Observed warming of sea surface temperature in response to tropical cyclone *Thane* in the Bay of Bengal

Simi Mathew, Usha Natesan, G. Latha, R. Venkatesan, Rokkam R. Rao and M. Ravichandran*

An unusual near-surface warming was seen in observations from a moored buoy BD11 at 14°N/83°E, and a nearby Argo profiling float in the Bay of Bengal, during the passage of tropical cyclone Thane, during 25–31 December 2011. The cyclone induced a warming of sea surface temperature (SST) by 0.6°C to the right of the track. Heat budget analysis based on moored observations and satellite data rules out the role of horizontal advection and net heat flux in warming the surface layer. We find that vertical mixing/entrainment in response to the cyclone, in conjunction with a pre-storm temperature inversion (subsurface ocean warmer than SST) led to the observed warming. Pre-storm and post-storm salinity and temperature profiles from an Argo float close to the mooring BD11 have higher vertical resolution than the moored data; they suggest vertical mixing of the upper 70 m of the water column. The moored observations show that the thermal inversion, erased by storm-induced mixing, reappears in a few days.

Keywords: Bay of Bengal, cyclone, OMNI buoy, SST.

The Bay of Bengal (BoB) experiences two to three cyclones per year. The BoB has two major seasons of cyclone occurrence with a primary season during October–December and a secondary season during March–April. The response of BoB to the cyclonic forcing varied with the season due to large variation in the thermodynamics of the bay associated with heavy river discharges. The changes in response to cyclonic forcing during pre- and post-monsoon season were studied using *in situ* and model studies. *Nargis* cyclone, one of the strongest cyclones of category 3–4 during the pre-monsoon season of 2008, produced the strongest turbulent mixing and cyclone-induced upwelling. The high net heat loss from the surface during cyclone resulted in cooling and deepening of the mixed layer[1,2]. But during the post-monsoon season the potential of the cyclone to cool the sea surface is very less compared to the pre-monsoon season due to the presence of deep and warm subsurface layer below a shallow fresh layer[3]. The response of the ocean to cyclonic forcing is three times larger during pre-monsoon season when compared to post-monsoon season due to seasonal changes in the stratification of the BoB[4].

The intensification of tropical cyclones is supported by strong ocean salinity stratification during post-monsoon as it prevents oceanic cooling effect. Intensification of tropical cyclones is suppressed by weak upper-ocean stratification during pre-monsoon[5]. It has been proven that variations in sea surface temperature (SST) and thermodynamics of the surface layer have a major role to play in the prediction of cyclone intensity[6]. The thickness of barrier layer along the east coast of India increases to ~50 m depth as the East India Coastal Current (EICC) flows equator-ward during November[7]. The response of the upper ocean to cyclonic forcing is reduced due to the presence of a thick barrier layer and temperature inversion during the post monsoon cyclone *Sidr* during November 2007 (ref. 8). Studies have shown that the thick barrier layer can contribute to intensification of cyclones by 50% with reduced storm-induced mixing and SST cooling[9]. In this article, we report the response of BoB to cyclonic forcing during *Thane* cyclone in December 2011, with strong temperature inversion, with the help of data collected from moored buoys. The two Ocean Moored buoy networks in the northern Indian Ocean (OMNI) buoys on either side of the cyclone track recorded surface meteorological parameters as well as subsurface variations in temperature, salinity and currents during the passage of the cyclone.

