

Strong solar influence on multi-decadal periodic productivity changes in the central-western Bay of Bengal

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Abstract

Oceanic productivity is a vital component of the global carbon cycle. The productivity in the tropical oceans is strongly modulated by the monsoon winds. The monsoon winds are driven by the temperature. Therefore, the oceanic productivity is most likely to be influenced by the increasing global warming. However, the projected response of oceanic productivity to global warming is ambiguous. The past records can help to better constrain the future response of oceanic productivity to different warming scenarios. Here, we reconstruct decadal monsoon and productivity changes from the central-western Bay of Bengal, covering the entire Holocene. We use both foraminiferal (relative abundance of *Globigerina bulloides*, stable oxygen isotopic ratio of surface dwelling *Globigerinoides ruber*) and geochemical [calcium carbonate (CaCO_3), organic carbon (C_{org}), organic carbon/total nitrogen ($\text{C}_{\text{org}}/\text{TN}$)] proxies to reconstruct productivity and associated parameters. All the proxy data suggests a large variation in productivity and carbon burial during the Holocene. A very intense upwelling, concomitant with a phase of increased precipitation and CaCO_3 burial is inferred during the beginning of Greenlandian (~12,000 - ~10,000 yrs BP). The intense upwelling, however, did not result in higher organic carbon burial. The beginning of Northgrippian (~8000 to 7000 yr BP) was a significantly wet phase followed by gradual decrease in precipitation. Incidentally, the reduced upwelling during the Northgrippian was synchronous with a large increase in organic carbon burial. The opposite trend in upwelling intensity and $\%C_{\text{org}}$ during the Meghalayan as well, suggests decoupling of upwelling induced productivity and organic carbon burial in the western Bay of Bengal. Towards the late Meghalayan (after ~1500 yr BP), we report a relatively enhanced precipitation with continual increase in CaCO_3 but with reduced C_{org} burial. Further, these long-term variations were accompanied by significant short-term periodic changes, closely resembling Gleissberg cycle as well as Seuss cycle, suggesting a possible link with the solar variability.

Keywords: Holocene, planktic foraminifera, productivity, carbon burial, cyclicity

1 Introduction

The oceans act as a source and sink for carbon (Sabine et al., 2004; Mendonca et al., 2017; Macreadie et al., 2017). The remains of the phytoplankton and zooplankton thriving in the upper few hundred meters of the water column in the productive regions, sink down and get sequestered in the sediments as inorganic (calcite, aragonite) and organic carbon (Muller and Suess, 1979; Emerson and Hedges, 1988; Kessarkar and Purnachandra Rao., 2007; Ramaswamy et al., 2008; Cui et al., 2016). The remineralization of a part of this downward flux along with the sinking of the cold and dense water in the polar regions, contribute to the huge deep ocean carbon pool (Kwon et al., 2009; Guidi et al., 2016). The upwelling of the deep ocean water thus results in enhanced ocean-atmosphere carbon dioxide (CO₂) flux (Sarma, 2013). The oceans, thus, are an important component of the global carbon cycle, including the atmospheric concentration of carbon dioxide (CO₂). The sequestration of marine organic and inorganic carbon in sediments is modulated by the ambient environmental conditions. Therefore, the sedimentary characteristics can provide useful clues to understand the effect of environmental conditions on ocean's contribution to the atmospheric CO₂ on different timescales (Cartapanis et al., 2016; 2018; Shah et al., 2018; Rixen et al., 2019). The ocean primary productivity, the major driver of the ocean carbon cycle, depends on several factors including the nutrient availability, water column stratification and temperature. Anthropogenic activities have warmed the world and also influenced the nutrient input to the oceans. The effect of anthropogenic activities on ocean productivity and thus global carbon cycling is debated (Prasanna Kumar et al., 2009; Roxy et al., 2016). The paleoclimate records on shorter time scale covering atleast the recent Holocene can help to better understand the implications of such anthropogenic activities on marine productivity and carbon burial in the oceans (Schewe & Levermann, 2012).

Holocene interglacial is less documented as compared to the glacial interval (Daansgaard et al., 1993; Mayewski et al., 2004), although this period has hosted the rise, growth and development as well as the demise of civilizations (Staubwasser et al., 2006; Wanner et al., 2008; Buckley et al., 2010; Achyuthan et al., 2013; Dixit et al., 2014a; Giosan et al., 2018; Shah et al., 2020). It is also opined that the Holocene climate changes have been larger and more frequent. The whole Holocene period is marked by alternating intervals of glacial advances and retreats, also referred to as Rapid Climate Change (RCC) events, with the strongest advances in the Neoglacial (~6000 yrs BP to pre-industrial times) particularly at ~200-350 yrs BP and ~2800-5000 yrs BP due to declining summer insolation (Denton and Karlen, 1973; Mayewski et al., 2004). More recent work from the Indian subcontinent also reveal important climatic variations within the Holocene period (Sarkar et al., 2000; Wang et al., 2005; Fleitmann et al., 2007; Sinha et al., 2011; Yadav et al., 2011; Ponton et al., 2012; Dixit et al.,

2014; Naik et al., 2014; Kotlia et al., 2015; Rawat et al., 2015; Saraswat et al., 2016). These datasets from the recent past are important as it will help to decipher short term climatic events. However, such records are not only limited but also have a relatively coarser centennial to millennial resolution.

The seasonal reversal of winds during the monsoon, strongly influences the biogeochemical processes in the Indian Ocean (Wrytki, 1973). The coastal and open ocean upwelling forced by the monsoon winds is responsible for a significant increase in the primary productivity, especially in the western Indian Ocean (Wrytki, 1971; Anderson et al., 1992; Anderson and Prell, 1993). The Bay of Bengal in the eastern Indian Ocean, on the other hand, is often reported as having poorer primary productivity. The region is, however, suggested to have a great potential to remove excess atmospheric CO₂ by high new production during both the summer and winter seasons (Kumar et al., 2004). Eddies, rather than regional upwelling, bring up the nutrients to the surface and thus enhance the overall productivity (Prasanna Kumar et al., 2007; Vidya and Prasanna Kumar, 2013). Additionally, the huge riverine influx, results in a very high sedimentation rate in the Bay of Bengal. The marginal regions of the Bay of Bengal, thus provide an opportunity to reconstruct high resolution, short-term changes in paleoproductivity and carbon burial. Here we reconstruct sub-decadal monsoon, paleo-productivity and carbon burial changes from the central-western Bay of Bengal.

2 Study area

Bay of Bengal is a unique bay in the eastern part of the Indian Ocean. The, average annual continental runoff into the bay is ~2950 km³ which is half the total influx in the entire Indian Ocean (Sengupta et al., 2006). This huge sediment accumulation defines and shapes the bathymetric features, whereby, very often the surficial topography is masked by the sediments giving it the appearance of a featureless area (Sarma et al., 2000). The northern part of the bay is shallower with the maximum depth of 2000 m while the central part is flatter with an average depth of 3000 m and further south west region is 3500 m deep (Sarma et al., 2000). The thickest pile of sediment cover (~21 km) is in front of the Ganga-Brahmaputra outfall and reduces from about 8 km to 2 km from central to southern Bay of Bengal (Curry, 2003). The contribution of lithogenic components is ~39% at the northern bay and ~12.6% at the southern bay (Unger et al., 2003). The clay minerals, including illite and kaolinite are dominant in the northern bay while smectite is dominant in the central bay (Subramanian et al., 1985; Bejugam & Nayak, 2016).

