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Interactive Comment

Interactive comment on "Evolution of cyclonic eddies and biogenic fluxes in the northern Bay of Bengal" *by* M. Nuncio and S. Prasanna Kumar

M. Nuncio and S. Prasanna Kumar

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We wish to thank the reviewer for the criticism which helped to improve the manuscript. We have incorporated all the suggested modifications in the modified manuscript and point-wise modifications are detailed below.

General comments Reviewer's Comment: (1) There are quite number of content in the text are not correct as in mention. (2) It is the good concept to try to understand the processes of formation of eddy and resulting to biogenic flux (downward). But when the authors try to explain the relation of the western boundary current. It may not clear much to the reader who is not familiar with BOB. If authors could provide a diagram (figure) of circulation of the current in the figure will be better. Author's Response: As per the suggestion Figure 1 has been modified to include the current vectors computed

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from SLA climatology during February to April assuming geostrophic balance. The western boundary current is clearly discernible as organized current vector.

Figure 1

Figure.1. Location map showing the position (17o 27'N, 89o 36'E) of northern Bay of Bengal sediment trap (NBBT-N; white cross inscribed within white circle) over laid with variance (cm2) of mean sea-level anomaly (SLA) during 1994-1998. Vectors indicate average surface current climatology for the period February to April obtained from SLA. Western boundary current is clearly discernible as organized current vector.

Reviewer's Comment: (3) In the page 4 line 15-18, the purpose of this study would like to understand the link between the production of organic matter in the upper ocean and its transportation into mid-depths in the BOB. But it is not clear that the results could show any about the production in the upper layer and its linkage to its flux into deeper water. This might need more information about the sediment property (biogeochemistry property) which might be in the reference of the data use in the study such as total sedimentation or organic content. As the origin of eddies sources could have different property of suspended such as from north-western and north-eastern part of BOB. This information might help to explanation more on the organic production and sedimentation.

Author's Response: Based on the comments we have largely modified the "Introduction" as well as part of the "Results and Discussion" under "3.1 Biogenic flux and sea level anomaly" The modifications are reproduced below: 1. Introduction The Bay of Bengal (BOB), located in the north-eastern part of the Indian Ocean, is one of the twin basins of the north Indian Ocean. The basin's waters have no connection with the northern polar waters as it is land-locked at 22oN by land mass of India. The dominant atmospheric forcing in the northern Indian Ocean being semi-annually reversing monsoon winds, south-westerly during June-September (summer/southwest monsoon) and north-easterly during November-February (winter/northeast monsoon),

