# Warm-Core Eddy and their Influence on the Jal Cyclone Over Bay of Bengal

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**Abstract:** ***Tropical cyclones are among the most dangerous and vulnerable natural disasters faced by people all over the world. The Bay of Bengal (BoB) is a potentially active zone for tropical cyclone generation. Eddies are well-known for their role in the abrupt strengthening of tropical cyclones. The influence of the eddy on the intensification of cyclone Jal in the BoB is investigated in this study utilising sea level anomaly (SLA) data from satellite altimetry. In the paper, We reported the evolution of mixed layer heat budget terms for the Jal cyclone's warm-core eddy area, as well as the influence of oceanic processes responsible for surface ocean changes (up to the MLD) connected with the cyclone's warm-core eddy. To understand the mechanisms and dominant processes associated with changes in the ocean mixed layer (i.e. during the active cyclone period, pre and post of the cyclone period) heat budget analysis is utilized. The present study exemplifies the role of a post-monsoon cyclone (Jal) is impacting the Bay of Bengal variability of surface Physical Oceanographic variables and associated processes.***

**Keywords:** Jal Cyclone, Bay of Bengal, Warm-core eddy, mixed layer heat budget

## 1. Introduction

The Bay of Bengal (BoB) is really a unique semi-enclosed tropical region that has reversible monsoons and depressions, as well as powerful cyclonic storms, and hence receives a lot of rain and river run-off regularly. The Bay is located in the Indian Ocean's northeastern region, completely separated from the Arabian Sea by the peninsula of India. The predominance of the Bay of Bengal's powerful cyclones forms during the post-monsoon season in October and November [10]. Tropical cyclones are well-known for their destructive nature, and they are the most deadly of all-natural catastrophes in terms of human and property damage. One of the major factors in the generation of eddies is the instability of the currents. These are barotropic instabilities and baroclinic instabilities, arising from the horizontal and vertical shear, respectively, with the horizontal currents. Meso-scale eddies form when two primary forces are in balance. The horizontal pressure gradient force is caused by changes in water density, while the Coriolis force is an apparent force created by the rotation of the earth. The Coriolis force causes cold-core eddies that rotate counterclockwise (cyclonic) in the northern hemisphere and warm-core eddies that rotate clockwise (anti-cyclonic). Their lifetime can range from a few days to over a year, with a few months being typical. The diameter of these eddies would range from a few meters to 200 kilometres. According to recent studies, tropical cyclones frequently strengthen rapidly and unexpectedly within 24-48 hours after approaching the shore after travelling over warm oceanic regimes. The Bay of Bengal is famous for its eddies [7].

## 2. Literature Survey

The most devastating post-monsoon cyclones in the BoB occur in October and November. Post-monsoon cyclones pose a threat to the whole Indian east coast, as well as the coasts of Sri Lanka, Bangladesh, and Myanmar. Earlier studies reported anti-cyclonic eddies to comprise relatively favorable conditions for enhancing cyclone intensity due to their capacity to hold high heat content in the center of the eddy associated with downwelling [3], [8]. Warm-core eddies are more common in the northern Indian Ocean (BoB and AS) before the monsoon season than thereafter. Many studies have indicated the presence of eddies in the BOB, but only a few have explicitly addressed their genesis and evolution [1]. Many studies think that the warm core eddy contributes more to cyclone intensification in the Bay of Bengal after the monsoon season than it does before. They've also discovered that when there's a warm core eddy, heat fluxes from the ocean to the atmosphere rise. The existence of mesoscale characteristics such as eddies has a large impact on cyclone strength. Warm core eddies are related to areas of downwelling, have absurdly high sea surface levels, and excessive heat content in the ocean [5]. The top surface layer heat potential of warm-core eddies serves as a fuel for cyclone intensification, providing positive feedback to the cyclones. The intensity of a cyclone entering a warm-core eddy is generally proportional to the eddy's strength and size. The existence of eddies along or near cyclone paths (which may be easily spotted with satellite altimetry SLA data sets) could be important in identifying cyclone strength fluctuations. In addition to other criteria, a comprehensive examination of the Jal cyclone in the Bay of Bengal in 2010 was done to examine the effect of warm characteristics on cyclone intensification. Because of the high ocean heat content in the water column, when a cyclone passes over a warm core eddy, it tends to intensify [6], [11].

