

Are eddies nature's trigger to enhance biological productivity in the Bay of Bengal?

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Abstract. The Bay of Bengal is traditionally considered to be a less productive basin compared to the Arabian Sea. Despite the contrasting chlorophyll and primary productivity pattern, sediment trap data shows that annual fluxes of organic carbon reach comparable rates in both the basins. The traditional mechanisms of nutrient supply to the upper ocean waters cannot account for this. We propose eddy pumping as a possible mechanism of vertical transfer of nutrients across the halocline to the oligotrophic euphotic zone during summer monsoon when upper ocean is highly stratified. This would induce rapid biological uptake and in turn significantly increase biological production. In the northern Bay, riverine input acts as an additional source of nutrients and augments the subsurface nutrient injection to the euphotic zone by eddy pumping. Notwithstanding this, the lower than expected primary production in the north suggests the possible role of riverine sediment in limiting the sunlight for photosynthesis.

1. Introduction

The Bay of Bengal situated in the eastern part of the north Indian Ocean, is traditionally considered to be a region of lesser biological production compared to its western counter part, the Arabian Sea. Recent study shows that the surface as well as the

integrated chlorophyll *a* in the Bay of Bengal during summer monsoon (June-September) is 4-5 times lesser than that in the Arabian Sea while the integrated primary productivity is about 8 times lesser [*Prasanna Kumar et al.*, 2002]. This is intriguing as both are tropical basins located in similar latitude, land locked in the north and subjected to similar atmospheric forcing – the seasonally reversing monsoon. There is no evidence of strong upwelling in the Bay of Bengal except for very localized ones close to the southwestern boundary during summer [*Shetye et al.*, 1991]. Though wind-driven mixing could potentially transport nutrients from upper thermocline to the euphotic zone, *Prasanna Kumar et al.* [2002] discounts this due to strong upper ocean stratification and weaker winds in comparison to the Arabian Sea. Despite the contrasting chlorophyll and primary productivity pattern, the average annual fluxes of organic carbon reach comparable rates in both the basins [*Ramaswamy and Nair*, 1994]. The traditional mechanisms of nutrient supply to the oligotrophic upper ocean waters such as wind-driven mixing, upwelling etc. cannot account for this. In this paper we explore the role of eddies in enhancing the biological productivity in the Bay of Bengal.

2. Data and Analysis

Onboard ORV Sagar Kanya, 24 CTD stations - 14 in the central Bay of Bengal along 88°E (open ocean transect) and 10 along the western margin (coastal transect) (Figure 1) - were occupied at 1-degree interval during summer 2001 (6 July to 2 August). Profiles of temperature and salinity in the upper 1000m were obtained using a Sea-Bird CTD. Water samples from various depths collected by a rosette sampler were analyzed for nitrate, silicate and phosphate with a SKALAR auto-analyzer having a sensitivity of 0.1, 0.5 and 0.03 μ M respectively. Apart from this, 9 biological stations (5 in the central Bay of Bengal and 4 along the western margin, Figure 1) were also occupied for measuring

chlorophyll *a* and primary production [see *Madhupratap et al.*, 2003]. Underway currents and surface meteorological parameters were measured using shipboard ADCP and automatic weather station respectively.

3. Results and Discussion

Thermal structure in the central Bay of Bengal showed oscillations in the upper thermocline with gradual shoaling of isotherms towards 20°N (Figure 2a). Signature of subsurface cold-core eddies was discernible from the upheaval of isotherms below the surface, centered at 10°N (southern eddy) and 19°N (northern eddy) respectively. For example, the 28°C isotherm in the southern eddy shoaled from 80m (7°N) to 15m (9°N) exhibiting a vertical displacement of about 60m, which tapered off towards the deep. The eddy depressed the ambient temperature at 60m (27°C) by about 5°C. Similar changes in the temperature structure were also noticed associated with the northern eddy. Below 300m, the thermal structure did not show any special features (not shown).

The salinity structure showed strong gradient in the upper 100m, followed by almost homogeneous waters down to 1000m (shown only up to 300m, Figure 2b). In the surface layer, salinity was about 33.5psu (practical salinity scale) between 7°N and 15°N but decreased rapidly towards north reaching a low of 27.6psu at 17°N. The salinity gradient in the upper 50m at 7°N was about 1.5psu while that at 20°N was about 7psu. This indicated a strong signal of freshwater influx, which masked the eddy's surface manifestation. In the region of strong salinity gradient, effect of eddy could be inferred by the upheaval of isohalines.