The freshwater influx from the rivers into the bay is evident from the lower salinity (~33-34 psu) at the proximity of the river mouth along the shallow coastline. The salinity increases further away in the deeper regions. The direct overhead precipitation also contributes a significant amount of fresh water to the bay. The maximum precipitation (318 mm/ month) over the Bay of Bengal is during

the summer and the minimum during the winter (88 mm/month) (Ramesh Kumar & Prasad, 1997). Overall, the surface salinity varies between ~33 to 34 psu. This freshwater enhances primary productivity by increasing nutrient supply (Ramaswamy & Nair, 1994). But, biological productivity in the Bay of Bengal is comparatively lower than that in the Arabian Sea due to strong stratification, more cloud cover and turbidity. The eddy pumping mechanism in the Bay of Bengal has, however, explained how the biological productivity is sustained (Prasanna Kumar et al., 2004) resulting in annual organic matter flux comparable with that of the Arabian Sea (Ramaswamy & Nair, 1994). In the western Bay of Bengal, there are two upwelling regions, namely Vishakhapatnam and Chennai wherein the salinity and nutrient concentrations are reported to be high. Further, stronger upwelling at Vishakhapatnam has been attributed to relatively stronger winds near Vishakhapatnam (deSousa et al., 1996). Additionally, Shetye et al (1991) reported a 40 km wide upwelling band driven by the local winds alone, along most of the coastline in the Bay of Bengal. The major rivers bring a relatively warmer freshwater into the bay and add to the strong stratification. The relatively warmer water (~29 to 30°C) covers the shallow depth areas of the western Bay of Bengal. The major ocean current in the western Bay of Bengal is the narrow East India Coastal Current (EICC). This current flows from the Bengal shelf southwards during the winter season while reversing its direction northward during the summer season (Schott and McCreary, 2001). The bottom water dissolved oxygen in the study area varies within a range of ~0.30 mL/L to 4.59 mL/L (WOA2009). The lower dissolved oxygen with an average value of ~0.5 mL/L lie within the depth range of ~100 m to ~1000 m (Suokhrie et al., 2020).

2.1 Methodology

A gravity core (SK308 GC02; 14.55° N; 80.94° E and water depth 2094 m) was collected off Pennar river onboard ORV *Sagar Kanya*. The core was sub-sampled at 1 cm interval (Figure 1). The total length of the core was 4.85 m but for this study we are focussing only on the top 3.85 m covering the Holocene. The sediments were processed by following the standard methodology (Naik et al., 2017). An appropriate aliquot (10-15 g) of the sediments was freeze dried. The completely dried samples were weighed and soaked overnight. The samples were then washed by using 63 µm sieves. The >63 µm fraction (coarse fraction, CF) retained on the sieve was dried, weighed and stored in plastic vials. The coarse fraction was dry sieved by using 125 µm sieve. A minimum of 300 planktic foraminifera were picked from >125 µm fraction. The relative abundance of *Globigerina bulloides* was counted.

For stable oxygen ($\delta^{18}\text{O}$), ~15-20 specimens of *Globigerinoides ruber* were picked from 250-355 µm sieved fraction and analysed at the Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany, by using a Finnigan MAT 251 isotope ratio gas mass spectrometer, coupled to an automatic carbonate preparation device (Kiel IV). The isotopic ratio was calibrated to Vienna

Pee Dee Belemnite (VPDB) by using standard NBS-19. The values are given in δ notation versus VPDB. The repeatability in measurements was better than 0.08‰. A part of the freeze dried sediment was powdered in a clean mortar and pestle. The dried and powdered sediment samples were utilized for inorganic carbon (IC) and total carbon (TC) analysis by using Coulometer (model CM 5015 CO₂) and CN analyser (model FLASH 2000 Thermo Scientific) at CSIR-National Institute of Oceanography, Goa. The organic carbon (C_{org}) was calculated by subtracting IC from the TC. The calcium carbonate (CaCO₃) concentration was calculated from the molecular ratio of CaCO₃ and IC i.e., CaCO₃ = IC * 8.33 (Espitalie et al., 1977; Zamelczyk et al., 2014).

2.2 Chronology

The chronology of the core is based on 6 accelerator mass spectrometer radiocarbon (¹⁴C) dates measured at the Center for Applied Isotope Studies, University of Georgia, University of Arizona Accelerator Mass Spectrometry Laboratory, USA and Inter University Accelerator Center, New Delhi, India. The ¹⁴C ages were calibrated by using Marine13 dataset (Reimer et al., 2013) in the online calibration programme “Calib7.1” (Stuiver & Reimer, 2016). The average reservoir correction (ΔR) of 108±208 yr for Pondicherry, India (12.1°N 80°E; Southon et al., 2002), Rameshwaram, Tamil Nadu (9.17°N 79.22°E; Dutta et al., 2001) and Mandapam, Tamil Nadu, (9.2°N 78.7°E; Dutta et al., 2001) was applied to calibrate all ages. The age of all samples was calculated by assuming a constant sedimentation rate between the dated intervals and thereby linearly interpolating the values. The core covers a time span of ~12,000 yrs BP (Figure 2, Table 1). The sediment core reveals decadal to multi-decadal resolution. The highest sedimentation rate (79.23 cm/kyr) is during the late Meghalayan Stage (after ~1500 yr BP). The sedimentation rate decreases during the early Greenlandian Stage (14.4 cm/kyr).

2.3 Spectral analysis

To infer periodicity in productivity and associated parameters, we performed spectral analysis on the faunal (*G. bulloides* relative abundance), geochemical ($\delta^{18}\text{O}_{\text{sw-ivc}}$, $\delta^{13}\text{C}_{\text{ruber}}$) and sedimentary parameters (CF, C_{org}, C_{org}/TN and CaCO₃), by using the Redfit 3.5 software (Schulz and Mudelsee, 2002).

3 Results

3.1 Coarse fraction (CF) (>63 μm)

The coarse fraction varies from 0.15% to 29.8% with higher CF being prior to Northgrippian (before ~8000 yr BP). CF mostly comprises of biogenic shells. Clearly, the fluctuation in CF% in the late Holocene is minimal as compared to the early Holocene (Figure 3).

3.2 Total Carbon (TC)

The total carbon varies from 1.39% to 3.64%. The changes in TC are similar to the inorganic carbon (IC), although the range at which it varies is comparatively higher. A notable opposite trend is observed during the Meghalayan Stage where TC decreases till present while the IC increases upto the present (Figure 3).

