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Research paper

Late Pleistocene to Holocene productivity changes in the western equatorial Pacific (Sulu Sea, Philippines) from calcareous nannofossils

Deborah N. Tangunan[a,b,*], Alyssa M. Peleo-Alampay[b]

[a] University of Bremen, MARUM Center for Marine Environmental Sciences, 28359 Bremen, Germany
[b] National Institute of Geological Sciences, University of the Philippines, 1101 Quezon City, Philippines

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ABSTRACT

We present a new calcareous nannofossil paleoproductivity reconstruction of the southeastern margin of the Sulu Sea to understand how marine productivity varied through time in one of the major fishing grounds of the Philippine archipelago. The study is based on two sediment cores obtained from two different hydrographic locations in the western equatorial Pacific region: an upwelling region off Zamboanga Peninsula (U-GC12) and a non-upwelling area off Panay Island (NU-GC14), covering the past 18,000 years before present (B.P.). Calcareous nannofossil assemblages in the investigated areas were of low diversity and largely dominated by *Gephyrocapsa oceanica* and *Florisphaera profunda*, followed by small placolith-bearing taxa, *Emiliania huxleyi*, small *Gephyrocapsa*, and *Reticulofenestra minuta*. Upwelling episodes off the Zamboanga Peninsula were recorded several times in the past as shown by an increase in the abundance of high productivity indicator species (*G. oceanica,* small *Gephyrocapsa, E. huxleyi)* and of bulk sediment $CaCO_3$ (%), and a concomitant decline in the total organic carbon (TOC; %). The high abundance of low surface water productivity species *F. profunda* and *Umbellosphaera irregularis* indicates a stratified water column with a deeper nutricline, probably caused by the reduced upwelling intensity. This condition was corroborated by the decrease in $CaCO_3$ (%) and an increase in TOC (%). We propose that the modern day high productivity conditions off Zamboanga Peninsula started at 2500 years B.P., whereas the low productivity off Panay Island was recorded from 4000 years B.P., and persists to the present day. Evidence of the Younger Dryas (YD) event was recorded from 11,100 to 10,400 years B.P. in U-GC12, synchronous to the YD event reported from other areas in the Northern Hemisphere, and in accordance with the timing in the Sulu Sea as reported from previous studies in this region. This event in the Sulu Sea is characterized by a decrease in total nannofossil abundance and estimated primary productivity, together with an increase in $CaCO_3$ (%) and a decrease in TOC (%). We interpreted that dilution caused by the increase in precipitation experienced in the Southeast Asian region during the YD event could have led to the decline of the total calcareous nannofossils whereas the recorded increase in $CaCO_3$ (%) is attributed to the high abundance of planktonic foraminifera during this interval.

1. Introduction

The Late Pleistocene to the Holocene is known as an interval that brought about significant changes in the Earth's climate system due to several episodes of glaciation and deglaciation events. During this time period, several remarkable global climatic events occurred, including the Last Glacial Maximum (LGM; 25,000 to 13,000 years before present; B.P.), the Late Glacial Maximum (13,000 to 10,000 years B.P.), and the present interglacial (the Holocene). The gradual climate warming toward the end of the Pleistocene was interrupted by three geologically brief and abrupt cold periods, referred to as the Oldest Dryas (18,000 to 15,000 years B.P.), the Older Dryas (13,960 to 13,090 years B.P.), and the Younger Dryas (YD; 11,280 to 10,030 years B.P.). Although these events were more pronounced in the Northern Hemisphere (NH), previous paleoceanographic reconstructions reveal that they also had major impacts in other parts of the world's oceans, including the South Pacific region (e.g., Peteet, 1995; Klitgaard-Kristensen et al., 1998; Rosenthal et al., 2003; Andres et al., 2003; Asami et al., 2009; Macleod et al., 2011). Some studies reveal that the effects of these climatic phenomena extended further south to the tropical Pacific, including the western tropical Pacific region (e.g., Oppo et al., 2003; Rosenthal et al., 2003; Asami et al., 2009). While some evidence contradicts the theory that glaciations had direct impacts on equatorial waters (e.g., Anderson and Thunell, 1993; Thunell and Miao, 1996), sea surface temperature

* Corresponding author at: University of Bremen, MARUM Center for Marine Environmental Sciences, 28359 Bremen, Germany.
E-mail address: tangunan@uni-bremen.de (D.N. Tangunan).

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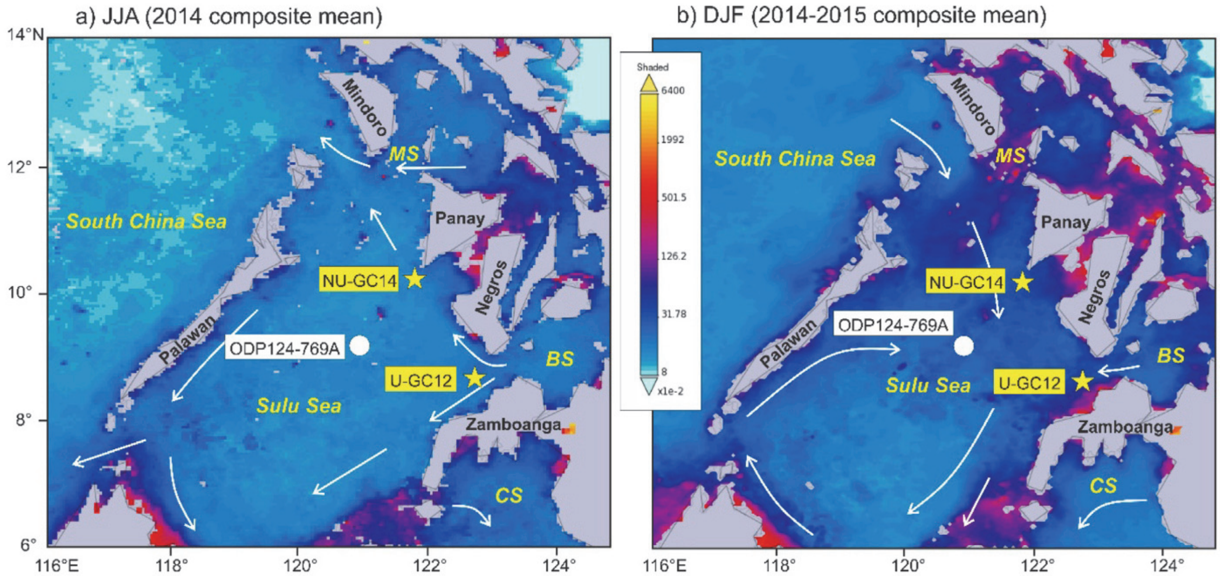