Thermal structure along the western margin (coastal transect) also indicated the signature of cold-core eddy (coastal eddy) centered at 17°N, 83.5°E (Figure 2c). Though

the salinity structure was similar to that of the open ocean, the gradient in the upper 50m was weaker (Figure 2d). However, the presence of eddy was discernible from the up sloping isohalines as in the case of open ocean.

The zonal velocities in the upper 150m derived from ADCP data revealed a strong eastward current in the eddy region between 7° and 10°N, with a maximum of 60cm/s at around 8°N, followed by a weak (<10cm/s) westward current up to 13°N (Figure 3, left). Interestingly, the eastward velocity occurred where we noticed an up sloping of isotherms/isohalines associated with the southern eddy. The weak westward flow coinciding with the down sloping isotherms/isohalines was confined within the upper 80m. Similar current structure was also noticed with the northern eddy, except for a weaker eastward velocity (maximum of 40cm/s). In the region of coastal eddy, the eastward velocity associated with the up sloping isotherm/isohaline was weaker (<10cm/s) compared to the westward velocity with a maximum speed of 50cm/s between 17° and 18°N (Figure 3, right).

The observed differential flows associated with the eddy could be understood in the context of basin-scale circulation. During this time of the year the eastward flowing strong summer monsoon current [*Cutler and Swallow, 1984*] brings saltier Arabian Sea high salinity waters (ASHSW) into the southern Bay of Bengal. The eastward flow is evident from the geostrophic circulation derived from Topex/Posidon altimetry for July-August (Figure1). The presence of 35psu salinity at the core of the southern eddy (Figure 2b) lends further support to the advection of ASHSW into the southern part of the Bay. When a cyclonic southern eddy is embedded in the monsoon current, the strong eastward monsoon current will augment (counteract) the eastward (westward) component of eddy

flow. In the northern Bay the wind-driven Ekman current, which dominates the flow field, is predominantly eastward. The stronger/weaker eastward/westward component of flow in the case of northern eddy is the manifestation of the eddy flow augmented/counteracted by the Ekman current. Along the western margin, north of 10°N, the East India Coastal Current is pole-ward during this time of the year [Shetye *et al.*, 1993], carrying warmer and saltier water. In the northern Bay, however, the low salinity plume moves equator-ward hugging the coast against local winds [Shetye *et al.*, 1993]. The observed stronger westward flow of the coastal eddy, contrary to that of the open ocean eddies, is linked to this equatorward flow, which augments (counteracts) eddy's westward (eastward) component.

Thus, from the hydrographic as well as ADCP data, we infer the presence of three subsurface cold-core eddies in the Bay of Bengal during summer monsoon. The strong stratification of the upper ocean by the warm and low-salinity waters inhibited the surfacing of the doming isopleths and confines it below 15m.

The nitrate distribution showed that though the upper 30-40m layer was devoid of nitrate, subsurface enhancement was observed in the eddy region (Figure 4). The 1µM nitrate isopleth, generally located at about 60m, shoaled to about 25m under the influence of eddies (Figure 4). Apart from the eddy-induced changes, there was a general northward shoaling of isopleths in the open ocean section consistent with the thermal structure. Note the shoaling of mixed layer depth (MLD, defined as the depth at which the sigma-t value is greater than surface value by 0.2) under the influence of eddies. The northward shoaling of MLD in the open ocean is due to the effect of fresh water influx. The surface waters along the western margin between 19° and 20°N showed up to 0.5µM

concentrations of nitrate. Silicate distributions were also similar to that of nitrate, except for much higher surface concentrations in the north with $2\mu\text{M}$ (open ocean) and $4\mu\text{M}$ (western margin) (not shown) probably indicating the riverine input.