3.3 Calcium carbonate (CaCO₃)

The CaCO₃ content of the sediment varies from 0.12% to 14.09% over the last 12,000 yrs BP. A decreasing trend is observed in CaCO₃ from 15.00% at the beginning of Greenlandian to 7.00% in the top ~387 cm of the core covering a time period of ~12,000 yrs BP (Figure 3).

3.4 Organic Carbon (C_{org})

The organic carbon varies from 1.11% to 2.44%. Within the Holocene, %C_{org} was lower during the early Greenlandian, followed by a gradual increase with a peak concentration during the mid Northgrippian (~8000 yrs BP to ~5000 yrs BP). The organic carbon subsequently decreased during the late Meghalayan, with the lowest concentration in the core-top (Figure 3).

3.5 C_{org}/TN

C_{org}/TN ranges from 4.61% to 14.44%. C_{org}/TN was lower during the mid Northgrippian (~8000 yrs BP to ~4000 yrs BP). A gradual increase in C_{org}/TN was observed during the Meghalayan Stage leading to a prominent high at ~800 yrs BP after which a steep decrease occurs towards the core top. The highest C_{org}/TN was between ~5000 to ~800 yr BP (Figure 3).

3.6 Regional Seawater Oxygen Isotopic ratio ($\delta^{18}\text{O}_{\text{sw-ivc}}$)

The stable oxygen isotopic ration of surface dwelling planktic foraminifera, *Globigerinoides ruber* ($\delta^{18}\text{O}_{\text{ruber}}$) was the highest during the early Greenlandian (1.24‰, at 11600 yr BP) and Late Meghalayan (1.14‰, at 850 yr BP). The most negative $\delta^{18}\text{O}_{\text{ruber}}$ (-3.29‰, at 7200 yr BP) was during early Northgrippian, thus varying by ~1.9‰ during the Holocene. $\delta^{18}\text{O}_{\text{ruber}}$ was corrected for the regional sea surface temperature by using the data from a nearby core (SO 188-17286-1, 19°44.58'N, 89°52.76'E, 1428 m water depth) (Lauterbach et al., 2020). Subsequently, the global ice volume contribution (Bintanja et al., 2008) was removed from the temperature corrected $\delta^{18}\text{O}$ to obtain the regional $\delta^{18}\text{O}_{\text{sw-ivc}}$ to understand the localized evaporation-precipitation changes. The most depleted $\delta^{18}\text{O}_{\text{sw-ivc}}$ (-0.95‰) was at ~7100 yr BP at the beginning of the Northgrippian while it was the most enriched (1.60‰) during the late Meghalayan (~840 yr BP). There is a gradual depletion in $\delta^{18}\text{O}_{\text{sw-ivc}}$ from the beginning of Greenlandian (~11,700 yrs BP) continuing upto the beginning of Northgrippian

(~7000 yr BP) where it is the most depleted. From ~6000 yr BP onwards, there is a gradual enrichment till ~4000 yr BP. The most enriched $\delta^{18}\text{O}_{\text{sw-ivc}}$ is seen after the end of Northgrippian (~4000 yrs BP) with the maximum enrichment at ~840 yr BP, after which a steep depletion follows till the present (Figure 4).

3.7 Planktic foraminiferal abundance

We have utilised the relative abundance of *Globigerina bulloides* to reconstruct the upwelling induced paleo-productivity in the western Bay of Bengal during the Holocene. *Globigerina bulloides* is present in all the sections of the core except at a few intervals (Figure 4). The relatively higher abundance of *G. bulloides* in the Greenlandian (~12,000 yr BP to ~10,000 yr BP) and also towards the Meghalayan (~4000 yr BP till present) has been observed. The maximum abundance of *G. bulloides* (15%) is in the core top section (0-1 cm) (present). The late and middle section of the core (~10,000 yr BP to ~4000 yr BP), has a comparatively decreased abundance of *G. bulloides*. The variation in *G. bulloides* abundance is more after ~4000 yr BP.

3.8 Spectral analysis

The statistically significant cyclicity peaks (>90% χ^2 for *G. bulloides* and 99% χ^2 for all other parameters) in the time series plot (Figure 5) are at 138, 153, 183 and 210 years for *G. bulloides*. The sedimentary data shows a significant periodicity at 87, 150 and 255 years for CF (%); 270, 180, 87 years for C_{org} ; 280, 150, 87 years for $\text{C}_{\text{org}}/\text{TN}$ and 273, 151, 87 years for CaCO_3 . Further, 247, 220, 149, 142, 117, 104 and 87 years for $\delta^{13}\text{C}_{\text{ruber}}$ and 469, 387, 303, 233, 198 and 153 years for $\delta^{18}\text{O}_{\text{sw-ivc}}$.

4 Discussion

The faunal and sedimentary proxies along with the stable isotopic data bring out significant variation in productivity and associated changes in the western Bay of Bengal during the Holocene. A distinct difference is observed in a majority of the proxy records between Greenlandian and Northgrippian as well as Meghalayan Stage (Figure 6).

4.1 Upwelling induced productivity changes

The relative abundance of *G. bulloides* was higher during the Greenlandian and decreased significantly during most part of the Northgrippian. Towards the end of the Northgrippian and beginning of the Meghalayan, we see a strengthened and increased trend in *G. bulloides*. *Globigerina bulloides* is a spinose planktic foraminifera associated with temperate to sub-polar water masses (Bé and Tonderlund, 1971). Interestingly, *G. bulloides* has also been reported from relatively cold, nutrient rich waters, usually found in the high productivity upwelling regions at lower latitudes (Rao et al., 1989; Prell et al., 1980; Naidu and Malmgren, 1996; Naidu and Niitsuma, 2004; Singh et al., 2011, Darling

et al., 2017). The maximum flux of *G. bulloides* in the Bay of Bengal sediment traps also suggests it as a monsoon induced upwelling indicator species (Guptha et al., 1997). The increased abundance of *G. bulloides* is thus suggestive of increased upwelling and productivity in the western Bay of Bengal. The increased relative abundance of *G. bulloides* during the Greenlandian matches with a relatively high C_{org}/TN (>12) (Figure 6). C_{org}/TN has been used as an index for the source of C_{org} with the molar ratio of marine phytoplankton being <6 , while values $>6-8$ are taken for terrestrial vascular plants (Emerson et al., 1988; Muller and Mathesius, 1999; Kessarkar and Rao, 2007; Ramaswamy et al., 2008; Saraswat et al., 2017; Saalim et al., 2019). The marine algal plants have higher proteins containing nitrogen, than cellulose as compared to the land plants and this is the reason for the difference in C/N values (Hedges et al., 1997, Meyers, 1994). Although diagenetic changes strongly modulate the elemental composition, the C_{org}/TN is comparatively less affected (Meyers, 1994) as compared to the carbon isotopic ratio of the organic matter (Lehmann et al., 2002). Therefore, such a high C_{org}/TN clearly suggests a terrestrial source of C_{org} during the Greenlandian. The significantly decreased abundance of *G. bulloides* during the Northgrippian, suggests reduced upwelling and productivity (Figure 6) and also corresponds to a low terrestrial influx as is evident from the drop in C_{org}/TN . Several episodes of increased upwelling in the western Bay of Bengal are inferred during the Meghalayan.

