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Title:
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Date:
2021-12-01

Citation:
Vats, N., Singh, R. K., Das, M., Holbourn, A., Gupta, A. K., Gallagher, S. J. & Pandey, D. K. (2021). Linkages Between East China Sea Deep-Sea Oxygenation and Variability in the East Asian Summer Monsoon and Kuroshio Current Over the Last 400,000 years. Paleoceanography and Paleoclimatology, 36 (12), https://doi.org/10.1029/2021PA004261.

Persistent Link:
https://hdl.handle.net/11343/299227

Linkages between East China Sea Deep-sea Oxygenation and Variability in the East Asian Summer Monsoon and Kuroshio Current over the last 400,000 years

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Key Points:

- Four distinct phases of bottom water oxygenation identified during the last 400 kyr in the East China Sea.
- East Asian Summer Monsoon and Kuroshio Current influence East China Sea productivity, organic export flux and bottom water oxygenation.
- Precessional variability modulates bottom water oxygenation in ECS.

Abstract

The East China Sea (ECS) seasonally receives a high organic input due to the terrestrial organic matter influx, which is controlled by the East Asian Summer Monsoon (EASM), and the increased productivity driven by upwelling of the subsurface Kuroshio Current (KC). Changes in benthic foraminiferal assemblage composition in combination with paleoceanographic proxy data ($CaCO_3$ (%), TOC (%), $\delta^{13}C_{pf}$, and $\delta^{18}O_{bf}$) are used to reconstruct bottom water oxygenation and organic export flux variability over the last 400 kyr in the ECS. Multivariate analyses of benthic foraminiferal census data identified six biofacies characteristic of varying environmental conditions. These results suggest that enhanced EASM precipitation and KC upwelling directly influenced organic export flux and bottom water oxygen content in the ECS. The ECS bottom water was suboxic during Marine Isotope Stage (MIS) 11 to 8; suboxic to dysoxic between MIS 7 and 6, strongly dysoxic between mid-MIS 5 and 4, and exhibited high variability between MIS 3 and 1. Spectral analysis of relative abundances of representative genera *Quinqueloculina* (oxic), *Bulimina* (suboxic), and *Globobulimina* (dysoxic) reveals a robust 23 kyr signal, which we attribute to precessionally-paced changes in surface productivity and bottom water oxygenation related to KC variability over the past 400 kyr.

Keywords: IODP Site U1429**,** Bottom water oxygenation**,** Precessional variability, East China Sea, Benthic foraminifera

1 Introduction

Deep-sea oxygenation of the East China Sea (ECS) is influenced by deep water circulation (Kao et al., 2005; Lim et al., 2017) and subsurface intrusion of the Kuroshio Current (KC) (P. Zhou et al., 2018a, b). Kuroshio intensification enhances deep water circulation and adds oxygen to the sediment-water interface (Kao et al., 2005; Lim et al., 2017), whereas upwelling of nutrient-rich subsurface Kuroshio water in the ECS drives higher productivity along the Zhejiang coast in the ECS (Chen & Wang, 1999; Zhang et al., 2007), promoting the decline in dissolved oxygen (P. Zhou et al., 2018b). Thus, deep-water circulation, primary productivity and the upwelling of the subsurface KC are the primary processes that contribute to dissolved oxygen in the ECS (Gallagher et al., 2009, 2015). Productivity in the upper water column of the ECS is also linked to nutrient arrival associated with the East Asian Summer Monsoon (EASM) (J. Hu & Wang, 2016; Watanabe et al., 2007). The influx of terrestrial organic matter in the ECS is regulated by active river discharge and run-off associated with seasonal EASM precipitation variability (Lee et al., 2001; Matsuzaki et al., 2016). This further affects primary productivity and may contribute to the higher rate of organic matter sinking to the sea floor. Today, hypoxia occurs in the Changjiang Estuary of the ECS during the summer season (Fig. 1; D. Li et al., 2002; B. Wang, 2009; B. Wang et al., 2012), which coincides with seasonal EASM riverine influx and KC influx in the ECS. The water column stratification and dissolved oxygen consumption by organic matter promote hypoxia formation in the ECS (D. Li et al., 2002; Wei et al., 2007; Zhu et al., 2011). The oxygen utilization profile of the Okinawa Trough (OT) in the ECS also suggests a higher rate (~5.3 ml/l) of dissolved oxygen consumption at the sediment water-interface (Fig. S1(a)). It is likely that the influence of EASM driven productivity and KC upwelling also varied on glacial-interglacial and shorter time scales. The long-term evolution of bottom water oxygenation has been reconstructed for the South China Sea (N. Wang et al. 2018) and Japan Sea (Manisha Das et al. 2021), using benthic foraminiferal proxies. In the ECS, Matsuzaki et al. (2019) used the deep-dwelling planktic radiolarian species *Cycladophora davisiana* to reconstruct sub-surface oxygenation. However, as a planktic species, this taxon cannot be used to estimate oxygenation at the sediment-water interface nor to monitor the variability in suboxic to dysoxic conditions during climate transition phases. Furthermore, the relative abundance of *C. davisiana* is generally low (~ 5%) between MIS 11 and MIS 6 and rare in strata younger than MIS 6 (Matsuzaki et al., 2019). Other deep-sea oxygenation reconstructions in the ECS and OT are only available back to the Last Glacial Maximum (LGM) (Kao et al., 2005; Lim et al., 2017). Hence, the factors influencing deep-sea oxygenation in the ECS and OT on longer time scales are yet to be fully understood. Thus, it is crucial to reconstruct long-term bottom water oxygenation for ECS over several glacial-interglacial cycles to better understand sub-orbital and orbital variability.