We investigated the influence of the 'Jal' cyclone in influencing upper oceanic characteristics (mixed layer heat budget terms and physical oceanographic parameters), with a focus on the warm-core eddy area over BoB. As stated in the next sections, the reason for selecting the Jal cyclone has substantially impacted its strength and influence on the BoB. The rest of the paper is structured as follows. Section

2 summarises the datasets utilised as well as explains the approaches and methodology. Section 3 uses the ocean mixed layer heat budget study to explore the influence of the Jal cyclone on key physical oceanographic characteristics as a warm-core eddy zone; Section 4 summarises our findings.

## 3. Data and Methods

### 3.1 Data sets used

The best-tracked cyclone data from the India Meteorological Department (IMD) from 1993 to 2019 (obtained from http://www.imd.gov.in) is utilised to calculate cyclone evolution tracks and dates over the Bay of Bengal area. This data includes the maximum three-minute continuous wind speed (in knots) and the lowest sea-level pressure (in Millibar). The Joint Typhoon Warning Center (JTWC) best tracks cyclone data every 6 hours to describe the tropical storm system (http://www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc). A maximum sustained wind speed (in knots) and a lowest sea-level pressure are included in this data collection (in Millibar). For the period 1993–2019, the Archiving, Validation, and Interpretation of Satellite Oceanographic Data (AVISO) integrated with a high resolution of 25 km (0.25° latitude x 0.25° longitude) altimeter SSHA data for the BoB is provided from the website (www.aviso.oceanobs.com). The website (http://www.esrl.noaa.gov/psd) provides daily data with a high resolution (25 km or 0.25°) optimal Interpolated Sea Surface Temperature (OISST) [4]. To compute different components in the mixed layer heat budget equation, a very high resolution (0.083 x 0.083 degree, horizontal) Ocean reanalysis product from Marine Copernicus (available at https://resources.marine.copernicus.eu; product ID: GLOBAL MULTIYEAR PHY 001 031) is utilised (Section 2.2). This information is accessible from January 1993 through December 2019. Because this Ocean reanalysis product incorporates real/near real-time ocean in-situ and satellite observations and is driven by high-resolution ERA-Interim and ERA5 atmospheric reanalysis, it can depict TC associated/induced Ocean variability.

These ocean observations are also used to evaluate the ocean's mixed layer depth (MLD) and the depth of the 20°C isotherms (D20). For defining the mixed layer, we used temperature-based criteria. The MLD is defined as the area of the ocean surface when the temperature lowers by 0.8°C from the surface temperature [14]. To investigate warm-core eddies and their impact on tropical cyclones over the BoB, we reviewed daily OISST, MLD, and D20 data from Marine Copernicus from 1993 to 2019. TropFlux [12] data are used to compute various terms in equation 2 (section 2.2) of study the mixed layer heat budget and they are accessible at www.incois.gov.in/tropflux. All of the data used in this research was obtained between 1993 and 2019.

### 3.2 Method - the Mixed Layer Heat Budget analysis

The ocean mixed layer heat budget study is performed to determine the major mechanisms responsible for the surface ocean changes (up to the MLD) connected with the Jal cyclone. The mixed layer heat budget analysis is used to comprehend the mechanisms and key processes underlying changes in the ocean's mixed layer (i.e. during the active cyclone period, pre and post-cyclone period). The MLD heat budget is computed using the method given in [14]. Surface heat fluxes, horizontally and vertical heat transfer, and heat diffusion all influence the temperature of the mixed layer. However, because heat diffusion via molecular processes is low in relation to the other components, it is neglected for simplicity of study. The ML heat budget equation [14] is provided hereunder.

$$\frac{\partial T}{\partial t} = \frac{Q_{net}}{\rho c_p h} - \left[\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) + H\left(Wh + \frac{dh}{dt}\right)\frac{(T - Th)}{h}\right] + \text{Residual} \quad (1)$$

The temperature tendency term is mentioned in Equation's LHS (1). The distinct components in the R.H.S of the equation are the net surface heat flow term, horizontal advection (zonal and meridional components), heat flux owing to vertical processes, and the residual term. Qnet represents the net surface heat flow.

$$Q_{net} = Q_{shortwave} - (Q_{pen} + Q_{longwave} + Q_{latent} + Q_{sensible}) \quad (2)$$

