

Numerical Simulations with WRF to Study the Impact of Sea Surface Temperature on the Evolution of Tropical Cyclones Over Bay of Bengal

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1 Introduction

Tropical cyclones (TCs) belong to the class of severe weather systems associated with strong ocean-atmospheric coupling. They are highly disastrous weather phenomena that cause damage to the life and physical infrastructure in tropical maritime countries. The Indian coastal lands, especially the east coast, are highly vulnerable to the TCs in the post-monsoon season of October to December. Weak vertical wind shear, high sea surface temperature (SST) (>26.5 °C), pre-existing disturbance like tropical easterly waves are some of the favorable conditions (Anthes 1982; Gray 1968) favouring the development and sustenance of TCs in this season in the North Indian Ocean (NIO). SST is a crucial influential parameter for the formation and development of TCs. A threshold SST value of 26.5 °C was defined by Gray (1968) for the genesis and further development of TCs. A TC is characterised with an outward diverging motion in the upper atmosphere and converging motion at the surface. Higher upper air divergence facilitates further deepening through enhanced convergence at the lower levels. The upper ocean provides heat energy to the overlying atmospheric boundary layer and for the deepening process by enhancing the convection. Earlier studies have shown that TCs experience sudden intensification when they entered oceanic areas with higher SSTs. There are several observational and modelling studies which explained the upper-ocean response to TCs (e.g. Price 1981; Price et al. 1994; Shay and Elsberry 1987; Sanford et al. 1987; Bender and Ginis 2000; Shay et al. 2000). Among a

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number of factors, the TC intensification is partly controlled by the surface heat and moisture fluxes that feed the energy to the storm and the dissipation by the roughness to the winds at the sea surface (Chen et al. 2013). The upper ocean heat content and surface temperature are influential in the ocean–atmosphere interaction and the supply of energy through sensible and latent heat fluxes for the development and sustenance TCs. Emanuel (2005) and Webster et al. (2005) suggested that the rising SSTs in the Atlantic Ocean are related to the increase in the hurricane activity. A number of studies have shown that the strong surface wind in a TC drives sea surface waves and underlying ocean currents and enhance upper-ocean turbulent mixing, cools the SST, and result in a cold wake behind (Price 1981), which, in turn, provides a negative feedback on TC intensity (Schade and Emanuel 1999; Chan et al. 2001). It has been reported that warmer SST associated with large ocean heat content causes TC intensification (Hong et al. 2000; Shay et al. 2000; Bright et al. 2002), whereas negative SST anomalies associated with cold-core eddies or TC-induced cold wake weakens TC systems (Walker et al. 2005). A few workers (Knutson and Tuleya 2004; Michaels et al. 2006) using computer models have shown that increase in SST due to green house warming leads to increase in hurricane intensity. Michaels et al. (2006) reported that the strong relationship of TC intensity with SST is not clear at the upper range of SSTs. Though SST is known to influence the intensity of TCs, it is still not clear how it influences the movement of the storms. It is necessary to investigate the air–sea interaction processes associated with SST parameter and upper ocean heat content by analysis of the air–sea fluxes through numerical experiments. In this study, an attempt is made to understand the role of SST on the movement and intensity of the TCs by performing numerical simulations with a mesoscale atmospheric model.

2 Data and Methodology

Weather Research and Forecast (WRF) mesoscale atmospheric model with Eulerian mass dynamical core developed and sourced by the National Center for Atmospheric Research (NCAR), USA is used to study the impact of SST parameter on the evolution of TCs. It is a non-hydrostatic model with terrain following vertical coordinate, accurate numerics, higher order mass-conservation equations and dynamical nesting (Skamarock et al. 2008) to simulate various scales of atmospheric motions. A two-way interactive double nested (27 km, 9 km resolutions) domain configuration with 40 vertical levels is used for the present study (Fig. 1). The outer domain covers the NIO region with 27 km resolution and 173×162 grids. The inner domain has 9-km resolution with 292×229 grids covering the Bay of Bengal (BOB) and adjoining coastal land areas. The data for the terrain elevation, land-use and soil types for the 27 and 9 km resolution domains are taken from the U.S. Geological Survey (USGS) topography data at 10' and 5' resolutions. The case of a very severe TC Thane-2011 is chosen for the study. The TC Thane formed as a depression on 25 December 2011 in the southeast Bay of Bengal (BOB),