Concurrent with the nutrient distribution, the chlorophyll *a* also showed enhanced concentrations generally coinciding with the location of eddies (Figure 5). Along the open ocean track, two regions of chlorophyll enhancement were noticed. The first region of higher chlorophyll *a* concentrations ($\sim 0.30\text{mg}/\text{m}^3$) was located between 9° and 12°N , centered at 40m, while the second region was between 18° and 20°N , located in the upper 30m with maximum close to the surface (Figure 5, left). The first one was obviously linked to the southern eddy. The cyclonic circulation associated with the cold-core eddy is capable of pumping up nutrient-rich deeper waters into the euphotic zone, as was evident from the doming of nitrate isopleths. The nutrient thus introduced triggers the new production and leads to the enhanced levels of chlorophyll *a* concentrations. Eddy pumping [Falkowski *et al.*, 1991] has been suggested to enhance the new production in the case of North Pacific subtropical gyre [Allen *et al.*, 1996], North Atlantic [Oschiles and Garcon, 1998] and Sargasso Sea [McGillicuddy *et al.*, 1998]. Enhanced primary production (PP) rates in the vicinity of the cold-core eddy were evident in the present case. We observed an integrated (down to 120m) PP of $220.7\text{ mg C m}^{-2}\text{ d}^{-1}$ in the vicinity of the southern eddy, which was more than double the value out side the eddy region ($107.2\text{ mg C m}^{-2}\text{ d}^{-1}$ at 12°N). The second region of enhanced chlorophyll *a*, although falls within the region of northern eddy, is not entirely driven by the subsurface nutrient pumping. In such case one would have expected a subsurface high chlorophyll *a* concentration consistent with the nutrient distribution instead of upper layer enhancement

close to the surface. High levels of silicate and trace levels of nitrate concentrations in the north, which falls close to the Ganges-Brahmaputra outflow, indicate the riverine source. There must have been some nitrate initially and the rapid biological uptake by phytoplankton would have resulted in complete depletion of nitrate near the surface. Thus, the observed enhanced chlorophyll in the northern edge of the transect might have resulted from a combination of processes such as nutrient pumping by eddy as well as the river input. However, the lowest value of PP ($89.4 \text{ mg C m}^{-2} \text{ d}^{-1}$) at 20°N points to the fact that though nitracline shoaled towards the north making nutrients available in the upper layers, the lack of sufficient light for photosynthesis might have led to the observed low PP. The elevated diffuse attenuation at 490nm along 88°E extracted from SeaWiFS and averaged for the months June to September 2001 (Fig.6) suggest low levels of in situ irradiance.

Along the western margin, the vertical distribution of chlorophyll *a* showed 3 locations of enhanced concentrations – the first one between the 50-70m depth ($\sim 0.25 \text{ mg/m}^3$), centered at 14°N , the second one between 30-50m depth ($\sim 0.35 \text{ mg/m}^3$) centered at 17°N , and a third in the upper 30m depth ($\sim 0.35 \text{ mg/m}^3$) between 19° - 20°N (Fig.5, right). From their location it is evident that the enhanced chlorophyll concentrations as well as the integrated PP ($328.4 \text{ mg C m}^{-2} \text{ d}^{-1}$) centered at 17°N is directly linked to the coastal eddy. The integrated PP in the eddy region is at least 8 times higher than that of the non-eddy region ($39.7 \text{ mg C m}^{-2} \text{ d}^{-1}$ at 15°N). From the nitrate distribution it is clear that in the absence of eddies, the upper 40m of the water column is depleted of nitrate. Once again, the higher chlorophyll in the upper 30m of the water column in the northern edge of the transect must be driven by a combination of the nutrient input from the Ganges-

Brahmaputra river system along with the eddy pumping of nutrient-rich deeper water into the upper layers.

In summary the traditionally well known nutrient supply mechanisms such as wind-mixing, upwelling etc. are unable to explain the comparable rates of annual mean fluxes of organic carbon in the less productive Bay of Bengal and highly productive Arabian Sea. We propose eddy pumping by the subsurface cold core eddies as a possible mechanism of nutrient injection to the oligotrophic waters in the Bay of Bengal during summer. The eddy enhances the biological productivity 2 to 8 times compared to the non-eddy region. Similar localized regions of very high phytoplankton biomass (53mg/m^2) and productivity ($4.5\text{ g C m}^{-2}\text{ d}^{-1}$) were reported near the western boundary associated with eddy-like structure during pre-southwest monsoon [*Gomes et al.*, 2000]. Thus, though the surface chlorophyll concentration remains low, the enhanced subsurface chlorophyll concentrations will result in net increased biological production in the Bay. Near the river mouths the plumes enriched in nutrients together with eddy pumping at the base of the halocline significantly increases the nutrient supply to the upper layers. The organic carbon thus produced in the Bay of Bengal may be lost from the euphotic zone much faster under the ballasting [*Ittekkot et al.*, 1992] by lithogenic sediments. The suspended sediment delivered by the rivers increases the turbidity of the water column, which in turn inhibits the light available for photosynthesis. The lower than expected primary productivity in the north suggests light limitation. The eddy mediated biological productivity though may not fully answer the observed comparable annual average rates of organic carbon fluxes in the Bay of Bengal and the Arabian Sea, this definitely