Various proxies have been used to assess variability in deep-water oxygenation including the benthic foraminiferal oxygen index (BFOI) (Kaiho, 1994, 1999; Kaminski, 2012; N. Wang et al., 2018), Mo/Al (N. Wang et al., 2018), I/Ca (Taylor et al., 2017), the number of pores in epifaunal benthic foraminifera (Rathburn et al., 2018), the grey color reflectance index (L*) (Huang et al., 2019; Irino et al., 2018; Kido et al., 2007; Tada et al., 1999; Watanabe et al., 2007). Benthic foraminifera inhabit the seafloor near sediment-water interface and are useful proxies to assess bottom water oxygenation (e.g., Burkett et al., 2016; Moumita Das et al., 2017; Lutze & Thiel, 1989; Rathburn et al., 2018). Surface productivity and the associated organic matter flux to the seafloor as well as the dissolved oxygen content in bottom water are major factors controlling the distribution of particular species of benthic foraminifera (e.g., Moumita Das et al., 2017; Fontanier et al., 2002; Jorissen et al., 2007; Sen Gupta & Machain-Castillo, 1993; Y. Zhou et al., 2016). The abundance, diversity and habitat (epifaunal, shallow infaunal and deep infaunal) of benthic foraminifera as well as the size and chemical composition of tests vary with bottom water conditions (Barik et al., 2019; Rathburn et al., 2018). Jorissen et al. (2007) suggested that foraminiferal diversity and density, in particular, are strongly influenced by the availability of food and the oxygenation of bottom and sediment pore water. Therefore, benthic foraminifera provide ideal proxies to retrace the evolution of bottom-water oxygenation and the organic export flux to the sea floor through time.

This study uses benthic foraminiferal assemblages from Integrated Ocean Drilling Program (IODP) Site U1429 to reconstruct shifts in bottom water oxygenation and variability in organic export flux in the ECS over the last 400 kyr. Multivariate analysis and environmental preferences of benthic foraminifera are used in addition to total organic carbon (TOC wt. %) and $CaCO_3$ (%) data (Black et al., 2018), the radiolarian species *Cycladophora davisiana* abundance (%) (Matsuzaki et al., 2019), planktic foraminiferal $\delta^{13}C$ values ($\delta^{13}C_{pf}$) and benthic foraminiferal $\delta^{18}O$ values ($\delta^{18}O_{bf}$) (Clemens et al., 2018) from the same site.

2 Site Location and Oceanographic Setting

IODP Site U1429 (31°37.04'N, 128°59.85'E) (Fig. 1) in the ECS was cored down to 182 meters below sea floor (mbsf) at a water depth of 732 meters below sea level (mbsl; Tada et al., 2015). This site is located in the Danjo Basin on the western continental slope of the northern OT in the northeastern ECS (Fig. 1). The sediment succession at this site is mainly composed of calcareous nannofossil ooze and calcareous nannofossil-rich clay (Tada et al., 2015; D. Zhao et al., 2019). The KC and the Taiwan warm Current (TC) strongly influence the surface and subsurface waters of the ECS (e.g., Matsuzaki et al., 2016), respectively. The KC intrusion into the ECS is seasonally controlled by volume transport fluctuations (Z. Liu et al., 2021; P. Zhou et al., 2018b) in the transport of warm, highly saline waters from low to middle latitudes (D. Hu et al., 2015; D. Zhao et al., 2017; Zheng et al., 2016). The KC brings oxygen-rich, warm, saline and oligotrophic water to the ECS from the north equatorial Pacific region (Gallagher et al., 2015; Lee et al., 2001; Matsuzaki et al., 2019, 2016; Vats et al., 2020), while subsurface KC-driven upwelling

(Chen et al., 1995; K. K. Liu et al., 1992; Vats et al., 2020; Wu et al., 2008; P. Zhou et al., 2018a) brings nutrients and influences primary productivity. The nutrient rich TC flows in to the ECS (Matsuzaki et al., 2019) from the Taiwan strait and increases the productivity in the continental shelf areas of the ECS, however, its influence gets restricted to the western part of the ECS. It flows northward throughout the year, even during winter, with strong northerly winds (Ji-lan et al., 1994; Qi et al., 2017).