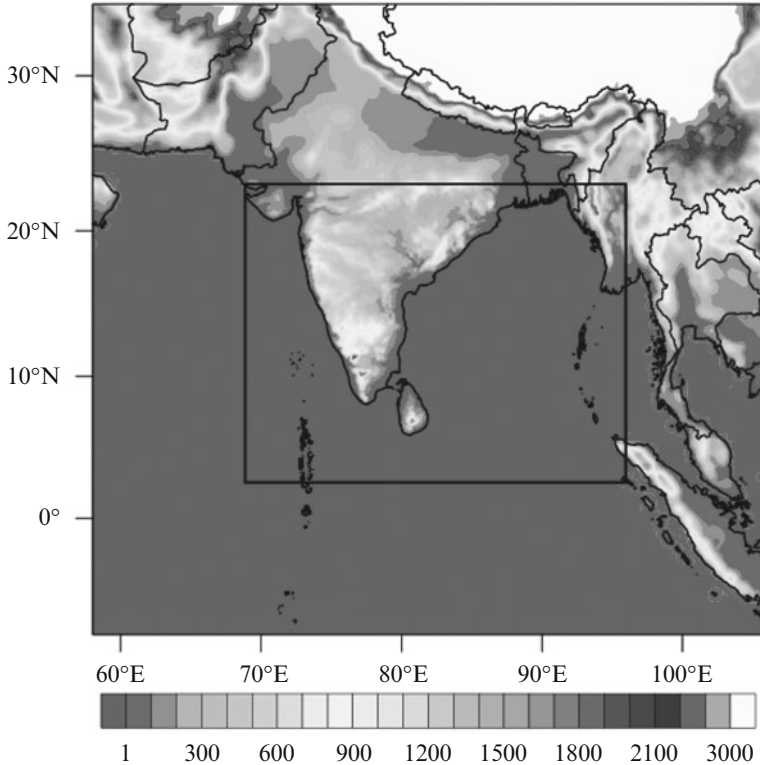


Fig. 1 Domains used for simulation of TC Thane. Shades give the terrain height

progressively intensified as a very severe TC, moved in a north-north-northwestward direction and crossed North Tamilnadu and Puducherry coast on 30 December 2011 (IMD 2012).

The model is initialised at 00 UTC 27 Dec 2011 and integrated up to 96 h. The US-National Centre for Environmental Prediction (NCEP) Global Forecasting System (GFS) analysis and 3-h forecasts available at 50-km resolution are employed for the initial and boundary conditions of Advanced Research WRF (ARW) model. No vortex initialisation and assimilation of observations are performed. For studying the impact of SST a series of experiments are performed in two groups. In the control simulation the SST is taken from NCEP real-time global SST analysis (http://polar.ncep.noaa.gov/sst/rtg_high_res/) for defining SST initial and boundary conditions. In the subsequent experiments SST is altered in steps of +1, +2, +3, -1, -2, -3 °C from the actual analysis SST at each grid point in the domains. All the experiments are performed with updation of SST at 3-h interval. In the second group of experiments the SST is altered as in the first group in steps of +1, +2, +3, -1, -2, -3 °C but over a limited region (300 × 300 km) around the TC and with updating of SST at 3-h interval. The names of the experiments along with the domain average SST used in each experiment are given in Table 1. India Meteorological Department (IMD) best track estimates for

Table 1 The details of the SST used in different experiments

Experiment name	SST data (°C)	SST used (°C)
CTL	NCEP analysis	~26.85
SST+1	NCEP+1	~27.85
SST+2	NCEP+2	~28.85
SST+3	NCEP+3	~29.85
SST-1	NCEP-1	~25.85
SST-2	NCEP-2	~24.85
SST-3	NCEP-3	~23.85

intensity and vector track positions are used for comparisons of simulated intensity and track parameters from each of the experiments.