$Q_{shortwave}$ = Net shortwave radiation,
$Q_{pen}$ = Shortwave radiation that penetrates below the ML,
$Q_{longwave}$ = Net longwave radiation,
$Q_{latent}$ = Latent heat flux,
$Q_{sensible}$ = Sensible heat flux.

where ρ (1,024 kg $m^{-3}$) is the density of seawater, Cp (3,993 J $kg^{-1}K^{-1}$) is the specific heat capacity of seawater, h (m) is the mixed layer depth (MLD), u is the zonal current velocity ($ms^{-1}$) and v is the meridional current velocity (m $s^{-1}$), T (°C) is then mixed layer temperature, $\partial T/\partial x$ and $\partial T/\partial y$ is the horizontal gradient of temperature, t is time (in days), $W_h$ is the vertical advection (m $day^{-1}$). $T_h$ is slightly below the MLD temperature [12].

The various data sets used in the ML heat budget analysis are explained in Section 2.1. To assess the effects generated by the Jal cyclone, all of the variables in the ML budget equation supplied in this study have been de-trended and deleted for the seasonal cycle.

## 4. Results and Discussion

### 4.1 The Mixed Layer Heat Budget Analysis with special emphasis on warm-core eddy along cyclone track

The ocean surface is the boundary between the atmosphere and the deep ocean; the transition of the ocean surface layer or mixed layer temperature is controlled by several aspects of both the earth's atmosphere and oceans, which are commonly referred to as the ML heat budget equation, which is provided in section 2.2, equation (1). Several case studies using both observations [2] and models [13] have revealed that oceanic vertically mixing, convection, and air-sea fluxes have a significant impact on the thermal behaviour of the ocean during cyclonic storms. The ML heat budget analysis is used to investigate the mechanisms and major processes connected with changes in the ocean mixed layer (i.e. throughout the active cyclone time, pre and post-cyclone period). The ML heat budget is computed using the method given in [14]. We reported the evolution of MLD heat budget terms for the warm-core eddy zone of cyclone Jal in this section.

### 4.2 Mixed Layer Heat Budget Analysis for Jal cyclone

On October 31st, 2010, a low-pressure region in the South Sea evolved into a depression (figure 1), which reached the eastern BoB on November 2nd. On November 4th, it became depression and drifted westward. The system strengthened to the level of a cyclonic storm as the sea level pressure dropped day by day. It then moved west-northwest, causing the sea level pressure to drop fast from 1005 millibar to 982 millibar [9]. By November 5th, the Jal had strengthened into a strong cyclonic storm. At this moment, the Jal storm has approached western BoB, with a low sea-level pressure of around 982 millibar [9], and high wind speeds of more than 55 knots (maintained for an extended period of time), and is expected to strengthen further into a very severe cyclonic storm. However, on November 7th, within the western BoB, it quickly deteriorated into a cyclonic storm [9]. We've chosen the Jal cyclone to use as a case study, as shown in the figure below (Figure 1).

