Reply to the Comments of Anonymous Referee #1

We thank the Anonymous Referee#1for reviewing our manuscript and for suggesting improvements. We have addressed all the concerns of the Referee#1.

General comments

- **Referee's Comment**

This paper studies the upper ocean physical and biogeochemical response to Cyclone Madi (2013) in the Bay of Bengal from the analysis of multiple atmospheric and oceanicdata. The topic is interesting. My understanding is that there are many studies regardingthe topic: the upper ocean physical and biogeochemical response to cyclones. Some of the studies have been referenced in this manuscript. Therefore, my concern is the novelty of this paper.

Author's Response

In this paper we not only bring out the cyclone-induced physical and biogeochemical response of the surface ocean using a suite of remote sensing data, we document the time-evolving depth-dependent temperature and chlorophyll response of the upper ocean to tropical cyclone, which is the novelty of this paper. We have used two Argo float data (WMO ID 2901288, 2901629) for temperature profiles that were in the vicinity of Track 2 and one Bio-Argo float (WMO ID 2902086) for chlorophyll profiles that was to the right of Track 1. Another novelty is that the enhancement of Chl-*a* and net primary productivity by cyclone Madi is much greater compared with previous cyclones that occurred in the BoB. We show that this is the combined impact of cyclone and oceanic cyclonic eddy. This is significant because BoB is known for its low upper ocean Chl-*a* and primary productivity.

- **Referee's Comment**

There are a few discussion points on this study.

1) I don't agree with the conclusion that "oceanic eddies affect the translation speed of Madi". This study lacks discussions on what factors do affect the movement of cyclones.In addition, there is no information regarding the atmospheric steering flow andwave-1 asymmetry of the inner core structure that is very important in understanding the movement of storms, although the authors showed the horizontal distributions of 500-hPa winds in Fig. 6. There is a cause-result confusion on the authors' conclusionthat the motion of the cyclone is mainly controlled by cold eddy when the cyclone stagnated over the cold eddy without any considerations of the variation of environmentalsteering flow.

Author's Response

To address the concern of the reviewer, especially the role of atmospheric steering, we wish to clarify this point with the help of additional computations and figures. We could include a summary of the following description, in very brief, in the discussion part of the modified manuscript.

Environmental conditions that are necessary for the formation of tropical cyclones are (1) SST in excess of 26.5°C, (2) low level wind convergence, (3) high relative vorticity, (4) weak vertical wind shear, and (5) high relative humidity.

Once formed cyclones generally move in a westerly/north-westerly direction due to the advection of potential vorticity field by storm circulation. In simple case, the background potential vorticity gradient is simply the meridional gradient of the Coriolis parameter (f) where $f = 2\Omega \sin \Phi$ and Φ varies with the latitude, beta ($\beta = \frac{\partial f}{\partial y}$). The Beta drift generally causes the tropical cyclone to move poleward and westward relative to the motion they would have if the background potential vorticity field were unperturbed by the storms.

Based on the comments by the reviewer, in order to examine the role of environmental steering flow, we show the analysis of the vorticity dynamics, which is the tendency of the absolute vorticity term ($\frac{\partial \eta}{\partial t}$), as per the following equation:

$$\frac{\partial \eta}{\partial t} = -\vec{\mathrm{v}}.\nabla\,(\zeta + f) - \ (\zeta + f)\,(\nabla.\,\vec{v}) - w\frac{\partial \varepsilon}{\partial p} + (\frac{\partial w}{\partial x}\frac{\partial v}{\partial z} - \frac{\partial w}{\partial y}\frac{\partial u}{\partial z}) + \ \vec{\mathrm{F}}$$

(1) (2) (3) (4) (5)

Where, u,v,w are the velocity component. The vertical component η of the absolute vorticity vector (as defined above) given by the sum of the vertical component of vorticity with respect to the earth (relative vorticity (ζ)) and the vorticity of the earth (equal to the Coriolis parameter f).

$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$ where u and v are zonal and meridional wind.

$f = 2\Omega \sin \Phi$ where Φ varies with the latitude, and $\eta = \zeta + f$

The local change of absolute vorticity is related to horizontal advection (term 1), stretching term (term 2; divergence multiplied by absolute vorticity), vertical advection (term 3), tilting term (term 4)and friction (term 5). The contribution from the each term in the absolute vorticity tendency equation was examined. The analysis has shown that at lower level (850hpa) stretching and horizontal advection in the vorticity equation are the major contributors of the absolute vorticity tendency term. The contribution from other terms being very small could be neglected.

Low level vorticity being one of the environmental factor which plays a key role in the formation and development of the tropical cyclone, the time evolution of vorticity tendency (Fig.A), horizontal advection (Fig.B) and stretching term (Fig.C), all at 850 hpa, were analyzed. Note that the absolute vorticity tendency in the area where the genesis of cyclone Madi took place was high before the genesis Madi and indicated the prevailing atmospheric condition congenial for its formation. The track of the cyclone moves through the region of high absolute vorticity tendency. Consistent with this the horizontal advection and the stretching term also showed higher values in the vicinity of the genesis of cyclone. The stretching term is related to absolute vorticity and divergence of wind. Increased divergence is related to increased convection and generation of more low pressure which is favourable for cyclone. On the 9-10th December when the northward movement of cyclone Madi was arrested the region showed increased absolute vorticity tendency and horizontal advection with increase in stretching term, all of which supported the strengthening and northward progression of Madi. However, contrary to this, the cyclone slowed down and finally became stationary. Recall that at this time the cyclone Madi was passing through the region of cold-core eddy.