Fig. 1. Seasonal surface circulation and mean chlorophyll-*a* concentration (mg/mg^3) of the Sulu Sea during the southwest monsoon (a: June, July, August; JJA) and northeast monsoon (b: December, January, February; DJF). Yellow stars represent the locations of the investigated cores while the white circle indicates the study site of Linsley and Thunell (1990). Chlorophyll maps were generated from http://giovanni.sci.gsfc.nasa.gov/giovanni/. Sea surface currents were redrawn from Wyrtki (1961). MS = Mindoro Strait; BS = Bohol Sea; CS = Celebes Sea. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(SST) estimates from alkenones ($U^{K'}_{37}$) showed a minor cooling event that is linked to the YD in the western tropical Indian Ocean (e.g., Bard et al., 1997; Sonzogni et al., 1998; Beaufort et al., 2008), and in the northern and southern South China Sea (SCS; Pelejero et al., 1999). Furthermore, planktonic foraminiferal oxygen isotope records from the SCS (Wang et al., 1999; Steinke et al., 2001) and Mg/Ca and oxygen isotopes using *Globigerinoides ruber* from the Sulu Sea (Linsley and Thunell, 1990; Rosenthal et al., 2003) suggested that the cold tongue of the glacial events reached the smaller and secluded basins of the Indo-Pacific equatorial region, such as the SCS and the Sulu Sea. These varying climate boundary events are thought to have driven the global ocean circulation and nutrient supply, and thus, the productivity of the oceans (Jansen et al., 1986; Sarkar and Gupta, 2014). Cold periods are often marked by upwelling events promoting increased surface water productivity. Warm periods, on the other hand, lead to an increase in water column stratification and a decrease in surface water productivity (e.g., Pedersen, 1983; Flores et al., 1999; Bard and Rickaby, 2009; Etourneau et al., 2013; Jakob et al., 2016).

Aside from long-term climate events, the Asian monsoon system is one of the major climate phenomena active today influencing the weather patterns of the tropical region (Clark et al., 2000). The seasonal reversal of the wind direction due to opposite summer and winter temperature gradients between the continents and the oceans plays a pivotal role in the surface water dynamics of the equatorial region (Su et al., 2013). The East Asian Monsoon (EAM) is the dominant wind system over the Philippines, the SCS, and the rest of East Asia (Wang et al., 2001). Most of the previous works, however, focused on the dynamics of the EAM in the SCS (Wang et al., 2005; Wang, 2009; Su et al., 2013) whereas little is known about the influence of this wind system over other marginal seas, such as the Sulu Sea. These previous studies used proxies such as stalagmite isotopes (Wang et al., 2008), planktonic foraminifera assemblages (Jian et al., 2001; Yu et al., 2008), alkenone-derived SSTs (Huang et al., 2011), and calcareous nannofossil abundances (Beaufort et al., 2003; Su et al., 2013) to reconstruct the role of the EAM in the past productivity and oceanographic conditions in the SCS.

The effect of these past climate events can be deduced from microfossil analysis. In particular, coccolithophores are highly sensitive to any changes in the water column, making them important proxies for paleoceanographic reconstructions. In general, coccolithophores are single-celled marine haptophyte algae with significant contribution to the oceanic primary productivity (Winter et al., 1994). Since they are photosynthetic, coccolithophores are primarily controlled by light and nutrients, as well as by temperature, salinity, among other environmental factors. Here we examine two sediment cores collected from two different environments in the Sulu Sea, western equatorial Pacific: a high productivity, upwelling area off Zamboanga Peninsula (U-GC12) and a low productivity, non-upwelling area off Panay Island (NU-GC14) to reconstruct the past productivity variations in the two locations based on calcareous nannofossil assemblage composition and bulk sediment carbonate chemistry. The two regions offer an opportunity for us to investigate the calcareous nannofossil fluctuations from the Late Pleistocene to the present, allowing us to characterize the upwelling history of the Sulu Sea region, and to infer the long- and short-term climatic factors that drove these changes. Knowledge of these short- and long-term trends through the study of biological responses is necessary for improving the management of fish and other marine resources in the Sulu Sea, which is at present, one of the major fishing grounds of the country.

2. Study area and oceanographic setting

2.1. The Sulu Sea basin

The Sulu Sea is a semi-enclosed deep marine basin completely surrounded by island arc and continental shelf, most of which is shallower than 100 m (Fig. 1). It is bordered by Sabah to the southwest, Palawan to the northwest, Panay and Negros to the northeast, and Zamboanga to the southeast. The basin is interpreted as being formed either as a result of back-arc spreading associated with the Cagayan de Sulu Ridge or the entrapment of an old piece of oceanic crust (Rangin, 1993). The Cagayan de Sulu Sea Ridge divides the basin into the northwest sub-basin with a sedimentary fill thickness of 6 to 8 km of either volcanic and/or continental basement (MGB, 2002) and the southeast sub-basin composed of an oceanic basement covered with a thin sedimentary fill of only about 1 to 2 km thickness (Rangin, 1993).

Table 1
Radiocarbon dates and calibrated ages for U-GC12 and NU-GC14.

Core	Laboratory ID	Core depth (cm)	C^{14} age years B.P.	Error ±	Calibrated C^{14} age years B.P.
U-GC12	OS-80900	19.5	2600	30	1741
U-GC12	OS-70523	63.5	6240	45	6207
U-GC12	OS-70524	150.5	13,000	55	14,040
NU-GC14	OS-80904	50.5	1880	30	987
NU-GC14	OS-80897	105.5	2700	35	1860
NU-GC14	OS-70525	179.5	4310	40	3826

2.2. General circulation pattern

The Sulu Sea has an approximate area of 250,000 km^2, with water depths reaching up to 5000 m, and connected to the SCS, Pacific Ocean and Celebes Sea by shallower straits. It was previously thought that only the SCS waters can enter into the Sulu Sea through the Mindoro Strait (Wyrtki, 1961; Calvert et al., 1993), but more recently, Villanoy et al. (2011) suggested that deeper Sulu Sea waters are also sourced from the Sulawesi Sea via the Sibutu Strait. The Sulu Sea Basin is distinguished from the adjacent SCS for having uniformly warm water (~10 °C) and oxygen-deficient bottom waters, indicative of poorly ventilated conditions in the basin (Vollbrecht and Kudrass, 1993; Takeda et al., 2006; Norisuye et al., 2006), making it characteristically unique in comparison to other marginal seas in the western Pacific region.

The surface waters of the Sulu Sea are driven by the seasonally reversing monsoon winds (Wyrtki, 1961). During summer (June to October), when the southwest (SW) monsoon winds prevail, surface waters flow into the Sulu Sea from the SCS via the Mindoro Strait, from the Pacific Ocean through the Bohol Sea, and from the Celebes Sea (Fig. 1). On the other hand, during the winter months (December to March), when the northeast (NE) monsoon blows, upwelling occurs off the Zamboanga Peninsula. The NE-SW orientation of the coast, similar to the monsoon wind axis, provides favorable conditions for coastal upwelling to occur in this region (Villanoy et al., 2011).

2.3. Primary productivity

A study by Jones (1996) in the central area of the Sulu Sea using the Ocean Colour Temperature Scanner revealed that the typical chlorophyll-*a* concentrations in this region is in the order of 0.28 mg/m^3 or ~270 g C/m^2/yr in Behrenfeld and Falkowshi (1997), values that are relatively low compared to more productive areas of the world's oceans, such as the Arabian Sea with a chlorophyll-*a* concentration of ~400 g/C/m^2/year (Antoine et al., 1996). The coastal regions of the Sulu Sea are more productive than the adjacent South China Sea, although its central area is still considered an oceanic desert, where the primary production is just sufficient to support the current fisheries (Jones, 1996).

