Reply to the Comments of Anonymous Referee #1

[Received and Published: 11 March 2019]

1. General comments:

- **Referee's Comment**

I am grateful for the authors' replies. Although the presentation of the paper might have been improved, I can not confirm it at the present moment, because I cannot find the revised paper in the web now. Therefore, my comments are only for the replies.

- **Author's Response**

We have gone through the comments of the Referee#1 very carefully. In fact, there are 4 comments this time and we addressed them point-by-point in the following section. However, all the 4 points broadly converge to Referee's reviews about (1) role of cold core eddy in controlling/arresting the northward movement of cyclone Madi and (2) how the present study on the out-gassing of CO_2 is quantitatively different from that of earlier studies.

(1) Role of cold core eddy in controlling/arresting the northward movement of cyclone Madi

It is unfortunate that Referee#1 still remains unconvinced about the role of cold core eddy in controlling the northward movement of the cyclone.

To quantify the eddy's contribution to the intensity of the cyclone Madi, we have calculated the eddy feedback factor following Wu et al. (2007). The analysis showed (for details see following section on Reply to Reviewer's specific comments) that from 7th to 8th December when the system intensified from CS to VSCS and was passing through the warm patch associated with warm core eddy (see spatial maps of OHC at Fig.2 & positive SLA at Fig.3 of original manuscript) the eddy feedback factor was positive and amounted to 59%. Thereafter, when the cyclone passed over the cold patch associated with cold core eddy during 9thand 10th December, the eddy feedback factor was negative and 69%. Thus, this analysis quantifies the contribution of both warm and cold core eddies; when cyclone passed through the warm patch the system intensified from CS to VSCS and its translation speed increased (see Table 1), while when it passed over the cold patch from 9thto 10th the system slowed down and its northward movement was arrested as noted under the section 2.3. We have elaborated the methodology of computation of eddy feedback factor under the "Response to specific comments" with a new diagram. The modification to the manuscript is also indicated there. We hope this will convince the Reviewer#1

2) How the present study on the out-gassing of CO_2 is quantitatively different from that of earlier studies

Based on the Reviewer's comment, in order to compare our CO_2 flux with that of previous studies, we have recomputed the CO_2 flux along Track 1, Track 2 and Boxes A and B in mmol per meter square per day. While re-computing CO_2 flux we noticed a bug in our previous calculation, which we rectified. The newly calculated values showed a cyclone-induced CO_2 out-gassing which was about 4-times greater than the pre-cyclone values along Track 1 and in Box B. The impact of CO_2 out-gassing in Box A and along Track 2 were much smaller as when the cyclone was in this box and was passing through this track it was in a formative and dissipative stage respectively.

Several studies have demonstrated that the passage of a tropical cyclone can lead to enormous amount of CO_2 flux from the ocean surface to the atmosphere. For example, based on observation from Sargasso Sea during summer 1995 Bates et al. (1998) showed that hurricanes accounted for nearly 55% of the CO_2 flux into the atmosphere, while based on moored buoy data from the East China Sea Nemoto et al. (2009) reported a 60% contribution from typhoon in summer. In the eastern Arabian Sea Byju and Prasanna Kumar (2011) noted that cyclone Phyan emitted ~8 mmol m^{2} day^{1} of CO_2 from ocean to atmosphere accounting for ~85% of the total out-gassing for the month of November (climatology) calculated by Takahashi et al. (2009). Our study show that during cyclone Madi (6-12 Dec) Maximum CO_2 flux observed was 13 mmol m^{-2} day^{-1}. Tropical cyclones have significant impact on the carbon cycle in the Bay of Bengal (Ye et al., 2019). Based on their study cyclone Hudhud and cyclone Roanu formed over the Bay of Bengal enhanced CO2 efflux (18.49 ± 3.70 mmol CO_2 m^{-2} day^{-1}) and (19.08 ± 3.82 mmol CO_2 m^{-2} day^{-1}) due to wind effect during the storm.

We have elaborated this under Response to specific comments with a new diagram. The modification to the manuscript is also indicated there.

- **Authors' Changes in Manuscript**

No change in the manuscript in response to this query.

