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Response of Upper Ocean during passage of *MALA* cyclone utilizing ARGO data

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ABSTRACT

In the present study an attempt has been made to study the response of the upper ocean atmospheric interactions during the passage of a very severe cyclonic storm (VSCS) '*MALA*' formed over the Bay of Bengal (BoB) on 24 April 2006. Deepening of mixed layer depth (MLD), weakening of barrier layer thickness (BLT) associated with a deeper 26 °C isotherm level (D26) is observed after the *MALA* passage. Tropical cyclone heat potential (TCHP) and depth averaged temperature ($T_{\overline{100}}$) exhibit a good degree of correlation for higher values. The passage of *MALA* cyclone also resulted in cooling the sea surface temperature (SST) by 4–5 °C. The findings suggest that turbulent and diapycnal mixing are responsible for cooler SSTs. Turbulent air–sea fluxes are analyzed using Objectively Analyzed air–sea Fluxes (OAFlux) daily products. During the mature stage of *MALA* higher latent heat flux (LHF), sensible heat flux (SHF), and enthalpy (LHF + SHF) are observed in the right side of this extreme event.

1. Introduction

Tropical cyclones are considered as one of the major natural hazards which inflict severe threat to human life and property having implications on socio-economic aspects in the affected regions. It is considered as the most intense case in air–sea interaction studies where energy from the warm ocean waters is supplied through surface heat flux (Emanuel, 1986). In a previous study (Emanuel, 1999) used a simple numerical model to demonstrate the evolution of hurricane intensity. The results advocate that in most cases the intensity depends on three factors viz.; initial intensity of cyclone, the thermodynamic state of atmosphere through which the cyclone propagate, and finally the heat exchange with the upper layer of the ocean underlying the core of the cyclone. The size of a tropical cyclone can vary from about 200 to 500 km during its entire life cycle (Liu and Chan, 1999). The primary mechanism that lowers the SST beneath a moving cyclone is accountable due to entrainment by turbulent mixing of irreversible heat flux from the ocean mixed layer, whereas air–sea heat exchange plays a minor role. In case of a slow moving cyclone, upwelling can significantly affect the SST, which is however reported negligible for fast moving cyclones (Price, 1981). Vertical mixing at the base of the mixed layer (ML) is another contribution for the upper ocean cooling (Black, 1983). In this context, Mahapatra et al. (2007) found the shift of the maximum sea surface cooling on the left side of the track prior to landfall. From observational support (Bender et al., 1993) it can be seen that magnitude of sea surface cooling (high, medium, and slow) depends upon the speed the cyclone (slow, medium, and fast). The response of ocean to cyclone utilizing numerical model for the Orissa super cyclone event was investigated by Rao et al. (2007). They found an inverse relationship between the sea surface cooling and translation speed.

In recent years, satellite observations have been widely used in understanding the upper ocean response to tropical cyclones (e.g. Lin et al., 2003; Goni and Trinanes, 2003). Subrahmanyam et al. (2005) utilized satellite and model simulated data to examine the thermal, salinity and circulation responses of the upper ocean during severe cyclone passage over the Bay of Bengal (BoB) and Arabian Sea (AS). It was reported that SST cooling is more in the AS compared to BoB due to contrasting hydrographic features viz. salinity stratification and associated mixing processes. High resolution SST data from TRMM satellite revealed that for pre-monsoon tropical cyclone tracks, the SST cools by 3 °C in the north Indian Ocean. Interestingly the strongest post-monsoon cyclones do not cool the north BoB, attributable due to shallow layer of freshwater layer from river runoff and torrential rainfall (Sengupta et al., 2008). In another study, Lin et al. (2009) used *in situ* ocean temperature measurements and satellite altimetry products to address the critical issue of rapid intensification of NARGIS cyclone (defined as ≥30 kts intensification in 24 h) just prior to the land fall. The implementation of international ARGO project is very useful to understand the variability and distribution of important air sea exchange parameters, viz. sea surface heat flux, freshwater storage, and transport during the passage of the tropical cyclone. Three dimensional temperature and salinity fields from ARGO floats are utilized to understand

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the upper ocean response to tropical cyclones in the northwestern Pacific by Liu et al. (2007) who examined dependence of the deepening in MLD, cooling of mixed layer temperature (MLT), and freshening of mixed layer salinity (MLS). In a recent study, Prasad et al. (2009) analyzed the water properties and geostrophic currents in Fiji waters during tropical cyclone *GENE* passage utilizing ARGO and satellite data. After the vaning away of GENE, thermocline depth was found to increase by 20 m, temperature drop by 3 °C and salinity profiles of 0.42 psu to a depth of 35 m were reported. Ramesh Kumar and Byju (2010) conducted a multi-sensor study to understand the formation of a cyclone over North Indian Ocean.

Park et al. (2005) studied the upper ocean response during typhoon passage and found high correlation between MLT and SST in the northern Pacific. In the present study an attempt has been made to understand the upper ocean atmospheric interactions and associated air–sea fluxes during the passage of *MALA* cyclone over the Bay of Bengal.

2. MALA cyclone

Tropical cyclone MALA was considered as one of the strongest cyclones in the year 2006 over the north Indian Ocean cyclone season. *MALA* cyclone developed as a depression over the southeast Bay of Bengal during 00 UTC 24 April 2006, and turned into a deep depression near 10°N/89.6°E at 06UTC on April 25. It traveled northwestward transforming into a cyclonic storm on 00UTC 26 April having a central pressure of 994 hPa and maximum sustained surface wind of about 80 km h^{-1}.

