Reply to the Comments of Anonymous Referee #2

[Received and Published: 26 March 2019]

1. General comments:

- **Referee's Comment**

Based a suite of atmospheric and oceanic datasets during the passage of TC Madi, Chowdhury et al. examined the upper ocean physical-biogeochemical response to the TC, mostly emphasized the effect of pre-existing cold core eddies underneath the TC. The topic of TC-ocean interaction in the BoB is interesting and important for TC forecasting. Generally, the effect of mesoscale eddy on TC-ocean interaction is well known at the present stage. Due the lack of in situ observations, studies on the Biogeochemical response to a TC is relatively less and this study may enrich our knowledge on the biogeochemical change induced by TC passage.

Author's Response

We thank the Reviewer#2 for reviewing the manuscript and for the comments.

- **Authors' Changes in Manuscript**

No change in the manuscript in response to this query.

2. Referee's General Comment

In the manuscript, I find some conclusions are inaccurate or unclear with not sufficient evidences, especially on the effect of mesoscale eddies. Therefore, I suggest a major revision prior publication. I hope the following comments are useful when the authors revise their manuscript.

(1) How does cyclonic eddy (also OHC in line 143) affect TC translation speed? The authors only described the time series of translation speed and position of eddy, but did not clearly demonstrate the related mechanisms. The authors should supply more evidence to demonstrate how the eddy modulates steering flow and then affect TC translation speed.

- **Author's Response**

To address the concern of the reviewer about the effect of mesoscale eddies and to demonstrate the role of eddies in modulating the translation speed of cyclone Madi we have used a two-prong approach. First, we calculated the time evolution maps of difference of SST of 5th December (pre-cyclone SST) from each day starting from 6th December to 14th December (See Figure A) to show the large SST cooling in the north (the location of cold core eddy), which led to the weakening of tropical cyclone Madi. Second, to quantify the role of eddy in reducing the speed of northward movement of tropical cyclone Madi in the region of eddy we have calculated the eddy feedback factor following Wu et al. (2007) which is presented in Figure B.