4.2 Carbon burial and sources

The change in $\%C_{org}$ abundance during the Greenlandian is intriguing. A relatively higher $\%C_{org}$ is expected during the intervals of high productivity. However, the organic carbon throughout the Greenlandian was lower than that during the subsequent Northgrippian interval. The increase in $\%C_{org}$ begins towards the end of Greenlandian (~ 8000 yr BP) and is at its maximum during the Northgrippian (~ 4849 yr BP) (Figure 4). But, $\%C_{org}$ during the Greenlandian was higher than that during the later phase of Meghalayan and also gradually decreased, similar to the relative abundance of *G. bulloides*. The organic carbon content of the sediments depends on the primary productivity, the efficiency of the burial of the resultant organic matter, sediment texture and oxygen availability (Arndt et al., 2013; Ausín et al., 2021). The higher terrigenous flux increases the sinking rate, reduces its remineralisation and results in faster burial of organic matter in the sediment. The higher productivity and increased runoff during the Greenlandian, thus should result in increased $\%C_{org}$. The low $\%C_{org}$ despite of the higher productivity and increased runoff is attributed to its poor preservation. The preservation of organic matter in the sediments is mainly modulated by the grain size and the dissolved oxygen concentration in the overlying waters (Bergamaschi et al., 1997). The core was collected, well below the oxygen deficient zone (Bristow et al., 2016). Thus, the sufficient oxygen availability can result in

faster and continued oxidation of organic matter, provided easy permeability of oxygen in the sediments. The availability of larger surface area results in increased preservation of organic matter in finer sediments (Mayer, 1994). Additionally, the reduced permeability in finer sediments restricts the oxygen mobility, thus reducing the oxidation of organic matter. Therefore, the coarser grain size is responsible for the reduced %C_{org}, despite of the higher productivity during the Greenlandian. The low sea-stand during the Greenlandian (~80 m) (Vaidyanadhan and Prudhvi Raju, 2000; Banerjee, 2000; Loveson and Nigam, 2019), would imply completely exposed continental shelf and thus debouching of the riverine influx, including the coarse fraction relatively closer to the core site. Both the CaCO₃ and coarse fraction were high during the Greenlandian, as compared to the rest of the Holocene. The increased CaCO₃ during the Greenlandian is inferred as an interval of higher productivity.

A significant increase in %C_{org} is observed throughout the Northgrippian. A relatively low abundance of *G. bulloides* suggests that this increase in %C_{org} during the Northgrippian was not modulated by the upwelling. The C_{org}/TN was at a minimum during the early Northgrippian (~7500 yr BP) as compared to the early Greenlandian, suggesting reduced terrigenous contribution as compared to the late Greenlandian. Barring a minor increase in the early part, C_{org}/TN was relatively stable during the larger part of the Northgrippian (~7000 to ~5000 yr BP), suggesting a similar source of organic matter. It is likely that a part of the increased organic matter during the Northgrippian was the result of higher convective mixing during the boreal winter monsoon season (Kumar et al., 2004). However, the terrestrial organic matter component was still dominant as evident from the C_{org}/TN being ~12. Additionally, the persistent increase in C_{org} during the Northgrippian can also be attributed to its better preservation in relatively finer grained sediments.

The organic carbon abundance decreased significantly during the Meghalayan, from being ~2.2% during the early Meghalayan to the lowest of ~1.1% during the recent times. Incidentally the large decrease in %C_{org} during the late Meghalayan is concomitant with a large increase in CaCO₃. The decrease in %C_{org} was synchronous with a huge decrease in C_{org}/TN, suggesting increased contribution by marine derived organic matter. Although, we do not find any linear increasing or decreasing trend, the relative abundance of *G. bulloides* was higher than that during the Northgrippian. Therefore, the decrease in %C_{org} during the Meghalayan was not because of the reduced upwelling and consequent low productivity. It is likely that the water at the sediment-water interface were well oxygenated leading to increased oxidation of the organic matter. The presence of well oxygenated waters is supported by a better preservation of CaCO₃, as well. A small but gradual increase in coarse fraction is also observed during the late Meghalayan, except the core top section. The relatively coarser fraction facilitated organic matter oxidation. A change in coarse fraction similar to that during the

Greenlandian is not expected due to the complete inundation of the continental shelf throughout the Meghalayan. The prominent increase in C_{org}/TN at ~1000 yr BP is inferred as an increase in terrestrial input in the central-western Bay of Bengal. Owing to the vicinity of the core location to the Pennar river outfall, it is expected that the increase in freshwater influx is a result of increased precipitation.

Overall, we suggest that C_{org} flux was mostly influenced by the terrestrial input in the central-western Bay of Bengal, as C_{org}/TN was >11 during more than 90% of the last 12,000 yr BP. However, during the Northgrippian, although the organic carbon peaked, from the decreased C_{org}/TN ratio it is evident that the organic matter was marine derived rather than being supplied by the terrestrial flux. Further, the $CaCO_3$ content shows an opposite trend with C_{org} (Figure 4) which indicates that fluctuation in organic matter may not be a controlling factor for the decrease in calcium carbonate and that the burial and hence preservation of $CaCO_3$ through rapid sedimentation is higher. Incidentally, the general trend in % C_{org} during both the Northgrippian as well as Meghalayan closely follows the average trend in sunspot numbers (Figure 6), suggesting a strong solar modulation of the organic carbon burial in the central-western Bay of Bengal.

4.3 Regional precipitation-evaporation changes

The $\delta^{18}O$ in the marginal seas with riverine influx, is mainly modulated by ice-volume, ambient temperature and fresh-water influx. The correction of planktic foraminiferal $\delta^{18}O$ for the ambient temperature and global ice volume contribution, leaves the signatures of local evaporation-precipitation changes ($\delta^{18}O_{sw-ivc}$) (Saraswat et al., 2012). The decrease in $\delta^{18}O_{sw-ivc}$ during the early Greenlandian clearly suggests increased fresh water runoff. The decrease in $\delta^{18}O_{sw-ivc}$ during the Greenlandian was 1.33‰ (from the highest of 0.75‰ at ~ 11,620 yr BP to the lowest of -0.57‰ at ~8600 yr BP). Considering the regional seawater salinity and $\delta^{18}O_{sw}$ relationship in the Bay of Bengal (Delaygue et al., 2001), this change in $\delta^{18}O_{sw-ivc}$ is equivalent to ~7.4 psu decrease in salinity. However, this salinity estimate should be taken with a caution as the seawater salinity- $\delta^{18}O_{sw}$ relationship in the Bay of Bengal, varies regionally, as well as seasonally (Achyuthan et al., 2013). Thus the Greenlandian is inferred as the interval of increased precipitation and intense upwelling. A general freshening with reduced salinity during the Holocene, as compared to the glacial interval, has previously been reported from the Bay of Bengal (Kudrass et al., 2001; Chauhan & Vogelsang, 2006; Rashid et al., 2007; 2011; Govil & Naidu, 2011). The increased chemical weathering from the deglacial to mid-Holocene reported from the Indian Ocean (Miriyyala et al., 2017), further supports the increased runoff during this interval. However, following the initial linear increase, the monsoon was stable during the mid-Greenlandian, with minor small scale fluctuations, as evident from a relatively stable $\delta^{18}O_{sw-ivc}$.