Upwelling-related physico-chemical water-column characteristics and elevated chlorophyll concentrations were observed in several areas in the eastern part of the Sulu Sea basin, between Mindoro and Panay, Panay and Negros, and Negros and Mindanao, especially during the stronger northeast monsoon (Villanoy et al., 2011; Fig. 1). Primary production was reported to be highest near the coastal areas of Negros and Zamboanga and eastern and southern Bohol Sea (San Diego-McGlone et al., 2008). The high chlorophyll-*a* concentration near these coasts (e.g., north of Zamboanga Peninsula) is attributed to the entrainment of the subsurface water and vertical mixing by intense tidal flow from the archipelago to the adjacent Celebes Sea due to wind-driven upwelling (Wang et al., 2006). The recorded primary production in the coastal Sulu Sea waters is 1.6 to 18 times higher than in the central regions of the Celebes, Philippine and Sulu seas (Jones, 1996). Its high chlorophyll waters in the coastal areas are dominated by chain-forming large centric diatoms indicating the importance of ocean water mixing in determining the amount of phytoplankton biomass in the area (Chen et al., 2006).

3. Materials and methods

3.1. Sample collection

Gravity cores were collected by the R/V Melville during the 2007 Joint Philippine-United States Scientific Expedition (Philippine Straits Dynamics Experiment) in Philippine inland waters. The sediment cores were taken from two sites: one from an upwelling/high chlorophyll region off Zamboanga Peninsula (U-GC12) at 2971 m water depth (8°45.1′N, 122°49.5′E) and the other from a non-upwelling/low chlorophyll area off Panay Island (NU-GC14) at 876 m water depth (10°16.3′N, 121°56.1′E; Fig. 1). The selection of the core locations was based upon the generated chlorophyll images from ocean colour satellite data obtained from SeaWiFS/MODIS averaged for the NE and SW monsoon seasons from 2004 to 2006. The sediment cores were subsampled at 1 cm intervals, with a total of 188 (U-GC12) and 177 (NU-GC14) samples, representing an average time resolution of ~100 and ~15 years, respectively.

3.2. Age model

The age model of the two cores was based on six accelerator mass spectrometry (AMS) ^{14}C analyses performed on bulk planktonic foraminifera from selected intervals out of the 250 μm size fraction (Table 1). All the ^{14}C ages were converted into calendar year B.P. using Calib 7.10 (Stuiver et al., 1993) with Marine13 calibration curve (Reimer et al., 2013). A reservoir age correction of 447 years (± 70 years) was estimated from the closest calibration point (Southon et al., 2002) in the Sulu Sea.

3.3. Calcareous nannofossil analysis

Slides were prepared following the settling technique used for slide preparation by Beaufort (1991). Calcareous nannofossils were then identified and counted with a 1000× magnification Carl Zeiss Axioplan research microscope. Species identification was based upon Hine and Weaver (1998), Young (1998), Jordan et al. (2004) and the electronic guide to the biodiversity and taxonomy of calcareous nannoplankton (Nannotax 3; http://www.mikrotax.or/Nannotax3/). A semi-quantitative estimate of species preservation similar to the preservation criteria of Flores and Marino (2002) was performed during identification and counting. Good preservation refers to little or no evidence of carbonate dissolution, with all diagnostic features fully identifiable. Moderate preservation means that the main morphological characteristics are partially altered but the specimens can still be recognized to the species level, and poor preservation is characterized by strong alteration (dissolution, fragmentation), hindering identification of the specimen to the species or even to the genus level.

The Shannon index (H) for diversity was calculated with the Paleontological Statistics Software (PAST) with values varying from 0 for communities with a single taxon to high values for communities with many taxa (Hammer et al., 2001). Coccolith abundance was calculated using the formula: Coccolith abundance = (D*n)/(d*g*v), with D = diameter of the petri dish (mm); g = weight of sediment (g); n = number of coccoliths; v = number of FOV; and d = diameter of field of view (FOV; mm). Counts were reported as number of coccoliths per gram of sediments (cc/g sed.). Estimated primary production (PP) expressed in g C/m^2/yr was estimated from the relative abundance (%) of *Florisphaera profunda* using the following formula by Beaufort et al. (1997): PP = 617 − (279*log (% *F. profunda* + 3)).

3.4. Bulk sediment geochemistry

The amount of calcium carbonate ($CaCO_3$) in the sediments was determined following the carbonate bomb method of Müller and Gastner (1967). A small amount (1–2 g) of oven-dried sediments and a flask with 6 ml of 5% hydrochloric acid (HCl) was placed inside the carbonate bomb. The sediments were then allowed to react with the HCl by shaking the carbonate bomb. The $CaCO_3$ content was computed using the reading on the pressure gauge and the calibrated pure $CaCO_3$.

Sediments for the total organic carbon (TOC) analysis were treated overnight with 6 N HCl to guarantee complete removal of the non-organic carbon binding with the carbonates. The remaining acid was washed from the sediments using distilled deionized water until the waste water becomes neutral. The sediments were then oven-dried at 60 °C for two days and were analyzed for TOC using a LECO 752–100 EC-12 carbon determinator. The TOC was measured through loss of infrared radiation and expressed in percentages.

4. Results

4.1. Chronology and sedimentation rates

Results of the AMS ^{14}C dating show that the ~2 m-long core off Zamboanga Peninsula (U-GC12) spans the period from the Late Pleistocene to the Holocene while the core off Panay Island (NU-GC14) only covers the late Holocene. The two cores comprise a record of hemipelagic sediments down to ~18,000 years B.P. and ~4000 years B.P., for U-GC12 and NU-GC14, respectively, both characterized by yellowish to greenish gray to gray, foraminifera-bearing nannofossil ooze, with varying amounts of terrigenous silt and clay. The sedimentation rate off the Zamboanga Peninsula (U-GC12) is relatively stable throughout the studied time period (Fig. 2d), with a sedimentation rate of 11.1 cm/kyr from the bottom of the core (~18,000 years B.P.) to ~ 6200 years B.P., and decreasing to 9.9 cm/kyr toward the present. By contrast, a higher sedimentation rate is recorded off Panay Island (NU-GC14, Fig. 2a). A sedimentation rate of 37.6 cm/kyr is recorded from the bottom of NU-GC14 (~4000 years B.P.) to ~1800 years B.P., and increasing to 63.0 cm/kyr toward the present day.

4.2. Calcareous nannofossil species diversity and relative abundance

In general, calcareous nannofossil assemblages in the studied Sulu Sea cores are characterized by moderate to relatively low species diversity (Fig. 2b and e), consisting of few to abundant cosmopolitan forms, such as the gephyrocapsids (*Gephyrocapsa oceanica,* small *Gephyrocapsa*), *Emiliania huxleyi*, and *Reticulofenestra minuta* (e.g., Winter and Martin, 1990; Brand, 1994; Winter et al., 1994), and by few to common subtropical to tropical species (*Calcidiscus leptoporus, F. profunda*, *Helicosphaera carteri, Umbilicosphaera* spp., *Umbellosphaera tenuis*) (e.g., Honjo and Okada, 1974; Winter and Martin, 1990) (Fig. 2c and f). Species that have a preference for cooler waters (*Coccolithus pelagicus*) (e.g., Winter et al., 1994; Molfino and McIntyre, 1990; Baumann et al., 2000; Baumann and Freitag, 2004) and warmer temperature (*Discoaster* spp., *Sphenolithus abies*) (e.g., Gibbs et al., 2004; Schueth and Bralower, 2015) also occurred in the samples as reworked forms. Generally, calcareous nannofossils are moderately- to well-preserved throughout the studied time interval.