3 Results and Discussion

The changes in the movement of the system and the variation in the central sea level pressure (CSLP), maximum tangential winds with respect to variation of SST parameter are analysed from various experiments. The experiments without alteration of SST in the first and second groups are considered as control (CTL) experiments in the respective groups. In both the groups of simulations it has been found that alteration of SST leads to large variations in both intensification as well as movement of the storm. The results are discussed below.

3.1 Experiments with Alteration of SST Over Simulation Domain

In the first group of experiments SST is changed from analysis value over the modelling domain by applying increments or decrements in steps of 1, 2 and 3 °C. The boundary conditions for SST are also updated from the NCEP real time SST data. The average SST from analysis corresponding to the model initial time (00UTC 27 December 2011) over the model inner domain is about 26.85 °C. With alteration of SST over the analysis (Table 1), considerable changes are noted in the simulated track positions and intensity parameters. It has been found that when the SST is increased from the analysis value the track of the storm deviates to the north of the track in the CTL (Fig. 2a). However, when SST is decreased from the analysis value, it is seen that the track deviates to the south of the track in CTL. Higher track deviations are obtained with larger SST changes (Fig. 2b). It has been found that the experiment SST-2 with reduction of SST by -2 °C provides minimum track deviations of all the experiments. The track errors (Table 2) in the control run (CTL) are found to be 34, 79, 99, 181 km at 12, 24, 48, 72 h forecasts, respectively. Of all the simulations the experiment SST-2

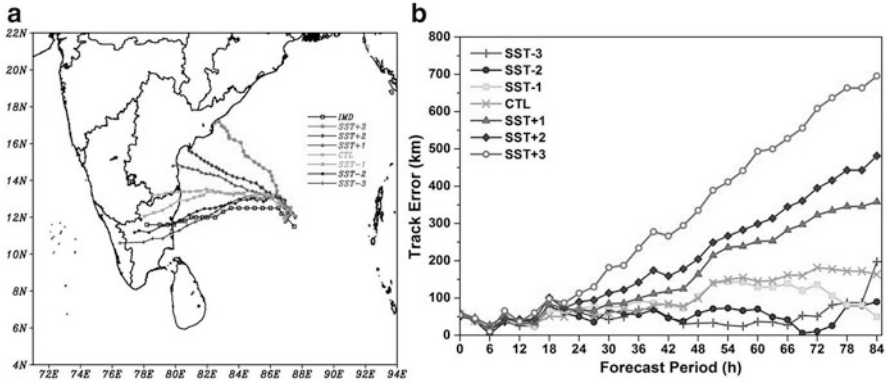


Fig. 2 (a) Simulated tracks of TC Thane and (b) time series of track errors from experiments using different SSTs over simulation domain

produced minimum track errors which are noted to be 39, 50, 59, 11 km at 12, 24, 48, 72 h forecasts, respectively. However, the simulation SST + 3 with an increase of SST by 3 °C produced maximum track errors (112, 334, 608 km at 24, 48, 72 h forecasts).

When the SST is increased from analysis value (SST ~26.85 °C) in steps of 1, 2, 3 °C it is found that the central pressure reduces and maximum tangential winds increase progressively leading to an increase in intensity (Fig. 3). However, when the SST is reduced from analysis value in steps of 1, 2, 3 °C it is found that the pressure drop reduces and maximum winds decrease progressively leading to weakening of the storm. The experiment (SST+2) with an increase of SST by 2 °C from analysis produced minimum errors in central sea level pressure (CSLP) and maximum sustained winds (MSW) (Tables 3 and 4). Thus, the use of SSTs lower than the analysis SST of ~26.85 °C, reduce the track errors appreciably, however, they increase the errors in maximum winds and central sea level pressure leading to underestimation of intensity of the storm. On the contrary, the use of SSTs higher than the actual analysis SST of ~26.85 °C, reduced the intensity errors but increased the track errors.