The lowest $\delta^{18}\text{O}_{\text{sw-ivc}}$ was during the early Northgrippian, suggesting increased precipitation/runoff. The subsequent increase in $\delta^{18}\text{O}_{\text{sw-ivc}}$ during the later part of the Northgrippian clearly suggests a reduced precipitation/runoff. The increased $\delta^{18}\text{O}_{\text{sw-ivc}}$, infact, begins by mid to later part of Northgrippian. Paleo-records from both the terrestrial and marine archives suggest a relatively warmer climate during the mid-Holocene transition, which represents the early part of Northgrippian with an enhanced precipitation (deMenocal et al., 2000; Roberts et al., 2011; Saraswat et al., 2016). Overall, our datasets also suggest a similar signature with the decreasing trend in $\delta^{18}\text{O}_{\text{sw-ivc}}$ from the Greenlandian continuing till ~ 7000 yr BP, where it is depleted the maximum. The enrichment in $\delta^{18}\text{O}_{\text{sw-ivc}}$ is seen more significantly only after the early Northgrippian, representing weakened precipitation. The $\delta^{18}\text{O}_{\text{sw-ivc}}$ is the most enriched during the later part of Meghalayan with a significantly enriched value of 1.57‰ at ~ 840 yr BP. The change in $\delta^{18}\text{O}_{\text{sw-ivc}}$ during the Meghalayan was 1.91‰ (lowest of -0.33‰ at ~ 3680 yr BP to the highest of 1.57‰ at ~ 840 yr BP). The $\delta^{18}\text{O}_{\text{sw-ivc}}$ was low during the beginning of Meghalayan, indicating increased precipitation. We suggest that the beginning of Meghalayan was relatively wetter as compared to the later part, where a visible increase in $\delta^{18}\text{O}_{\text{sw-ivc}}$ indicates a gradual weakening of monsoon.

4.4 Periodic change in productivity and associated parameters

We observed several prominent short term variations superimposed on the long term increasing or decreasing trend in many of the proxies. Therefore, we analysed the proxy data for the presence of any significant short-term periodic changes. Such short-term periodic changes should, however, be considered cautiously due to the error associated with the chronology. The cyclicity in our faunal and geochemical datasets show a close resemblance to the periodicity in sunspot numbers (227, 210, 149, 138, 128, 104 years) inferred from radiocarbon ($\Delta^{14}\text{C}$) variations in tree rings (Stuiver and Brazuinas, 1993; Solanki et al., 2004) (Figure 5, 6). The 200 year Seuss cycle (Stuiver and Brazuinas, 1993) has also been an important cycle linked to solar variations and described by many as a possible forcing mechanism for monsoon (Fleitman et al., 2003; Gupta et al., 2005; Tiwari et al., 2005; Rana and Nigam, 2009; Thamban et al., 2007; Suokhrie et al., 2018; Azharuddin et al., 2019). The centennial periodicities in our dataset are a resemblance to the 200 year cyclicity. Further, the sedimentary data and the stable isotope data show a distinct cycle of ~ 87 years in addition to 150 and 250 years cyclicity (Figure 5) which is a resemblance to the Gleissberg cycle (Nigam et al., 1995; Panchang et al., 2012). We suggest and support that the solar forcing has a possible linkage to the precipitation changes in the western Bay of Bengal and this is also supported by previous datasets from the Indian subcontinent.

5 Conclusion

The upwelling intensity and carbon burial during the last 12,000 yr BP varied significantly in the central-western Bay of Bengal. The intense upwelling during the Greenlandian and Meghalayan was in contrast with the weaker upwelling during the Northgrippian. The opposite trend in organic carbon and upwelling intensity suggests a decoupling of primary productivity from the upwelling of nutrient enriched waters in the central-western Bay of Bengal. The Greenlandian, and Northgrippian were a phase of strengthened precipitation and/or runoff as indicated by the depleted isotopic signatures. The precipitation/runoff decreased rapidly during the Meghalayan, beginning with a prominent drier phase at ~4200 yr BP. The preservation of CaCO₃ in the central-western Bay of Bengal indicates stronger influence of the rapid sedimentation rate and not necessarily increased productivity over the studied time period. Our productivity proxy records also reveal notable cyclicities with high significance at centennial scales (153, 183, 210 years for *G. bulloides* and 87, 150 and 255 years for the sedimentary and isotopic datasets). The periodicities in marine datasets correspond to the solar cycles and hence suggest that precipitation changes in the central-western Bay of Bengal are possibly linked to variations in solar intensity.

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Legend to Figures and Tables

- Figure 1: Location map with salinity contours. SK308 GC02 is highlighted as a red dot.
- Figure 2: Age-depth profile of SK308 GC02. The sediment accumulation rates (cm/kyr) have been plotted assuming linear sedimentation between the dated intervals.
- Figure 3: Down-core variation in coarse fraction (CF), total carbon (TC), total inorganic carbon (TIC), organic carbon (C_{org}), and C_{org}/TN in the core.
- Figure 4: Variation in relative abundance and 3-point running average of *Globigerina bulloides*, and the stable oxygen isotopic ratio ($\delta^{18}O_{G.ruber}$) of surface dwelling planktic foraminifera *Globigerinoides ruber*.
- Figure 5: The time-series plot of a. *Globigerina bulloides*, b. $CaCO_3$, c. coarse fraction (CF), d. organic carbon (C_{org}), e. C_{org}/TN and f. $\delta^{18}O_{sw-ivc}$. The cyclicities which show >90% significance have been marked.
- Figure 6: Comparison of the relative abundance and 3-point moving average of *Globigerina bulloides* and the environmental parameters ($CaCO_3$, C_{org} , C_{org}/TN , $\delta^{18}O_{sw-ivc}$) in the western Bay of Bengal, with the sunspot numbers (Solanki et al., 2004), during the Holocene.
- Table 1: Details of Accelerator Mass Spectrometer radiocarbon dates.