The Shannon Diversity Index (H) calculated for both cores ranges from 0.6 to 1.9. A relatively stable diversity occurred from ~18,000 to ~2550 years B.P. in U-GC12 (Fig. 2e). Diversity gradually declines and reaches a minimum between ~2000 and ~ 1850 years B.P. This low diversity in U-GC12 coincides with one of the highest peaks of *G. oceanica* in this core (Fig. 2f) and high diversity in NU-GC14 (Fig. 2b). Calcareous nannofossil diversity in U-GC12 slightly increases from ~1850 years B.P. toward the present, but remains low (mean = 1.1) in comparison to NU-GC14 (mean = 1.6), and to the older part of U-GC12.

On average, 21 species and species groups were identified in both cores although the assemblage is almost entirely dominated only by *F. profunda* and *G. oceanica*, which together vary from 55 to 93% in NU-GC14 and from 49 to 93% in U-GC12. In both cores, the most abundant species is *G. oceanica* with a mean relative abundance of 35% in NU-GC14 (Fig. 2c) and 52% in U-GC12 (Fig. 2f), followed by *F. profunda* with a mean relative abundance of 34% in NU-GC14 and 19.9% in U-GC12. *Reticulofenestra minuta* is the third most abundant species (8% mean relative abundance) recorded in NU-GC14, followed by *E. huxleyi* (6.9%), and small *Gephyrocapsa* (6.7%). On the other hand, *E. huxleyi* has a mean relative abundance of 8.2% in U-GC12, followed by *Reticulofenestra minuta* (6.2%) and small *Gephyrocapsa* (5.5%). Over the past 4000 years B.P., a notably higher *G. oceanica* mean relative abundance (62.9%) occurred in U-GC12 than in NU-GC14 (35.1%) (Fig. 2c and f) and higher *F. profunda* mean relative abundance in NU-GC14 (34.0%) than in U-GC12 (16.5%).

A number of species recording very low abundances, including *C. pelagicus*, *Ceratolithus cristatus*, *C. telesmus*, *G. muellerae*, *G. caribbeanica*, *Rhabdosphaera clavigera*, *Syracosphaera lamina*, and *U. irregularis* were grouped together as “other species”. This group shows minor but consistent contribution to the assemblages, usually comprising less than 5% of the total assemblages. Their distribution did not yield any consistency or regularity in the pattern, from which an interpretation could be made with regards to productivity.

4.3. Downcore abundances of paleoproductivity indicator species

The most abundant species in U-GC12 off Zamboanga Peninsula covering the last 18,000 years B.P. is *G. oceanica*, with a mean absolute concentration of 540 × 10^6 cc/g sed. (Fig. 3d). This species exhibits high amplitude variability throughout the record, reaching a maximum concentration of 945 × 10^6 cc/g sed. at ~16,900 years B.P. and a minimum of 192 × 10^6 cc/g sed. at ~14,700 years B.P. A decline in the absolute concentration of this species is recorded from ~10,900 to ~8800 years B.P. This is followed by peak abundances from ~8800 to ~7200 years B.P., ~6200 to ~5500 years B.P., and at ~4400 years B.P. Following these peaks, *G. oceanica* registers a consistently reduced concentration, with low amplitude change from ~4400 toward the present.

The variations in *G. oceanica* concentrations show a relatively strong negative correlation with the species *F. profunda* in U-GC12, except for the last 4000 years B.P., when both generally decrease toward the present (Fig. 3i). *Florisphaera profunda* shows a much lower absolute concentration in this core, with a minimum value of 2.5 × 10^6 cc/g sed. at ~1400 years B.P. and a maximum of 743 × 10^6 cc/g sed. at ~9300 years B.P. (Fig. 4b). Distinct minima of low abundances of this species are observed from ~15,000 to ~12,200 years B.P., ~8000 to 6800 years B.P., and almost completely disappeared in the core from ~2500 to the present day.

The species *E. huxleyi* exhibits a highly variable pattern in absolute concentrations with a mean of 94 × 10^6 cc/g sed. in U-GC12. Its maxima appear from ~13,200 to ~13,100 years B.P. and at ~5900 years B.P. whereas the minima are recorded at ~10,600 years B.P. and ~9900 years B.P. (Fig. 4a). Similar to *G. oceanica*, this species registers a consistently low abundance from ~4400 years B.P. toward the present.

Small *Gephyrocapsa* and *R. minuta* follow a slightly similar trend over the last ~18,000 years B.P. in U-GC12, both showing a generally decreasing pattern toward the present day (Fig. 4c and e). *Umbellosphaera* spp. comprising *U. irregularis* and *U. tenuis* display an analogous pattern with *F. profunda* (Fig. 4f). *Umbilicosphaera sibogae* and “other species” show a highly variable pattern, with the latter observed to show a decreasing trend toward the present starting at ~6200 years B.P. (Fig. 4g and h).