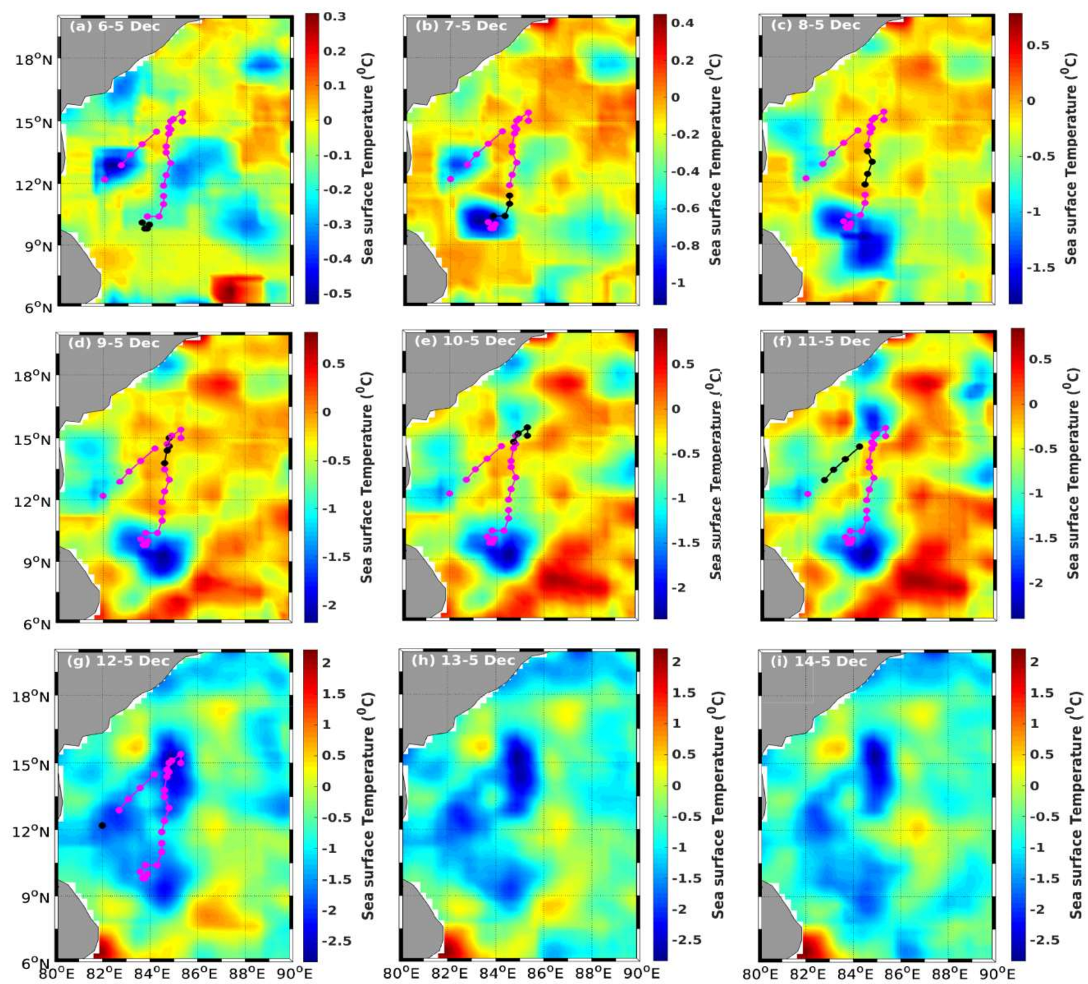

Figure A. Time evolution maps of difference of SST of 5th December (pre-cyclone SST) from each day starting from 6th December to 14th December.

The time evolution of difference in SST showed from 6th to 14th December showed a distinct cooling of 2 to2.5°C in the region affected by the cyclone Madi. A comparison of these maps with Fig.3 of the manuscript clearly points that in the northern most region of the cyclone track, where there a cyclonic eddy was pre-existing; the cooling of SST was 2.5°C, which was 0.5°C colder than the rest of the region. The excess cooling of 0.5°C noticed in the eddy region lends support to the notion that the slow translation speed led to the further cooling of SST, which contributed to the weakening of the cyclone from VSCS to SCS, through negative feedback.

Note also that after the passage of cyclone Madi, the SLA in the region of cyclonic eddy changed from -0.1 to -0.2 m. This SLA decrease of 10 cm is a combined 3-diminsional response of the cyclone Madi induced upward Ekman-pumping along with the cold core eddy induced eddy-pumping of subsurface waters.

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 and presented in Fig.B

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

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.

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)	$^{o}Cm^{-1}$	0.06
Translation speed (U_H)	ms^{-1}	1.63-5.41