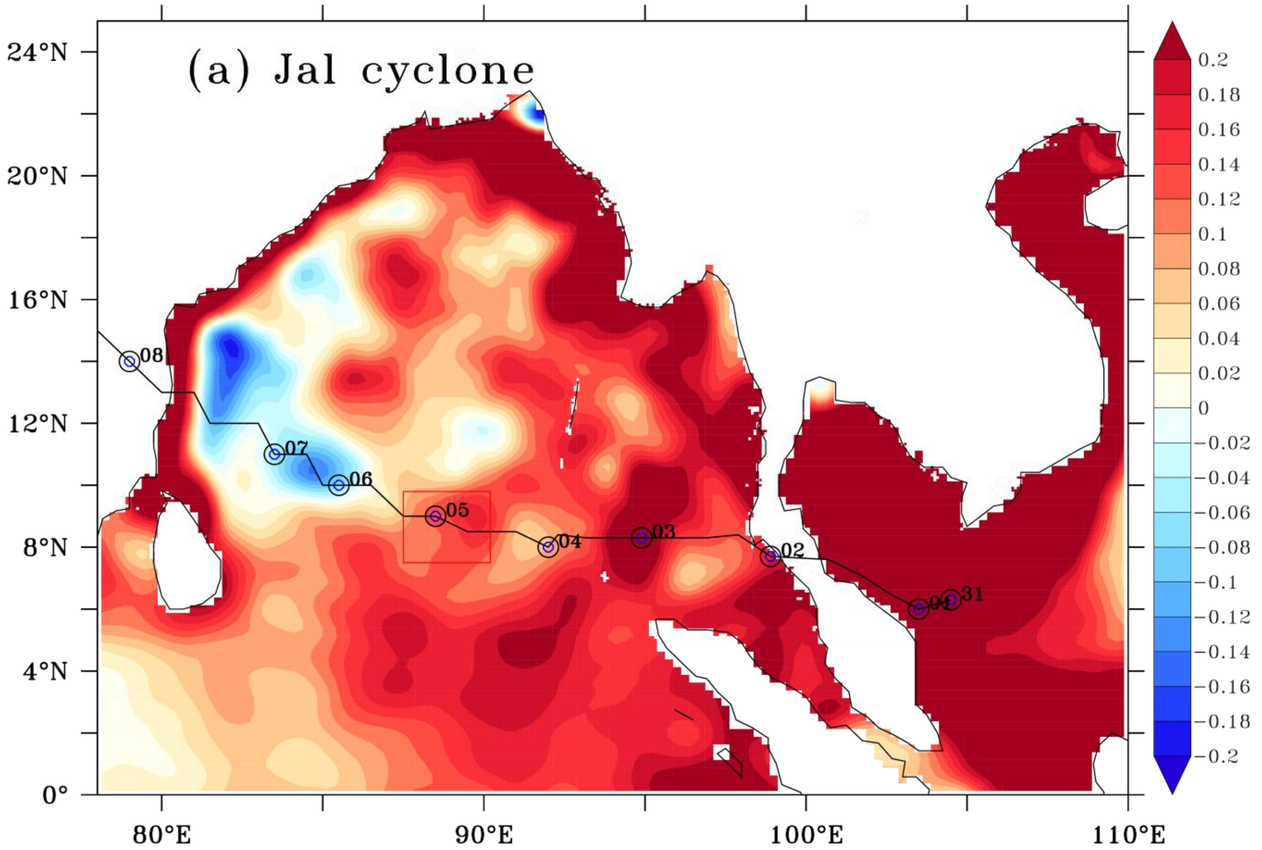


**Figure 1:** Post-monsoon season Jal cyclone formed over the Bay of Bengal in the 2010 year. During the cyclone period, the sea level anomaly (m) and red color box indicate the existence of a warm-core eddy.

In this section, we examine the ML heat budget terms to know about the importance of different physical phenomena over a warm-core eddy in controlling or influencing TC activity. The values (area averages across the warm-core eddy region) of the different components included in the MLD budget analysis are shown in Table 1 [section 2.2] 5 days before and during the cyclone, and 5 days after going through a cyclone with warm-core eddies, according to Equation (1).

**Table 1:** Values Mixed Layer Heat Budget anomaly terms (area averages for respective warm-core eddy region) for the cyclone Jal. Units for all the terms are ($^0$C per day)

| Cyclone Name | Location of Eddy | Period | Tendency | Qnet | Entrainment | Zonal | Meridional | Lateral induction |
|---|---|---|---|---|---|---|---|---|
| Jal cyclone | Lon:87.5$^0$E - 90.2$^0$E, | 5 days before | 0.008 | -0.013 | -0.359 | -0.002 | -0.001 | 0.002 |
| 04– 08 Nov | Lat:7.5$^0$N-9.8$^0$N | During the cyclone | -0.083 | 0.001 | -1.495 | 0.006 | 0.003 | 0.006 |
| (5 Days) (2010) | Warm core Eddy | 5 days after | 0.003 | -0.005 | -0.386 | -0.003 | -0.005 | -0.004 |