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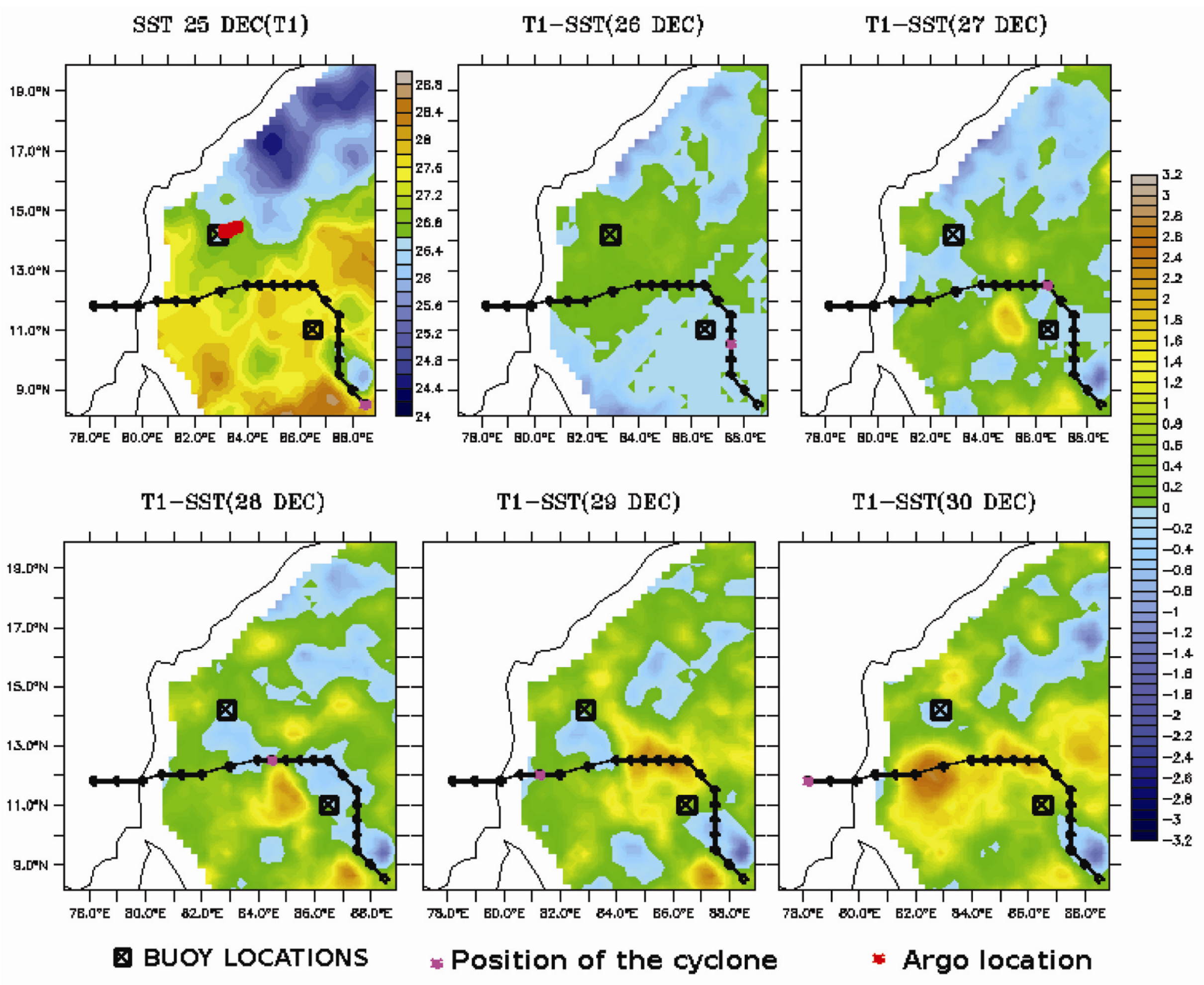

Figure 1. The first figure in top panel shows the track of *Thane* cyclone with TMI SST on the background, the buoys 11°N/86.5°E (BD13) and 14°N/83°E (BD11) locations are marked on either side of the cyclone track, and Argo float with WMO-ID 2901293 is marked with red dots. The deviation of SST from the day 1 is shown in the rest of the panels.

Data

Seven OMNI buoys were deployed at specific locations in the BoB with sensors for measuring surface meteorological as well as oceanographic parameters up to 500 m depth. The surface meteorological parameters include air pressure, temperature, humidity, windspeed, radiation and rainfall. The buoy recorded subsurface temperature and salinity up to 500 m depth using conductivity temperature (CT) sensors attached to the mooring line at discrete depths. It also made current measurements up to 105 m depth with a downward looking Acoustic Doppler Current Profiler (ADCP) of 150 kHz. This study mainly focuses on the observed response at 14°N/83°E (BD11) and 11°N/86.5°E (BD13) OMNI buoys during the passage of a very severe cyclonic storm, *Thane* during 25–31 December 2011. The impact of cyclonic forcing was studied more precisely with data obtained from the two buoys BD13 and BD11 located at a distance of 107 km to the left and 113 km to the right of the cyclone track respectively. The buoys had continuous record of the surface as well as subsurface responses to the cyclonic forcing. The accuracy and resolution of various sensors used in the OMNI buoys are of World Meteorological Organization (WMO) standards and are calibrated once in a year[10]. The surface mixed layer heat budget analysis was carried out to explain the observed warming during the cyclone. The rate of change of mixed layer temperature