The other major component in the ECS is the Changjiang Diluted Water (CDW), which brings freshwater from northwestern China and lowers the salinity and temperature in the ECS (Ichikawa & Beardsley, 2002). The CDW is associated with EASM precipitation, and its influence is seasonal (Lee et al., 2001; Matsuzaki et al., 2016). The CDW discharge also brings nutrients affecting biological productivity and the accumulation of terrestrial organic matter in the ECS. The sinking of organic matter to the bottom of the ECS consumes the available bottom water dissolved oxygen. Hence, enhanced subsurface KC upwelling and stronger EASM strongly influence bottom water oxygenation in the ECS. The modern annual oxygen utilization and dissolved oxygen concentration at the sediment-water interface near to the studied site is ~5.3 ml/l and ~1.6 ml/l, respectively (Fig. S1(a-b); Garcia et al., 2013). The decadal average (1955-2017) bottom water temperature and salinity at sediment-water interface are ~4°C (Fig. S1(c); Locarnini et al., 2019) and ~34.35 (Fig. S1(d); Zweng et al., 2019), respectively.

3 Materials and Methods

A total of 225 sediment core samples (of 10 cc volume) were analyzed from IODP Site U1429, down to 182 mbsf. We used the high-resolution age model published by Clemens et al. (2018), which shows that the sediment succession extends back to ~400 ka. The upper part of the succession (back to 40 ka) was further constrained by 16 AMS ^{14}C dates (10 from Vats et al., 2020 and 6 from D. Zhao et al., 2017). The average temporal resolution per sample is ~2 kyr (Vats et al., 2020). The same age model was also used to plot TOC (%), $CaCO_3$ (%) (Black et al., 2018), $\delta^{13}C_{pf}$ and $\delta^{18}O_{bf}$ (Clemens et al., 2018) and the *Cycladophora davisiana* (%) abundance data (Matsuzaki et al., 2019). Out of 225 samples, 36 samples yielded fewer than 30 specimens of foraminifera per 10 cc sediment, and these samples were discarded from the statistical analysis, as they may lead to artefacts. Most of these discarded samples are from the tephra layers within the core (Sagawa et al., 2018; Tada et al., 2015).

The samples were processed and analyzed following the standard methods outlined by Manisha Das et al. (2018). Benthic foraminiferal census data were generated for each sample from the >125 μm size fraction, and species abundance (percentage) was calculated. Benthic foraminiferal classification follows Loeblich and Tappan (1988) at the genus level and Manisha Das et al. (2018, 2021), Gallagher et al. (2018), Holbourn et al. (2013), Scott et al. (2000), and Zwaan et al. (1986) at the species level. Two hundred thirty-six species of benthic foraminifera belonging to 96 genera were identified.

Of the 236 species identified, only 32 species (Fig. 2) with an abundance of ≥5% in 5 or more samples were selected for multivariate analysis. Exploratory factor analysis was performed on these species and to maximize the variance “fa” function and “pa” method (principal axes) of Psych package (Revelle, 2019; RStudio Team, 2020) were used. Based on scree-plot (X-Y) of eigenvalues, five factors were retained. Hierarchical cluster analysis was performed using Ward’s minimum linkage method for the same 32 species, which enabled to retain 6 clusters (Manisha Das et al., 2021; RStudio Team, 2020; R. K. Singh et al., 2021; Fig. S2). Incorporating consistent results from exploratory factor analysis and hierarchical cluster analysis, six biofacies of benthic foraminifera were identified in the ECS (Table 1). Each biofacies was named after the most dominant species with the highest factor loadings within each factor association. Biofacies abundance (%) was calculated based on cumulative percentages of all species contributing to that particular biofacies (Fig. 3). We have further classified and grouped these dominant 32 species into oxic, suboxic, and dysoxic species based on their environmental (oxygenation) preferences (Table 2).

The diversity among benthic foraminifera was calculated using the Shannon Index (H) (Shannon & Weaver, 1949), given by the formula:

$$\mathrm{H} = -\sum_{i=1}^{S} \boldsymbol{p_i} \, \boldsymbol{ln} \, \boldsymbol{p_i} \qquad (1)$$

where, S is the number of species in a given sample, p_i is the proportion of the i^{th} species in the sample, and ln is the natural logarithm.