suggests alternate processes and mechanisms that may be unique to the Bay of Bengal and the need for more research.

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Figure Caption

Figure 1. Location of CTD (filled circle) and biological (small open circle) stations occupied during summer (6 July to 2 August) 2001 overlain on the map of mean sea level anomaly (shaded) for 10 July – 10 August, 2001 from T/P. The big shaded circles indicate the position of cold core eddies. Black and white arrows denote the currents derived from ADCP and T/P respectively.

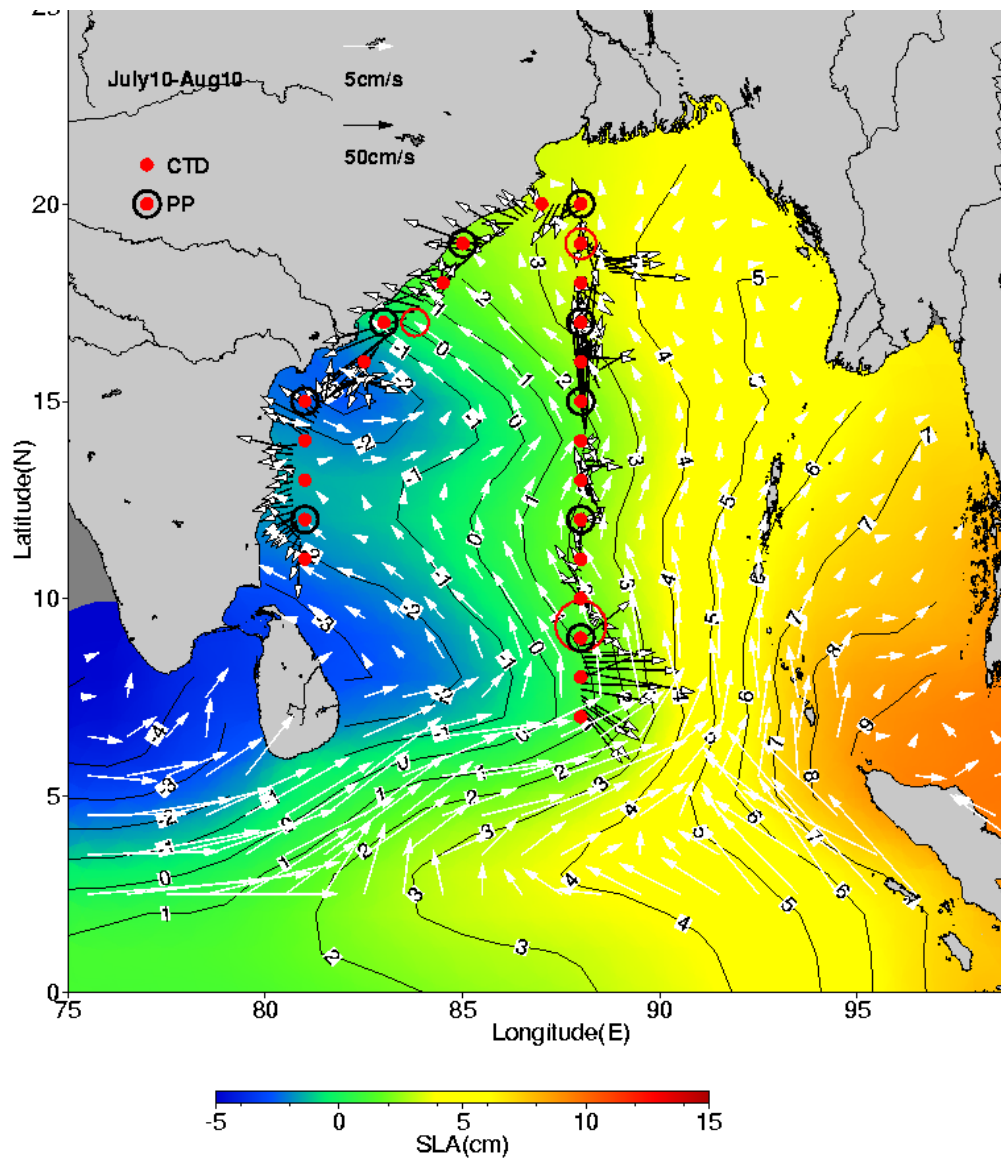
Figure 2. Vertical distribution of (a,c) temperature ($^{\circ}\text{C}$) and (b,d) salinity (psu) in the upper 300m along the open ocean (88°E : a,b) and coastal (c,d) transects.