$$\frac{\partial T}{\partial t} = \frac{Q_{\text{net}} - Q_{\text{pen}}}{\rho C_p h} - \left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} \right)$$

$$-H\left(W_h + \frac{\partial h}{\partial t} \right).[(T - T_h)/h],$$

was evaluated following Rao and Sivakumar[11]. The net heat flux term (Q_{net}) was taken from the tropflux data[12]. The penetrative radiation (Q_{pen}) lost below the mixed layer depth (MLD) was computed as $Q_{\text{pen}} = Q_{\text{sw}}$

$[V_1 e^{-h/\zeta_1} + V_2 e^{-h/\zeta_2}]$, following Morel and Antoine[13] where V_1, V_2, ζ_1 and ζ_2 were estimated using the equations following Sweeny *et al.*[14]. The chlorophyll-*a* value used in the equations for estimation of V_1, V_2, ζ_1 and ζ_2 was obtained from the weekly chlorophyll-*a* data provided by MODIS Aqua Ocean Colour data during the time of the cyclone. The Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) version 7.1 SST data, produced by Wentz[15] was used for computation of zonal and meridional temperature gradients. The sea water density (ρ) and mixed layer depth (h) were computed from the moored buoy data for salinity and temperature. The daily current data with 0.25° spatial resolution obtained from Gekco[16] was used to compute the advection term for heat budget analysis. The term W_h, entrainment velocity at the thermocline below the mixed layer, is calculated from

$$W_h = 1/\rho f\left(\frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y}\right),$$

where the meridional and zonal wind stress terms were obtained from Advanced Scatterometer (ASCAT) data and H is the heaveside step function [= 0 if $(W_h + \mathrm{d}h/\mathrm{d}t) < 0$, =1 if $(W_h + \mathrm{d}h/\mathrm{d}t) > 0$] followed by Hayes *et al.*[17], where $(W_h + \mathrm{d}h/\mathrm{d}t)$ represents a combination of entrainment and vertical velocities. T is the mixed layer temperature and T_h is the temperature of the layer just beneath the mixed layer. Soil moisture and salinity (SMOS) data obtained[18] was used for understanding the monthly sea surface salinity (SSS) distribution over BoB.

Thane cyclone

The very severe cyclonic storm *Thane* was formed as a tropical disturbance within the monsoon trough to the west of Indonesia, during the last week of December 2011. The system later moved north and then westward and further developed as a very severe cyclonic storm. But on its path, it encountered marginal temperature as low as 27°C on 25 December 2011, as recorded by TMI SST in the southwest BoB as shown in Figure 1. The cyclone gained strength over its course and hit Puducherry coast close to Cuddalore with a maximum wind speed of 140 kmph on 30 December 2011. Out of the five cyclonic disturbances formed in the BoB during 2011, only *Thane* cyclone developed into a very severe cyclonic storm[19].

Warming of surface waters

The ocean responded in an unusual manner post-*Thane* cyclone, with a warming of the surface layer by 0.6°C as recorded by OMNI buoy located at 14°N/83°E (BD11) at a distance of 113 km to the right of the cyclone track. The satellite-derived SST data obtained from TMI during 25–30 December was used to understand whether similar ocean response was observed in a wider region. As the cyclone progressed, the variation of SST for each day from the initial day SST (25 December) is shown in Figure 1. Along the cyclone track, a cooling of SST by 3.2°C was observed around 12°N/83°E on 30 December. Patches of large SST cooling are unreliable since satellite microwave SST is erroneous in the presence of heavy rainfall associated with tropical cyclones. On 29 December a warming of the ocean surface was observed along the track, which disappeared the next day. The warmed ocean surface is confined to the right of the cyclone track in support of buoy observation. The warming of the ocean surface to the right of cyclone track has raised a relevant question. How did the SST increase during the period of very high vertical mixing and latent heat loss? To address this we looked into the salinity and temperature structure of the surface layer of the ocean at the same location for a period of two months prior to the occurrence of the cyclone.