Figure 2 depicts line plots of several elements of the MLD heat budget, such as temperature tendency, zonal and meridional advection terms, net heat flow, and entrainment, and lateral induction term, averaged across the warm-core eddy area. The Jal cyclone approached the warm core eddy (Longitude: 87.5$^0$E-90.2$^0$E, Latitude: 7.5$^0$N-9.8$^0$N) on November 4, 2010 (Table 2). The temperature tendency plot (figure 2a), which indicates a quick rate of decreasing tendency up to 0.083°C/day from November 4th to November 5th, 2010, demonstrates the shallow of the mixed layer. Within the selected region (4th November), the entrainment term generated up to -1.49°C/day decreasing the rate (figure 2b), whilst advection (Zonal and Meridional) of warmer water into the eddy region contributed up to 0.002°C/day warming rate (figure 2c & 2e). When the cyclone was above the warm-core eddy on November 4th, the net heat flux term was negative (-0.038 °C/day), favouring heat loss from the mixed layer (figure 2d). On November 5th, it was positive, with the mixed layer gaining temperature. The observed cooling of the mixed layer is due to a combination of horizontal advection, vertical entrainment from below the mixed layer, and lower net heat flow at the sea surface (figure 2). Other term, such as lateral induction make insignificant contributions (figure 2f). In our analysis, the ML heat budget parameters contributed more to the cyclone entering the warm-core eddy region. Figure 2 depicts the budget equation's different variables. We can clearly demonstrate that there are no substantial changes in the eddy region before 5 days of cyclone Jal entering, but tremendous changes occur throughout the active cyclone period. Also, after five days of the cyclone, we found positive values in the eddy area.