Over the central Bay of Bengal at 1530 UTC on 26 April it further intensified into a severe cyclonic storm (SCS). At 12 UTC on 27 April, MALA had a central mean sea level pressure of 984 hPa with maximum sustained surface wind speed around 120 km h^{-1}. The event further accelerated in the northeast direction and rapidly intensified into an equivalent Category 4 cyclone in the Saffir–Simpson scale with maximum surface winds. The system continued to move in the same (NE) direction towards the Arakan coast and rapidly weakened over land after attaining its peak intensity and made landfall near Gwa around 09UTC of April 29 and quickly dissipated over Myanmar region. More details of *MALA* event can be found in the published work of Rajesh Kumar et al. (2009) and Dube et al. (2009). In a very recent work Badarinath et al. (2009) evaluated the relationship between the SST and meteorological parameters over BoB region during the passage of this *MALA* cyclone using satellite data. Along the trail of the cyclone a cold patch, weakening of wind speeds, and associated cooling of 4–5 °C SST was reported.

3. Data

The message files of cyclone track for *MALA* and relevant information of cyclonic storm were obtained from the India Meteorological Department (IMD) and Joint Typhoon Warning Center (JTWC) tropical cyclone best track data site. Tropical Rainfall Measuring Mission (TRMM) accumulated Precipitation data corresponding to before, during, and after the *MALA* event were obtained from the NASA web site (http://disc2.nascom.nasa.gov/Giovanni/tovas). To evaluate the feedback mechanism between ocean and atmosphere during the *MALA* cyclone passage, data corresponding to air–sea fluxes such as sensible heat flux (SHF), latent heat flux (LHF) were obtained from Objectively Analyzed air–sea Fluxes (OAFlux) (http://oaflux.whoi.edu/) project available daily at 1° × 1° resolution. NASA QuikSCAT ocean surface wind vectors during the MALA passage (27 and 28 April, 2006) was taken to evaluate the symmetry of the storm (ftp://ftp.ssmi.com/qscat/qscat_wind_vectors_v04/).

Temperature and salinity profiles for the present study were obtained from eleven different ARGO floats for the period 14 April to 9 May 2006 (±10 day's window of *MALA* passage) in the study domain encompassing geographical coordinates bounded by latitude 5–20°N and longitude 85–95°E within the vicinity of cyclone track. Park et al. (2005) proposed a criterion in selection of the ARGO floats to study the upper ocean temperature response to typhoons. Based on this study the distance between two profiles should be within a range of 200 km. The positions of the ARGO floats (blue diamonds) along with the track of *MALA* cyclone are shown in Fig. 1. Based on the criterion as postulated by Park et al. (2005), it is clearly noticed that the spacing of ARGO floats satisfy the necessary condition for analysis.

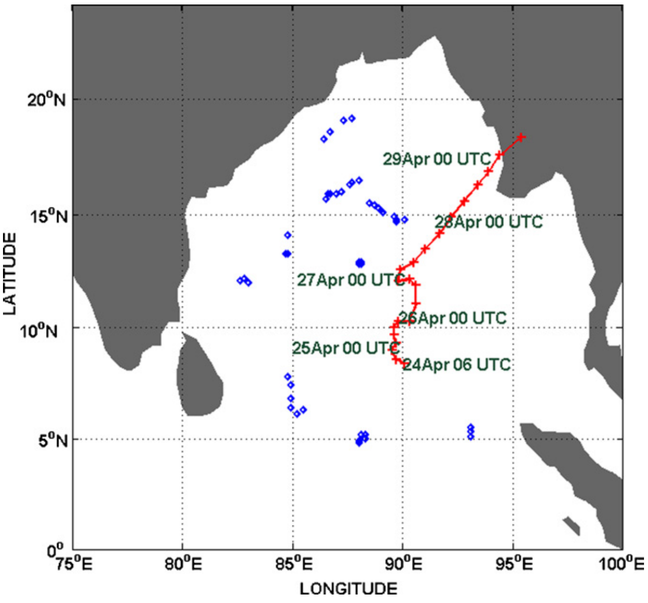

Fig. 1. Track of the *MALA* cyclone (red line) and the corresponding position of the ARGO (blue diamonds) floats during the *MALA* passage (±10 day's window). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

In this study, ARGO floats with similar float ID has been used to assess the upper oceanic process before, during and after the passage of *MALA* cyclone. The data availability of ARGO float with same ID has a repetitive interval of 5 days. The details of float ID are provided in the subsequent section.

4. Methodology

4.1. Estimation of mixed layer depth

A variable density criteria is chosen for the determination of MLD as proposed by Kara et al. (2000) wherein MLD is constructed using density variability ($\Delta\sigma_t$) determined from the corresponding temperature change ΔT (0.8 °C) in the equation of state. The following relation is used in estimation of MLD:

$$\Delta\sigma_t = \sigma_t(T + \Delta T, S, P) - \sigma_t(T, S, P) \qquad (1)$$

where T, S, and P corresponds to temperature, salinity and pressure at the surface.

The isothermal layer depth (ILD) was determined from the temperature based criteria, where the temperature decreases to a value of 0.8 °C compared to the surface (shallowest level obtained from the ARGO profile). The intermediate layer which prevails between the mixed layer and thermocline is named as barrier layer, which forms over the salinity stratified regions (Lukas and Lindstrom, 1991). The implication of this barrier layer is to inhibit cooling of sub-surface waters, which can eventually energize tropical storms in the Bay of Bengal (McPhaden et al., 2009). In another study,