Signatures of temperature inversion

In order to understand the observed warming of sea surface to the right of the cyclone track, the temporal evolution of temperature, salinity and density in the upper 80 m water column was examined from 25 October 2011 to 15 January 2012 as shown in Figure 2. The temperature and salinity structure showed tremendous cooling and freshening since the last week of November (Figure 2 *a* and *b*). The associated shoaling of the MLD calculated based on the density difference (>0.05 kg m^{-3} from 5 m level) is also shown in Figure 2 *c*. The MLD was confined to the top 6–8 m during the last few days of November and first week of December. Even though this resulted in the warming of the surface layer for a shorter duration, the cooling and freshening of the top layer continued till the passage of the cyclone, while the subsurface layer remained warm resulting in temperature inversion. The EICC with its southward flow along the entire east coast of India during the northeast monsoon season[20], must have contributed to the advection of low saline waters. These waters retain fresh water characteristics such as low salinity and cool temperature due to high stratification of BoB during this season. The SSS was plotted (Figure 3) against surface current for September–December 2011 to understand the advection pattern of freshwater. The presence of anti-cyclonic eddy centered at 16°N, 84°E to the north of the buoy during September restricted southward influx of freshwater. The disappearance of the eddy during October and southward flowing EICC extended the advection of low saline waters further south. Strong north-westward current across the bay in November, along 15°–18°N latitudinal band also

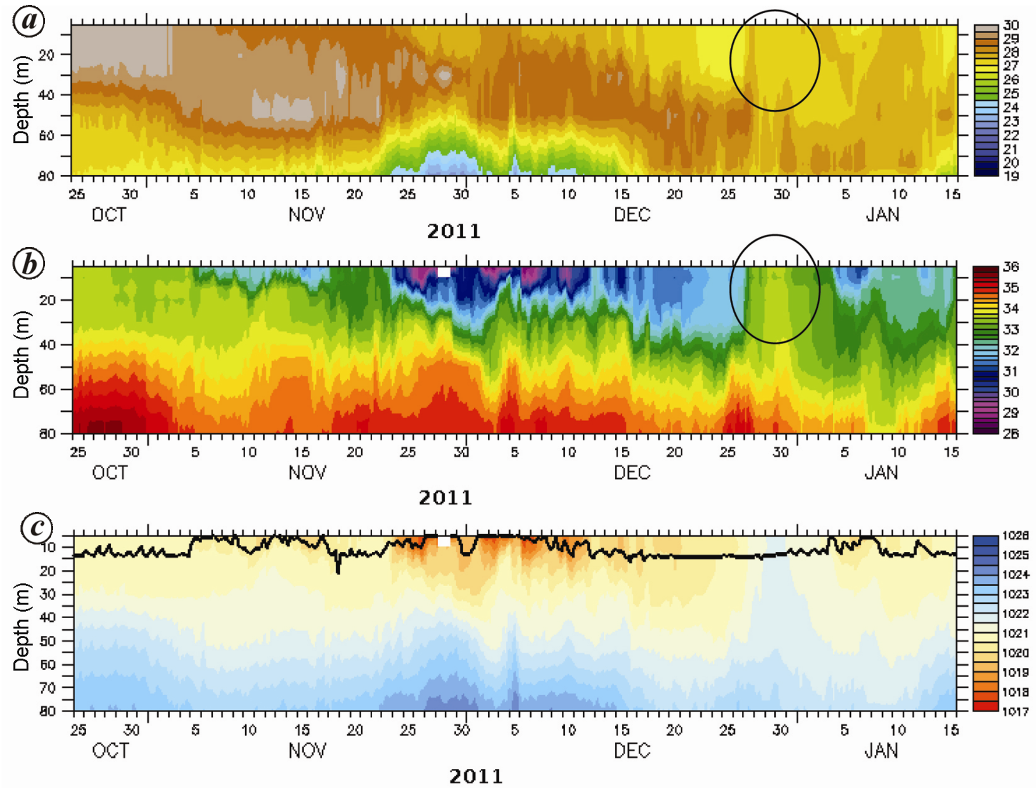

Figure 2. Temperature (***a***), salinity (***b***) and density (***c***) structures up to 80 m depth with the mixed layer depth over plotted in the last panel as obtained from 14N/83E BD11 OMNI buoy during October 2011 to January 2012.