2. Referee's Specific Comment

For the biogeochemical oceanic response to a storm, I understand that the observation itself is new. However, the authors did not reply (and revise) the following scientific themes: What kind of processes did the oceanic response occur by? What effects did the response have on?.

- **Author's Response**

Sorry to say that we did not quite understand the question of the Reviewer. Assuming that the Reviewer is enquiring about the oceanic processes that are responsible for the response in terms of enhanced chlorophyll concentration and enhanced CO_2 out-gassing, following is our reply.

As the tropical cyclone Madi passes over the BoB, the upper ocean experiences strong vertical mixing associated with strong winds, which is essentially a one-dimensional response. In addition to this, the cyclonic winds lead to strong Ekman divergence, which is a three-dimensional response. This, in turn, forces the subsurface cold and nutrient rich waters to come to the surface under the upward Ekman pumping. Increased availability of nutrients to the upper ocean will initiate the carbon fixation by phytoplankton in the euphotic zone and results in the enhancement in chlorophyll biomass. In addition to the enhancement of chlorophyll biomass with time, the upward Ekman pumping also would result in an increase in the CO_2 out-gassing in the following manner. As the cold subsurface waters comes to the surface it also brings with it higher concentration of dissolved CO_2. Once at the surface, the warmer temperature and strong winds will initiate a strong out-gassing of CO_2 from ocean surface to the atmosphere. This happens under the action of all tropical cyclone. What is distinct in our case is that the cyclone Madi is passing over cold core eddy. Under this condition the upward transport of CO_2 rich subsurface water occurs due to both Ekman pumping driven by cyclonic winds associated with the cyclone Madi as well as eddy-pumping driven by cyclonic circulation of water in a cold core eddy. Accordingly, in our study we see a nearly 4-fold increase in the CO_2 out-gassing compare to its pre-cyclone values, when the cyclone passes over track 1 and Box B which has cyclonic eddy. See more details under the next reply.

- **Authors' Changes in Manuscript**

No change in the manuscript in response to this query.

3. Referee's Specific Comment

I also understand that there was a sudden change in the biogeochemical components such as Chl-a and outgassing of CO2 from the background before the passage. However, the authors have not shown any evidence of the difference quantitatively from the present study to Bate et al. (1998) and Nemoto et al. (2009). According to Wada et al. (2011), the amount of outgassing of CO2 is greatly affected by the error of surface wind speed analysis data. Therefore, I think that the difference the authors found is not a new finding but the result including the observational error.

Author's Response

The air-sea CO_2 flux at the sea surface depend on the difference between the partial pressure of CO_2 at the sea surface (pCO_2^{sea}) and in the overlying atmosphere (pCO_2^{air}), the wind speed, sea surface temperature and sea surface salinity as per the equations 4, 5 and 6 in the manuscript. Among these factors, the wind speed plays an important role in determining the value of air-sea CO_2 flux due to the quadratic functional dependence of the gas transfer velocity with the wind speed. Several studies have demonstrated that the passage of a tropical cyclone can lead to enormous amount of CO_2 flux from the ocean surface to the atmosphere. For example, based on observation from Sargasso Sea during summer 1995 Bates et al. (1998) showed that hurricanes accounted for nearly 55% of the CO_2 flux into the atmosphere, while based on moored buoy data from the East China Sea Nemoto et al. (2009) reported a 60% contribution from typhoon in summer. In the eastern Arabian Sea Byju and Prasanna Kumar (2011) noted that cyclone Phyan emitted ~8 mmol m^2 $day^1$of CO_2 from ocean to atmosphere accounting for ~85% of the total out-gassing for the month of November (climatology) calculated by Takahashi et al. (2009). Our study show that during cyclone Madi (6-12 Dec) maximum CO_2 flux observed was 13.73 mmol m^{-2} day^{-1}. Tropical cyclones have significant impact on the carbon cycle in the Bay of Bengal (Ye et al., 2019). Based on their study cyclone Hudhud and cyclone Roanu formed over the Bay of Bengal enhanced CO2 efflux (18.49 ± 3.70 mmol CO_2 m^{-2} day^{-1}) and (19.08 ± 3.82 mmol CO_2 m^{-2} day^{-1}) due to wind effect during the storm.