Figure 3. Vertical distribution of zonal velocity (shaded eastward) in the upper 150m derived from ship-mounted ADCP along the open ocean (left) and coastal (right) transects.

Figure 4. Vertical distribution of nitrate (μM) in the upper 120m along the open ocean (left) and coastal (right) transects. Dashed line indicates the depth of mixed layer. Thick line indicates $1 \mu\text{M}$ contour. The filled circles represent bottle sample distribution.

Figure 5. Vertical distribution of chlorophyll *a* (mg/m^3) in the upper 120m along the open ocean (left) and coastal (right) transects. Dashed line indicates the depth of mixed layer. Note that chlorophyll observation along coastal transect starts from 12°N . The filled circles represent bottle sample distribution.

Figure 6. Diffuse attenuation at 490nm obtained from SeaWiFS averaged for the months of June, July, August and September 2001 along 88°E .



Sea Level Anomaly, Geostrophic current and ADCP velocities in BoB during July10-Aug10 2001

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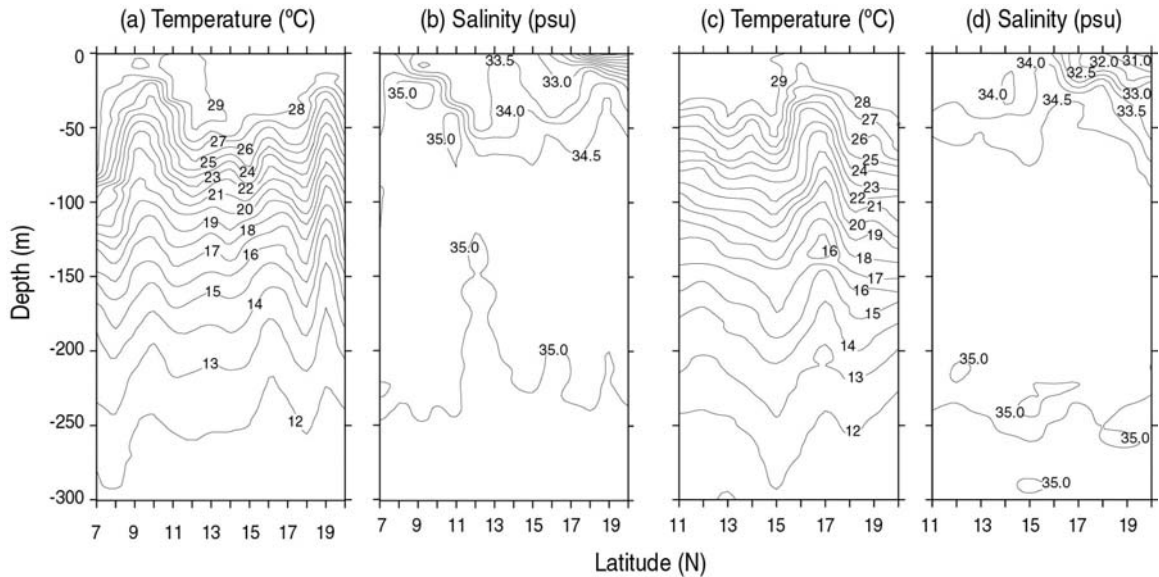


Figure 2. Vertical distribution of (a, c) temperature (°C) and (b, d) salinity (psu) in the upper 1000 m along open ocean (88° E: a, b) and coastal (c, d) transects.