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

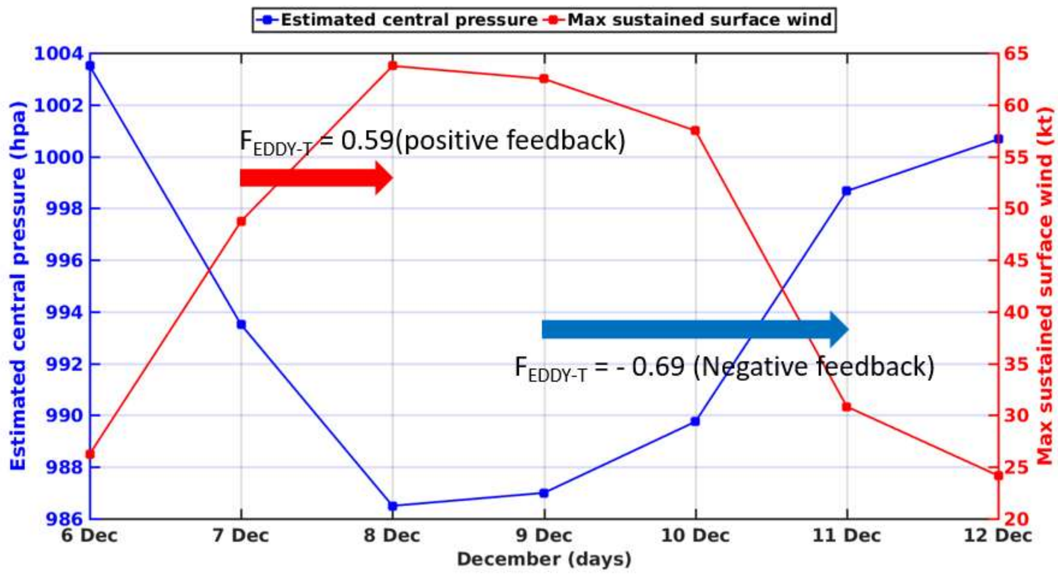

FIGURE B. Time evolution of the estimated central pressure (hpa) (blue solid line) and maximum sustained surface wind (knots) (red solid line) of the cyclone Madi. The red and blue horizontal solid arrows denote positive and negative eddy feedback factor respectively.

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 9^{th} to 10^{th} the system slowed down and its northward movement was arrested as noted under the section 2.3.

A time-latitude plot of the OHC and TCHP with cyclone track superimposed on (Figure C) clearly shows 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.

Thus, based on the time evolution of (1) difference in SST showed from 6^{th} to 14^{th} December and (2) eddy feedback factor, our argument is that slow translation speed of Madi over cyclonic eddy can cause rapid weakening of tropical cyclone Madi when it stalled over a cyclonic eddy during 10^{th} December. We infer that the 3-dimensional response of the cyclone Madi in terms of SST cooling was a significant factor in Madi's rapid weakening, as also suggested by the eddy feedback factor which showed that the contribution of cyclonic eddy in reducing the storm intensity was 69%.

We will include the above additional information with diagrams in the modified manuscript at line 187 of the previous version of the manuscript.

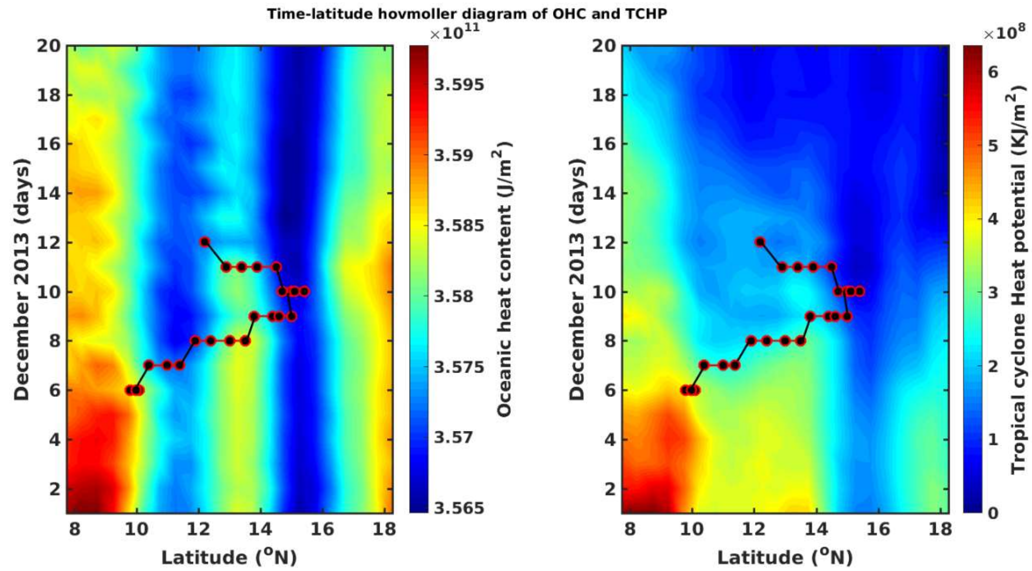

FIGURE C. Time-latitude plot of (left panel) oceanic heat content (J/m^2) and (right panel) tropical cyclone heat potential (KJ/m^2) with cyclone track superimposed on it.

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

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

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.

Table I. 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 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.