Based on the Reviewer's comment in order to compare our CO_2 flux with that of previous studies we have recomputed the CO_2 flux along Track 1, Track 2 and Boxes A and B in mmol per meter square per day. While re-computing CO_2 flux we noticed a bug in our previous calculation, which we rectified and a new figure is generated as given below.

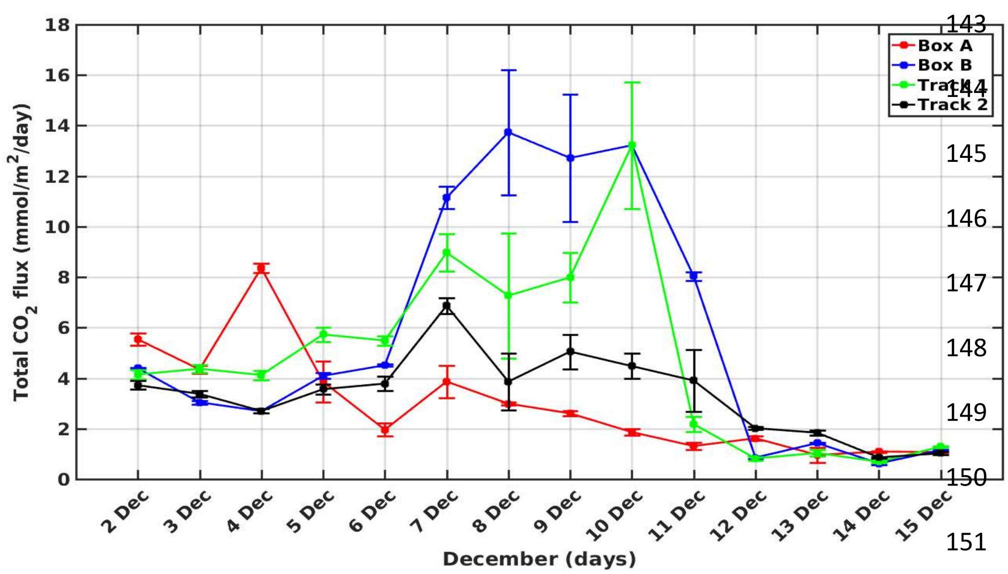

Fig A. Daily variation total CO_2 flux (mmol/m^2/day) in the Box A (red) and B (blue) and along Track 1 (green) and 2 (black) from 2 to 15 December 2013. The vertical lines are the standard deviations.

The newly calculated values showed a cyclone-induced CO_2 out-gassing which was about 4 and 4-times greater than the pre-cyclone values along Track 1 and Box B respectively. The impact of CO_2 out-gassing in Box A and along Track 2 were much smaller because when the cyclone was in Box A and passing through Track 2 it was in a formative and dissipative stages respectively.

Regarding the observational error associated with wind data used in our present study, the bias and root-mean-square differences of the wind speed between ASCAT and dropwindsonde data are -1.7 and 5.3 ms^{-1} (Chou et al., 2013). ASCAT winds are most reliable when the wind speeds are in the range of 12 and 18 m s^{-1} and can be applied to determine the radius of 34 knot winds, a critical parameter in operational tropical cyclone analysis (Chou et al., 2013).

In our case the wind speed used for the computation of CO_2 flux ranged from 2.72 to 10.38 ms^{-1}. We have calculated the correlation between Rama buoy and ASCAT wind data in BoB region. We have chosen wind speed data from the RAMA buoy located at 12 N 90 E and 15 N 90 E for the comparison with ASCAT wind product which is used for the CO_2 flux calculation in our study. The location of the Rama buoy was nearby the track of the cyclone Madi. Rama data was taken from Global tropical moored buoy array (https://www.pmel.noaa.gov/tao/drupal/disdel/). The correlation Coefficient values are 0.89 and 0.83 respectively indicating the quality of the ASCAT data