BGD
10, C9526–C9540, 2014

the basin's water experiences semi-annual reversal in the surface circulation. Three major river systems – the Ganges-Brahmaputra, Irrawaddy-Salween and the Krishna-Godavari – drain into the BOB. The total runoff from the peninsular rivers, which peaks during summer monsoon amounts up to 2.95 x 1012 m3 yr-1 (Sengupta et al., 2006). In the BOB precipitation exceeds the evaporation ($\sim$ 2 m yr-1) (Prasad, 1997). This huge quantity of river runoff coupled with the excess precipitation induces large changes in the upper ocean salinity. The low salinity with high insolation (Narvekar and Prasanna Kumar, 2006) makes the BOB a highly stratified basin. Accordingly, the upper water column stability in the BOB is 3-4 times greater than that in the Arabian Sea, making it increasingly difficult to perturb the upper water column in the BOB (Prasanna Kumar et al., 2002). Though the river inputs of nutrients are expected to increase the biological productivity, the data from the International Indian Ocean Expedition (Kabanova, 1968; Krey and Babenerd, 1976; Qasim, 1977) suggests to the contrary. Subsequent biological data (see Table 1 in Prasanna Kumar et al., 2010) substantiated the view that the BOB is a region of low biological productivity. A comparison of the surface as well as column integrated chlorophyll a during summer monsoon showed that it was 4 and 8 times respectively higher in the Arabian Sea compared to that in the BOB (Prasanna Kumaret al., 2002 & 2004). This characteristic of low biological productivity in the BOB is attributed to several factors such as lack of prominent upwelling areas (La Fond, 1957; Murty and Varadachari, 1968; Shetye et al., 1991), strong stratification and absence of deep wind-mixing (Gomes et al, 2000; Prasanna Kuamar et al., 2002; Narvekar and Prasanna Kumar, 2006), cloud cover, sediment load (Qasim, 1977; Radhakrishna, 1978), and lack of winter-driven convective mixing (Jyothibabu et al., 2004; Prasanna Kumar et al., 2010). In contrast to the above mentioned low surface and column integrated chlorophyll a values in the BOB, the sediment trap data revealed that the mid-depth biogenic flux in the BOB is comparable to that of the AS (Ramaswamy and Nair, 1994). This is intriguing since BOB lacks the traditional mechanisms of nutrient supply to the oligotrophic upper waters such as upwelling and winter convection that enhances the biological production. Based on in situ data collected during summer monsoon 2001 and with the help of satellite remote sensing data Prasanna Kumar et al. (2004) identified cold-core eddies in the BOB and found that eddy-enhanced biological productivity was more than double compared to the ambient values. They proposed that during summer monsoon when the upper water column was highly stratified, the vertical transfer of nutrients across the halocline was mediated by the eddy-pumping. Subsequently, Nuncio (2007) and Prasanna Kumar et al. (2007) with the help of hydrographic data collected during fall (September-October, 2002) and spring (April-May 2003) intermonsoons and satellite-derived sea-level anomaly (SLA) maps concluded that eddies were ubiquitous in the BOB and eddy-pumping of nutrients enhanced primary productivity by $1\frac{1}{2}$ to 2 times its ambient value. Later, synthesizing the co-located physical and biogeochemical data collected during 2001 to 2006 under the Bay of Bengal Process Study (BOBPS) program and satellite-derived SLA maps Prasanna Kumar et al (2010) and Nuncio and Prasanna Kumar (2012) further consolidated the importance of eddies in fertilizing the euphotic zone through eddy-pumping and underscored role of cold-core eddies in enhancing the primary productivity in the BOB. The next logical step is to examine the mechanistic connection between the organic carbon production in the euphotic zone and its export to mesopelagic waters in the BOB in the context of cold-core eddies. It is in this context that in the present study we (1) delineate the periods of enhanced biogenic flux in the northern BOB from sediment trap data, (2) identify the role of meso-scale eddies in mediating the observed enhancement, and (3) explore the generating mechanism of meso-scale eddies in the northern BOB.

2nd Para under 3. 1(Biogenic flux and sea level anomaly) Ittekkot et al. (1991), while analyzing the sediment trap data for the one year period from October 1987 in the same location of the present study, found a strong association between elevated particle flux and monsoon-driven freshwater flux. Another interesting process suggested by Ittekkot et al. (1992) in the BoB during southwest monsoon was the much faster loss of organic carbon from the euphotic zone under the ballasting by lithogenic sediments. Stoll et al. (2007) showed that during low flux periods the dominant species in the BOB were cocolithophores. More recently, based on the component fluxes from the sediment trap

BGD

10, C9526–C9540, 2014

data in the northern and central BOB Vidya and Prasanna Kumar (2013) showed that low values of carbonate to opal ratio along with high organic carbon indicated large export via eddy-mediated diatom bloom. Considering the geographic location of the sediment trap and the time of occurrence of the peak biogenic flux, it is quite tempting to surmise that the enhanced biogenic flux during June 1994 and July 1998 were due to the river runoff-driven nutrient enrichment by southwest monsoon. However, the magnitude of the enhancement of the biogenic flux the 1994 and 1998 were the least compared to other years. Based on more recent in situ measurements during summer monsoon (July 2001) Prasanna Kumar et al. (2004) showed the presence of river plume enriched surface nitrate near the river mouth along the coast, while away from the river mouth in the open waters no such enrichment was noticed. In addition, they also showed the presence of cyclonic eddies in the northern BOB, both in the open as well as coastal waters, which shoaled the nutracline through eddy-pumping. From the above we conclude that since the location of NBBT-N trap was much away from the Ganges-Brahmaputra and other river mouths, it is quite unlikely that advection of river plume enriched nitrate could reach the trap location without being utilised en-route. Hence, the role of river-plume advected nutrients, if any, in driving the observed biogenic flux enhancement at NBBT-N to be small. In addition, the occurrence of enhanced biogenic flux in April and September suggests the role of physical forcing other than the seasonal variability driven by monsoons in governing the export of biogenic flux. Cyclonic eddies have been suggested as one potential candidate capable of enhancing the biological (primary) productivity (see for e.g., Prasanna Kumar et al., 2004 & 2007; Nuncio, 2007; Nuncio and Prasanna Kumar, 2012; Vidya and Prasanna Kumar, 2013), we examined the satellite derived sea-level anomalies (SLA) in the northern BOB during 1994 to 1998 to decipher their role in augment the biogenic flux.