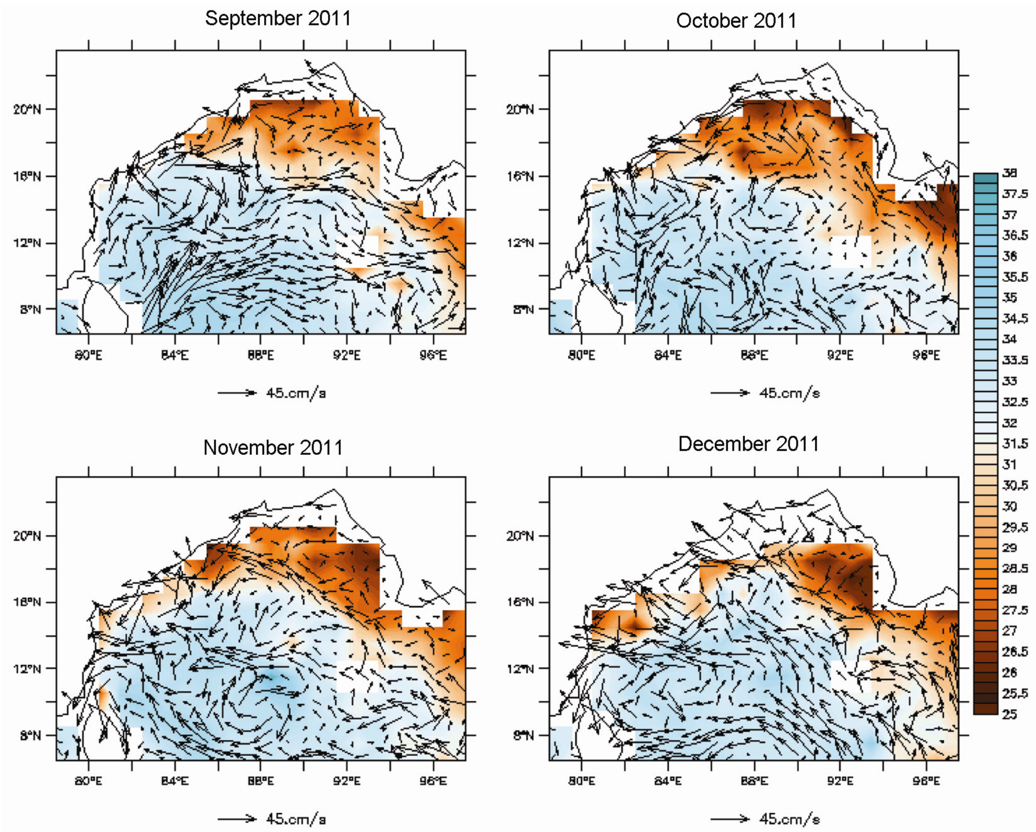

Figure 3. SMOS salinity data over plotted with monthly mean Gekco current data with marked low salinity of 25 PSU at 82°–83°E and 14°–15°N during December 2011.