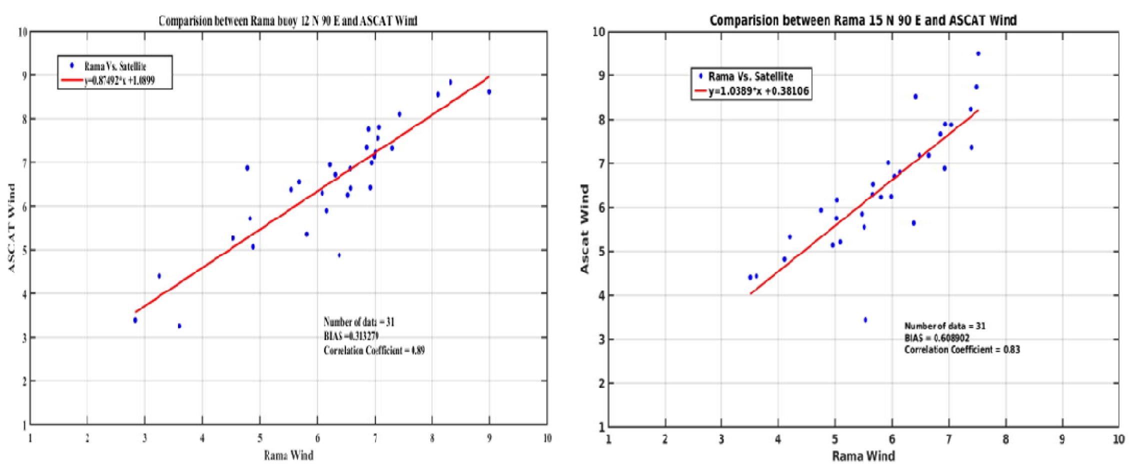

Fig B. Comparison between wind data from RAMA buoy and ASCAT wind data for December 2013

- **Authors' Changes in Manuscript**

Following text will be added to the original ms at line no. 327:

Consistent with Chl-*a* and NPP, the maximum CO_2 out-gassing to the atmosphere was seen in Box B and along Track 1. In Box B, the maximum CO_2 out-gassing was 13.73 ± 2.47 mmol m^{-2} day^{-1} to the atmosphere which was nearly 4-fold higher its average pre-cyclone value (3.50 ± 0.07 mmol m^{-2} day^{-1}). The maximum CO_2 out-gassing along Track 1 was 13.22 ± 2.50 mmol m^{-2} day^{-1} to the atmosphere which was nearly 3-fold higher its average pre-cyclone (4.59 ± 0.20 mmol m^{-2} day^{-1}). The impact of cyclone Madi on CO_2 out-gassing in Box A and along Track 2 were much smaller due to the less wind effect as the cyclone was in a formative and dissipative stage respectively.

We will also replace the Fig.14 with the following new Figure (Fig.16) at line no. 968 of the original manuscript.