Reviewer's Comment: (4) Could authors get some more satellite information of chlorophylls (ocean color) during the period of study? If you could have it then it might help a lot on organic flux, especially on productivity and its linkage to cyclonic eddies. Author's

Response: Ocean color data is available from September 1997 onwards only and our study period is from 1994 to 1998. During this period eddy-driven enhancement in the biogenic flux was noticed during September 1997 and July 1998. We try to obtain the ocean color data during the above period but was disappointed as there were huge data gaps due to heavy clouds associated with southwest monsoon. Nonetheless, we prepared a diagram (Figure 2) with available data coinciding with eddy (identified from altimeter data) for February 1998. The diagram presented below depicts the chlorophyll pigment concentration overlaid with SST contours.

Figure 2

Figure 2. Chlorophyll images overlaid with SST contours in the Bay of Bengal during February 1998. Note that the surface expression of eddy is weak. Nonetheless in the northern Bay of Bengal, on 11- Feb-1998 centred about 19oN, 87oE enhanced chlorophyll can be seen with a reduction in SST, indicating the presence of a cold-core eddy.

Reviewer's Comment: (4) The cyclonic and anticyclonic is cause of upwelling and downing respectively. As the wind control the SLH (sea level height) in the BOB. There are some recently study show that the tropical Equatorial Indian Ocean wind effect to the SLH along the coast of BOB (related to Figure 9). In the low SLH are should be the upwelling area (compensation of deep water to the surface) and vice versa in high SLH (down welling). As the data of our buoy in Andaman Sea, we found that during the weak cyclonic pass by the buoy. There was the water at the depth of about 100-120 m move upward. I therefore do not think that the biogenic flux as refer in this study came from the upper layer and directly related to production in the surface layer. It could be from the deeper water surrounding the cyclonic eddy, which high accumulate organic material (below thermocline), move to compensate in the deep water under cyclonic area that move upward. This could bring high organic material with this water mass and resulting high sedimentation in the deep part under cyclonic area and cloud be high sedimentation. If the author could find more information in the study area may

BGD

10, C9526–C9540, 2014

could explain more and may explain on the difference of production in upper layer of Arabian Sea (high production) and BOB (low production) but have the same biogenic flux in the mid depth. The author could explain this process in the northern part of BOB by using data of RAMA buoy programme and select the period when the cyclonic eddies part the buoy.

Author's Response: We agree with the reviewer that the anticyclonic and cyclonic circulation associated with meso-scale eddies in the Bay of Bengal leads to sinking and upwelling respectively. We also agree that apart from eddy-induced nutrient enhancement leading to enhancement in the phytoplankton, the physical vertical advection of water mass associated with cylonic eddies would also result in physical transport of chlorophyll from subsurface. Therefore, the observed enhancement at any given location would be a resultant of the two. We have included this in the modified manuscript in the last paragraph under section "3.1" and modified portion is reproduced below. It is important to note that apart from eddy-induced nutrient enhancement in the euphotic zone leading to an enhancement in the chlorophyll, the vertical advection subsurface chlorophyll along with the water mass associated with cylonic eddies would also contribute towards the oval enhancement.

As suggested, we extracted RAMA buoy data from www.pmel.npaa.goa/tao/datadeliv/deliv-nojava-rama.html. But the data was restricted up to 15°N and from 2008 till 2014. We have used the 20° isotherm to depict the oscillations in the thermocline (Figure 3).

Figure 3

Figure 3. Depth of 20° isotherm obtained from RAMA buoy located at 15°N, 90°E. Interestingly, the dominant oscillations are not in the seasonal time-scale. The FFT of the time series of 20° isotherm, though revealed seasonal and annual periodicity, most significant periods were close to 40 – 45 days (Figure 3). Interestingly, the peak corresponding to 75 days was just short of 95 % significance.