In the experiment with reduction of SST by 2 °C from analysis (Fig. 3), the track errors are reduced by 4.5 %, 36.7 %, 40.6 % at 24, 48, 72 h predictions, respectively. This experiment also simulated the timing of landfall (00 UTC 30 December 2011) with least error of -1 h (early landfall) and with least position error of 14 km (Table 5).

Table 2 Errors in vector track position from experiments using different SSTs

Forecast period (h)	Track error (in km)						
	SST - 3	SST - 2	SST - 1	SST	SST + 1	SST + 2	SST + 3
0	58.97	53.89	59.98	56.45	59.98	49.48	54.23
12	25.22	38.89	32.68	34.33	31.36	43.01	37.28
24	61.33	50.02	70.82	79.14	66.61	90.33	112.72
36	68.49	55.40	93.56	63.78	99.25	142.14	234.05
48	32.40	58.92	104.42	99.12	164.14	204.47	334.86
60	36.81	70.38	129.66	144.62	251.98	298.97	493.62
72	50.86	10.75	136.10	181.66	322.85	394.95	608.41
84	197.74	89.65	49.44	163.71	357.87	481.64	695.66

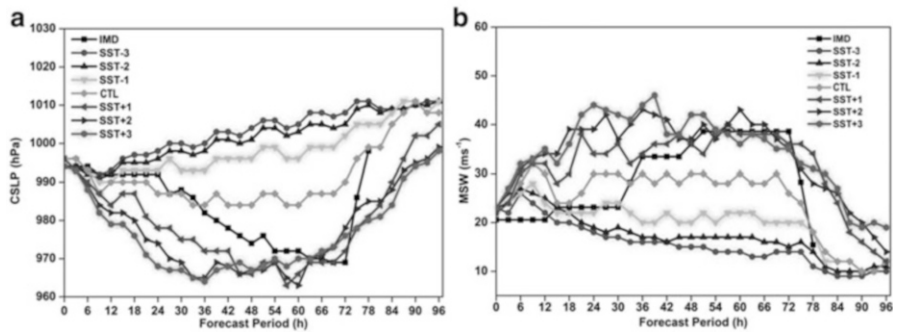


Fig. 3 Simulated central sea level pressure (a) and maximum sustained winds (b) of TC Thane in experiments with different SST values

Table 3 Errors in central sea level pressure from experiments using different SSTs

Forecast period (h)	CSLP error (in hPa)						
	SST - 3	SST - 2	SST - 1	SST	SST + 1	SST + 2	SST + 3
0	0	0	2	2	2	0	0
12	1	0	-2	-2	-8	-10	-13
24	6	4	1	-5	-14	-18	-24
36	18	16	11	2	-10	-17	-18
48	30	27	22	10	-8	-7	-7
60	33	31	24	12	-6	-9	-2
72	39	36	33	21	3	9	7
84	9	9	8	5	-10	-12	-16

Table 4 Errors in maximum surface winds from experiments using different SSTs

Forecast period (h)	MSW error (in m/s)						
	SST - 3	SST - 2	SST - 1	SST	SST + 1	SST + 2	SST + 3
0	2	2	1	1	1	2	2
12	1	4	3	9	11	13	14
24	-5	-4	-1	7	11	16	21
36	-17	-16	-13	-3	1	10	11
48	-21	-19	-16	-6	0	1	6
60	-25	-22	-17	-9	-1	4	-3
72	-25	-24	-19	-13	-3	-4	-4
84	-4	-3	-1	-1	11	13	14

Table 5 Errors in position and time of land fall from experiments using different SSTs

Experiment	Landfall point error (km) (experiment-actual)	Landfall time error (h) (experiment-actual)
SST + 3	603.00	8
SST + 2	397.13	12
SST + 1	301.66	8
SST	168.12	-2
SST - 1	122.80	-2
SST - 2	14.69	-1
SST - 3	68.33	-1