Comparison of the two investigated cores revealed the same

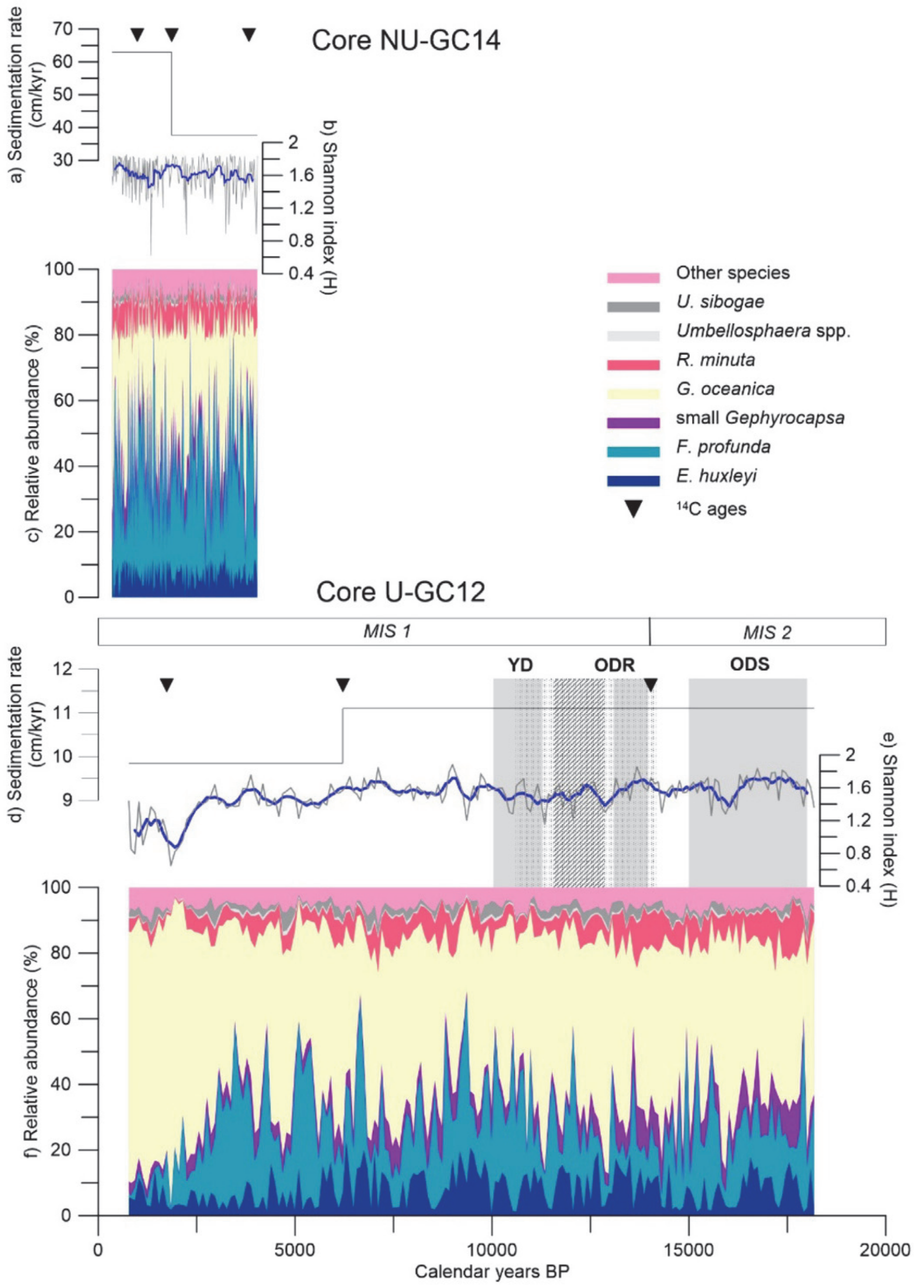

Fig. 2. Paleoceanographic records of the Sulu Sea over the last 18,000 years B.P. from NU-GC14 (a, b, c) and U-GC12 (d, e, f): sedimentation rates (a, d), Shannon diversity indices (H; b, e), and relative abundance of all calcareous nannofossil species (c, f). Carbon-14 ages are marked by triangles. Gray bands represent the Younger Dryas (YD), Older Dryas (ODR), and Oldest Dryas (ODS) events recorded in the Northern Hemisphere while the dotted pattern (Hong et al., 2010) and diagonal lines (Ma et al., 2012) correspond to the timing of these events in the South Pacific region. MIS = Marine Isotope Stage.

dominant taxa over the last ~4000 years B.P., with greater counts of *G. oceanica* and low counts of *F. profunda* in the core off Zamboanga Peninsula (U-GC12) compared to low *G. oceanica* and high *F. profunda* counts in the core off Panay Island (NU-GC14) (Fig. 5). In NU-GC14, the highest concentration of *G. oceanica* occurs at ~3300, ~2900, and ~ 1500 years B.P., with a maximum abundance of 755 × 10^6 cc/g sed. at ~3300 years B.P. (Fig. 5l). These peaks in *G. oceanica* abundance are associated with low concentrations of *F. profunda* at NU-GC14. On the other hand, several peaks in the record of *F. profunda* are observed at ~3800, ~ 3500, ~3000, ~ 2400 years B.P., and a highest concentration of 805 × 10^6 cc/g sed. at ~800 years B.P. (Fig. 5b). The small placolith-bearing species, *E. huxleyi*, small *Gephyrocapsa*, and *R. minuta* significantly contributed to the total calcareous nannofossil concentrations in the study area off Panay (Fig. 5a, c, and e) compared to the area off Zamboanga Peninsula.

5. Discussion

5.1. Paleoproductivity in the Sulu Sea over the last 18 kyr

Calcareous nannofossil species identified in the Sulu Sea cores are typical of the assemblages observed in other Philippine inland and marginal seas, with *G. oceanica*, *F. profunda*, *E. huxleyi*, small *Gephyrocapsa*, and *R. minuta* comprising most of the total assemblage (e.g., Peleo-Alampay et al., 2002). The overall low calcareous nannofossil diversity in the study area can be explained by the preference of coccolithophores for a more open marine environments, whereas only few species proliferate in marginal seas and inland bodies of water