BGD

10, C9526–C9540, 2014

Figure 4

Figure 4. Frequency power spectrum of 20oC isotherm obtained from RAMA mooring at 15°N, 90°E during the period 2008 to 2014. Red line represents 99% significance level. At 95 % significance peaks close to 75 days are just short of significance. Reviewer's Comment: PAGE 3 Line 12: intermonsoon, which is generally ologotrophic in the northern Indian Ocean northern Bay of Bengal (if not BOB, is it North Arabian Sea). I am not understand........What is it mean?

Author's Response: We have completely modified this section and removed this sentence. See Author's response under "General comment 3"

Reviewer's Comment: Line 15-17: " ....A comparison of the surface as well as column integrated chlorophyll a in the BOB with that of the AS during summer monsoon showed that it was 1/4th and 1/8th respectively of the AS values " I am not understand........What is it mean

Author's Response: We have removed this sentence in the modified manuscript. .

Reviewer's Comment: PAGE 6 Line 7-9: "........For example, during 1994 the peak anomalies were 40 and 50mg m -2 d -1 respectively, while in 1996 it was 45mg m -2 d -1. Similarly, in 1997 and 1998 it was 95 and 40mg m -2 d -1 respectively. "The description in these line show the value of each peak anomalies do not response to the figure 2 (green line). It might be something wrong in figure or text.

Author's Response: We thank the reviewer for pointing out the mistake. We have modified the test as follows: "For example, during 1994 the peak anomalies were 30 and 40mg m -2 d -1 respectively, while in 1996 it was 60 mg m -2 d -1 . Similarly, in 1997 and 1998 it was 70 and 40mg m -2 d -1 respectively."

Reviewer's Comment: Line 10-11: " Also note that the peak biogenic fluxes during the above four years were one-and-half to two-and-half times higher than the annual mean flux......."

BGD

10, C9526–C9540, 2014

Interactive Comment

Author's Response: To remove the ambiguity we have added the value of annual mean flux in the brackets. The modified text reads as follows. Also note that the peak biogenic fluxes during the above four years were one-and-half to two-and-half times higher than the annual mean flux(62 mg m -2 d -1).

Reviewer's Comment: Line 24-25: "....This Kelvin wave is the upwelling Kelvin wave that propagates 25 along the rim of the BOB during January–March (Rao et al., 2010; Srinivas et al.,2012)...... " I could not see that how can this paragraph support upwelling Kelvin wave in Figure 3. As it was different period. The Figure 3 is during March-June 1994 but in the reference was January-March (did not mention about year).

Author's Response: The sentence has been modified as below. With the help of in situ and satellite data Rao et al. (2010) and Srinivasan et al. (2012) identified two sets of upwelling and downwelling Kelvin waves propagating along the boundaries of the BOB. The first pair of the upwelling Kelvin propagates along the BOB boundary during January – March. Hence, we identify the negative SLA close to the coast during March as the first upwelling Kelvin wave identified by Rao, et al. (2010).

Reviewer's Comment: PAGE 7 Line 1: "first week of April the eddy moved offshore and the positive SLA anomaly west (it should be east not west) of it began to dissipate...."

Author's Response: Reviewer is right. We have replaced "west" with "east".

Reviewer's Comment: Line 6: "...while the eddy was undergoing an eastward translation...." What is translation? Author's Response: The sentence is modified as "During this time the biogenic flux showed gradual increase and reached a maximum value of 103.6 mg m -2 d -1 during June 1994 (Fig. 2), while the eddy moved eastward."

Reviewer's Comment: Line 12-14: "Note that CE2-1994 was located in the close proximity of NBBT during August and by September it started moving slowly northwestward, finally merging with CE1-1994..." CE2-1994 is not finally merge with CE1-1994. But CE2-1994 move away on southwest direction/dissipate (14 Sep).

Author's Response: We modified the sentence as follows. Note that CE2-1994 was located in the close proximity of NBBT-N during August and by September it started moving slowly north-westward towards the coast.

Reviewer's Comment: Page 8 Line 5: "was associated with the presence of cyclonic eddy (CE1-1998) (Fig. 8). The cyclonic.." Figure 8.: the correct one is Fig.7

Author's Response: The error is rectified.

Reviewer's Comment: Line 20-22: Two of the cyclonic eddy CE1-1994 and CE1-1996 were formed in the northern and north-western BOB respectively, while CE1-1997 and CE1-1998 was formed in the north-eastern BOB. the cyclonic eddy CE1-1994 and CE1-1996 were formed in the north-western BOB,................