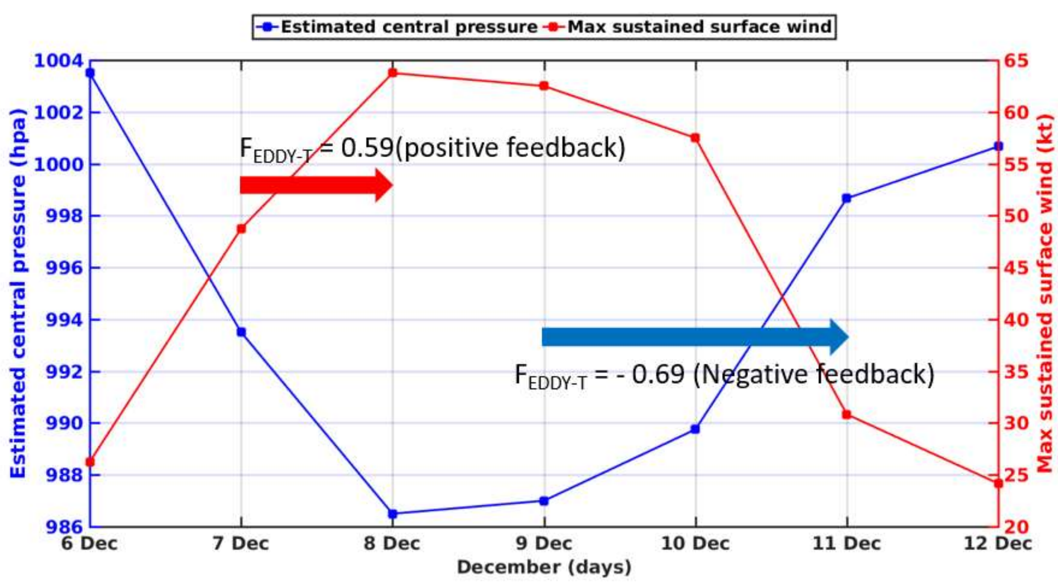

Figure 6 Time evolution of the estimated central pressure (hpa) (blue solid line) and maximum sustained surface wind (kt) (red solid line) of the cyclone Madi. The red and blue horizontal solid arrows denote positive and negative eddy feedback factor respectively.

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 9^{th} to 10^{th} 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.

3. Referee's General Comment

(2) On the effect of mesoscale eddy on TC intensity change. The authors just described the movement of TC Madi and relative position with respect to the eddies and then concluded the intensity change of Madi was dominated by the eddies. I do know the authors show OHC change during the TC passage, but actually the key (oceanic) factor controlling TC intensity change is SST. At least, the time series of SST like figures 2-4 should be given to substantiate the eddy effect. Furthermore, the slow TC translation speed may induce large SST cooling and contribute to the weakening of Madi.

Author's Response

We thank the reviewer for the suggestion and based on the suggestion we prepared the time evolution of SST maps (FIGURE D). We found that presenting the time evolution maps of difference of SST of 5^{th} December (pre-cyclone SST) from each day starting from 6^{th} December to 14^{th} December, presented in Figure A under the "Author's Response to previous question, is more effective to bring out clearly the SST cooling . We also showed there that the translation speed of the tropical cyclone Madi reduced during 9^{th} and 10^{th} when the system was passing through the region of cold core cyclonic eddy. The excess cooling of $0.5^{o}C$ noticed in the eddy region lends support to the notion that the slow translation speed led to the further cooling of SST, which contributed to the weakening of the cyclone from VSCS to SCS.

As suggested by the reviewer#2, we have prepared the SST maps and presented in Fig. D.