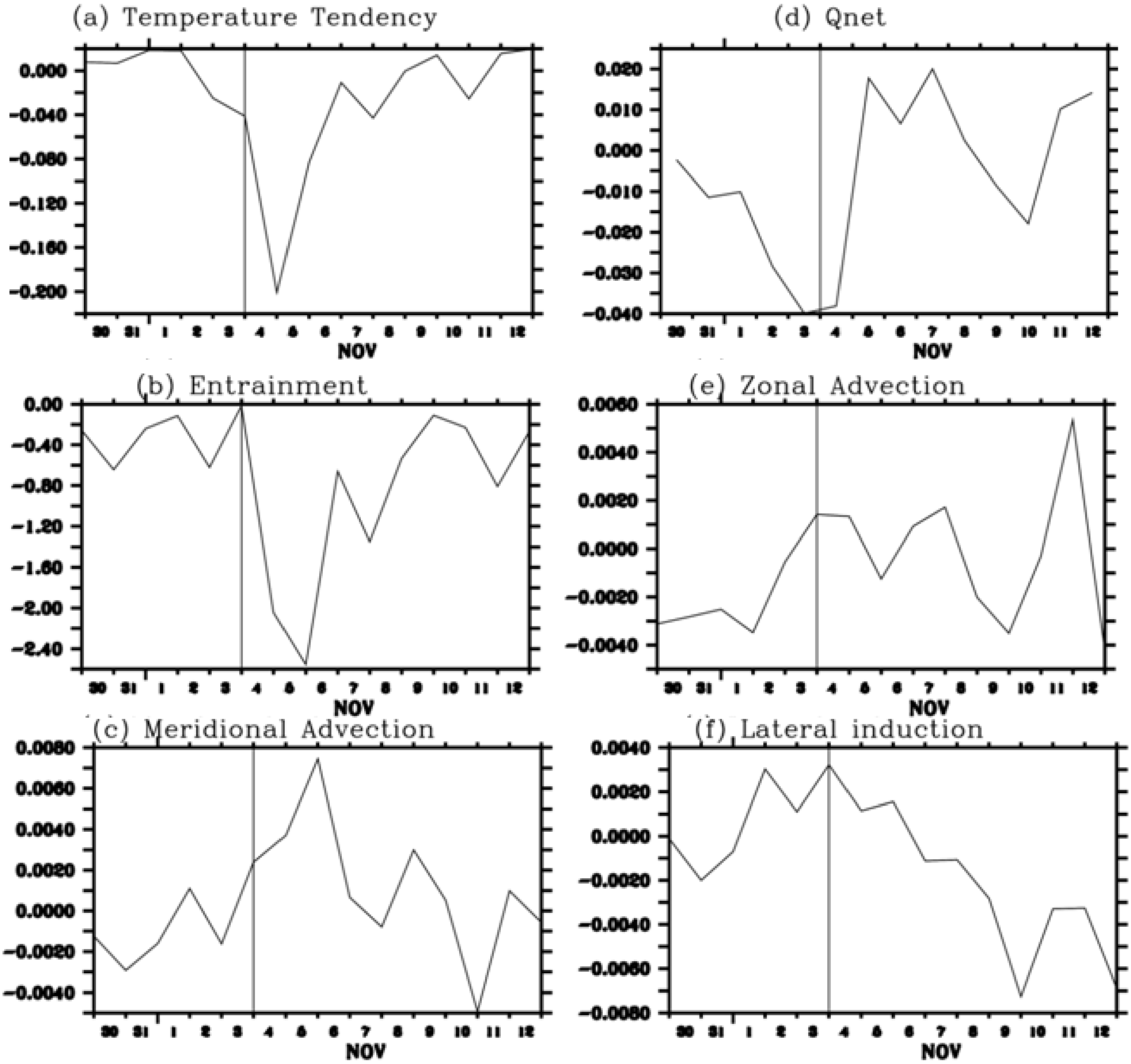


**Figure 2:** Values of anomalies in mixed layer heat budget terms (°C/day), for warm-core eddy region (87.5°E - 90.2°E, 7.5°N - 9.8°N) of Jal cyclone, viz - (a) Temperature tendency term, (b) Entrainment term, (c) Meridional advection term, (d) Net heat flux $Q_{net}$ term, (e) Zonal advection term and (f) Lateral induction term. The black vertical line shows the entry of the Jal system to the warm-core eddy region.



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**Table 2:** Oceanographic metrics for a typical warm-core eddy in the Bay of Bengal during an active Jal cyclone phase

| S. No. | Name of the cyclone | Date of Cyclone Arrival in eddy region | Location of Eddy present | Dates | SST anomaly ($^o$ c) | SSH anomaly (m) | MLD anomaly (m) | D20 anomaly (m) | BLD anomaly (m) | Wind speed (Knots) | Cyclone Departure Date from eddy region |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Jal 30th October to 08th November (10 Days) (2010) | 4-11-2010 | Lon:87.5$^0$E - 90.2$^0$E, Lat:7.5$^0$N-9.8$^0$N Warm Core Eddy | 04-11-2010 | 0.0362 | 0.1307 | -0.053 | 11.57 | 6.438 | 04-11-10 [25-D] | 05-11-2010 |
| | | | | 05-11-2010 | -0.1567 | 0.1247 | 4.902 | 12.39 | 2.988 | 05-11-10 [45-CS] | |

Further, we have examined the nature of these physical oceanographic parameters by considering the Bay of Bengal (Longitude: 87.50E-90.20E, Latitude: 7.50N-9.80N). Figure 3 shows the evolution of SST, SLA, MLD, D20 and BLD anomaly during the pre-cyclone period (i.e., 30th October to 03rd November 2010, 5 days), during the Jal cyclone period (04th to 08th November 2010), and 5 days past the decay of the cyclone (i.e. 09th to 13th November 2010). Table 3, shows the Jal cyclone's arrival in the eddy region on November 4th, 2010 with a wind speed of 25 knots and then departure date from the eddy region on November 5th, an increasing trend was observed. So the warm-core eddy boosts the cyclone intensity by 45 knots. So a cyclone changes its intensity depression to the cyclonic storm, so a warm-core eddy can help to fuel the cyclonic storm. The Jal cyclone approaches the pre-existing eddy (warm-core). The cyclone approaches the eddy area, indicating the strengthening of the cyclonic eddy. On November 4th, 2010, the Jal cyclone entered the warm-core eddy region, with SST rapidly decreasing (Figure 3a) and SLA showing positive trend values (Figure 3b). The mixed layer depth also shows positive values up to 4 m (Figure 3c), revealing a thick barrier layer (BLT) between 2 and 6 meters (Table 2 and Figure 3d). The d20 values are deepened to 11 meters (Figure 3e). The thick barrier layer is also important in cyclone intensity changes.