Spectral analysis was carried out using the PAST 4.03 program (Hammer et al., 2001) for the oxic genus *Quinqueloculina* (%), suboxic genus *Bulimina* (%), and dysoxic genus *Globobulimina* (%) and the productivity indicator $\delta^{13}C_{pf}$ (Clemens et al., 2018) over the investigated interval. We selected a ‘Welch’ window parameter to obtain the spectra at a 90 % confidence level (REDFIT). The spectrum was bias-corrected using the Monte Carlo simulation option (Schulz & Mudelsee, 2002). Further, the cross spectral analysis of oxic genus *Quinqueloculina* (%), suboxic genus *Bulimina* (%), dysoxic genus *Globobulimina* (%) with U1429 $\delta^{18}O_{Seawater}$, U1429 $\delta^{13}C_{pf}$ (Clemens et al., 2018), and Kuroshio Current Index- Factor 4 loading (Vats et al., 2020) and among these parameters, were performed in Analyseries 2.0.4 (Paillard et al., 1996). The analysis was performed using the Blackman-Tukey method with 50% lag and Bartlett window at 80% confidence level. All the data were linearly interpolated at 2 ka resolution prior to the cross-spectral analysis.

4 Results

4.1 Temporal variability of oxic, suboxic and dysoxic species in the ECS

Following previous approaches, we use the term dysoxic, when dissolved oxygen (DO) is 0.1–0.3 mL/L, suboxic, when DO is 0.3–1.5 mL/L, and oxic, when DO is >1.5 mL/L (e.g., Gallagher et al., 2018; Kaiho, 1994; N. Wang et al., 2018). At Site U1429, most of the oxic species are epifaunal, the suboxic species are shallow to deep infaunal, and the dysoxic species are deep infaunal (Table 2). Since MIS 11 (~400 ka), oxic species were relatively less abundant in the ECS and did not show any significant variations in trends except for a peak just after T-III followed by intermittent occurrences during MIS 1 (Fig. 4). However, temporal variability of the dominant oxic genus *Quinqueloculina* has low abundance during certain peak abundance of oxic species (Fig. S3). Suboxic species were abundant between MIS 11 and 6, subsequently decreased during MIS 5 and 4, and increased once again between MIS 3 and 1 (Fig. 4). The temporal variation of the dominant suboxic genus *Bulimina* exhibits an overall similar trend, but displays higher variability (Fig. S3). Dysoxic species were relatively abundant during MIS 7 and 5, but decrease after MIS 4, and they became relatively rare between MIS 3 and 2 (Fig. 4). The dominant dysoxic genus *Globobulimina* generally follows the same trend (Fig. S3).

4.2 Biofacies interpretation

For the identified six biofacies *Gavelinopsis* sp. (Gv), *Chilostomella oolina* (Co), *Hyalinea balthica* (Hb), *Cassidulinia teretis* (Ct), *Uvigerina mediterranea* (Um), and *Martinottiella communis* (Mc) (Table 1), environmental significance is inferred, based on environmental preferences of individual species of that particular biofacies.

4.2.1 Biofacies Gv

The biofacies Gv has high negative factor loading on Factor 1 and includes four species: *Gavelinopsis* sp., *Oridorsalis umbonatus*, *Gyroidinoides cibaoensis*, and *Quinqueloculina seminulum* (Table 1). This biofacies occurs almost continuously in 13 samples between 23 and 14 ka (Fig. 3). *Gavelinopsis* sp. is an epifaunal species found in the inner sublittoral zone of the Japanese coast (Akimoto & Hasegawa, 1989; Takata et al., 2018) and often inhabits high energy environments affected by wave and current processes (Takata et al., 2018). *Oridorsalis umbonatus* is a cosmopolitan species present over a range of water depths and trophic levels (Gupta et al., 2006; Schmiedl & Mackensen, 1997; R. K. Singh et al., 2021; Takata et al., 2019). It has also been reported as a suboxic and shallow infaunal to epifaunal species (Bubenshchikova et al., 2010; Jorissen et al., 1998). *Gyroidinoides cibaoensis* is found in a wider range of oxygen conditions with variable food availability (De & Gupta, 2010). *Quinqueloculina seminulum* is a cold-water dweller (Hayward et al., 1997), found in high-energy conditions (Laprida et al., 2007) with a pulsed food supply (Gupta & Thomas, 2003; Sarkar & Gupta, 2014; Takata et al., 2018), generally in shallow marine environments (Murray, 2006). Biofacies Gv overall indicates relatively high energy within an inner to outer shelf environment with a pulsed food supply and overall oxic to slightly suboxic bottom water conditions.