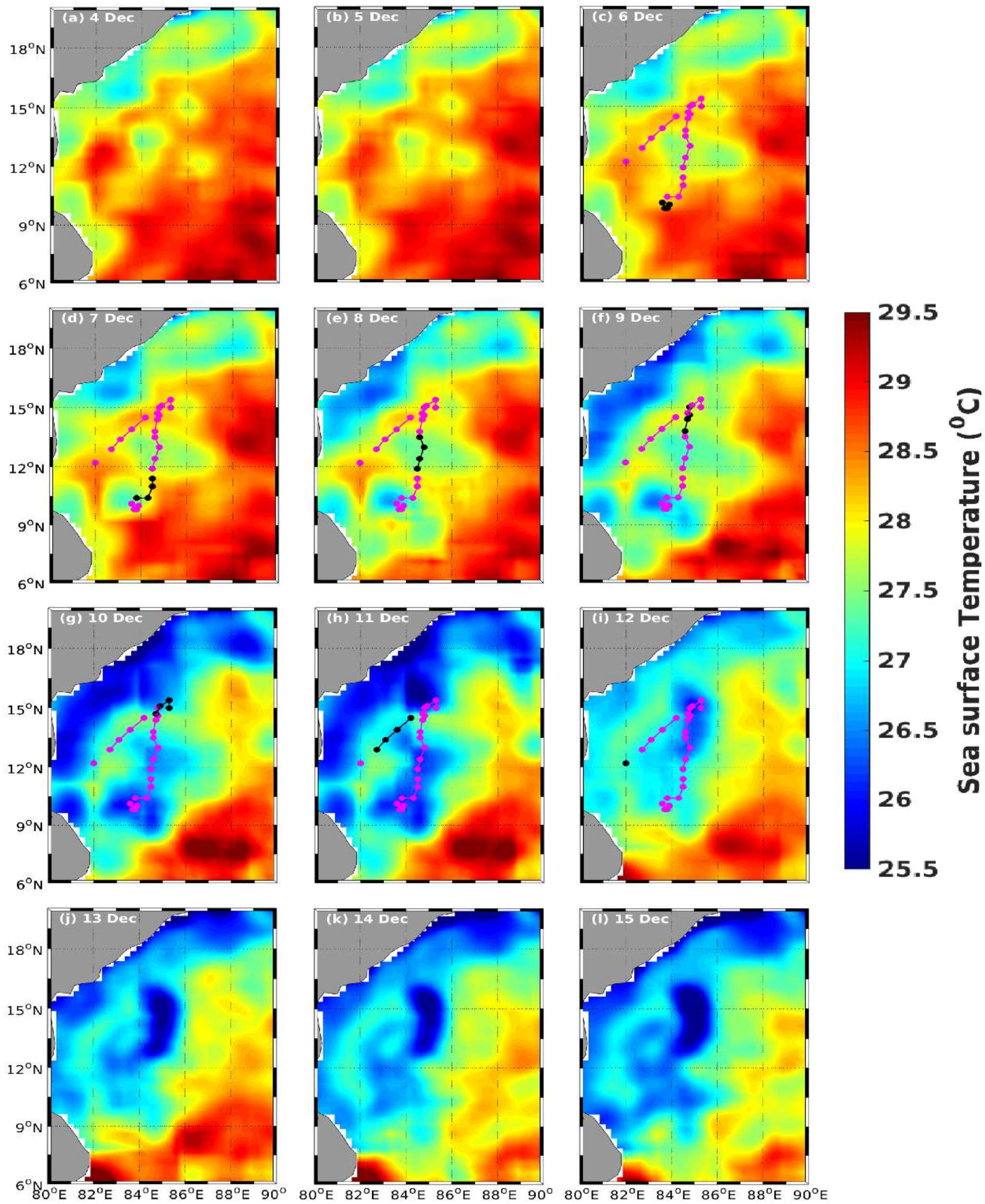

Figure D. Spatial map of Sea surface temperature (°C) from 4th (a) to 15th (l) December 2013 with track of the cyclone overlaid. The black filled circles represent the position of the cyclone on a particular day, while the magenta filled circles indicate the track.

- **Authors' Changes in Manuscript**

Following text will be added to the original ms at line no. 177:

In order to decipher the cooling of sea surface due to the passage of cyclone the time evolution of SST from 4th to 15th December was examined. Compared to the pre-cyclone values of 5th December 2013, a distinct cooling of 2 to 2.5°C was noticed in the region affected by the cyclone Madi (Fig 4). In the northern most region of the cyclone track where a cyclonic eddy was pre-existing, the cooling of SST was 2.5°C, which was 0.5°C colder than the rest of the region. The excess cooling of 0.5°C noticed in the eddy region lends support to the notion that the slow translation speed led to further cooling of SST, which contributed to the weakening of the cyclone from VSCS to SCS, through negative feedback.