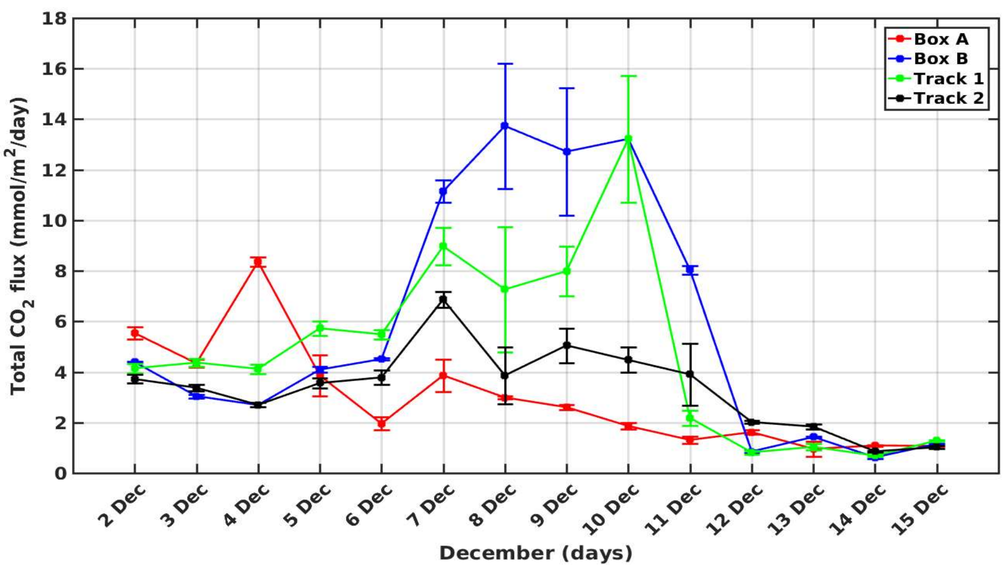

Figure 16. Daily variation total CO_2 flux (mmol/m^2/day) in the Box A (red) and B (blue) and along Track 1 (green) and 2 (black) from 2 to 15 December 2013. The vertical lines are the standard deviations.

4. Referee's Specific Comment

I am not convinced that the cold eddy controlled the movement of the typhoon (arresting of the northward movement). I understand that the results of absolute vorticity budget analysis do show the processes that dominates the storm by solving the given atmospheric field diagnostically. However, I confirm that the authors' analysis did not clarify the relation between the vorticity balance and oceanic cold eddy scientifically although the timing that a storm was arresting of the northward movement matched when a storm was over the cold eddy.

The fact that the vertical shear is small and the moving speed is slow is also related to the environmental steering flow of the storm. In such an environmental field, the axis of the storm tends to stand up, the storm weakened due to sea surface cooling, and the influence on the inner-core structure become more clear. This is a well known mechanism about tropical cyclone-ocean interactons. However, the authors do not show the influence of the intensity and structure of the storm on the environmental steering flow. Therefore, the authors do not demonstrate the mechanism regarding the arresting of the northward movement over the cold eddy. Conversely, it is easy to understand the arresting of the northward movement over the cold eddy led to decreases in TCHP and increases in Chl-a and outgassing of CO2.

- **Author's Response**

To quantify the eddy's contribution to the intensity of the cyclone Madi we have calculated the eddy feedback factor F_{EDDY-T} following Wu et al., (2007) based on the following equation

F_{EDDY-} = 0.38 $(SST_{Eddy}-26^{o}C)^{2.08}(SST-26^{o}C)^{-1.88}$ $(ML_{Eddy})^{0.98}$ x $(ML)^{-0.97}$ $(\eta)^{0.22}$ $(1-RH)^{-0.74}(\Gamma)^{0.45}$ $(U_H)^{-0.83}$

The Table below gives the description of the parameter, its value and unit used for the computation of eddy feedback factor. The values for the SST, SST_{Eddy}, ML, ML_{Eddy}, and Γ were obtained from the Argo float data, while the translation speed were calculated from IMD data.

Table 2. Value of the parameters, their unit and range used in the calculation of eddy feedback factor.

Parameter	Unit	Range
SST-26^{o}C	^{o}C	2.2-2.4
SST_{Eddy}-26^{o}C	^{o}C	1-1.2
Mixed layer Depth (Standard Ocean) (ML)	m	20
Mixed layer Depth (Eddy Ocean) (ML_{Eddy})	m	50
Storm size (η)	1	1
Relative Humidity (1-RH)	1	60-90%
Stratification below the Mixed layer (Γ)	$^{o}Cm^{-1}$	0.06
Translation speed (U_H)	ms^{-1}	1.63-5.41

The eddy feedback factor could be positive or negative; $F_{EDDY-T} = +0.5$, indicatesan increase in the storm intensity by 50% due to the interaction with the warm ocean region, while a $F_{EDDY-T} = -0.5$ indicates a decrease in storm intensity by 50% due to the interaction with cold ocean region (Wu et al., 2007).

The analysis showed that from 7th to 8th December when the system intensified from CS to VSCS and was passing through the warm patch associated with warm core eddy (see spatial maps of OHC at Fig.2 & positive SLA at Fig.3) the eddy feedback factor was positive and amounted to 59%. Thereafter, when the cyclone passed over the cold patch associated with cold core eddy during 9th and 10th December, the eddy feedback factor was negative and 69%. The figure below (Fig. C) pictorially represents the time evolution of the estimated central pressure (hpa) and maximum sustained surface wind (in knots) of the cyclone Madi along with eddy feedback factor.