3.2 Experiments with Alteration of SST Over the Region of TC

In the second group of experiments the SST alteration was done over an area of 300 × 300 km of the T region. It is noticed that the SST variation over a limited ocean region around the TC has a smaller effect on the motion of the TC but has a greater impact on the intensification of the system. As in the first group of experiments higher SSTs (>26.85 °C) led to north/northwestward drift of the system leading to large track errors (Fig. 4a, b). However, lower SSTs (<26.85 °C) did not result in southwestward drift as in first group. The smaller effect of SST changes on the motion of the TC can be identified from the relatively lesser track errors (maximum track error ~400 km for SST + 3) in this group (Fig. 4b) as compared to the track errors (maximum track error ~600 km for SST + 3) in the first group. This shows that the variation of SST over a limited ocean region does not cause drastic influence on the dynamics of the system. As in the first group, use of higher SSTs (>26.85 °C) led to large intensity changes (Fig. 4c, d) with maximum impact given by SST + 3 °C in terms of reduction in central pressure and enhancement of MSW. However, the MSW increased upto 46 m/s and CSLP dropped upto 950 hPa which are much larger values relative to the first group. This suggests that the intensity increments in the case of limited area SST variation are much larger than

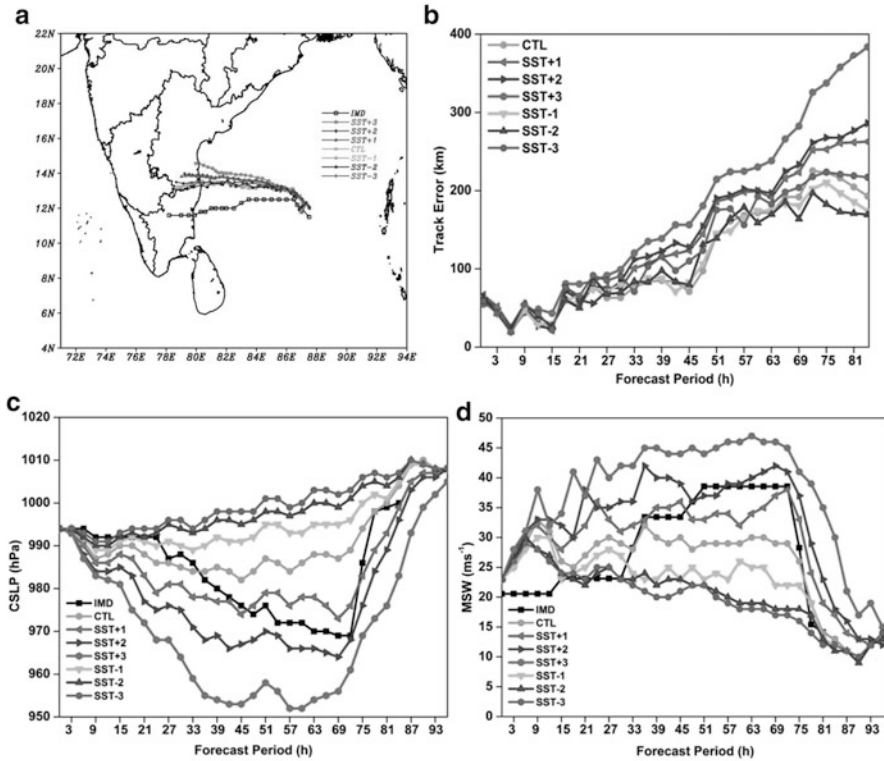


Fig. 4 Simulated tracks (a), track error (b), central sea level pressure (c) and maximum sustained winds (d) of TC Thane in experiments with different SST values for the experiments using SST change over a 300 × 300 km area

the intensity changes obtained due to domain wide SST variation. In TCs the processes of convergence of moist air, its upward motion and warming of the atmosphere occur more rigorously in the inner and outer core regions. These processes would more rigorously influence the thermodynamics of the atmosphere in a limited region of the TC, leading to enhancements in convection and further intensification. Further, the SST changes in TCs would also occur more rigorously in the region of the TC due to TC-induced wind and wave forcing and ensuing ocean mixing. Thus the results of limited area SST changes discussed above on the motion and intensification of the TCs assume importance.