Note also that after the passage of cyclone Madi, the SLA in the region of cyclonic eddy changed from -0.1 to -0.2 m. This SLA decrease of 10 cm is a combined 3-diminsional response of the cyclone Madi induced upward Ekman-pumping along with the cold core eddy induced eddy-pumping of subsurface waters.

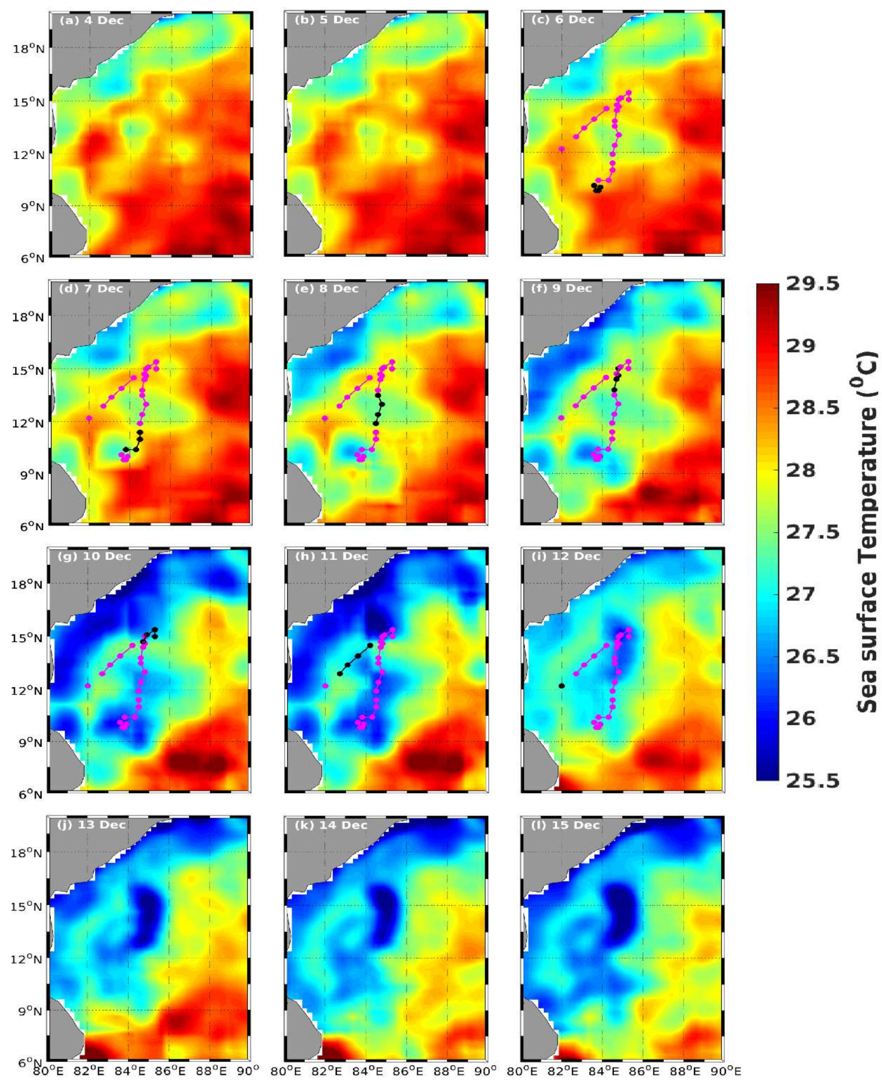

Figure 4. Spatial map of Sea surface temperature (°C) from 4th (a) to 15th (l) December 2013 with track of the cyclone overlaid. The black filled circles represent the position of the cyclone on a particular day, while the magenta filled circles indicate the track.

The Above Figure (Figure 4) will be added to the original ms at line no. 776:

4. Referee's General Comment

(3) On the mechanism of SST and biogeochemical response. The authors concluded that the SST cooling and Chl a increase was due to eddy-pumping of subsurface waters. However, there were clear subsurface temperature increase and Cha decrease in the thermocline in Fig. 11, indicating a non-negligible role of diapycnal mixing. This was also consistent with results from many previous studies, i.e., the SST change was mainly due to diapycnal mixing (Price 1981).