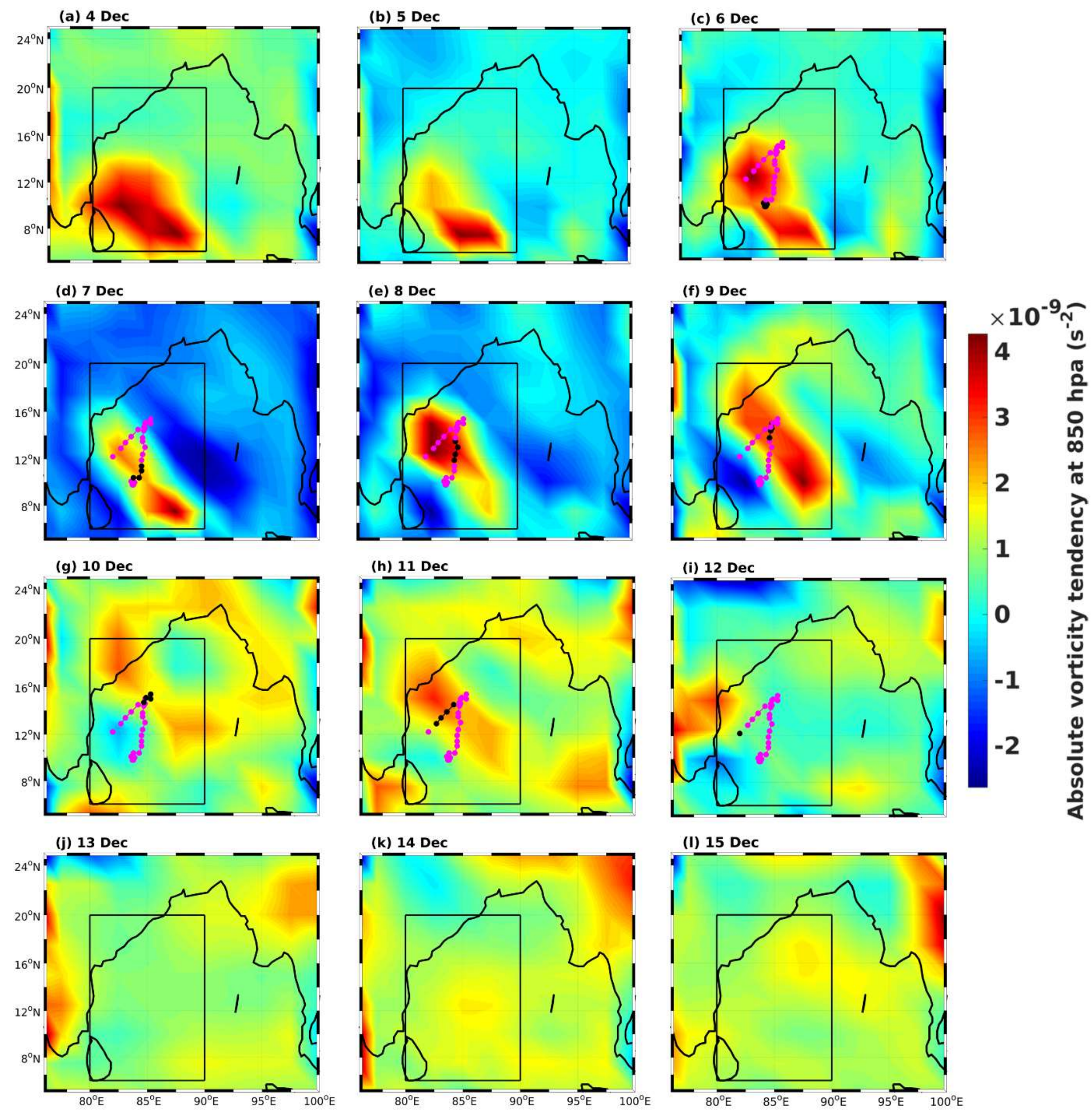


Figure A. Time evolution of absolute vorticity tendency at 850 hpa (s^{-2}) from 4th to 15th December 2013 superposed with track of cyclone indicated by black (current position) and magenta (track).

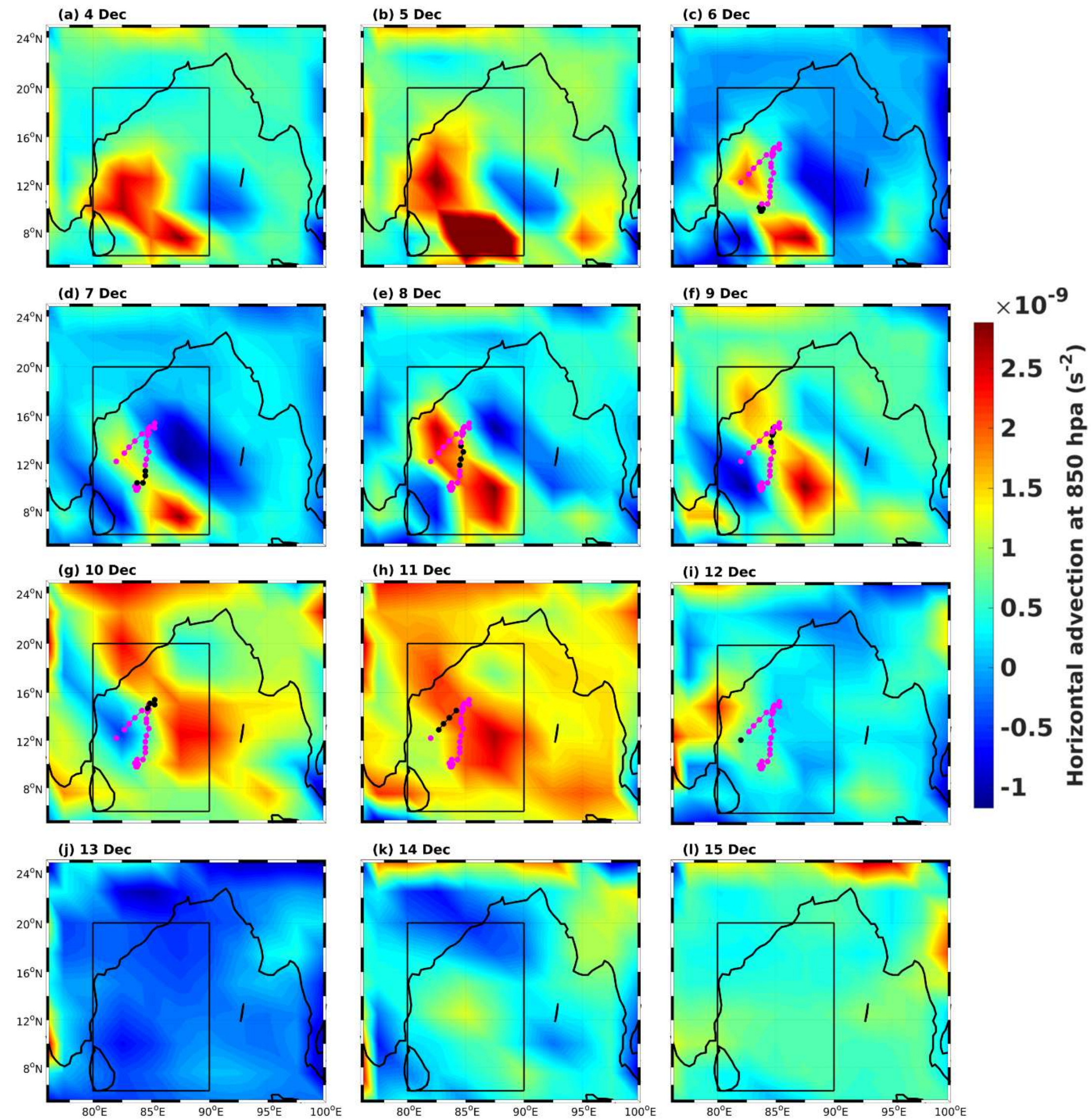


Figure B. Time evolution of horizontal advection at 850 hpa (s^{-2}) from 4th to 15th December 2013 superposed with track of cyclone indicated by black (current position) and magenta (track).