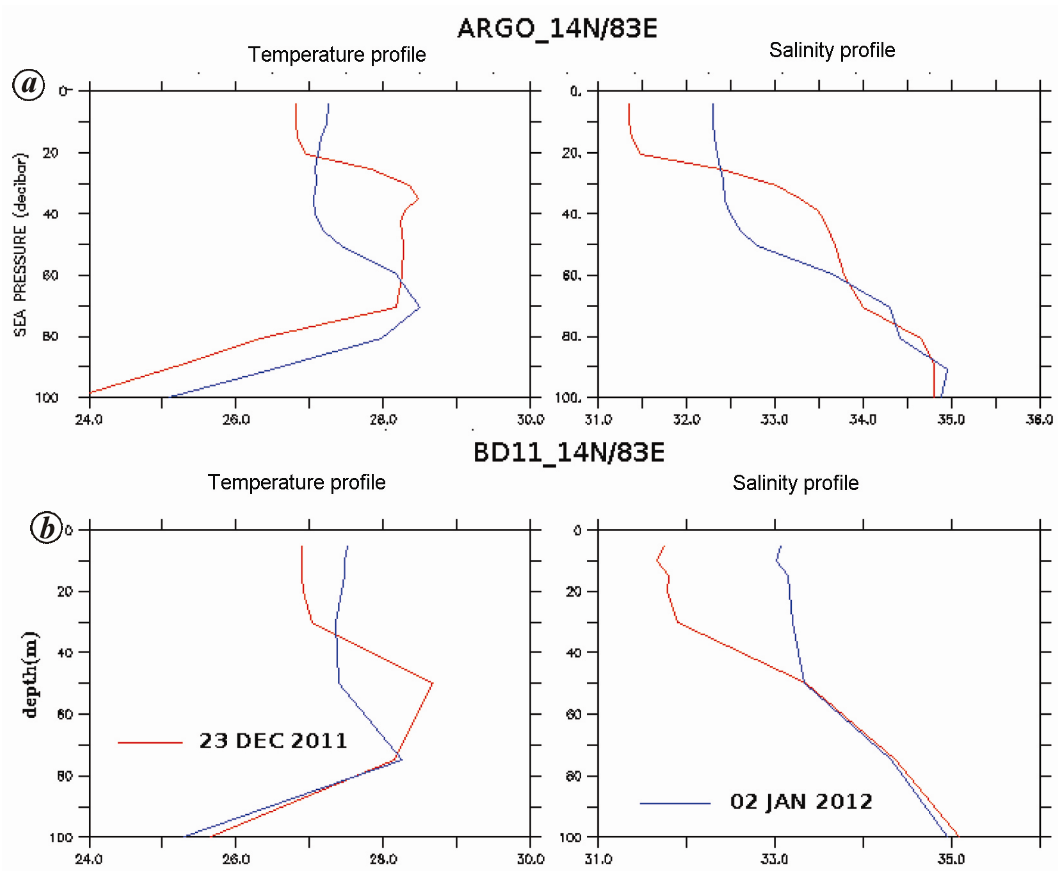

Figure 4. ***a***, Temperature and salinity profile as recorded by the Argo float near the BD11 location. ***b***, The temperature and salinity profile at BD11_14°N/83°E on 23 December and 2 January 2012.

favoured advection of freshwaters from the eastern BoB. The presence of cyclonic eddy at the western rim of this strong current during November, entraped the cool and low saline waters near the buoy location with observed very low salinity (~28 PSU) as recorded by the buoy during 25 November–15 December 2011 (Figure 2 *b*). The monthly SMOS data plotted for the period September–December 2011 also recorded low salinity of around 25 PSU near the buoy location during December (Figure 3). The surface temperature also showed corresponding cooling at the same time with a recorded low value of 27°C near the buoy location. The continuous influx of fresh and cool waters lowered the SST by 3°C, along with reduction of surface salinity by 5 PSU within a span of one month (Figure 2). However, the subsurface waters still remained warm and resulted in strong temperature inversion of 2°C towards the last week of November and throughout December.

The vertical mixing during the *Thane* cyclone eradicated the stratification and the whole water column up to 50 m depth, showed uniform temperature as shown in Figure 4. The response in temperature and salinity prior to and after the cyclone as captured by one of the Argo floats very close to BD11 location is shown in Figure 4. The deepening of the thermocline and halocline from 20 m to 60 m was observed by the buoy as well as the nearby Argo float during post-cyclone period as represented by the bottom and top panel of Figure 4 respectively. The temperature and salinity profiles are smoother for Argo data since they have a better vertical resolution, whereas the buoy has measurements only at discrete depths. Strong thermocline and halocline observed just below 20 m depth on 23 December disappeared completely after the cyclone, due to strong cyclonic mixing. The warming of the surface layer by 0.6°C and 0.45°C was recorded by the buoy and the Argo respectively. The surface salinity also increased by 1.3 PSU and 0.93 PSU at the buoy and the nearby Argo location during post cyclone period. The higher temperature and saline waters at subsurface level when mixed with the cool and fresh waters at the surface layer resulted in warming and saltification of the surface layer.