3.3 Changes in Air–Sea Fluxes

The SST parameter is likely to influence the development of the storm through the transport of energy at the Ocean–Atmosphere interface. Upward fluxes of sensible,

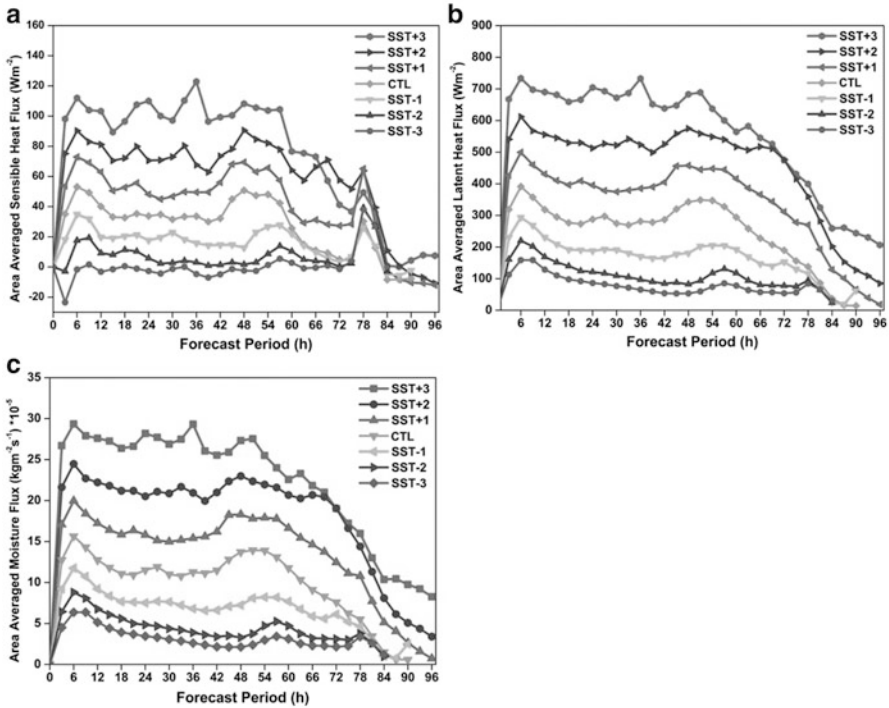


Fig. 5 Time series of area averaged ($4 \times 4^\circ$ rectangular area around the cyclonic centre) fluxes (a) Sensible heat flux (Watts/m²), (b) Latent heat flux (Watts/m²) and (c) Moisture flux (Kg/m²/s)

latent heat and moisture averaged over an area of $4^\circ \times 4^\circ$ ($\sim 400 \times 400$ km) around the storm are analysed from different experiments to examine the changes in the fluxes due to changes in SST parameter. The time series of the surface fluxes from the first group of experiments with alteration of SST are presented in Fig. 5. It is found that as the SST increases all the three fluxes are enhanced throughout the life cycle of the storm, and the experiment with a rise of 3°C in SST yielded highest fluxes. The larger upward fluxes would feed more moisture to the system and would enhance the warming of the atmosphere by release of latent heat leading to development of further convection, convergence and overall intensification.

These results suggest that the transport of energy to the TCs increases with higher SST values and thereby leads to intensity amplification and explains the mechanism for the air–sea interaction through SST parameter and its impact on the TC development.