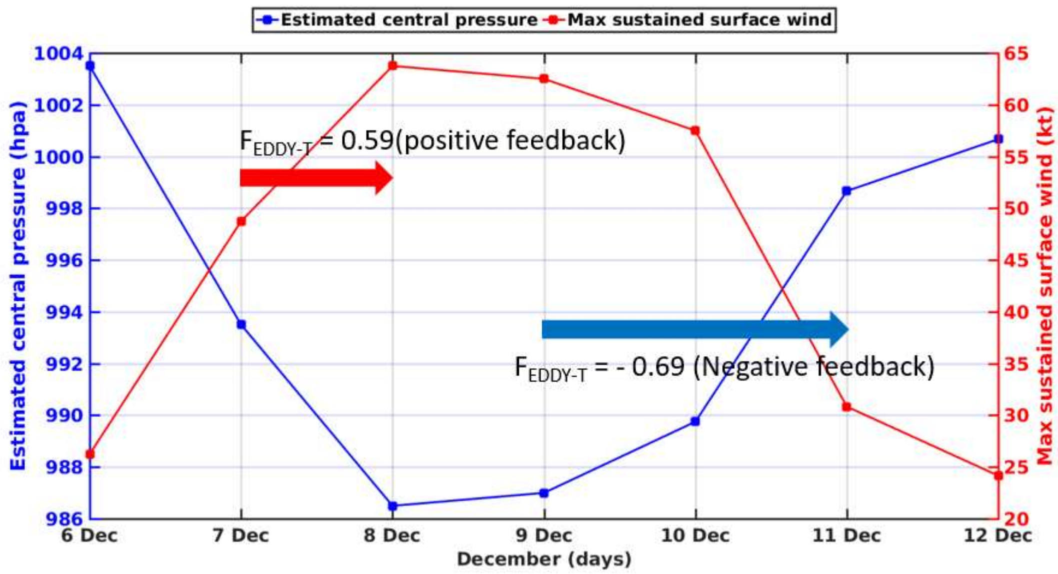

Fig C. Time evolution of the estimated central pressure (hpa) (blue solid line) and maximum sustained surface wind (knots) (red solid line) of the cyclone Madi. The red and blue horizontal solid arrows denote positive and negative eddy feedback factor respectively.

Thus, the present analysis quantifies the contribution of both warm and cold core eddies; when the cyclone Madi passed over the warm patch the system intensified from CS to VSCS and its translation speed increased (see Table 1), while when it passed over the cold patch from 9th to 10th the system slowed down and its northward movement was arrested as noted under the section 2.3.

In summary, we infer that the slowing down of the northward movement of cyclone Madi and its final arrest was mediated by the presence of oceanic cyclonic eddy. Once the system became stationary, the prevailing large scale environmental steering flow effected its track reversal.

- **Authors' Changes in Manuscript**

Following text will be added to the original ms at line no. 187:

3.2.1 Role of eddy feedback mechanism on cyclone intensity

To quantify the eddy's contribution to the intensity of the cyclone Madi we have calculated the eddy feedback factor F_{EDDY-T} following Wu et al., (2007) based on the following equation

$$F_{EDDY-} = 0.38\ (SST_{Eddy}\text{-}26^{o}C)^{2.08}(SST\text{-}26^{o}C)^{-1.88}\ (ML_{Eddy})^{0.98}\ \times\ (ML)^{-0.97}\ (\eta)^{0.22}\ (1\text{-}RH)^{-0.74}(\Gamma)^{0.45}\ (U_H)^{-0.83}$$

The Table below gives the description of the parameter, its value and unit used for the computation of eddy feedback factor. The values for the SST, SST_{Eddy}, ML, ML_{Eddy}, and Γ were obtained from the Argo float data, while the translation speed were calculated from IMD data.

Insert Table 2 at line no. 571 of the original ms:

Table 2. Value of the parameters, their unit and range used in the calculation of eddy feedback factor.