Role of vertical mixing, advection and heat flux

The variation in SST was analysed with the help of heat budget of the mixed layer, with the computation of net heat flux terms, horizontal advection and vertical entrainment as shown in Figure 5. The net heat flux term

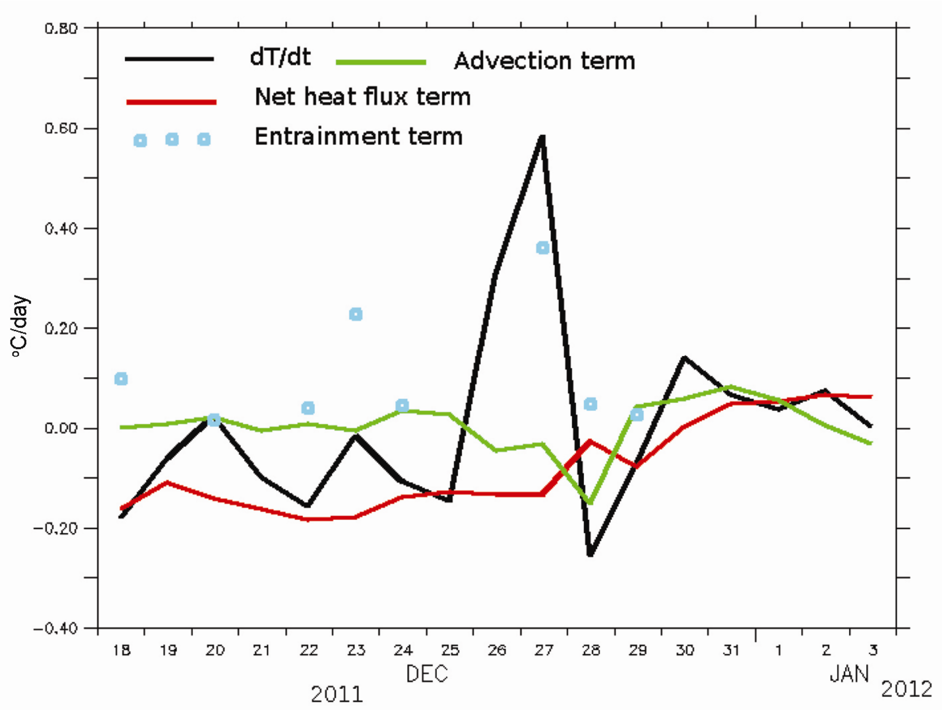

Figure 5. Rate of change of temperature (black line) plotted against net heat flux (red line), advection term (green line) and entrainment term (blue dots).

was negative and favoured the loss of heat from the mixed layer prior to the cyclone. Post-cyclone it was positive, with the mixed layer gaining a temperature of around 0.06°C per day. While the advection term was neutral with no support for any variation of temperature prior to cyclone, post-cyclone it supported a reduction of mixed layer temperature by 0.16°C as shown by the green line in Figure 5. So the huge increase in temperature during the cyclone was not supported either by horizontal advection or by net heat flux terms. The increase of mixed layer temperature during the cyclone was mainly due to vertical entrainment which measured around 0.36°C/day on 27 December 2011. Thus strong entrainment during the cyclone resulted in the warming of the surface layer during *Thane* cyclone.

Results

The temperature inversion in BoB during post-monsoon season is a hidden source for intensification of cyclone due to warming of sea surface by intense vertical mixing during cyclone. An increase in sea surface temperature by 0.6°C was recorded to the right of the cyclone track, post-*Thane* cyclone during December 2011. In the top 50 m water column, the top layer showed an increase in temperature, and a decrease in temperature was observed in the bottom layers. This was due to strong vertical mixing during the cyclone. Strong vertical entrainment during the cyclone contributed to an increase in mixed layer temperature by 0.36°C/day which also supported the post-cyclone warming of the surface layer. The continuous advections of low saline and cool waters, from northern as well as eastern BoB made the surface waters near the buoy location very fresh and cool since the last week of November. The presence of cyclonic eddy centered at 16°N/84°E during the same time trapped the waters at this location for a longer period leading to temperature inversion of 3°C. The cyclone-induced vertical mixing resulted in warming of surface waters with null contribution from net heat flux or advection. This strange response of the ocean to cyclonic forcing emphasizes the importance of an uninterrupted source of sub-surface data on temperature and salinity for better prediction of cyclones.

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