4.2.2 Biofacies Co

Biofacies Co is defined by the species having high positive factor loadings on Factor 2 (Table 1). *Chilostomella oolina*, *Fursenkoina rotundata*, and *Globobulimina pacifica* are characteristic of this biofacies. This biofacies occurs in 29 samples, almost continuously between

~93 and 41 ka and occasionally at other times (Fig. 3). *Chilostomella oolina* is a deep infaunal species typifying dysoxic conditions (Jorissen et al., 1998; McGann & Conrad, 2018) with high productivity (N. Wang et al., 2018). *Fursenkoina rotundata* is an infaunal, dysoxic, opportunist species (Moumita Das et al., 2017), present in areas where there is significant organic matter influx associated with high surface productivity leading to low-oxygen conditions (Patarroyo & Martínez, 2015). *Globobulimina pacifica* is also a low oxygen tolerant taxon (Ballesteros-Prada, 2019; Bernhard et al., 1997; McGann & Conrad, 2018). It occupies intermediate to deep-infaunal microhabitats in dysoxic conditions (Moumita Das et al., 2017) and is commonly associated with poorly ventilated deep-water (Ma et al., 2019). Biofacies Co indicates strongly dysoxic bottom water conditions in the ECS associated with high productivity.

4.2.3 Biofacies Hb

Biofacies Hb has high negative factor loadings on Factor 4 (Table 1). *Hyalinea balthica*, *Bulimina mexicana*, *Hoeglundina elegans*, and *Valvulineria sadonica* are characteristic species of this biofacies. This biofacies is present in 22 samples at ~302-295, ~39-30 and ~15-0 ka (Fig. 3). *Hyalinea balthica* is a shallow infaunal, opportunistic species present in food-abundant regions with suboxic conditions (Charrieau et al., 2018; Moumita Das et al., 2017). *Bulimina mexicana* is a cosmopolitan taxon that thrives in intermediate (bathyal) water depths in all ocean basins (Culver & Buzas, 1980; Grunert et al., 2018; Jones & Brady, 1994; Van Morkhoven et al., 1986). It generally prefers a shallow infaunal microhabitat, high fluxes of organic matter and oxygen-depleted sediments (Grunert et al., 2018). *Hoeglundina elegans* is a shallow infaunal taxon (Gonzales et al., 2017; Jorissen et al., 1998) and was reported in the upwelling zones of the Bay of Biscay (Martínez-García et al., 2013). The species is present in moderately oxygen-depleted environments in the Arabian Sea and is considered as suboxic species (Gupta & Thomas, 1999; Kaiho, 1994, 1999; Sarkar & Gupta, 2014). *Valvulineria sadonica* is found in areas with a high flux of degraded and refractory organic matter in shallow subsurface water (Gorbarenko et al., 2010; Phleger & Soutar, 1973; Smith, 1964). It is an intermediate infaunal species typifying mostly suboxic conditions and within the Oxygen Minimum Zone (OMZ) in the Okhotsk Sea

(Bubenshchikova et al., 2010). Biofacies Hb suggests a high influx of organic matter and overall suboxic bottom water conditions.

4.2.4 Biofacies Ct

Biofacies Ct is characterized by five species *Cassidulina teretis*, *Epistominella exigua*, *Cassidulina laevigata*, *Bolivina robusta*, and *Globocassidulina subglobosa* with positive high factor loadings on Factor 3 (Table 1). This biofacies occurs sporadically in 13 samples during 331, 278-262, ~153, 114-107, ~60 and ~57 ka (Fig. 3). *Cassidulina teretis* is a common high latitude species present in the cold Arctic Ocean and off Alaska (Cronin et al., 2019; Mackensen & Hald, 1988). This species typifies seasonally ice-free regions and is associated with high productivity and high phytodetritus influx (Cronin et al., 2019; Scott et al., 2008). *Epistominella exigua* is a cosmopolitan species feeding opportunistically on phytodetritus deposited seasonally on the seafloor and can tolerate a varying organic export flux (Manisha Das et al., 2021; Gooday, 1988; R. K. Singh & Gupta, 2004, 2010). *Cassidulina laevigata*, is a shallow infaunal taxon (Fontanier et al., 2002), typifying relatively cold waters with high organic matter content (Pascual et al., 2020), and is tolerant of moderate oxygen depletion in the bottom and pore water under high organic flux rates (Manisha Das et al., 2021; Nardelli et al., 2014; Sen Gupta & Machain-Castillo, 1993). *Bolivina robusta* is an open ocean infaunal species found in temperate to subtropical middle to upper bathyal depths (Haller et al., 2018; B. Zhao et al., 2018). *Bolivina robusta* may be able to tolerate high eutrophication and is a useful indicator of low oxygen condition at the seafloor (B. Zhao et al., 2018). *Globocassidulina subglobosa*, which prefers oxic conditions and high to intermediate food supply, is a cosmopolitan epifaunal species (Araújo et al., 2018; Manisha Das et al., 2021; Kaminski, 2012; Martins et al., 2007; Murray, 2006; R. K. Singh et al., 2021; Verma et al., 2013). Biofacies Ct indicates an enhanced phytodetritus flux into the ECS associated with suboxic conditions that occasionally become dysoxic, as shown by the presence of *B. robusta*.

