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# *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 appreciate the suggestions and wish to thank the reviewer for the constructive criticism. In the light of the comments, we modified the manuscript and point-wise modification is detailed below.

Reviewer's Comment: Although I think that the premise of the paper which attempts to link mesoscale eddies to biogenic fluxes collected in sediment traps is important as well as interesting, a great deal of work would be required to make it more robust. The authors have been addressing the problem of comparable carbon fluxes in the Bay of Bengal and Arabian Sea in spite of considerably lower productivity in the Bay of Bengal for several years. In several papers they have explored the possibility of eddies as a mechanism to fertilize the euphotic zone by eroding into persistent stratification from



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river runoff. Their attempt to explore the variability in carbon fluxes is the logical next step in their continuing work so this paper would have been a good opportunity to summarize the past work and lead it to the present conclusions. However the authors have not made any effort to summarize their previous work which would not only enhance the value of the paper but also bring the reader up to date on the work that has been undertaken.

Author's Response: Based on the suggestion we have completely rewritten the introduction providing the summary of the previous work. This is 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), 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



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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.

Reviewer's Comment: (1) Very little effort has been made to give details on the sediment trap data e.g. where it was downloaded from, how it was collected and how the samples were processed. All that we know is the type of trap, the location, depth and the total biogenic flux. (2) The only reference Unger et al. (2003) is missing from the list of references. (3) Is this data open source? (4) The trap is actually NBBT-N not NBBT as mentioned in this paper.

Author's Response: (1) As per the suggestion we have completely modified the first paragraph under"Data and Methods" giving details on the sediment trap data such as its source, method of collection and data processing. (2) We have also included the reference of Unger et al. (2003) in the list of references. (3) The data is not open source but provided by Daniela Unger.We have indicated this in the modified text. (4) Yes, we agree with the reviewer that the trap is NBBT-N. This has been corrected in the modified first paragraph"Data and Methods". The modified first paragraph"Data and Methods" is reproduced below.

The biogenic flux data used in this study was collected from the northern BOB by using PARAFLUX Mark VI time-series sediment trap deployed at 17o 27'N, 89o 36'E (Fig.1). Though two traps, shallow and deep, were deployed at the northern BOB (NBBT-N), for the present study we only used the data from shallow trap located at nominal depth of ∼800-900m (Unger et al., 2003). This is because our objective is to examine the processes influencing the biological production in the euphotic zone and its link to biogenic flux at mid-depth. The sediment trap data at NBBT-N is available from 1987 to 1997, with a data gap in 1993. Since the satellite data on sea-level anomaly (SLA) was available only from 1993, for the present study the biogenic flux data from January 1994 was used (courtesy Daniela Unger). The sampling intervals of the sediment trap varied between 26 days to 42 days. We first converted original data into respective calendar month using linear interpolation and generated the monthly data for the entire time period from January 1994 to December 1998.

Reviewer's Comment: Unger et al. (2003) suggested that enhanced fluxes at NBBT-N during the Southwest monsoon were the result of nutrient enrichment from the large river runoff during the southwest season which is not farfetched considering the amount of runoff from the three major river systems. This was indicated by the strong signal of freshwater that masked the signature of the northern eddy in Prassana Kumar et al. (2004) and the shoaling of the Mixed Layer at the open ocean eddy location as well as the elevated nutrient concentrations. Also as noted in Prassana Kumar et al. (2004) as well as by other workers is that light limitation curtails primary production in the north even if nutrients are available. So in spite of the high nutrients possibly pumped by eddies, PP could still be light limited. To imply that the negative sea level indicates a cold core eddy which pumps nutrients into the euphotic zone, which in turn enhances phytoplankton productivity and consequently carbon fluxes to the deep depths requires we ignore light limitation, influence of rivers, horizontal advection etc.

Author's Response: We agree with the reviewer that role of nutrient enrichment by monsoon-driven fresh water plume from rivers needs to be addressed. This we have done in the modified text under the subheading "3.1 Biogenic flux and sea level anomaly" The new paragraph which is added in the modified manuscript is reproduced below. Considering the geographic location of the sediment trap and 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. A similar result was obtained by Ittekkot et al. (1991) while



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analyzing the sediment trap data for the one year period from October 1987. Based on more recent in situ measurements during summer monsoon (July 2001) Prasanna Kumar et al. (2004) showed that 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. Thus, assuming the role of river-plume advected nutrients to be small the observed biogenic flux enhancement, which also occurs in April and September, in the above four years suggests the role of physical forcing other than the seasonal variability driven by monsoons in governing the export of biogenic flux.

Reviewer's Comment: It would have been more plausible if the workers had shown at least some ocean colour images for 1998 and co-registered SST images for the period of their study.