- **Author's Response**

We agree with the reviewer that diapycnal mixing is an important mechanism that redistributes the vertical properties of within the Ocean. The occurrence of subsurface temperature increase of 0.2 to 0.3^{o}C is discussed under section 3.4 of the manuscript. This is associated with mild thermal inversion, which is commonly observed in Bay of Bengal in this time. As per the suggestion of the reviewer we will include the role of diapycnal mixing in the modified manuscript after line 261.

- **Authors' Changes in Manuscript**

Following text will be added to the original ms at line no. 258:

The occurrence of subsurface thermal inversion is common in the BoB during this time of the year. Another mechanism that could bring about cooling of SST is the diapycnal mixing which redistributes the vertical properties within the ocean (see for e.g., Price, 1981).

5. Referee's Specific Comments

(1) line 67: the Unisys Weather does not give TC track information right now. Actually, the TC track information of Unisys Weather is originated from the Joint Typhoon Warning Center.

Author's Response

Thank you for point out this. We will modify and include this in the modified manuscript.

- **Authors' Changes in Manuscript**

Following text will be added to the original ms at line no. 67:

while the track information was taken from Joint Typhoon Warning Centre (JTWC) (http://www.usno.navy.mil)

6. **Referee's Specific Comments**

(2) line 80: The temperature profiles should be indicated to calculate OHC.

- **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^{o}C is 4.0 kJ kg^{-1} K^{-1} (kindly note that the value given in the manuscript is 3.87 is not correct and we will rectify it by replace it with 4.0). We will include this and modify the line 80.

- **Authors' Changes in Manuscript**

Following text will be added to the original ms at line no. 80:

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).

7. **Referee's Specific Comments**

(3) line 123-124: Most people may be not familiar with the classification of intensity of IMD. Please give the range of wind speed of different IMD categories or use the more popular Saffir-Simpson scale.

- **Author's Response**

As suggested by the reviewer we will provide the range of wind speed by adding a new column in Table 1

- **Authors' Changes in Manuscript**

Following modification will be done to Table at line 565 of original manuscript:

Table 1 Translation speed of the cyclonic disturbance along with its category during the life cycle of cyclone Madi. L-low pressure, DD-deep depression, CS-cyclonic storm, SCS-severe cyclonic storm, VSCS-very severe cyclonic storm.

Date	Translation Speed (m/s)	Category of Cyclonic Disturbance	Range of wind speed in km/h
06/12/2013	1.63	DD	52-61
07/12/2013	2.48	CS to SCS	62-87 to 88-117
08/12/2013	2.81	VSCS	118-221
09/12/2013	1.96	SCS	88-117
10/12/2013	2.32	CS	62-87
11/12/2013	3.44	DD	52-61
12/12/2013	5.41	L	<31

8. **Referee's Specific Comments**

(4) line 149 & 150: Compared with the huge OHC of the ocean, the heat uptake by a TC was very small. The decrease of local OHC may be subject to the advection of TC induced strong currents.

- **Author's Response**

We agree with the reviewer. We will add a couple of sentences to include this aspect after line 150.

- **Authors' Changes in Manuscript**

Following text will be added to the original ms at line no. 150:

In addition to the heat uptake by the tropical cyclone, the local decrease in OHC may also be caused by advection of strong currents induced by the tropical cyclone.

9. Referee's Specific Comments

(5) line 189 & 200: To examine the effect of vertical wind shear on TC, people mostly average the vertical wind shear azimuthally around the TC center, not the spatial map as in Fig. 5. Relatively, vertical wind shear of 10-15 m/s is not small and may compromise TC intensification.

- **Author's Response**

We have calculated the vertical wind shear based on following formula (Balaji et al., 2018, Evan & Camergo 2011)

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

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 cyclogenesis. Hence, we have used the time evolution of this parameter to assess the suitability of the atmosphere in the formation of cyclone Madi.

We will include the above information and modify the lines 87-88.