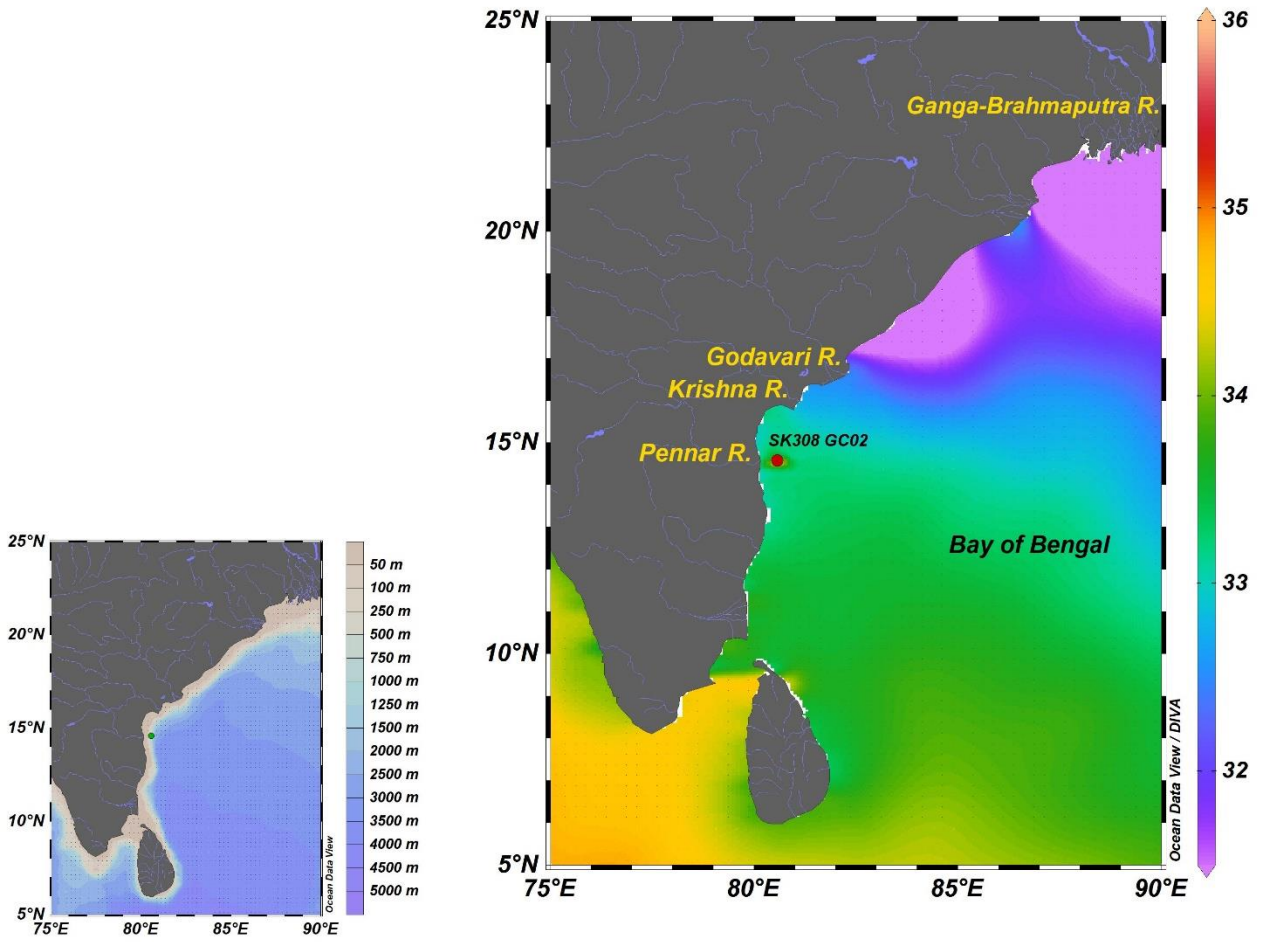


Figure 1

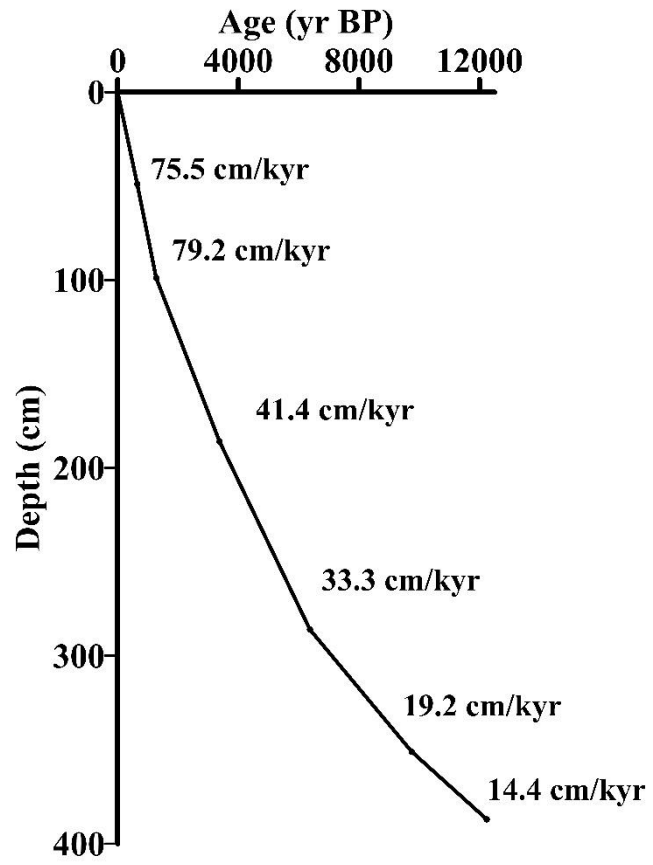


Figure 2

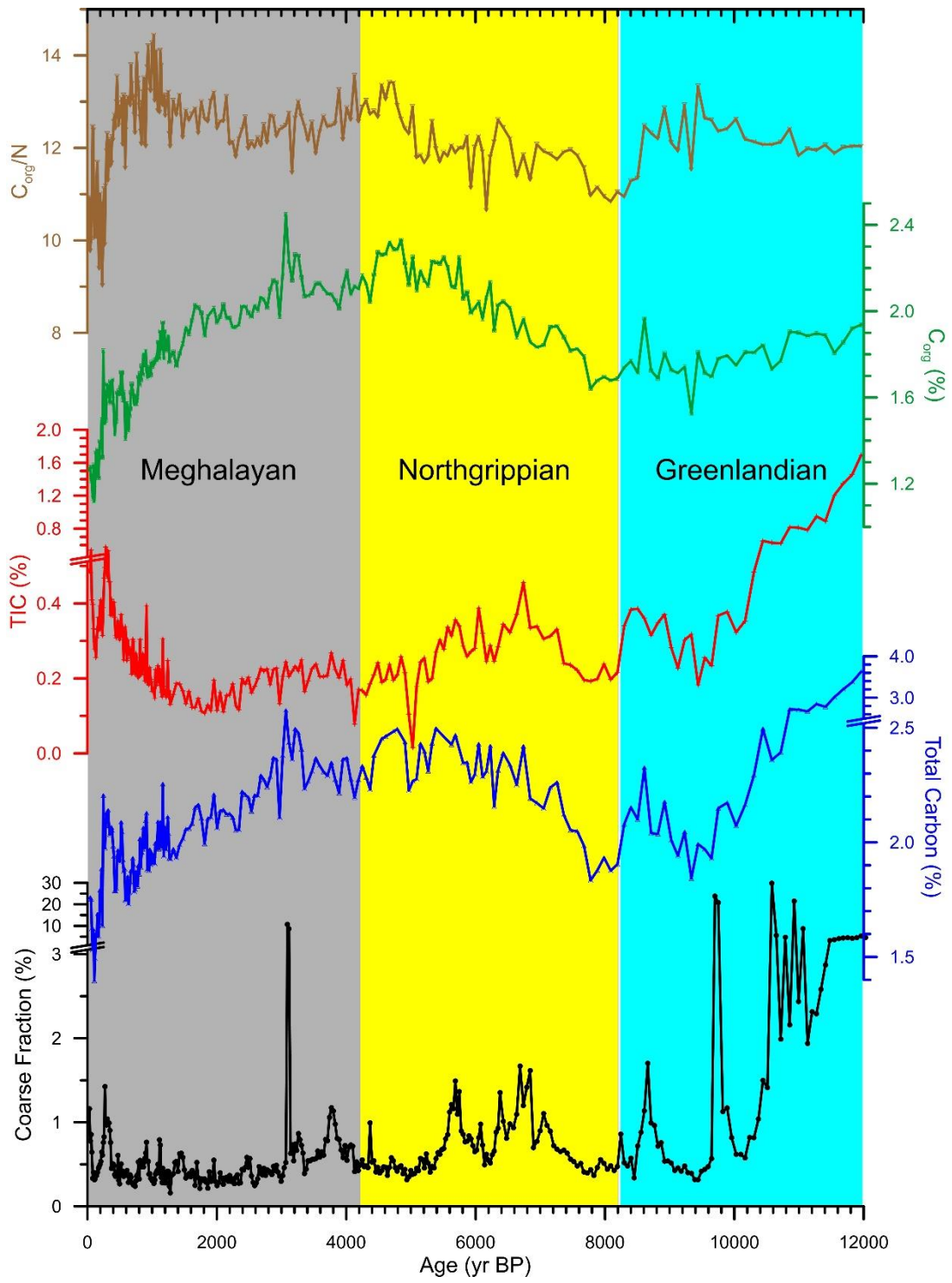


Figure 3

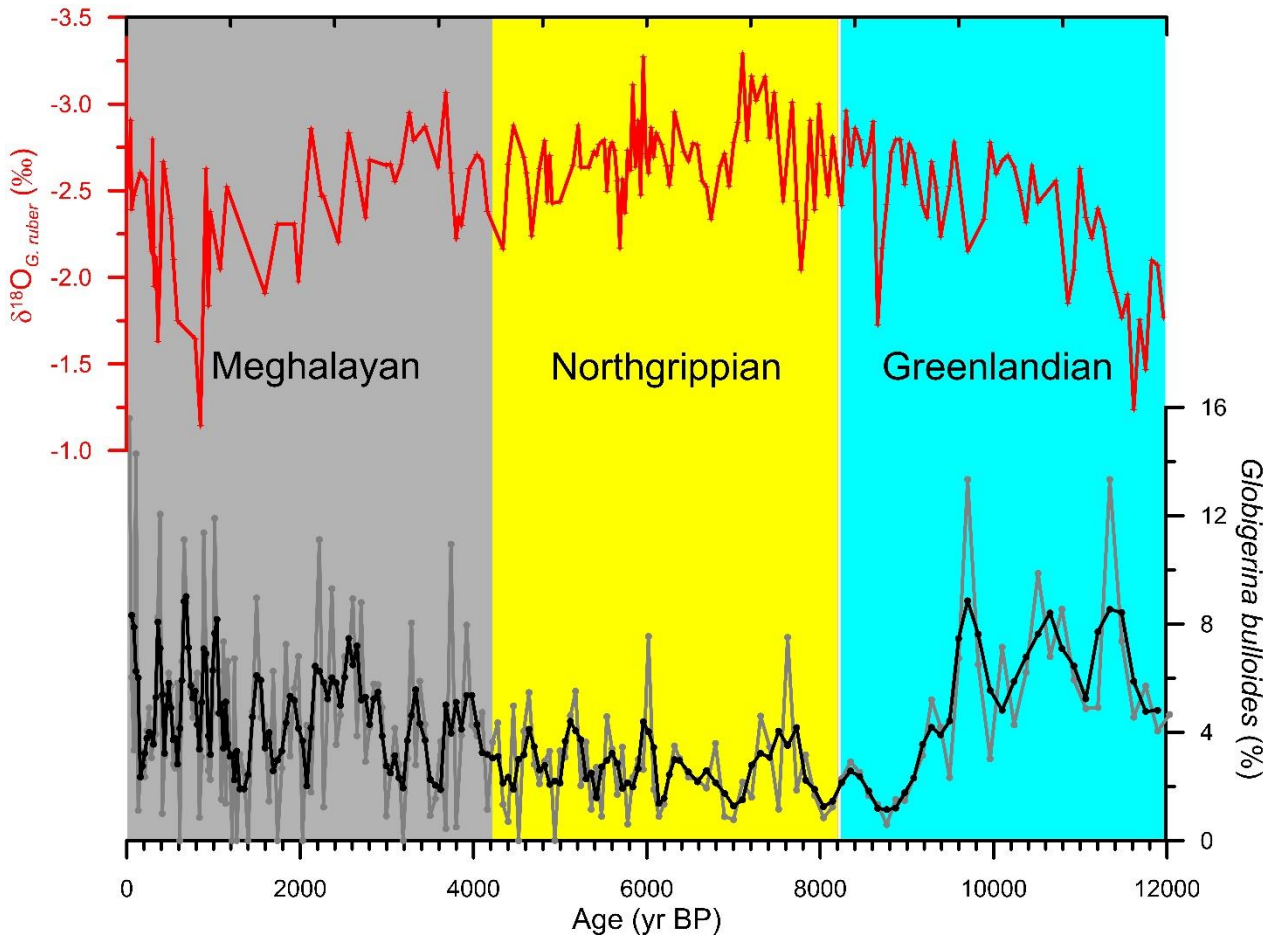


Figure 4

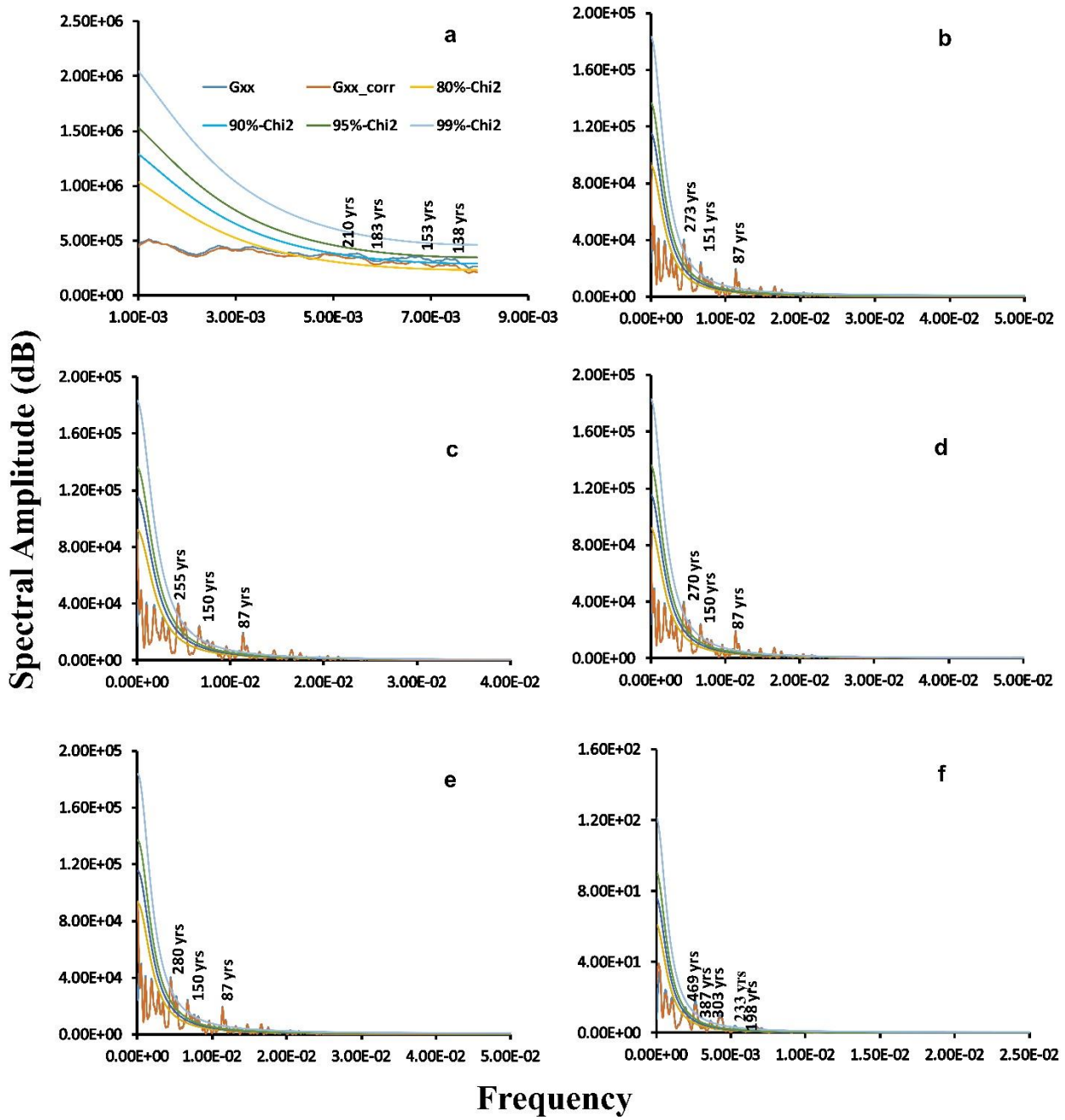