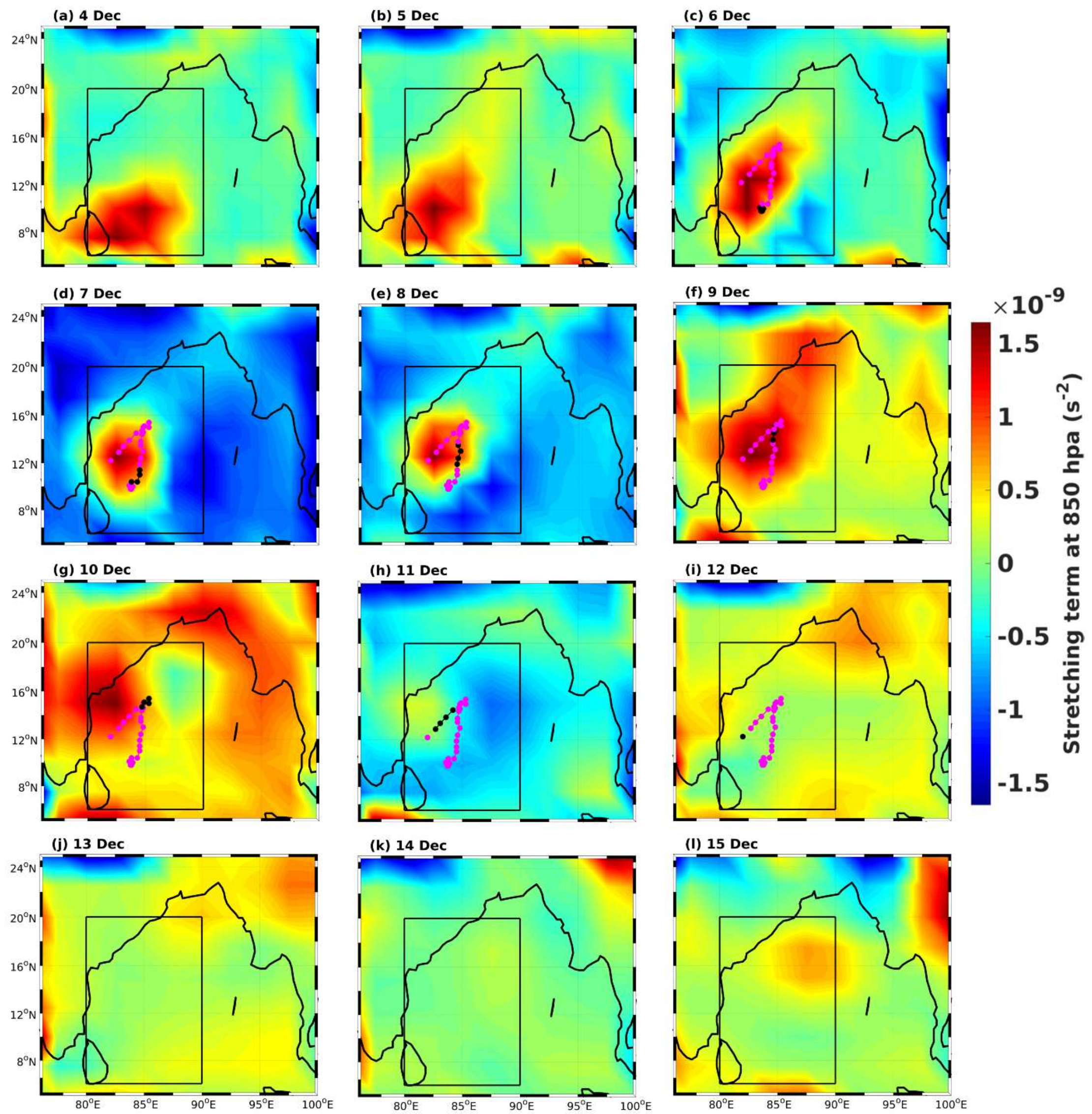


Figure C. Time evolution of stretching term at 850 hpa (s^{-2}) from 4th to 15th December 2013 superposed with track of cyclone indicated by black (current position) and magenta (track).

To further illustrate the role of cold-core eddy in arresting the northward motion of the eddy, which then was acted upon by the background wind, we generated hovmoller diagrams of oceanic heat content (OHC) and tropical cyclone heat potential (TCHP) (Fig. D) along with zonal and meridional components of wind (Fig. E). From Fig. D, it could be clearly seen that when the cyclone Madi reached its northern most position on 9th before its track reversal, it was moving over a region of small values of OHC as well as TCHP. We have already showed in the manuscript that these small values of OHC and TCHP were associated with cold-core cyclonic eddies.

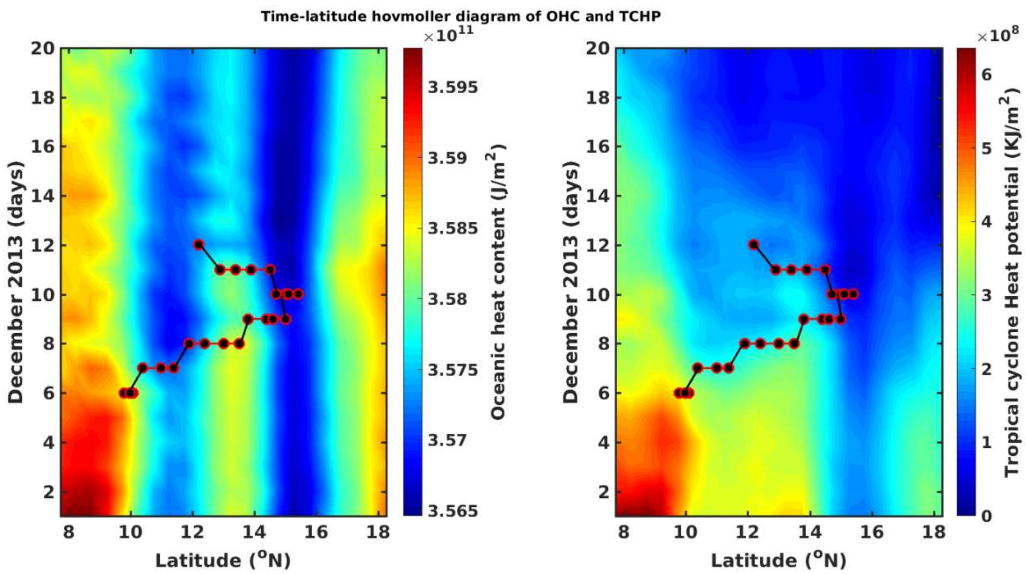


Figure D. Time-latitude plot of (left panel) oceanic heat content (J/m^2) and (right panel) tropical cyclone heat potential (KJ/m^2) with cyclone track superposed on it.