Author's Response: As suggested a diagram is presented depicting the chlorophyll pigment concentration overlaid with SST contours (Figure New) for the month of February. However, the surface expressions of eddies are weak. Nonetheless in the northern Bay of Bengal, on 11- Feb-1998 (Figure New b) centred about 19oN, 87oE enhanced chlorophyll can be seen with a reduction in SST, indicating the presence of a cold-core eddy. Unfortunately, due to heavy cloud cover, it was not possible to get ocean colour data coinciding with the period of high biogenic flux in July 1998.

Figure New:

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



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Reviewer's Comment: Vinaychandran et al. (2003) used ocean color to track eddies in winter but this study has not referenced.

Author's Response: In the paper Vinaychandran and Simi Mathew (2003) the authors do not deal with eddy-induced chlorophyll enhancement, instead they argue that wind-stress curl driven Ekman Pumping during winter in the south BOB is weak but positive. This combined with the tropical cyclone, which often occurs during October-November and sometimes in December, drives enhanced chlorophyll blooms. The tropical cyclone driven chlorophyll bloom is a short lived (few days) phenomenon in comparison to the eddy-induced process, which lasts for several weeks. Since the above mentioned reference does not deal with eddy processes and the theme of our paper is eddy-induced enhanced chlorophyll leading to the observed enhancement of biogenic flux at mid-depth, the above reference is not included in out manuscript.

Reviewer's Comment: Two important aspects that the authors surprisingly failed to address is 1) the seminal paper of Ittekkot et al. (1991) and others that followed which suggest that organic matter maybe ballasted by heavier lithogenic material which enables it to sink faster. 2) The other is the work of Stoll et al. (2007) which uses the material from the same sediment traps including NBBT-N to identify certain regime indicators that show that peak organic carbon export precedes cyclonic eddy pumping. Perhaps a closer look at the relationship of these indicators with evolution and movement of the cold core eddy towards the trap would yield a better picture then the one presented in this paper. Author's Response: We have incorporated these information and appropriate references in the 2nd paragraph under "3.1 Biogenic flux and sea level anomaly. The modified text is reproduced below:

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 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.

Reviewer's Comment: Other comments include: 1. I am not sure I agree with the comment that there is no seasonality in phytoplankton biomass or productivity. Other studies have shown it.

Author's Response: We have modified he sentence by replacing lack of seasonality with weak seasonality in comparison to the Arabian Sea. . Reviewer's Comment: Fig.

3, 4, 5 should have been extended to 95oE so we can see the situation when the northwest vs northeast eddy is dominant.

Author's Response: Suggestion is incorporated be extending the longitude to 95oE in 3, 4 and 5.

Reviewer's Comment: There are a lot of spelling and grammatical errors which need to be corrected. Author's Response: We corrected the grammatical and spelling errors.

Reviewer's Comment: Once formed, they translated to the trap location leading to the enhanced downward biogenic flux" and replace 'translated' with a more appropriate word.

Author's Response: The sentence is corrected as "Once formed, they moved towards the trap location leading to the enhanced downward biogenic flux" Reviewer's Comment: Edit the sentence" It is well known that these Kelvin wave radiate upwelling Rossby waves in to the interior ocean" Author's Response: The sentence has been modifies as "These Kelvin wave radiate upwelling Rossby waves in to the interior ocean".

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

## Reply to Reviewer #1

**Reviewer's Comment:** *It would have been more plausible if the workers had shown at least some ocean colour images for 1998 and co-registered SST images for the period of their study.*

**Author's Response:** As suggested a diagram is presented depicting the chlorophyll pigment concentration overlaid with SST contours (Figure New) for the month of February. However, the surface expressions of eddies are weak. Nonetheless in the northern Bay of Bengal, on 11- Feb-1998 (Figure New b) centred about 19°N, 87°E enhanced chlorophyll can be seen with a reduction in SST, indicating the presence of a cold-core eddy. Unfortunately, due to heavy cloud cover, it was not possible to get ocean colour data coinciding with the period of high biogenic flux in July 1998.

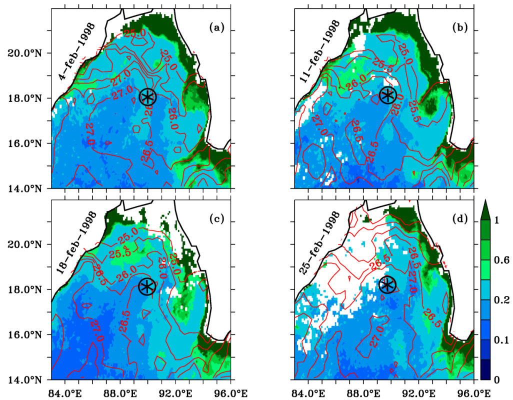


**Figure New**. Chlorophyll images overlaid with SST contours in the Bay of Bengal during February 1998.

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**Fig. 1.** Figure New. Chlorophyll images overlaid with SST contours in the Bay of Bengal during February 1998



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