The dynamical structure of tropical TCs consists of convergence and cyclonic motion at lower levels and divergence and anti-cyclonic motion at the upper atmosphere. The thermodynamical structure of the TCs gets modified due to changes in release of large amounts of latent heat flux associated with strong convection. The modification in temperature structure leads to vertical wind

shear. Convection results in raising air motion and compensating sinking motion which transports heat and momentum between different vertical layers. The coupling of thermodynamical and dynamical quantities at various levels in the atmosphere is thus very important for the prediction of TCs in baroclinic flow. Some of the recent studies (Chan 2005; Wu and Wang 2000) have indicated that potential vorticity, which represents a coupling of the dynamic and thermodynamic variations can be used to study the TC movement. Wu and Wang (2000) have shown that the gradient towards the center of positive potential vorticity tendency (PVT) strongly coincides with the direction of the TC and so can be used as a tool for prediction of the movement. For the purpose of understanding the changes in the dynamics of the system resulting from changes in air–sea fluxes, a preliminary analysis is performed by computing different terms of vorticity equation from CTL, SST + 2, SST – 2 experiments from the first group. The equation for the tendency of the relative vorticity in the Cartesian coordinate system (x,y,z) can be written as

$$\begin{matrix} & \text{A} & & \text{B} & & \text{C} & & \text{D} & & \text{E} & & \text{F} & & & & \text{G} \\ \frac{\Delta \xi_r}{\Delta t} = & - \left(u \frac{\xi_r}{\Delta x} + v \frac{\Delta \xi_r}{\Delta y} \right) & - & w \frac{\Delta \xi_r}{\Delta z} & - & v \frac{\Delta f_c}{\Delta y} + f_c \frac{\Delta w}{\Delta z} & + & \xi_r \frac{\Delta w}{\Delta z} & + & \left(\frac{\Delta u}{\Delta z} \cdot \frac{\Delta w}{\Delta y} - \frac{\Delta v}{\Delta z} \cdot \frac{\Delta w}{\Delta x} \right) \end{matrix}$$

where u , v and w are zonal, meridional and vertical wind components, ξ_r is the relative vorticity and f_c is the Coriolis parameter. Here, A is the Relative vorticity tendency (VORTED), B is the Horizontal advection (HADV), C is the vertical advection (VADV), D is the Beta term (BETA), E is the Stretching term 1 (STR1), F is the stretching term 2 (STR2), and G is the tilting term (TILT). The various terms (A–G) of the vorticity tendency equation are computed at every 6 h interval starting at 12 h of the model integration. The vorticity analysis is done for the cases CTL, SST + 2 and SST – 2. Figure 6 shows the vorticity variations in experiments with different SST values.

It is seen that in the control run the horizontal advection, and tilting terms mainly contributed for the vorticity tendency. In the advanced stages (36–66 h) the tilting and advection terms are almost equal in magnitude and have opposing effects. It has been found that notable differences arise in the advection, tilting and stretching terms with variation of SST. In the experiment (SST + 2) with SST enhanced by 2 °C, the contribution of vorticity from the above terms increases to the positive side. In this case (SST + 2) the horizontal advection of vorticity especially increased from 36 to 72 h over other terms. The maximum vorticity tendency occurred at the lowest CSLP i.e. during peak intensification of the system. From the earlier discussions it has been found that this case (SST + 2) also simulated least intensity errors. It is seen that all the three terms (advection, stretching term2 and tilting term) show positive contributions during the peak intensification of the TC. The positive changes in advection, tilting and stretching terms seem to be responsible for the northward drift of the cyclonic systems with SST + 2 °C. In the experiment (SST – 2) with reduction of SST by 2 °C all the above terms are very small and