4.2.5 Biofacies Um

Biofacies Um has high negative factor loadings on Factor 5 (Table 1). It is comprised of *Uvigerina mediterranea*, *Uvigerina pygmaea*, and *Uvigerina peregrina*. This biofacies is present in 55 samples during ~390-386, ~282-218, 188-138, and ~29-1 ka (Fig. 3). *Uvigerina mediterranea* is a low to intermediate oxygen tolerant shallow infaunal species of middle to lower bathyal depths (Manisha Das et al., 2018, 2021; Duros et al., 2011; Schmiedl et al., 2000; Schweizer, 2006; A. D. Singh et al., 2015). *Uvigerina pygmaea* is also a shallow infaunal species, typical of intermediate to low oxygen environments in deep-water masses (Kastens & Mascle, 1990; Lutze, 1979). The environmental preferences of *Uvigerina pygmaea* are similar to that of *Uvigerina peregrina* (Manisha Das et al., 2018). *Uvigerina peregrina* is a shallow infaunal species (Jorissen et al., 1998) typical of middle neritic to lower bathyal depths (Schweizer, 2006). It is often associated with high productivity and sustained flux of organic matter and can tolerate lower food levels and oxygen deficiency (Manisha Das et al., 2018, 2021; Moumita Das et al., 2017; Gupta et al., 2008; Mazumder & Nigam, 2014). Biofacies Um suggests suboxic to dysoxic bottom water conditions in the ECS with a relatively higher influx of organic matter.

4.2.6 Biofacies Mc

Biofacies Mc has high positive factor loadings on Factor 1 (Table 1) and is characterized by two agglutinated species: *Martinottiella communis* and *Gaudryina* sp. along with the calcareous species *Amphicoryna scalaris, Melonis barleeanum*, *Uvigerina auberiana*, and *Bulimina aculeata*. It is present in 57 samples during ~396-283, ~248-242, ~212-193, ~158, ~135-122, 74 and ~61 ka (Fig. 3). *Martinottiella communis* is an agglutinated foraminifera, often found in shelf to bathyal conditions (Kaiho & Nishimura, 1992). It may be present in regions with a high organic carbon flux and is tolerant of moderate to low oxygen settings (Kender & Kaminski, 2017). It is found within a DO range 4.7 to 5.7 mL/L in the Scotia Sea and Argentine Basin (Harloff & Mackensen, 1997). *Gaudryina* sp. is also an agglutinated species that has a shallow to deep infaunal habitat (Reolid et al., 2012). It has been reported as an endobenthic species associated with moderately oxygenated environments (Rostami et al., 2020). *Amphicoryna scalaris* is a shallow infaunal species (Balestra et al., 2017), associated with a high input of labile organic matter (Fontanier et al., 2008), and has been reported in moderately oxygenated environments (García-Sanz et al., 2018). *Melonis barleeanum* is often associated with degraded refractory organic matter, and is an infaunal species found in moderately oxygen-depleted conditions (Fontanier et al., 2002, 2005; Schmiedl et al., 2000). The shallow infaunal *Uvigerina auberiana,* reported as a suboxic species in the Okhotsk Sea (Bubenshchikova et al., 2010; Gorbarenko et al., 2004), prefers a higher organic carbon flux and has also been reported in the South China Sea (Kuhnt et al., 1999). *Bulimina aculeata* is an intermediate to deep infaunal taxon, most abundant in suboxic bottom water conditions (Moumita Das et al., 2017; Kaiho, 1994; Kaminski, 2012). Biofacies Mc suggests suboxic bottom water conditions in the ECS with moderate organic export flux.