Author's Response: The sentence is corrected as suggested " Two of the cyclonic eddy CE1-1994 and CE1-1996 were formed in the north-western BOB."

Reviewer's Comment: Line 26-27: One source is the northern and north-western boundary of the BOBand another one is the eastern boundary. In the north-western boundary cyclonic eddies.....

Author's Response: The suggested correction is incorporated; the line is modified as "One source is the north-western boundary of the BOB and another one is the eastern boundary. In the north-western boundary....... "

Reviewer's Comment: Page 11 Line 1: in summer in case of CE1-1994, whereas for CE1-1996 maximum biogenic . Feb.-Mar. is winter monsoon period (not summer monsoon).

Author's Response: Though eddies CE1-1994 and CE1-1996 were formed during February-March period of the respective years, the peak biogenic flux occurred at different times. For CE1-1994 the peak flux was in summer, while for CE1-1996 it was in spring intermonsoon.

Reviewer's Comment: Line 4-6: Time-latitude plots of SLA in the northern Bay of Bengal showed that formation of these eddies and its subsequent southward translation occurs almost every year.... I do not think that it is a good idea to use data of time-latitude of 2005-2009 to explain of situation in 1994-1998 . As how can you know that the climate and ocean condition in 2005-2009 was same period of 1994-1998 in your study.

Author's Response: We apologise for this confusion. In fact the time - latitude plots are from 1994 to 2009. However, in the figure legend we indicated it as 2005-2009 wrongly. We have now corrected this as follows. Figure.8. Latitude-time plots of SLA along 88oE for the northern Bay of Bengal during 1994 to 2009. The solid black lines indicate the southward motion of eddies formed in the northern-western Bay of Bengal during late winter monsoon and spring intermonsoon.

Reviewer's Comment: Line 9-11 and 12-13: The present study reiterates the importance of meso-scale cyclonic eddies in the production and subsequent downward transfer of carbon to mesopelagic layer in the Bay of Bengal (9-11)...................... it is not known whether this eddies would be biologically productive throughout their life span and how much would they contribute towards carbon sequestration of the basin.(12-13). I feel there is some conflict of conclusion of these two sentences.

Author's Response: Considering the comments, we have modified the sentence as follows. The present study reiterates the importance of meso-scale cyclonic eddies in the production and subsequent downward transfer of carbon to mesopelagic layer in the Bay of Bengal. This is a vital missing link that baffled the comparable rates of average annual fluxes of organic carbon in the Arabian Sea and the Bay of Bengal despite their large difference in the seasonal chlorophyll and primary production. However, presently we do not have a robust eddy statistics and their contribution to annual primary production in the Bay of Bengal, neither do we know quantitatively how much would they contribute towards carbon sequestration of the basin.

Reviewer's Comment: Figure: 1. The maps of Fig.3 & 5 should use the same scale of fig.4&6. It will be easily for comparison of the locate of eddies. Author's Response: Figures are modified accordingly

Reviewer's Comment: Figure:2. The fig.8 did not show the longitude of data. It could not see that the data came from with side of BOB.

Author's Response: The longitude is 88°E. We have modified the figure legend to include this information. Modification is as follos. Figure.8. Latitude-time plots of SLA along 88oE for the northern Bay of Bengal during 1994 to 2009. The solid black lines indicate the southward motion of eddies formed in the northern-western Bay of Bengal during late winter monsoon and spring intermonsoon.

Interactive comment on Biogeosciences Discuss., 10, 16213, 2013.

BGD

10, C9526–C9540, 2014

Interactive Comment

Reply to Reviewer #2

Reviewer's Comment: (1) *There are quite number of content in the text are not correct as in mention.* **(2)** *It is the good concept to try to understand the processes of formation of eddy and resulting to biogenic flux (downward). But when the authors try to explain the relation of the western boundary current. It may not clear much to the reader who is not familiar with BOB. If authors could provide a diagram (figure) of circulation of the current in the figure will be better.*

Author's Response: As per the suggestion Figure 1 has been modified to include the current vectors computed from SLA climatology during February to April assuming geostrophic balance. The western boundary current is clearly discernible as organized current vector.

