

Reply to the Comments of Anonymous Referee #1 posted on 11 March 2019

General Comment

- **Referee's General 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 CO₂ 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 uncorrected 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 9th and 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 9th to 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 CO₂ is quantitatively different from that of earlier studies

Based on the Reviewer's comment, in order to compare our CO₂ flux with that of previous studies, we have recomputed the CO₂ flux along Track 1, Track 2 and Boxes A and B in

mmol per meter square per day. While re-computing CO₂ flux we noticed a bug in our previous calculation, which we rectified. The newly calculated values showed a cyclone-induced CO₂ out-gassing which was about 4-times greater than the pre-cyclone values along Track 1 and in Box B. The impact of CO₂ 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 CO₂ 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 CO₂ 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 m² day⁻¹ of CO₂ 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 CO₂ 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 CO₂ m⁻² day⁻¹) and (19.08 ± 3.82 mmol CO₂ 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.

Specific Comments and Point-wise Reply to Referee#1

Author's Response

- **Referee's 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 CO₂ 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 CO₂ out-gassing in the following manner. As the cold subsurface waters come to the surface it also brings with it higher concentration of dissolved CO₂. Once at the surface, the warmer temperature and strong winds will initiate a strong out-gassing of CO₂ 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 CO₂ rich subsurface water occurs due to both Ekman pumping driven by cyclonic winds associated with the cyclone Madi as well eddy-pumping driven by cyclonic circulation of water in a cold core eddy. Accordingly, in our study we see a 4-fold increase in the CO₂ 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.

- **Referee's 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 Bates 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 CO₂ flux at the sea surface depends on the difference between the partial pressure of CO₂ at the sea surface ($p\text{CO}_2^{\text{sea}}$) and in the overlying atmosphere ($p\text{CO}_2^{\text{air}}$), 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 CO₂ 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 CO₂ 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 CO₂ 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 $\sim 8 \text{ mmol m}^{-2} \text{ day}^{-1}$ of CO_2 from ocean to atmosphere accounting for $\sim 85\%$ 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 $13 \text{ mmol m}^{-2} \text{ day}^{-1}$. 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 CO_2 efflux ($18.49 \pm 3.70 \text{ mmol CO}_2 \text{ m}^{-2} \text{ day}^{-1}$) and ($19.08 \pm 3.82 \text{ mmol CO}_2 \text{ m}^{-2} \text{ day}^{-1}$) 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 $\text{mmol per meter square per day}$. 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.

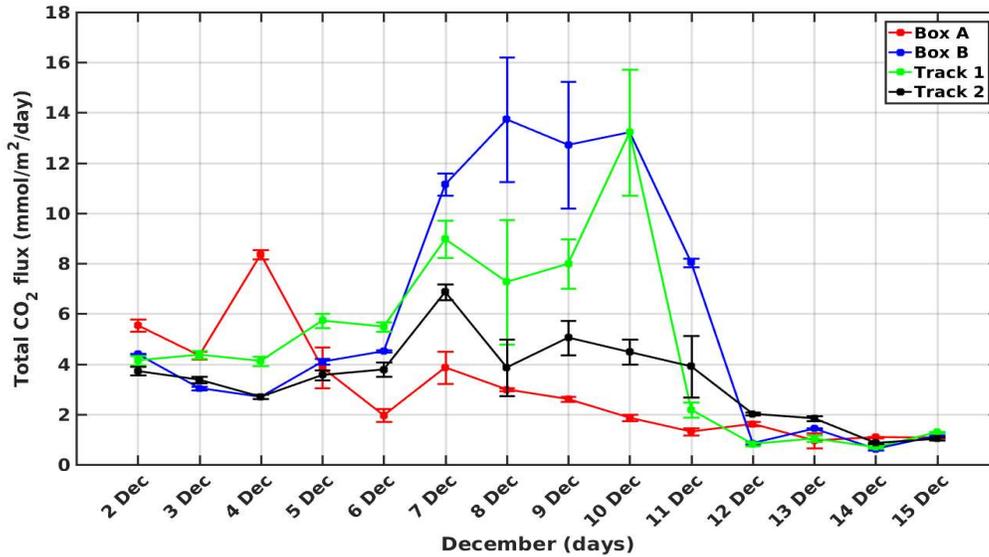


Fig A. Daily variation total CO_2 flux ($\text{mmol/m}^2/\text{day}$) in the Box A (red) and B (blue) and along Track 1 (green) and 2 (black) from 2 to 15 December 2013. The vertical lines are the standard deviations.