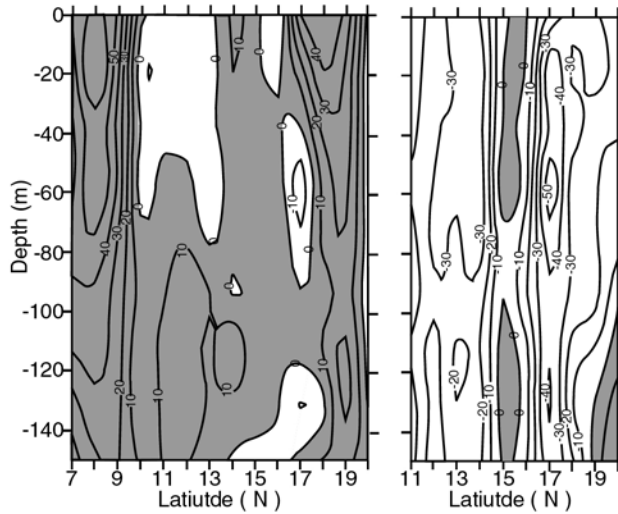


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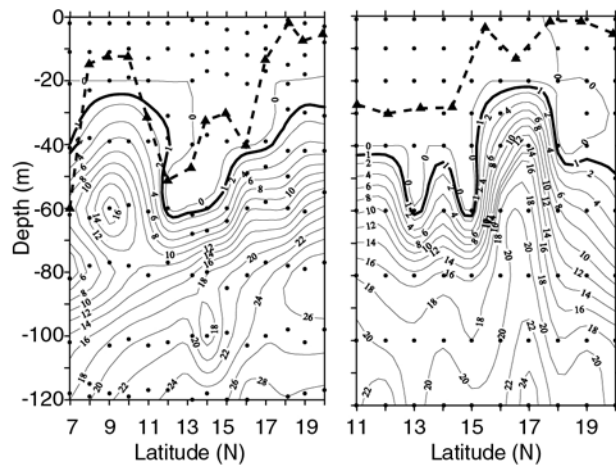


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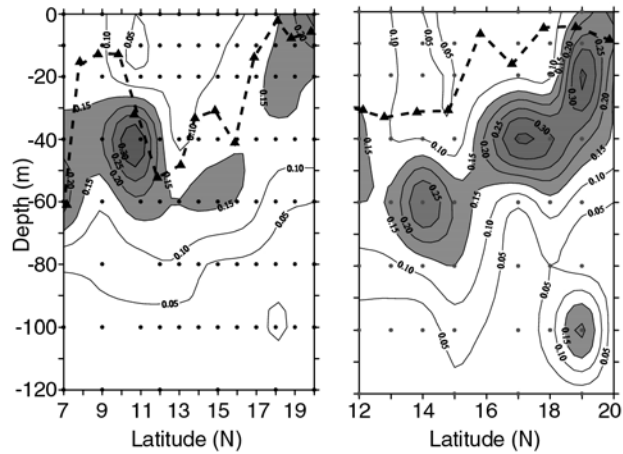


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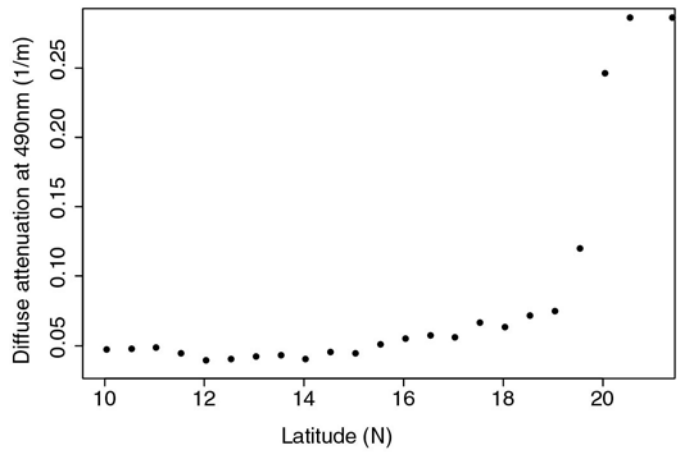


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