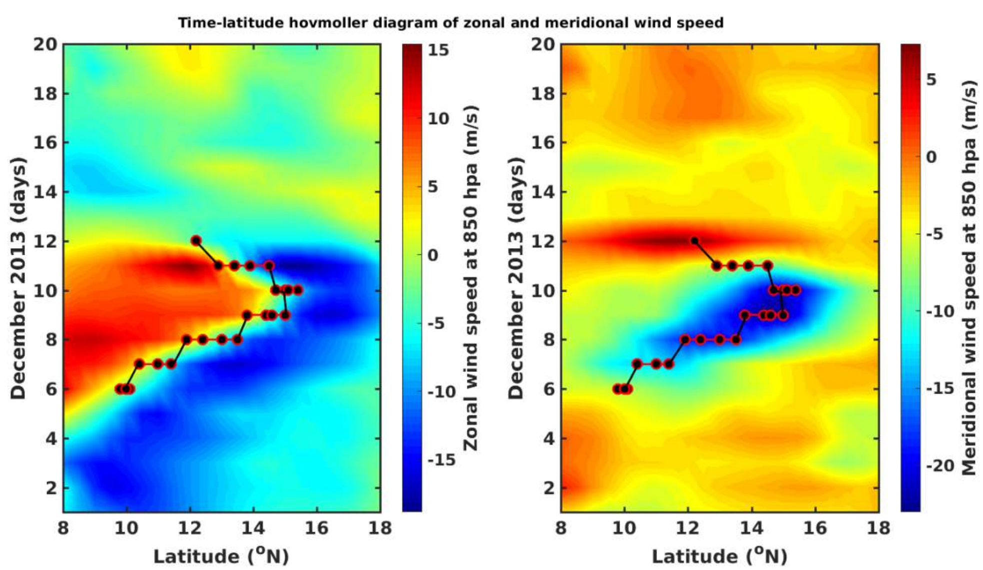


Figure E. Time-latitude plot of (left panel) zonal and (right panel) meridional wind speed (m/s) at 850 hpa with cyclone track superposed on it.

Note that during this time the translation speed of the cyclone Madi reduced from 2.81m/s to 1.96 m/s (Table 1). Once the translation speed of the cyclone reduces, the background north-easterly winds (Fig. E) are able to reverse the direction of motion of the cyclone from north/north-westerly to south-westerly. We hope we have adequately addressed the concern of the reviewer.

- **Referee's Comment**

Looking at Fig.5, there seems to be no interaction between Madi and mid-latitude westerlies. I don't understand the role of vertical wind shear shown in Fig. 5 in the evolution of Madi. According to Fig. 6, the movement of Madi seems to be affected by highpressurearea east of the cycle, moisture transport along the edge of the high-pressurearea, and high-pressure area west of the cyclone with dry airs after the recurvature (north-easterlies pointed out by Bhattacharya et al. 2015). In my opinion, the synopticvariations did affect the movement of Madi rather than the cold eddy underneath thecyclone. In that sense, I agree with Bhattacharya et al. (2015).On the other hand, the impact of cold eddies on cyclone intensity is well known. What are new findings regarding TC-ocean interactions in this study? On the other hand, the impact of cold eddies on cyclone intensity is well known. What are new findings regarding TC-ocean interactions in this study?

Author's Response

Wind shear is defined as the amount of change in the wind speed and direction with increasing altitude. As indicated in our reply to the previous query, vertical wind shear is also an important factor for the genesis and intensification of the tropical cyclone. Here we have calculated vertical wind shear (layer vertical shear is defined as the difference between the 200-850hpa layers) before, during and after the passage of the cyclone Madi. Vertical wind shear (shown in Fig.5) is one of the parameters that are examined to see if the atmospheric condition could support the formation of a cyclone. For example, a low vertical wind shear is usually congenial for cyclogenesis. Hence, we have used the time evolution of this parameter to assess the suitability of the atmosphere in the formation of cyclone Madi. On 9-10th December 2013 when cyclone trapped into the cold core eddy region the vertical shear was low (~10-15 m/s). Though the wind shear was favourable cyclone Madi did not move further in the northward direction, instead its speed reduced and finally it turned to the south-westward direction.

We wish to clarify that while the high pressure area east of the cyclone and moisture transport along the edge of the high pressure (Figure 6 in the manuscript) might have played a role in the evolution of cyclone Madi, it is the passage over cold-core cyclonic eddy that led to the slowing down and finally arresting of its northward movement, as elaborated in the previous "Reply to referee's comment". This is the new finding, which is different from that of Bhattacharya et al. (2015). Once the cyclone becomes stationary the prevailing large-scale background winds were able to steer it away in a south-westward direction and the cyclone undergoes a reversal from its original track. In addition to the slowing and arresting the northward motion of the cyclone, the cold-core cyclonic eddy augments upward transport of subsurface nutrients through eddy-pumping in tandem with Ekman suction under the cyclone. These two mechanisms together led to the enhancement of Chl-*a* and net primary productivity which was much greater compared with previous cyclones.

- **Referee's Comment**

2) I do not understand how to calculate net primary production (NPP). Anyway, thestudy of the upper ocean biogeochemical response to Cyclone Madi is one of thetopics of this study. As for the sudden increases in total CO_2 flux, Bates et al. (1998)and Nemoto et al. (2009) have already reported it from the analysis based on theobservations. In addition, Wada et al. (2011) conducted numerical simulations by anocean general circulation model to clarify the mechanism and relation to the relative position to the storm center regarding the variation of the sudden increases in total CO_2flux. My question is what are new findings in this study regarding the relation of oceaniceddies to the sudden increases in total CO_2 flux. This also applies to chlorophyll-aconcentrations. In the abstract, the authors only show the number of folds regardingrapid increases in chlorophyll-a concentrations, NPP and total CO_2 flux. Without anyinformation on these background values, readers cannot understand the importance ofthese extreme events.

Author's Response

As detailed under section 2.2 the net primary production (NPP) has been estimated based on vertically generalized productivity model (VGPM) of Behrenfeld and Falkoswski (1997). The model was developed by assembling a dataset of 11,283 ^{14}C-based measurements of daily carbon fixation collected at 1,698 oceanographic stations in both open ocean and coastal waters. It is a light-dependent, depth-resolved model for carbon fixation that partitions environmental factors affecting primary production into those that influence the relative vertical distribution of primary production and those that control the optimal assimilation efficiency of the productivity profile. The weekly Chl-*a* data along with the MODIS daily mean photosynthetically available radiation (PAR) and TMI-MODIS SST (https://modis.gsfc.nasa.gov/data/) were used for the computation of NPP along the track of the cyclone using the algorithm of VGPM.