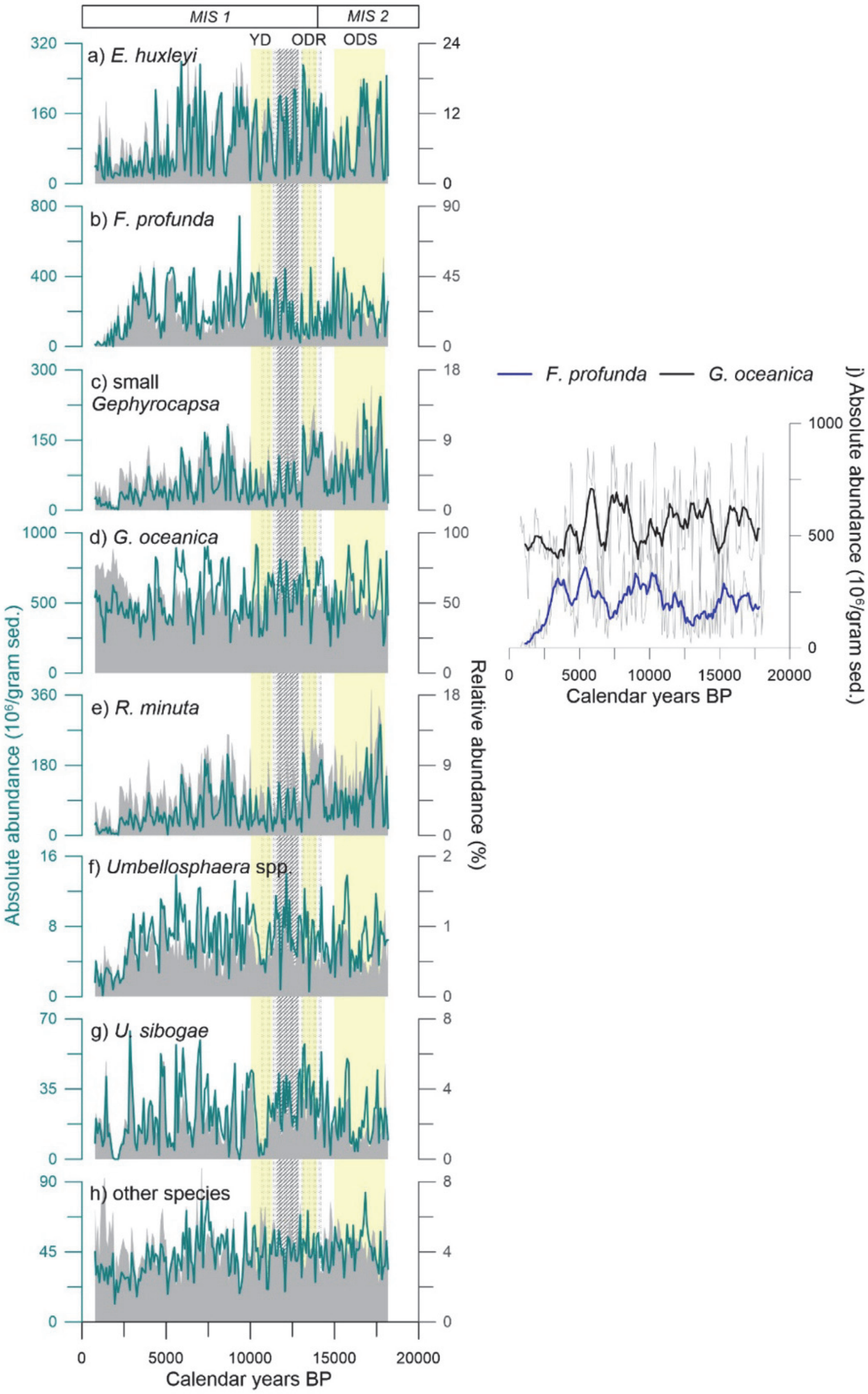

Fig. 3. Absolute (green) and relative (gray) abundances of calcareous nannofossil species in U-GC12 over the past 18,000 years B.P. (a to h). Also shown is a comparative plot between *F. profunda* and *G. oceanica* (i). Gray bands represent the Younger Dryas (YD), Older Dryas (ODR), and Oldest Dryas (ODS) events recorded in the Northern Hemisphere while the dotted pattern (Hong et al., 2010) and diagonal lines (Ma et al., 2012) correspond to the timing of these events in the South Pacific region. MIS = Marine Isotope Stage. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Winter et al., 1994; Fernando et al., 2007; Alvarez et al., 2010). This low diversity is in accordance with findings from previous coccolithophore studies in coastal regions where the assemblage is commonly dominated by opportunistic species such as *Gephyrocapsa* spp. and *E. huxleyi* (e.g. Peleo-Alampay et al., 2000; Baumann and Freitag, 2004; Alvarez et al., 2010; Guerreiro et al., 2015a; Stolz et al., 2015).

Increased abundances in total nannofossil concentrations are observed from 18,000 to 17,700 years B.P., 13,900 to 13,100 years B.P., and 10,000 to 6000 years B.P., coinciding with low surface water productivity as inferred from the estimated primary productivity (PP) values (Fig. 5f). Consequently, a decline in the total nannofossil concentrations coincided with high productivity peaks as shown by the estimated PP from 14,500 to 12,500 years B.P. (Fig. 5e), coinciding with the ODR cold period from 14,200 to 10,600 years B.P. in the South Pacific region (Hong et al., 2010). A general increase in the total nannofossil concentration occurs from 12,500 to 11,500 years B.P., concurring with the Bølling-Allerød, a warming period preceding the YD. During the Bølling-Allerød, a decline in the estimated PP and in TOC, and increasing $CaCO_3$ contents are observed. This indicates that the total nannofossil concentrations could not be used as an adequate proxy to decipher the variations in paleoproductivity in the Sulu Sea coastal region; individual species abundances (e.g., *G. oceanica*, *F. profunda*) show a more reliable productivity trend. A study by Guerreiro et al. (2015b) in a coastal-neritic environment off Portugal showed a greater

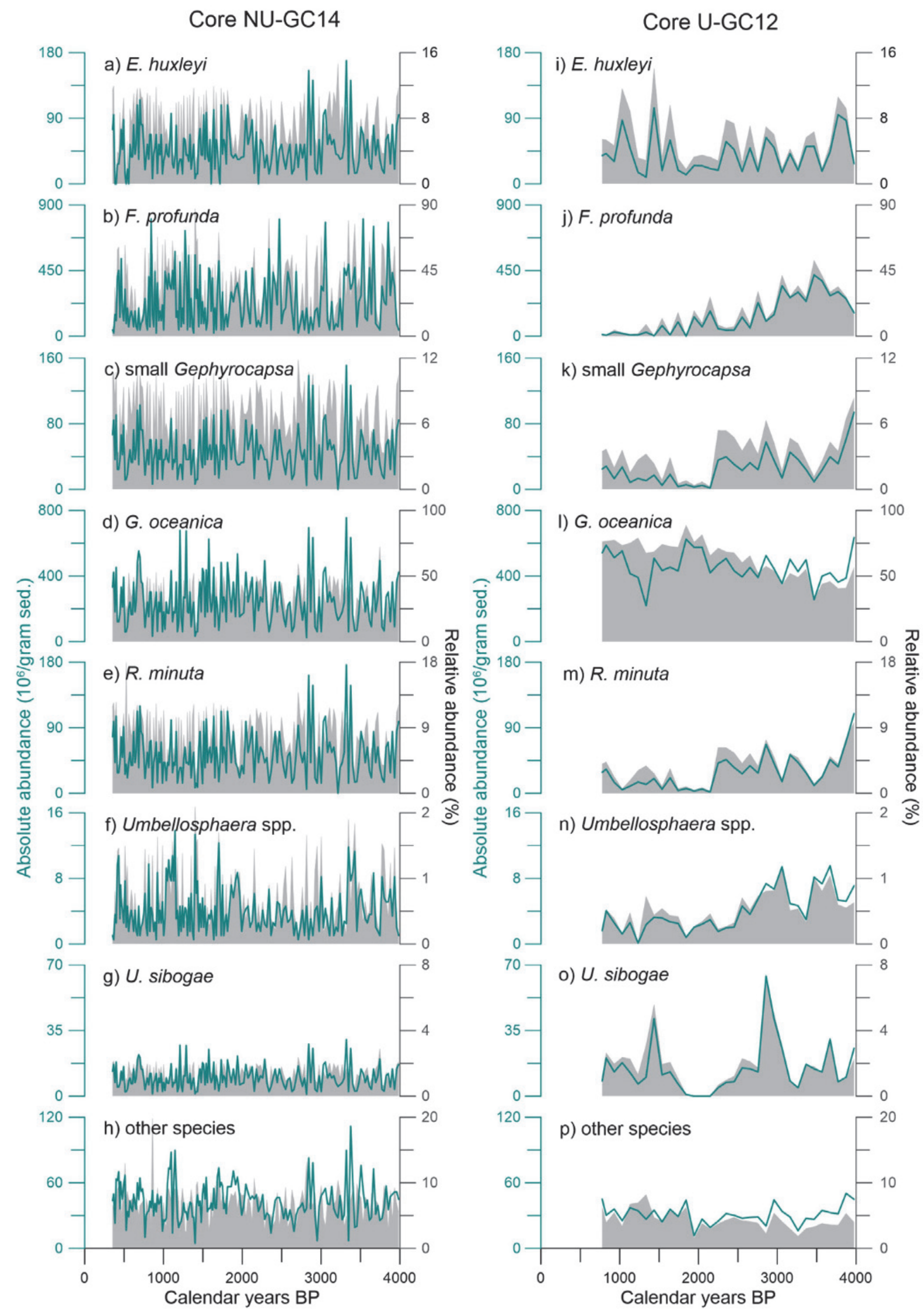

Fig. 4. Absolute (green) and relative (gray) abundances of calcareous nannofossil species in cores NU-GC14 and U-GC12 over the past 4000 years B.P. (a to p). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

influence of taphonomy in the nannofossil concentrations toward the coast, suggesting the inefficacy of the nannofossil concentrations as paleoecological proxies in such a highly dynamic setting.