Figure 5

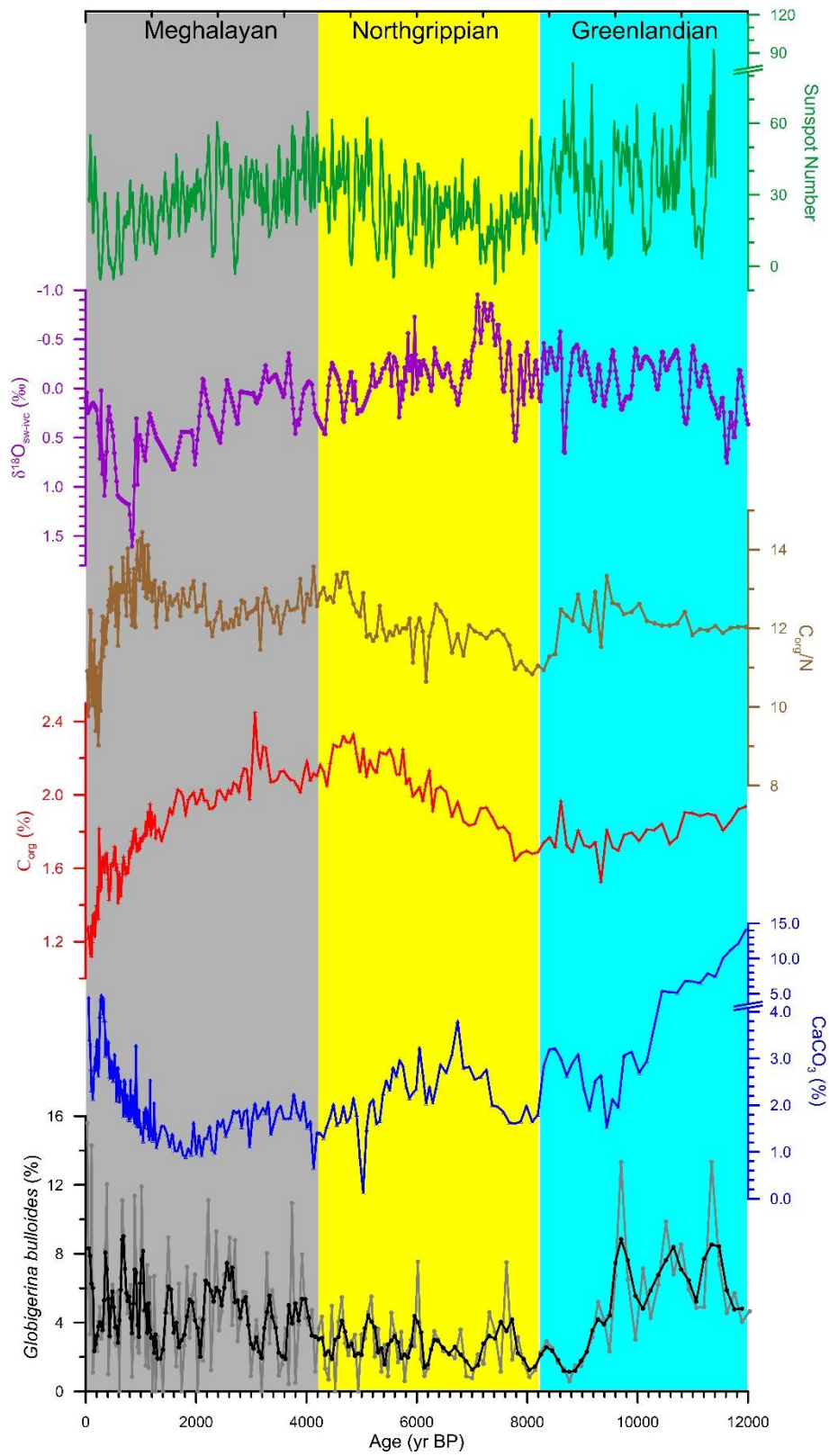


Figure 6

Table 1: Details of Accelerator Mass Spectrometer radiocarbon dates.

Lab Code	Sample Interval (cm)	Depth (cm)	¹⁴C Age (yr BP)	Calibrated Age (Median Probability) (yr BP)	Sed Rate (cm/kyr)
UGAMS23864	48-50	49	1170	649	75.5
UGAMS23865	98-100	99	1830	1280	79.2
UGAMS23866	185-187	186	3610	3381	41.4
X30562	285-287	286	6058	6377	33.4
IUAC	351-352	351	9120	9752	14.4
X30563	387-388	387	10951	12236	17.2

Table 1