We have referred the work of Bates et al. (1998) and Nemeto et al. (2009) in our manuscript, both studied the out-gassing of CO_2 under the influence of tropical cyclones. What is different in our study is the magnitude of the out gassing which varied from 2 to 3.7-fold. This is very significant in the Bay of Bengal, which is known to be a sink for atmospheric CO_2. Since 3-5 cyclones occur every year in the BoB, and the number and intensity of cyclones are reported to increase under global warming, this will have a decisive impact on the regional basin-scale CO_2 balance.

Based on the comment of the reviewer to add information about background values of Chl-a, NPP and total CO_2 flux in the abstract we would modify the lines 22 to 26 in the abstract as the following:

Cyclone-induced enhancement in the chlorophyll *a* ranged from 5 to 7-foldfrom its pre-cyclone value of 0.2 to 0.4 mg/m^3, while increase in the net primary productivity ranged from 2.5 to 8-fold from its pre-cyclone value of 320 mg C m^{-2} day^{-1}. This enhancement of chlorophyll *a* and net primary productivity was much higher than previous cyclones that occurred in the BoB. Similarly, the CO_2 out-gassing into the atmosphere showed a 3.7-fold increase compared to the pre-cyclone value of 1.27 Tg carbon per day.

- **Referee's Comment**

In that sense, the authors did not present in-depth analysis on the time series of thevertical profiles of water temperature, salinity and chlorophyll-a concentrations. Theseprofiles may show the ocean response to a storm occurred on the right-hand side of amoving storm (in the Northern Hemisphere). Certainly, sea surface temperature in themixed layer decreased due to vertical turbulent mixing, but sea surface temperaturein the thermocline increased during the passage of the storm and then decreases.There is no discussion regarding this oceanic response and its relation to variation inchlorophyll-a concentrations although they have been already studied.I hope the above mentioned discussion points will be clear.

Author's Response

Please note that the Argo profiles that were used in the present study is not from the right-hand side of the moving storm, but from the left-hand side. Notwithstanding this the time evolution of subsurface temperature and salinity in response to the cyclone was well captured by the Argo floats as described under section 3.4. The subsurface thermo-haline response of the water column to the passage of cyclone is described in brief in the first paragraph under 3.4, while the 2nd paragraph describes the Chl-a response using a bioargo profile which is on the right side of the cyclone track.

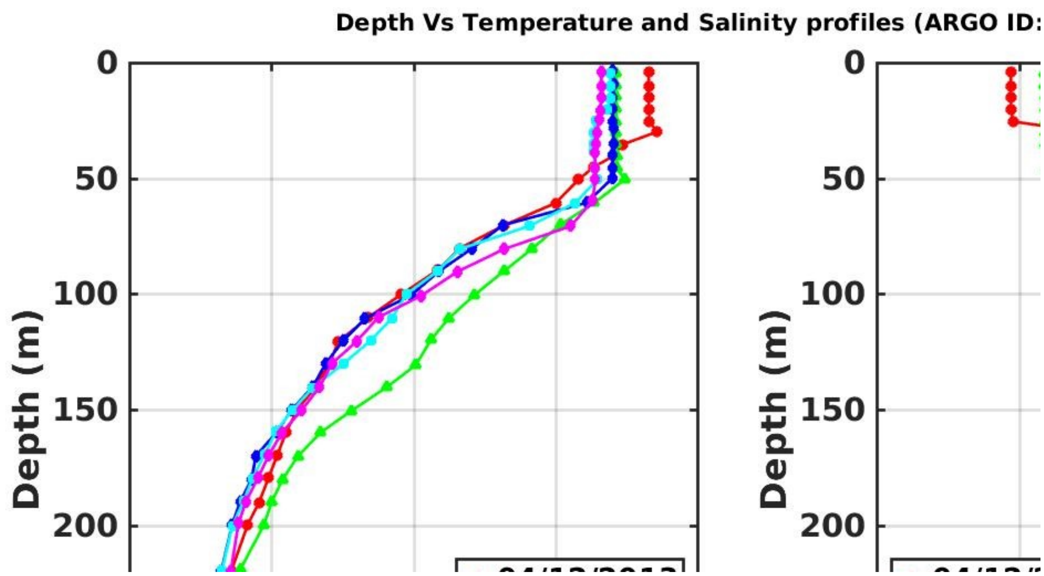
Specific comments

3) Referee's Comment

I suspect the calculation method (equation (3)) of ocean heat content (OHC) in thisstudy. First, there is no information on the oceanic dataset in the manuscript. At least,water temperature from the surface to 300-m depth is needed in equation (3). Second,3.574x1011 (Q) / 1.026x103 (density) / 3.87x103 (Cp) / 300(m) ~ 300 K. This meansthat water temperature should be 300K from the surface to 300-m depth so that thisresult is not consistent with Fig. 11(a). Therefore, Fig. 3 only shows information whichis the same as the horizontal distribution of sea surface temperature.

Author's Response

We clarify that we have not calculated the upper oceanic heat content (OHC), but the data has been taken from climate forecast system reanalysis (CFSR) of National Centre for Environmental Prediction (NCEP) climate forecast system (CFS) version 2 (http://www.ncep.noaa.gov) (Saha et a., (2014).The oceanic temperature data used for the calculation OHC as per equation 3 is from the ocean model GFDL MOM version 4 which is configured for the global ocean. The horizontal grid resolution of the OHC data in our study domain is 0.5 x 0.5 degree latitude by longitude. The value of Cp for a sea water salinity of 35 and temperature in the range of 30to 0°C is 4.0 kJ kg^{-1} K^{-1} (kindly note that the value given in the ms is 3.87 is not correct and we will rectify it by replace it with 4.0). With this the calculated temperature at 300 m is ~ 11.2°C, which is consistent with the vertical profiles of temperature obtained from Argo in the upper 300m (see figure below) and given in Figure 11 (a) in the upper 250m.



We would modify the manuscript in lines 80 & 82 as follows:

The oceanic heat content (OHC) in the upper 300m, calculated using the following Eq. (3), were obtained from the climate forecast system reanalysis (CFSR) of National Centre for Environmental Prediction (NCEP) climate forecast system version 2 (http://www.ncep.noaa.gov) (Saha et al. 2014).

where, ρ is the density of seawater, c_p is the specific heat capacity of sea water taken as 4.0 kJ kg^{-1} K^{-1}, h_1 and h_2 are the lower and upper water depths, and $T(z)$ is the temperature profile measured in Kelvin.

4) Referee's Comment

In equations (1) and (2), there is no information regarding how to calculate windstresses.