Results of this study were also compared with the EAM system, a tropical monsoon driving the sea surface currents of the SCS and the East Asia, including the Sulu Sea (Wang et al., 1999). This monsoon is characterized by strengthened intensities during the winter and the summer in the SCS leading to high precipitation and increase in fluvial runoff from southern China. The strong influence of the EAM system in the Sulu Sea is evident from 15,000 to 11,000 years as observed in the increased estimated PP, and even more intensified from 3000 years B.P. to the present. Total coccolith concentrations started to generally decline at 6000 years B.P., when *G. oceanica* was the only main contributor to the counts.

From 4000 years B.P., estimated PP from the *F. profunda* relative abundance shows a similar pattern with the total abundances for both U-GC12 and NU-GC14 cores (Fig. 6). Estimated PP remains lower than the average modern PP in the central Sulu Sea, although a slight increase is observed at ~700 years B.P. in core NU-GC14. This relatively low estimated PP, matching with low and stable TOC (%), indicates the prevalence of low productivity conditions in the area off Panay from 4000 years B.P. and continues until the present.

5.2. The Holocene and modern productivity conditions

During the past 10,000 years B.P., calcareous nannofossil records and TOC (%) showed a highly varying pattern while $CaCO_3$ (%) shows a rather similar level (Fig. 5). A reduction in the total nannofossil concentration toward the present day is observed, a trend that is contrary to the estimated PP and TOC (%) (Fig. 5d, e, f). Total calcareous

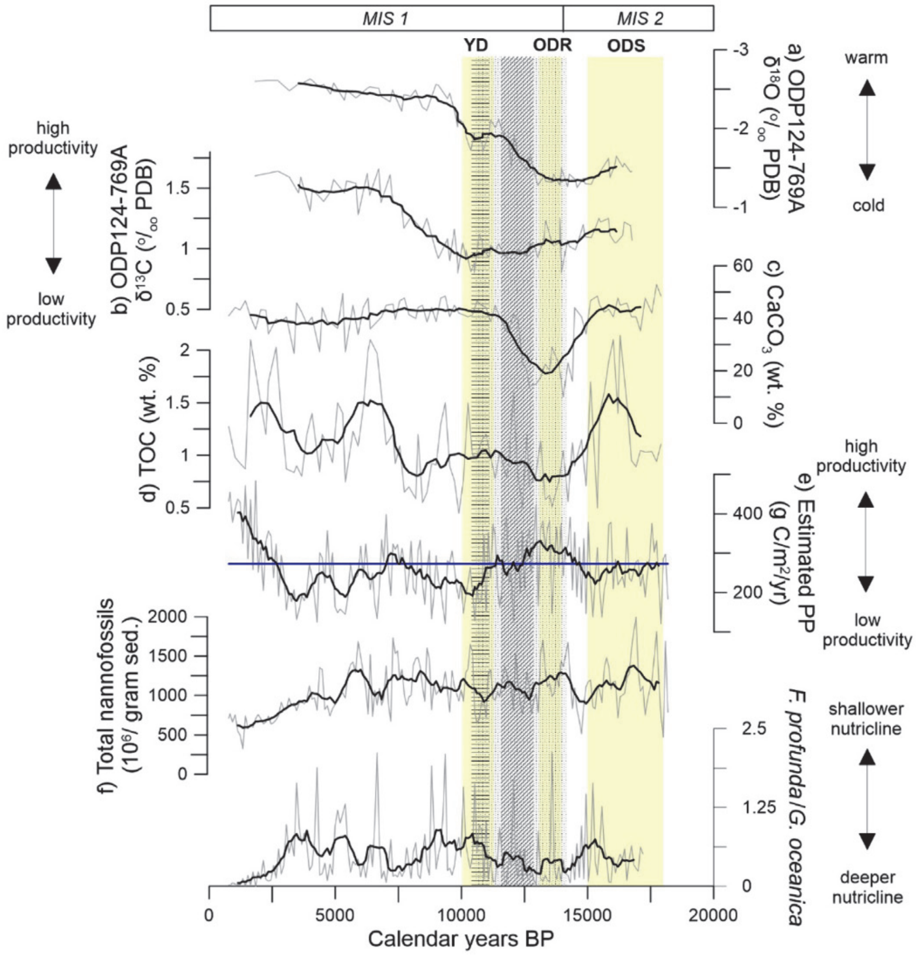

Fig. 5. Paleoceanographic data of U-GC12 off Zamboanga Peninsula over the past 18,000 years B.P. in comparison with data from previous studies in the Sulu Sea: (a) $\delta^{18}O$ and (b) $\delta^{13}C$ records from planktonic foraminifera *G. ruber* of ODP124-769A (Linsley and Thunell, 1990), (c) bulk sediment calcium carbonate, (d) bulk sediment total organic carbon content, (e) estimated primary productivity (PP) calculated from *F. profunda* (%), (f) total calcareous nannofossil records, and (g) *F. profunda*/*G. oceanica* ratio. Blue line represents the average present-day primary production (273 g C/m^2/year; Antoine et al., 1996) in the Sulu Sea central area. Raw data are plotted as gray lines while the solid black lines are calculated nine-point moving average to highlight general trends. Gray bands represent the Younger Dryas (YD), Older Dryas (ODR), and Oldest Dryas (ODS) events recorded in the Northern Hemisphere (NH) while the dotted pattern (Hong et al., 2010) and diagonal lines (Ma et al., 2012) correspond to the timing of these events in the South Pacific regions. Kudrass and Erlenkeuser (1991) proposed that the YD event in the Sulu Sea is synchronous to the NH. The horizontal lines represent the timing of the YD in the investigated core. MIS = Marine Isotope Stage. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

nannofossil concentrations and $CaCO_3$ (%) for the two sites are almost at a similar level over the past 4000 years B.P. Nevertheless, higher estimated PP is observed in U-GC12 than in NU-GC14 starting at 2800 years B.P. onward.

In a study by Andruleit and Rogalla (2002) on the surface sediments from the northern Indian Ocean, total coccolithophore abundances was found to be low within the vicinity of the upwelling area off Oman and increase toward more oligotrophic regions, suggesting the more oligotrophic preference of coccolithophores (Winter et al., 1994). Increasing *G. oceanica* relative abundance is observed from the Holocene toward the present day coincident with declines in small *Gephyrocapsa* and *R. minuta* (Fig. 4c, d, e), indicating intensification of the monsoons that further led to upwelling. *Gephyrocapsa oceanica* is indicative of high surface water productivity in low latitudes (Andruleit et al., 2008; Broerse et al., 2000) and a well-mixed water-column typical of an upwelling region (Rogalla and Andruleit, 2005). This is also shown in the increasing estimated PP toward the present, ranging from 484 g/C/m^2/yr to 121 g/C/m^2/yr, with mean of 260 g/C/m^2/yr and reaching maximum values (Fig. 5e). *Emiliania huxleyi* shows a similar pattern to the other two small placolith-bearing taxa, although greater in abundance until 6000 years B.P. and decreasing thereafter. In the Indian Ocean, the combined record of *E. huxleyi* and *G. ericsonii* is not an indicator of upwelling processes at low latitudes but characteristic of a stable regime with relatively high nutrient concentrations at the surface (Andruleit et al., 2008; Rogalla and Andruleit, 2005).