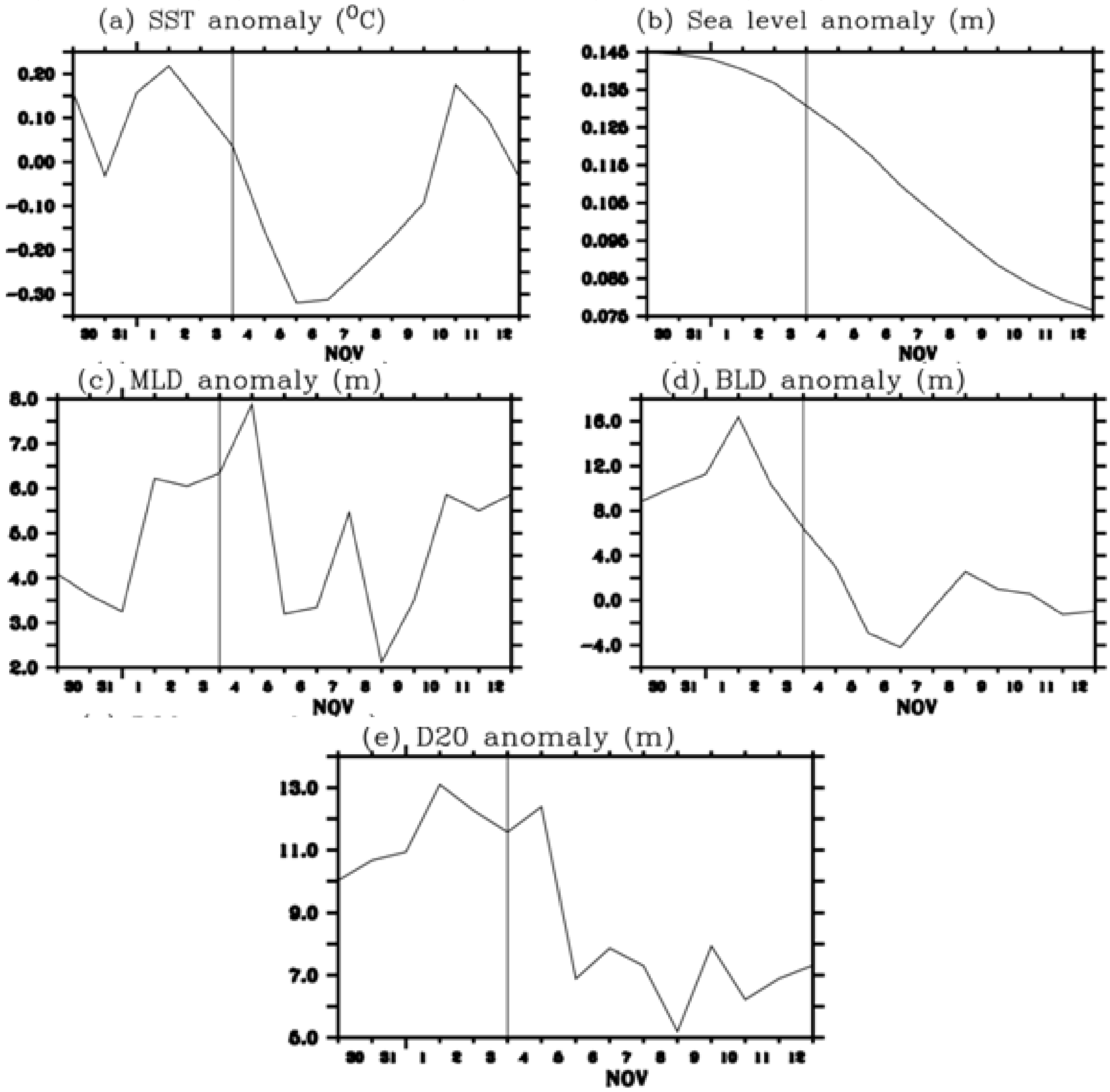


**Figure 3:** Evolution of different Oceanographic parameters for the warm core eddy region of Jal, viz. (a) SST anomaly ($^o$C), (b) Sea level anomaly (m), (c) MLD anomaly (m), (d) BLD anomaly (m), and (e) D20 anomaly (m); The black vertical line shows the entry of Jal system to the warm-core eddy.

## 5. Conclusions

Because of their diverse socioeconomic repercussions, tropical cyclones have received the most attention from meteorological groups. The rise of cyclone strength over the eddy is a distinguishing feature of all warm-core eddies. In the example of Jal, who entered the warm-core eddy with the strength of Depression (Table 2), the cyclone intensifies into a cyclonic storm when it exits the eddy. As a result of the cyclone, we discovered that the Jal storm had a major influence on SST, SLA, MLD, BLD, and D20 anomalies. In our analysis, the ML heat budget parameters contributed more to the cyclone entering the warm-core eddy region. Figure 2 depicts the budget equation's different variables. We can clearly demonstrate that there are no substantial changes in the eddy region before 5 days of cyclone Jal entering, but tremendous changes occur throughout the active cyclone period. It should be noted that, despite the fact that the net fluxes are favorable for warming the ocean, the Bay of Bengal exhibits a cooling trend in mixed layer temperature for 5 days after the cyclone has passed. The dense barrier layer also contributes significantly to cyclone intensity changes. Physical oceanographic variables have also played a key influence in the evolution of the Jal cyclone in the warm core eddy region.

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