The newly calculated values showed a cyclone-induced CO_2 out-gassing which was about 4-times greater than the pre-cyclone values along Track 1 and Box B, i.e., from 3 to $13 \text{ mmol m}^{-2} \text{ day}^{-1}$. 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 CO₂ 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 CO₂ 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

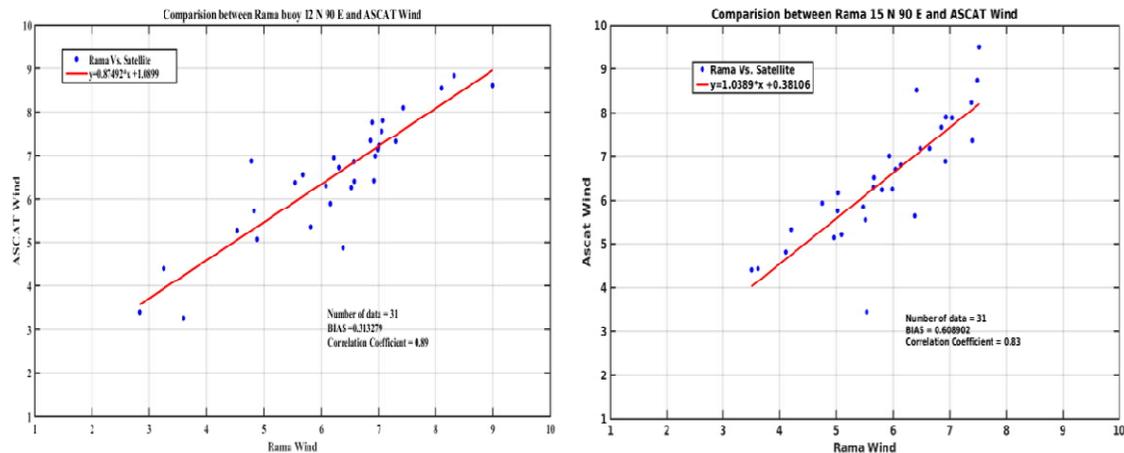


Fig B. Comparison between wind data from RAMA buoy and ASCAT wind data for December 2013

In the modified manuscript we will include the above matter in place of the matter between lines 320 to 333 of the pre-modified version of the manuscript. We will also replace figure 13 with Fig.A.

- **Referee's 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 interactions. 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} following Wu et al., (2007) based on the following equation

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

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 I. 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)	°Cm ⁻¹	0.06
Translation speed (U _H)	ms ⁻¹	1.63-5.41

The eddy feedback factor could be positive or negative; $F_{EDD} = +0.5$, indicates an increase in the storm intensity by 50% due to the interaction with the warm ocean region, while a $F_{EDD} = -0.5$ 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.

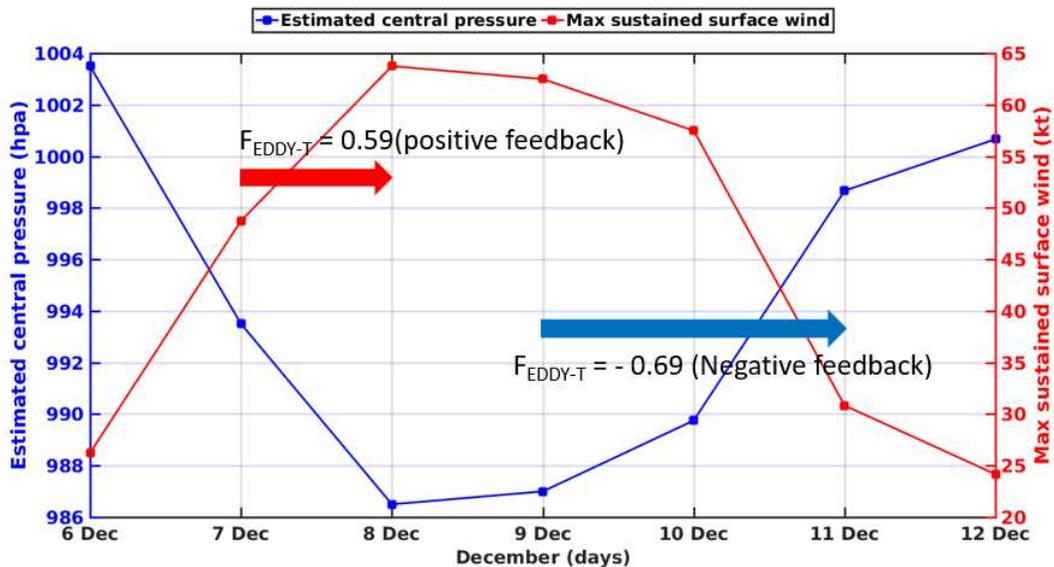


Fig C. Time evolution of the estimated central pressure (hpa) (blue solid line) and maximum sustained surface wind (knots) (red solid line) of the cyclone Madi. The red and blue horizontal solid arrows denote positive and negative eddy feedback factor respectively.

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.

In the modified manuscript we will add the above matter after line no 184 of the previous version of the manuscript.

References

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