5.3. Timing of the younger Dryas in the Sulu Sea

Using a high resolution benthic and planktonic foraminifera data, the timing of the YD event in the Sulu Sea has been previously proposed by Kudrass and Erlenkeuser (1991) to be synchronous with the northern Atlantic Ocean and northwest Europe occurring from 11,065 to 10,800 years B.P. This was demonstrated by a drop in temperature by ~3 °C and salinity by 1‰, a decrease in the abundance of the planktonic foraminifera *G. ruber*, and an increase in the abundance of the cool water species *Neogloboquadrina pachyderma*. In the present study, we observed this timing between ~11,100 to ~10,400 years B.P., characterized by a reduction in the total calcareous nannofossil concentrations and estimated PP, and an increase in the TOC (%) and $CaCO_3$ (%) (Fig. 5). The onset of the YD event in the Sulu Sea led to an increase in both the total calcareous nannofossil concentration and estimated PP, possibly due to a strengthened NE monsoon, driving upwelling in the study area. However, as the cooling event progresses, a decline in the total counts and all the other species except for *F. profunda*, a deep-photic zone taxon is observed (Fig. 5b). A stable water-column and deeper nutricline in the Sulu Sea during this period is shown by the high abundances of this species (Fig. 5g). In the conceptual model of Kudrass and Erlenkeuser (1991), the reduction in the meltwater supply during the YD event led to the intensification of oceanic surface mixing and deep water circulation that consequently resulted in increased oceanic productivity. Alvarez et al. (2010) also observed an increase in *F. profunda* counts during the YD in the Gulf of California, also an upwelling site. Weakening of the upwelling signal during the YD in the Gulf of California was interpreted by the authors to be due to the southward migration of the intertropical convergence zone (Garcin et al., 2007), preventing the inflow of the southeasterly winds that drive upwelling in the area (Molina-Cruz, 1988), and favoring water-column stratification, thus low surface water productivity.

The decline in the estimated PP during this period is coincident with a slight increase in the TOC (%) (Fig. 5d and e). High TOC (%) values

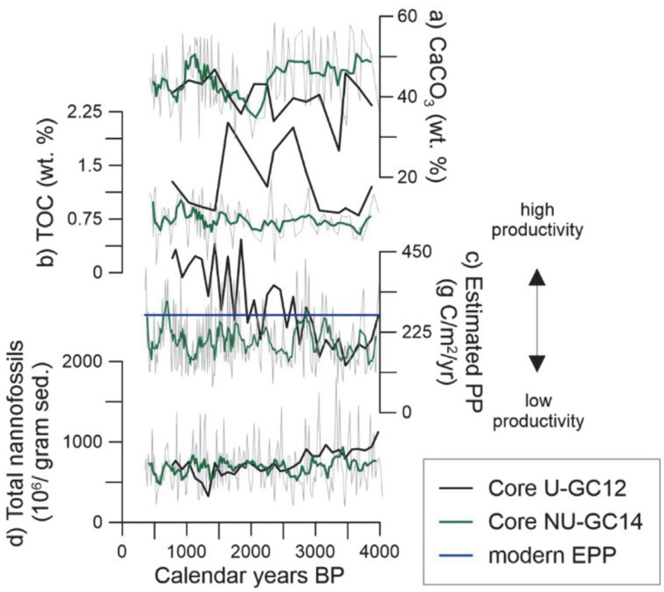

Fig. 6. Paleoceanographic data of cores NU-GC14 off Panay Island and U-GC12 off Zamboanga Peninsula over the past 4000 years B.P. in comparison to data from previous studies in the Sulu Sea: (a) $\delta^{18}O$ and (b) $\delta^{13}C$ records from planktonic foraminifera *G. ruber* of ODP124-769A (Linsley and Thunell, 1990), (c) bulk sediment calcium carbonate, (d) bulk sediment total organic carbon content, (e) estimated primary productivity (PP) calculated from *F. profunda* (%), and (f) total calcareous nannofossil records. Blue line represents the average present day primary production (273 g C/m^2/year) in the Sulu Sea central area. Raw data are plotted as gray lines while the solid black (U-GC12) and green lines (NU-GC14) are calculated nine-point moving averages to highlight general trends. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

are typically regarded as a good productivity proxy in areas where the preservation factor does not play a dominant role (Rühlemann et al., 1999). While we observed moderate to good preservation of the calcareous nannofossils in the study area, we cannot rule out the dilution effect of terrigenous materials. In particular, the YD event experienced over Asia was wet, characterized by an increase in precipitation (Oppo et al., 2003; Hong et al., 2010) and could have led to an increase in terrigenous material deposition in the Sulu Sea, hence contributing to the TOC (%). This increase in terrestrial input accompanied by the freshening of the surface waters caused by high precipitation during the YD event may have caused the decline of the total calcareous nannofossils in the investigated area. The intensified rainfall during this time could have created a barrier layer of low salinity water in the Sulu Sea, creating unfavorable conditions for the coccolithophores. Alternatively, it can also be possible that other plankton groups (e.g., diatoms, foraminifera) other than coccolithophores are responsible for high TOC (%) and high $CaCO_3$ (%) in the study area during this time.

6. Conclusions

As in many other parts of the world oceans, major oceanographic signals are reflected in calcareous nannofossil assemblages, and thus, reflect spatial and temporal changes in surface ocean circulation. Calcareous nannofossils in the Sulu Sea were of low diversity (up to 26 species identified) and dominated by *G. oceanica* and *F. profunda*, followed by the small placoliths group (*E. huxleyi,* small *Gephyrocapsa,* and *R. minuta*). Almost all of the identified species were consistently present throughout the core. Results of this present study showed that significant productivity indicator species can be used in marginal seas in tropical settings. A high productivity group (*E. huxleyi,* small *Gephyrocapsa, G. oceanica*, *R. minuta*, and *U. sibogae*), which is more commonly found in well-mixed water column conditions, and a low productivity group (*U. irregularis*, *F. profunda*), which is usually more associated with a stratified water column conditions, were determined.

The greater counts of the high productivity taxa at ~18,000 years B.P. indicated the initiation of upwelling off Zamboanga Peninsula. By contrast, a weakening of an upwelling intensity signal in U-GC12 was evidenced by the higher counts of low productivity indicator species, *U. irregularis* as well as by the increased abundances of *F. profunda*, which reflect a deeper nutricline. This time interval coincided with the period analogous to the YD event, occurring from 11,100 to 10,400 YD in U-GC12. During the onset of these cooling periods, a more intensified EAM occurred, leading to a stronger upwelling event off Zamboanga, which consequently supplied nutrients to the surface that resulted in high abundances of *E. huxleyi,* small *Gephyrocapsa, G. oceanica*, *R. minuta*, and *U. sibogae*. However, the increase in precipitation over Asia during the YD event resulted in high sediment deposition and freshening of the surface waters during this time thus, resulting in low calcareous nannofossil productivity.

Results of this study suggest that the high productivity waters off Zamboanga Peninsula observed in the present day have been experienced several times in the past as recorded by the abundances of certain calcareous nannofossil species in the area. There are significantly greater abundances of the high productivity indicator species, *G. oceanica* and low abundances of the low productivity indicator species off Zamboanga Peninsula than off Panay Island. Greater concentrations of *F. profunda* are observed off Panay Island. These records suggest that the modern day upwelling off Zamboanga Peninsula probably started as early as 2500 years B.P. while the low productivity conditions off Panay Island have been prevailing since 4000 years B.P. and continue to the present day.

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