4.3 Temporal variability of marine productivity indicators in the ECS

Marine productivity indicators such as $CaCO_3$ (%), TOC (%) (Black et al., 2018), and $\delta^{13}C_{pf}$ (‰) (Clemens et al., 2018) are used to complement the benthic foraminiferal distribution data. $CaCO_3$ (%) was relatively high (41.17 %) during mid-MIS 11, but gradually decreased to 10.13 % during MIS 10 (Fig. 4). $CaCO_3$ (%) increased again during MIS 9 with an average of 28.24 %, then decreased to its lowest value of 3.65 % during MIS 8 with an average value of 11.51 % during this interval. $CaCO_3$ (%) continued to be relatively low (average value 16.66 %) during MIS 7 and 6 (Fig. 4) before increasing to its highest value (42.84 %) during MIS 5 (average 29.76 %), then gradually decreased to modern-day values (21.54 %) after MIS 5 (Fig. 4). The TOC (%) trend at Site U1429 is comparable to that of $CaCO_3$ (%) between MIS 11 and MIS 8 with values between 2.2 % and 0.13 % (average 1.33 %), followed by small variations between 2.17 % and 0.77 % (average 1.39 %) until MIS 6 (Fig. 4). TOC (Wt %) increased between MIS 5 and 1, and reached a maximum value of 2.85 % during MIS 1 (Fig. 4). The $\delta^{13}C_{pf}$ (‰) values exhibit a decreasing trend toward MIS 10, ranging between 1.29 and 0.3 ‰ (VPDB), then gradually declined to -0.15 ‰ during MIS 10. During MIS 9, $\delta^{13}C_{pf}$ (‰) increased to 1.35 ‰, then declined to -0.08 ‰ during MIS 8. The $\delta^{13}C_{pf}$ (‰) values ranged between -0.06 ‰ to 1.22 ‰ during MIS 7 and MIS 6 with an average of 0.55 ‰ before increasing to 1.44 ‰ during MIS 5 and later declining during MIS 2. $\delta^{13}C_{pf}$ (‰) increased to 1.58 ‰ during MIS 1. Overall, the $\delta^{13}C_{pf}$ (‰) values exhibit a declining trend during all glacial intervals (MIS 2, 4, 6, 8, and 10) (Figs. 4, 5).

4.4 Spectral and cross-spectral analysis

Spectral analysis of oxic genus *Quinqueloculina* (%) shows prominent cyclicity of 106, 23, 7, and 6 kyr (Fig. 6a). The suboxic genus *Bulimina* (%) shows abundance peaks at 44, 23, 13, 11, 10, 5, and 4 kyr (Fig. 6b) and the dysoxic genus *Globobulimina* (%) at 132, 24, 8, 7, and 6 kyr (Fig. 6c). The spectral analysis of $\delta^{13}C_{pf}$ exhibits peaks at 105, 40, 28, 23 kyr (Fig. 6d). The cross-spectral analysis of benthic genera (*Quinqueloculina* (%), *Bulimina* (%), and *Globobulimina* (%)) versus $\delta^{18}O_{Seawater}$ (precipitation run-off proxy, Clemens et al. (2018)) and Factor 4 loadings (KC Index, Vats et al. (2020)) show a broad coherency range (0.45 to 0.87) on both 100 kyr band and

23 kyr band (Table S1). The cross-spectral analysis of U1429 $\delta^{13}C_{pf}$ versus U1429 $\delta^{18}O_{Seawater}$ show a higher coherency (0.90) in 100 kyr band, and of U1429 $\delta^{13}C_{pf}$ versus KC Index show a very high coherency on both 100 kyr band (0.89) and 23 kyr band (0.90) (Table S1).

5 Discussion

5.1 ECS Bottom water oxygenation history

The bottom water oxygenation history of the ECS over the last 400,000 years is reconstructed using environmental significance of individual biofacies (Table 1, Figs. 3, 5) in addition to the abundance of oxic, suboxic and dysoxic species (Table 2, Fig. 4).

5.1.1 MIS 11 to MIS 8

The consistent occurrences of the suboxic biofacies Mc, Ct, and Hb suggest that the ECS bottom water remained overall suboxic between MIS 11 and 8 (Fig. 3). The dominance of suboxic species and the lower abundance of dysoxic species also support the presence of suboxic bottom water conditions at the sediment-water interface in the ECS during MIS 11 to 8 (Fig. 4). The water column above the sediment-water interface may have remained oxic, as evidenced by the abundance of the oxic radiolarian species *C. davisiana* (Matsuzaki et al., 2019). The relatively constant benthic foraminiferal diversity suggests no major benthic foraminiferal turnover occurred during this phase (Fig. 5).