We agree that the wind shear of 10-15 m/s is not a small value and hence may impact the further development of cyclone. **We will include the following matter and modify lines 200.**

Where the cyclone Madi was formed the observed shear value was 5m/s, which is very low and represented a favourable condition for cyclogenesis. Subsequently, when the tropical cyclone Madi attains its maximum intensity, the shear value was between 5-10m/s. On 10th December when the intensity of Madi reduced from VSCS to SCS it was moving towards a region where shear was very high 10-15m/s. This relatively high value of shear is not congenial for the further development of the tropical cyclone.

Hence, the slow translation speed of Madi over cyclonic eddy can cause rapid weakening of tropical cyclone Madi when it stalled over a cyclonic eddy during 10th December. We infer that the 3-dimensional response of the cyclone Madi in terms of SST cooling was a significant factor in Madi's rapid weakening, as also suggested by the eddy feedback factor which showed that the contribution of cyclonic eddy in reducing the storm intensity was 69%. Further, the relatively strong vertical wind shear would add to negate the strengthening and further northward movement of cyclone.

- **Authors' Changes in Manuscript**

Following text will be added to the original ms at line no.88:

We have calculated the difference in the magnitude of the vertical wind velocity between 850 and 200 hpa based on following formula (Balaji et al., 2018; Evan and Camergo, 2011):

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

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.

Following references will be added to the original ms at line no. 387 & 406

Balaji, M., Chakraborty, A., Mandal, M.: Changes in tropical cyclone activity in north Indian Ocean during satellite era (1981–2014), International Journal of Climatology, 1–19, 2018.

Evan, A.T., Camargo, S.J.: A climatology of Arabian Sea cyclonic storms, Journal of Climate, 24, 140-158, 2011.

Following text will be added to the original ms at line no.200-206:

At this time the moderate vertical shear (10-15m/s) (Fig.8f), though was not congenial for the further intensification of the cyclone, the high relative humidity (60-80%) (Fig.9f) was favourable for its further intensification of at least to sustain its intensity. Note that the translation speed of the system showed a decline (Table 1) and the system weakened from VSCS to SCS. At this time the system was passing through the low sea level anomaly region and on 10th December when the system became stationary it was sitting right on the top of the cold-core of the cyclonic eddy (Fig. 3g). We infer that the 3-dimensional response of the cyclone Madi in terms of SST cooling was a significant factor in Madi's rapid weakening, as also suggested by the eddy feedback factor which showed that the contribution of cyclonic eddy in reducing the storm intensity was 69%. Further, the relatively strong vertical wind shear would add to negate the strengthening and further northward movement of cyclone. Once the system became stationary the prevailing north-easterly winds were able to reverse the direction of motion of the cyclone to south-westerly direction, a result consistent with that of Bhattacharya et al. (2015).

The following text will be added to the original ms at line no.208:

and moderate vertical wind shear between 200 and 850 hpa,

The following text will be added to the original ms at line no.341:

The reduction in the intensity of the cyclone was mainly due to its interaction with cold-core eddy. The combined effect of upwelling due to Ekman-pumping and edd-pumping cools the upper ocean through vertical transport of sub-surface waters. This along with prevailing moderate wind shear between 200 and 850 hpa resulted the weakening and arresting of the northward movement of the system. At this stage the background

10. Referee's Technical corrections

(1) line 25: "occurred" should be "ever reported"

- **Author's response**

  We will correct it to "ever reported"

- **Authors' Changes in Manuscript**

The text at line 25 of the original ms will be corrected to "ever reported"

11. Referee's Technical corrections

(2) line 153: delete the first "it"

- **Author's response**

  We will delete

- **Authors' Changes in Manuscript**

The text at line 153 of the original ms will be corrected by delete first “it”

12. **Referee’s Technical corrections**

(3) line 339: delete the second “and”

- **Author’s response**

  We will delete the second “and” in line 339

- **Authors’ Changes in Manuscript**

The text at line 339 of the original ms will be corrected by delete second “and”

13. **Referee’s Technical corrections**

(4) Line 875-883: The line number overlaying the figure legend is confusing.

- **Author’s response**

  Thank you for the suggestion. We will rectify this.

- **Authors’ Changes in Manuscript**

The line numbers overlay with Figure from 875 to 885 in the original ms will be corrected.