Author's Response

We have calculated the wind stress (τ) as follows:

$$\tau = \rho \; C_D \; U_{10}^2$$

Where ρ is the density of airtaken as 1.22 kg m^{-3}, C_D is the dimensionless drag coefficient and U_{10} is the wind speed at 10m above the sea surface. As the drag coefficient varies wind speed we have used the following values as per Large and Pond (1981)

C_D= 1.2 x 10^{-3} for $4 < U_{10} < 11$ m/s

C_D = 10^{-3} (0.49+.065U_{10}) for $11 < U_{10} < 25$ m/s

Large, W.G., Pond, P.: Open ocean momentum flux measurements in moderate to strong winds, Journal of Physical Oceanography, 11, 324-336, 1981.

5) Referee's Comment

In the abstract, there are many descriptions regarding a lifecycle of Madi. It seemsthat the authors intentionally increased the number of characters of the abstract.

Author's Response

We have not "intentionally increased the number of characters of the abstract". It would have helped us if referee would have pointed out to specific sentences or expressions that were of concern.

6) Referee's Comment

The reference of O'Brian et al. is not correct. Maybe this paper shows the results ofidealized numerical experiments regarding the upper ocean response to a vortex.

Author's Response

Thank you. We agree. We would remove this reference from the text (line 46) as well as from the list of references (lines 456-458).

7) Referee's Comment

In general, vertical wind shear is calculated as an areal average. How did the authorscalculate the vertical wind shear? What did the authors intend to analyze the vertical wind shear?

Author's Response

We have calculated the difference in the magnitude of the vertical wind velocity between 850 and 200 hpa as given below:

Vertical wind shear = $\sqrt{(U_{200hPa} - U_{850hPa})^2 + (V_{200hPa} - V_{850hPa})^2}$

We would modify the lines 87-88 to make this explicit as follows:

Winds at 850 and 200 hpa were used for the calculation of wind shear (Saha et al., 2014) (http://www.ncep.noaa.gov) by determining the difference in the magnitude of the vertical wind velocity between 200 and 850 hpa.

Vertical shear is one of the parameters that are examined to see if the atmosphere could support the formation of a cyclone. For example, a low vertical wind shear is usually congenial for cyclogenisis. Hence, we have used the time evolution of this parameter to assess the suitability of the atmosphere in the formation of cylone Madi.

8) Referee's Comment

How did the authors calculate weekly composite of daily chlorophyll-a concentrations? Because the moving speed of Madi is relatively slow, there seem to be a lot ofdata missing areas.

Author's Response

Cloud cover during cyclone is a major concern for the data on chlorophyll-*a* pigment concentrations determined by optical remote sensing method. Hence to reduce the areas of missing data we have averaged daily data into weekly time scale to come up with composite map.

9) Referee's Comment

In equation (5), salinity data are required. However, there is no information on salinitydata used in this study.

Author's Response

The daily salinity profile data for December 2013 were taken from HYCOM global 1/12 degree GOFS 3.1reanalysis (http://apdrc.soest.hawaii.edu/las_ofes/v6/constrain?var=234)

We would include this information in the manuscript in line 108 as follows:

The daily salinity profile data for December 2013 were taken from HYCOM global 1/12 degree GOFS 3.1reanalysis (http://apdrc.soest.hawaii.edu/las_ofes/v6/constrain?var=234).

10) Referee's Comment

In Table 1, the category of the intensity of Madi is not based on the Saffir-Simpsonscale.

Author's Response

The classification of the intensity of the system is based on Indian Meteorological Department (IMD) (http://imd.gov.in/section/nhac/termglossary.pdf) and it is mentioned in the manuscript in lines 123-124.

11) Referee's Comment

It is very hard to see black arrows in Figs. 3-6. The marks in all figures tend to besmall.

Author's Response

We have increased the size of the black arrow and the marks and redrawn the figures 3 to 6 which are appended below and would be used in the modified manuscript:

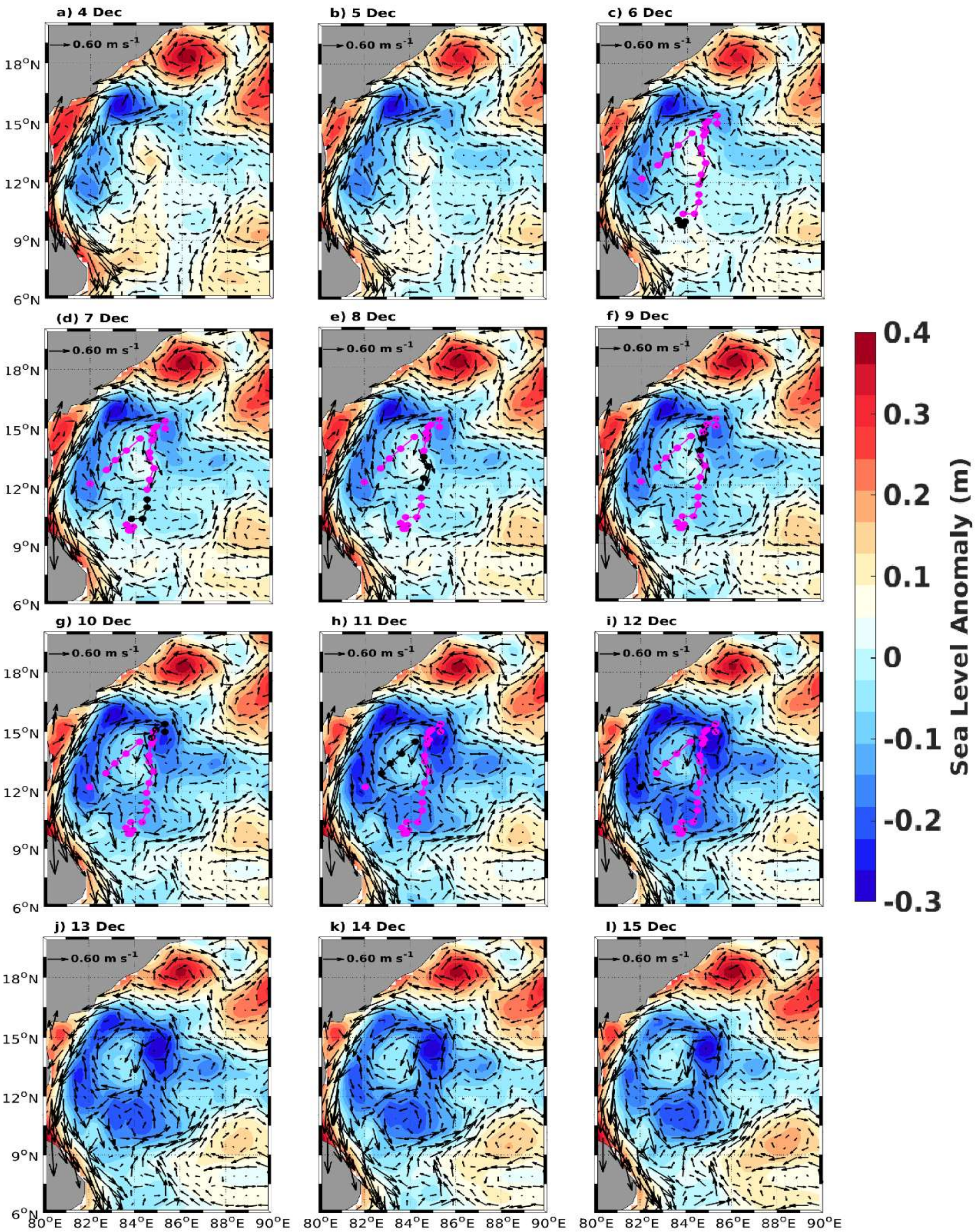


Figure 3 Spatial maps of sea level anomaly (m) from 4th (a) to 15th (l) December 2013 with track of the cyclone overlaid on it. The black filled circles represent the position of the cyclone on a particular day, while the magenta filled circles indicate the track.