Parameter	**Unit**	**Range**
SST-26°C	°C	2.2-2.4
SST_{Eddy}-26°C	°C	1-1.2
Mixed layer Depth (Standard Ocean) (ML)	m	20
Mixed layer Depth (Eddy Ocean) (ML_{Eddy})	m	50
Storm size (η)	1	1
Relative Humidity (1-RH)	1	60-90%
Stratification below the Mixed layer (Γ)	$^{o}Cm^{-1}$	0.06
Translation speed (U_H)	ms^{-1}	1.63-5.41

The eddy feedback factor could be positive or negative; $F_{EDDY-T} = +0.5$, indicatesan increase in the storm intensity by 50% due to the interaction with the warm ocean region, while a $F_{EDDY-T} = -0.5$ indicates a decrease in storm intensity by 50% due to the interaction with cold ocean region (Wu et al., 2007).

The analysis showed that from 7th to 8th December when the system intensified from CS to VSCS and was passing through the warm patch associated with warm core eddy (see spatial maps of OHC at Fig.2 & positive SLA at Fig.3) the eddy feedback factor was positive and amounted to 59%. Thereafter, when the cyclone passed over the cold patch associated with cold core eddy during 9th and 10th December, the eddy feedback factor was negative and 69%. The Fig.6 also represents the time evolution of the estimated central pressure (hpa) and maximum sustained surface wind (kt) of the cyclone Madi along with eddy feedback factor.

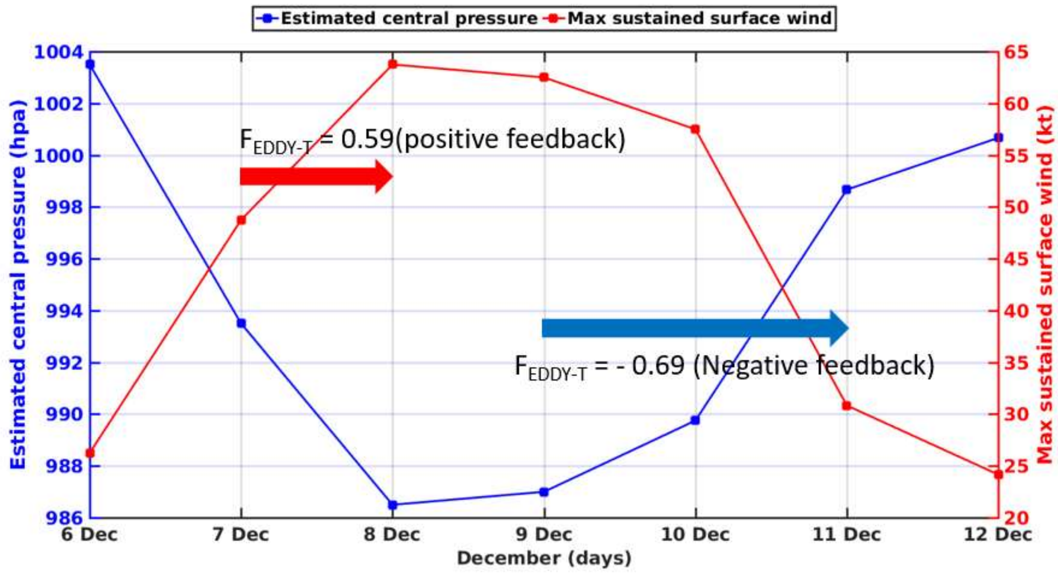

Figure 6. Time evolution of the estimated central pressure (hpa) (blue solid line) and maximum sustained surface wind (kt) (red solid line) of the cyclone Madi. The red and blue horizontal solid arrows denote positive and negative eddy feedback factor respectively.

The present analysis quantifies the contribution of both warm and cold core eddies; when the cyclone Madi passed over the warm patch the system intensified from CS to VSCS and its translation speed increased (see Table 1), while when it passed over the cold patch from 9th to 10th the system slowed down and its northward movement was arrested as noted under the section 2.3. In summary, we infer that the slowing down of the northward movement of cyclone Madi and its final arrest was mediated by the presence of oceanic cyclonic eddy.

Following reference will be added to the original ms at line no. 540

Wu, C.-C., Lee, C-Y., Lin, I.-I.: The effect of the ocean eddy on tropical cyclone intensity, Journal of the Atmospheric Sciences, 64, 3562-3578, DOI: 10.1175/JAS4051.1, 2007.