CONTROL experiment showed a maximum precipitation of 33 cm compared with 34 cm in the observation. On this day, rainfall associated with the storm was better simulated compared with the other two experiments. It should be

Table 4 Model-simulated and observed 24-h accumulated maximum precipitation (cm) of the storm over Orissa

Time (03:00 UTC)	Control	Experiment 1	Experiment 2	Observed
Day 3 (29.10.99)	3	1	5	9.0
Day 4 (30.10.99)	29	31	34	42.6
Day 5 (31.10.99)	33	23	30	36.0

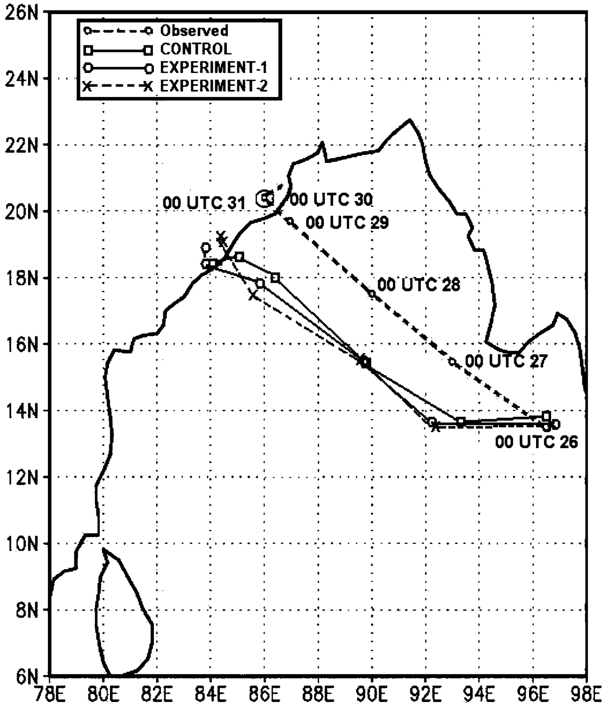

Fig. 9 Track of the storm during 26–31 October 1999, observed track obtained from the India Meteorological Department (IMD), and the tracks obtained from CONTROL, EXPERIMENT 1, and EXPERIMENT 2 simulations

mentioned here that climatological SST showed a warm surface temperature near the coastline, which helped the storm to maintain the intense stage and thus resulted in more rainfall.

5.2 Influence on track

The tracks of the storm obtained from all (three) model simulations and the observed track obtained from IMD with the position of the storm every 24 hours are presented in Fig. 9. The figure shows that the SST had a notable impact on the movement of the storm as well as on the track errors (shown in Table 5) in three simulations, which varied within the range of 10–50% from 1 day to the other. As

Table 5 Displacement error (km) in track forecast in all experiments compared with the observed track in the case of the Orissa super cyclone

Time (UTC)	Control	Experiment 1	Experiment 2
Day 1	213.72	228.14	234.81
Day 2	273.75	245.56	235.69
Day 3	188.79	221.69	282.01
Day 4	235.83	320.95	213.99
Day 5	298.53	275.90	236.34

shown, the model-simulated tracks followed nearly the same trend and to the left of the observed track of the storm. The maximum difference in track errors in the three simulations occurred on day 3 with location of the storm in the last two simulations (EXPERIMENT 1 and EXPERIMENT 2) to the left of that obtained from the CONTROL simulation. This is probably due to the presence of the warm SST region to the left of the track (Fig. 2b, c), which drags the storm toward it (Orlanski 1998). The figure also shows that the track of the storm is relatively better simulated with the use of satellite-derived SST.

6 Conclusions

In the light of the results and discussions presented in the previous section, the broad conclusions drawn from this study can be put forward as follows.

The SST and its gradient have a significant impact on modulating intensity (as reflected from the mean sea level pressure) of the storm, with the peak intensity of the storm reached over the warmest SST. This finding corroborates that of Joly et al. (1999).

Model simulation also shows that SST modulates the track of the storm as well the storm, showing the tendency to move toward a warmer ocean surface, as mentioned by Orlanski (1998).

The track and intensity of the storm is relatively better simulated with the use of satellite-observed SST to force the mesoscale model.

It should be mentioned here that along the track of the storm, the NCEP skin temperature and observed SST are mostly over 29°C. According to DeMaria and Kaplan (1994), SST has relatively less impact on the intensification and movement of the storm when it is within this temperature range. This important aspect could not be clarified in the present study, as it was a single-storm simulation.

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