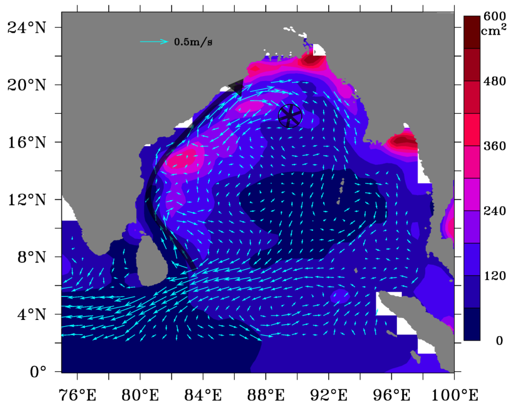

Figure.1. Location map showing the position (17° 27'N, 89° 36'E) of northern Bay of Bengal sediment trap (NBBT-N; white cross inscribed within white circle) over laid with variance (cm^2) of mean sea-level anomaly (SLA) during 1994-1998. Vectors indicate average surface current climatology for the period February to April obtained from SLA. Western boundary current is clearly discernible as organized current vector.

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Fig. 1. Figure 1

BGD

10, C9526–C9540, 2014

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Author's Response: Ocean color data is available from September 1997 onwards only and our study period is from 1994 to 1998. During this period eddy-driven enhancement in the biogenic flux was noticed during September 1997 and July 1998. We try to obtain the ocean color data during the above period but was disappointed as there were huge data gaps due to heavy clouds associated with southwest monsoon. Nonetheless, we prepared a diagram (Figure 1) with available data coinciding with eddy (identified from altimeter data) for February 1998. The diagram presented below depicts the chlorophyll pigment concentration overlaid with SST contours.

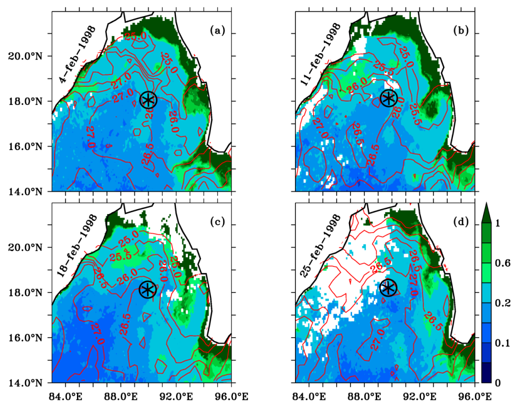

Figure 2. Chlorophyll images overlaid with SST contours in the Bay of Bengal during February 1998.

Note that the surface expression of eddy is weak. Nonetheless in the northern Bay of Bengal, on 11- Feb-1998 centred about 19°N, 87°E enhanced chlorophyll can be seen with a reduction in SST, indicating the presence of a cold-core eddy.

1

Fig. 2. Figure 2

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BGD

10, C9526–C9540, 2014

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As suggested, we extracted RAMA buoy data from www.pmel.npaa.goa/tao/ datadeliv/deliv-nojava-rama.html. But the data was restricted up to 15°N and from 2008 till 2014. We have used the 20° isotherm to depict the oscillations in the thermocline (Figure 2).

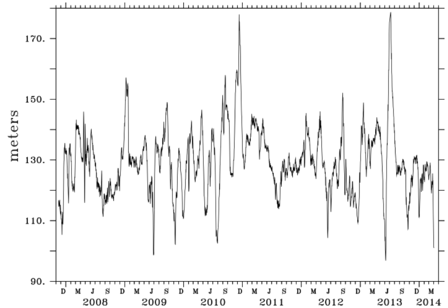

Figure 3. Depth of 20° isotherm obtained from RAMA buoy located at 15°N, 90°E.

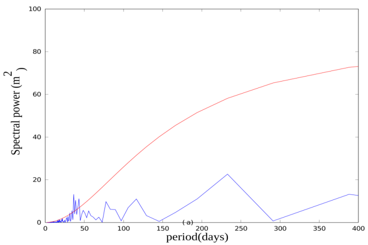

Figure 4. Frequency power spectrum of 20^{o}C isotherm obtained from RAMA mooring at 15°N, 90°E during the period 2008 to 2014. Red line represents 99% significance level. At 95 % significance peaks close to 75 days are just short of significance.

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Fig. 3. Figure 3-4