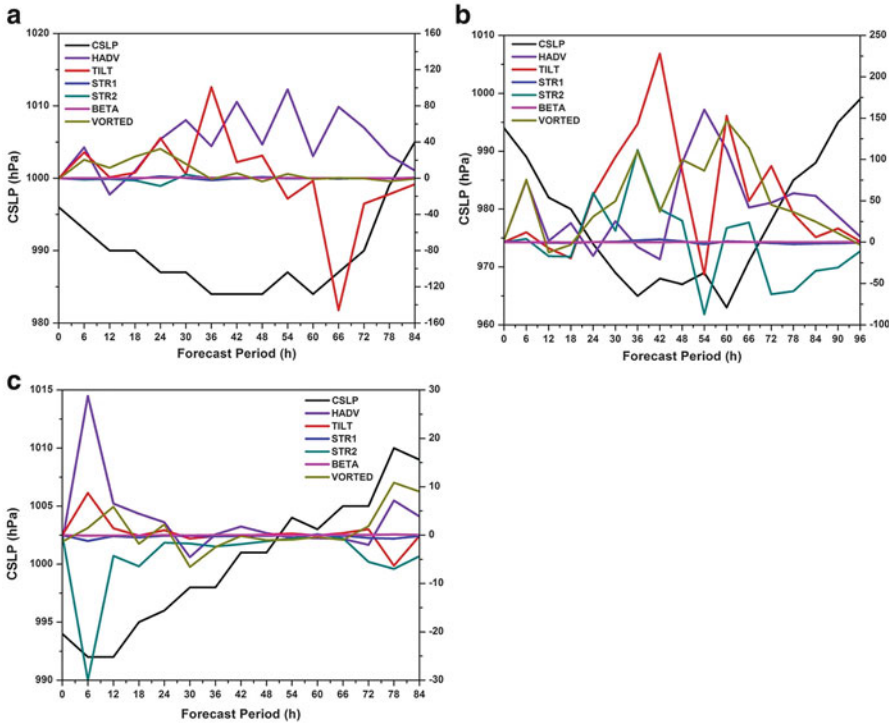


Fig. 6 Time series of various terms in vorticity equation (HADV, advection; TILT, tilting term; STR1, Stretching term1; STR2, Stretching term2; BETA, beta term) for (a) control experiment, (b) SST + 2 °C and (c) with SST - 2 °C experiments. The *left side* vertical axis is for CSLP and the *right side* vertical axis is for magnitude of vorticity terms

become nearly equal to the beta term but have a negative contribution. The negative changes in the vorticity terms seem to be responsible for the southward drift of the storm in the case of SST - 2. The results of the above experiments provide a mechanism for the air-sea interaction through SST parameter and its impact on the TC development. Among various predicted parameters the movement of the TC (or track) is more important as the final landfall position is often given more attention than the storm intensity in disaster mitigation (Mohapatra et al. 2015). From the perspective of track prediction the SST change by -2 °C simulated closer track to the observed track. This experiment (SST - 2) also produced the landfall position close to observations. Considering the intensity parameter, the SST change by +2 °C produced CSLP and winds closer to observations. For both intensity and track estimates the experiment (SST - 1) with reduction of SST by 1 °C produced minimum track as well as intensity errors.

4 Conclusions

An attempt is made to understand the role of SST on the evolution of TCs by performing numerical simulations with ARW mesoscale model. The case of a very severe TC Thane-2011 is simulated with a high resolution (9 km). Preliminary results indicate that SST has a large impact on the movement and intensification of the TCs. Significant differences are noticed in predictions for both track and intensity estimates when SST is altered over the analysis. While lower SSTs ($<26.85\text{ }^{\circ}\text{C}$) led to southward deviation of the track higher SSTs ($>26.85\text{ }^{\circ}\text{C}$) resulted in northward deviation of the track from the control experiment. The experiment with reduction of SST by $-2\text{ }^{\circ}\text{C}$ simulated minimum track errors. It has been found that SST changes influence the intensity of the storm, with positive (negative) increments of SST leading to enhancement (reduction) in pressure drop and maximum tangential winds. The experiment (SST + 2) with an increase of SST by $2\text{ }^{\circ}\text{C}$ from analysis ($\sim 26.85\text{ }^{\circ}\text{C}$) produced intensity estimates close to observations. Results suggest SST changes produce opposite impacts on the movement and intensification of the storm. Analysis of average upward fluxes of sensible, latent heat and moisture in the region of TC indicated that SST changes alter the transport of heat and moisture to the TC. All the three fluxes are enhanced with higher SST values leading to enhancement of energy transport and amplification of intensity. A preliminary analysis of vorticity equation revealed that the SST changes lead to variation in the contribution by components advection, stretching and tilting terms leading to changes in the motion of the TC.

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