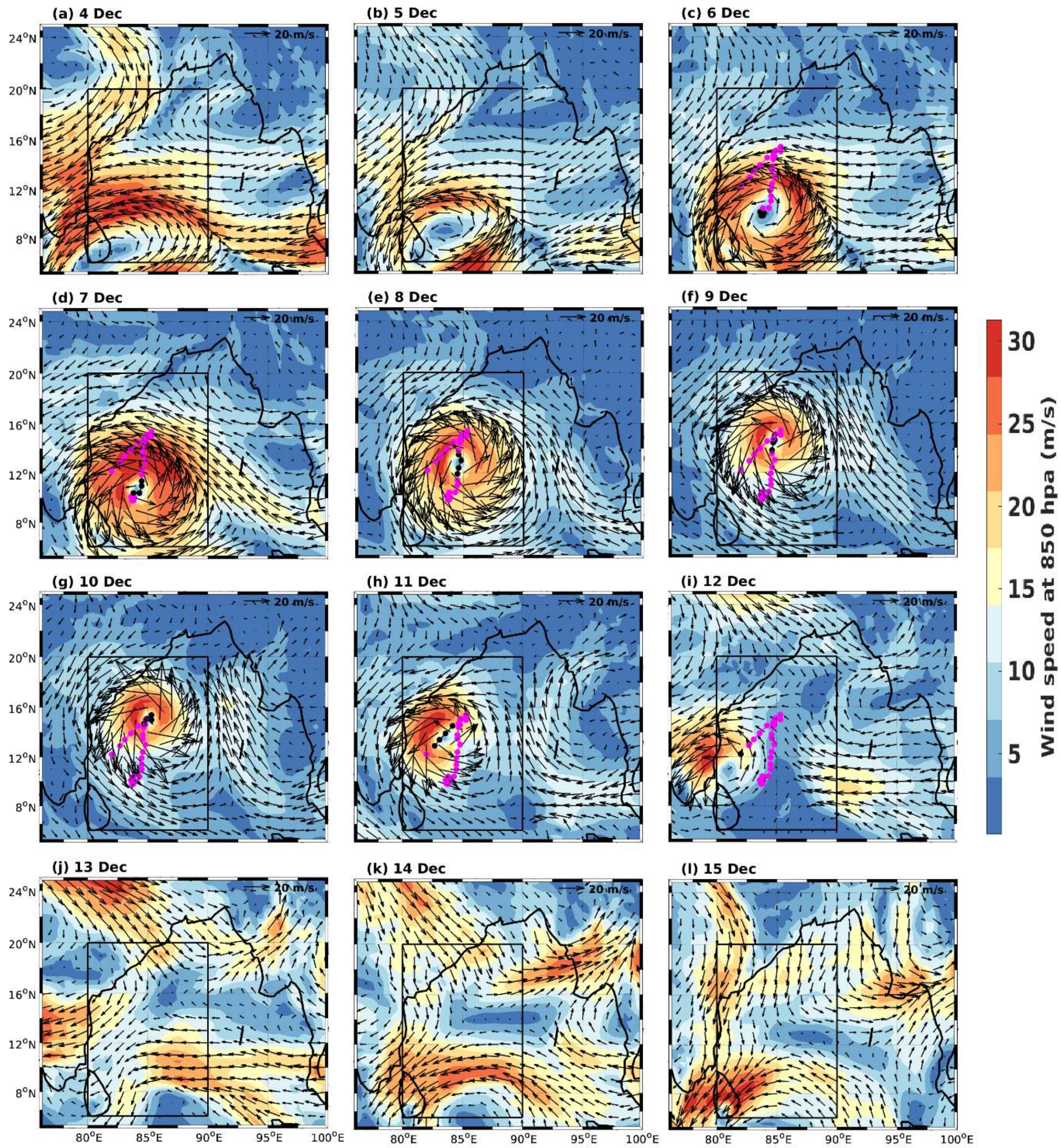


Figure 4 Spatial maps of wind speed (shading, m/s) overlaid with wind vectors (thin arrow) at 850 hpa from 4th(a) to 15th (l) December 2013 with track of the cyclone overlaid on it. The black filled circles represent the position of the cyclone on a particular day, while the magenta filled circles indicate the track.

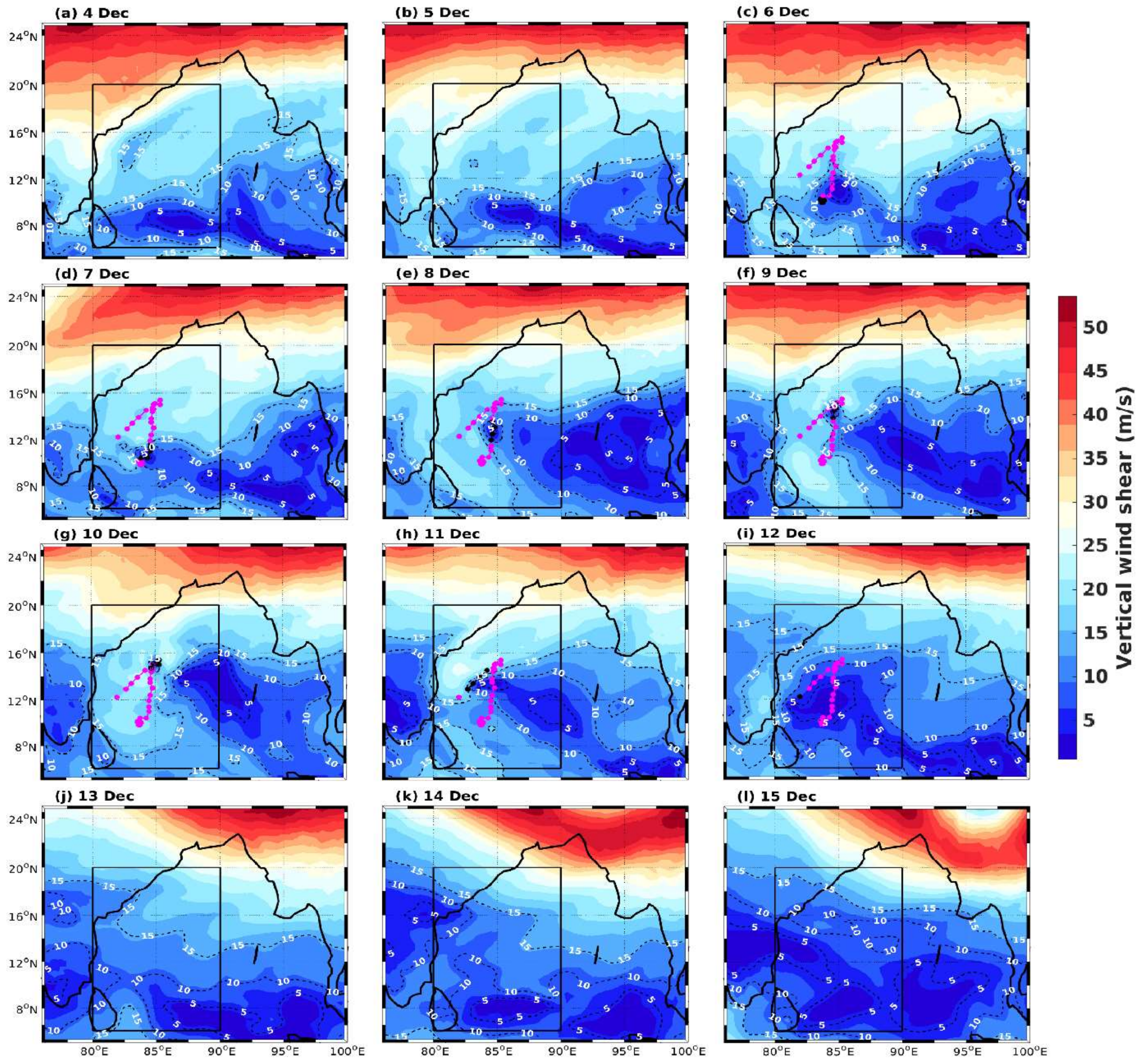


Figure 5 Spatial maps of vertical wind shear between the 850 and 200hPa (shading, m/s)from 4th (a) to 15th (l) December 2013 with track of the cyclone overlaid on it. The black filled circles represent the position of the cyclone on a particular day, while the magenta filled circles indicate the track.

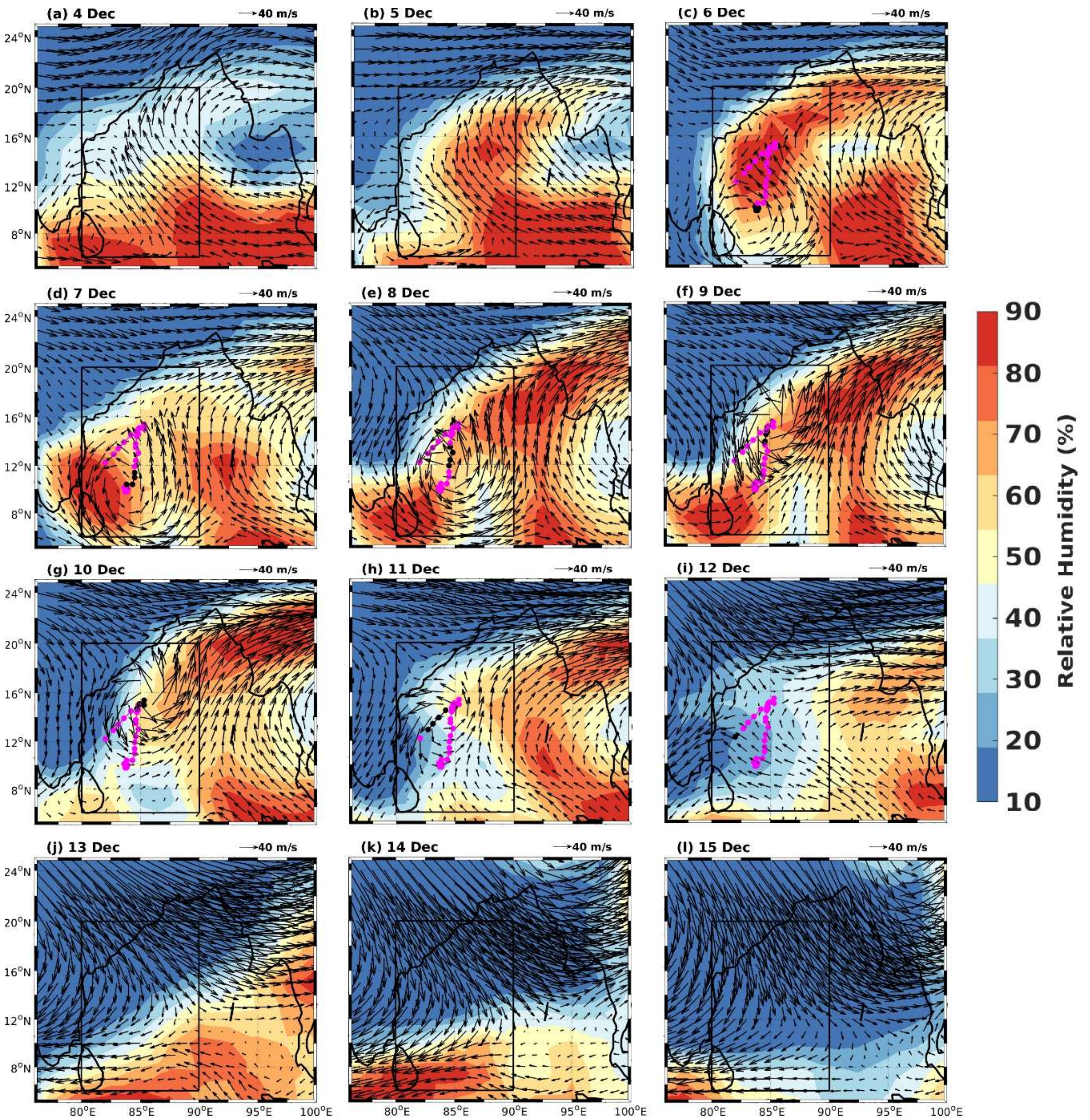


Figure 6 Spatial maps of relative humidity (%) overlaid with winds at mid-troposphere (500 hpa) from 4th (a) to 15th(l) December 2013 with track of the cyclone overlaid on it. The black filled circles represent the position of the cyclone on a particular day, while the magenta filled circles indicate the track.