5.1.2 MIS 7 to MIS 6

A slight decline in suboxic species and an increasing trend of dysoxic species indicate that bottom water became suboxic to dysoxic towards the end of MIS 8 (Fig. 4). The occurrence of biofacies Um suggest that ECS bottom water was overall suboxic to dysoxic during MIS 7 (Figs. 3, 5), except for some transient moderate productivity events characterized by intermittent increases in the suboxic biofacies Mc (Fig. 3). The overall low diversity and relatively higher abundance of dysoxic species further support suboxic to dysoxic conditions during this period

(Figs. 4, 5). The continuation of biofacies Um (Figs. 3, 5) suggests that suboxic to dysoxic conditions even during MIS 6.

5.1.3 MIS 5 to MIS 4

The occurrences of biofacies Mc and Ct suggest that the ECS bottom water was suboxic during MIS 5 with intermittent dysoxic pulses (Figs. 3, 5) between T-II and ~110 ka. The occurrence of biofacies Ct during MIS 5 indicates enhanced pulsed phytodetritus input in the ECS. The abundance of the dysoxic species, *Globobulimina* genus, and biofacies Co suggest prevalence of dysoxic conditions from mid-MIS 5 (~110 ka) to MIS 4 (Figs. 3, 5; Fig. S3). During the termination event, T-II, a major switch in deep-sea oxygenation occurred at the sediment/water interface as well as within the water column, which corresponds to a decrease in the oxic radiolarian species *C. davisiana* (Matsuzaki et al., 2019). The biofacies Ct (Fig. 3) at the end of the glacial MIS 4 marks an improvement in bottom water oxygenation in the ECS. The marine productivity indicators and the dysoxic species exhibited declining trends, whereas the suboxic species displayed an increasing trend, which together suggests that productivity decreased by the end of MIS 4 (Fig. 4).

5.1.4 MIS 3 to MIS 1

The occurrence of biofacies Um, Hb, Co, and Gv (Figs. 3, 5) suggests that bottom water conditions in the ECS were characterized by variable oxygen concentrations between MIS 3 and 1. An increase in suboxic species abundance suggests the prevalence of suboxic as well as intermittent dysoxic conditions during MIS 3. The occurrence of biofacies Gv and a slightly increasing trend of oxic species coincident with a declining trend of suboxic species (Figs. 3, 4, 5) suggest that ECS water became oxic during the glacial MIS 2. The alternations between biofacies Hb and Um and the shifts in the abundance of suboxic species (Figs. 3, 4, 5) during MIS 1 suggest variable bottom water oxygenation.

5.2 Kuroshio Current as a forcing factor of ECS bottom water oxygenation

The KC intrusion onto the ECS shelf was stronger during interglacial periods (Vats et al., 2021; MIS 11, 9, 7, and 5), whereas the lowering of sea level adversely influenced KC intrusion in the ECS. For instance, a 43 % reduction in KC inflow occurred during the LGM linked to the low sea-level stand (Kao et al., 2006). Thus, the KC strength also reflects sea-level changes to the paleoceanography of the ECS. The upwelling of subsurface KC, a major nutrient supplier in the ECS (Chen et al., 1995; K. K. Liu et al., 1992; Vats et al., 2020; Wu et al., 2008; P. Zhou et al., 2018b), significantly increases primary productivity in the upper layer, leading to the sinking of organic matter to sea floor. In addition, the shallow nature of the ECS and its trough-like bathymetry promote the sinking of organic matter. During interglacial periods (MIS 11, 9, 7, and 5), rapid utilization of dissolved oxygen by sinking organic matter in the ECS water column caused suboxic to dysoxic bottom water conditions, which varied in relation to the intensity of KC upwelling. By contrast, KC intrusion was low during glacial periods (10, 8, 6, and 2), when sea level was relatively low (Vats et al., 2020; Spratt & Lisiecki, 2016; Figs. 5, 7), and EASM precipitation played a major role in controlling primary productivity during glacial periods.

5.3 East Asian Summer Monsoon as a forcing factor of ECS bottom water oxygenation

The EASM influences the ECS bottom water oxygenation by supplying massive terrigenous (refractory) organic matter and/or nutrients (Lee et al., 2001; Matsuzaki et al., 2016). The Yangtze River estuaries exhibit summertime hypoxia due to increased primary productivity, which may extend from the continental shelf area to the OT (D. Li et al., 2002; Wei et al., 2007; Zhu et al., 2011; Fig S1). Lower sea-level during extreme glacial stands lead to migration of the river mouth further towards OT (D. Zhao et al., 2017), and stronger/weaker EASM in such setup could be crucial in determining the amount of organic export flux and thus the bottom water oxygenation in the ECS.

During MIS 10, the EASM was relatively weak, as suggested by the composite δ^{18}O values from the Sanbao cave (Cheng et al., 2016; Clemens et al., 2018; Figs. 5, 7), and productivity was low (lighter $\delta^{13}C_{pf}$, low TOC (%) and low $CaCO_3$) in the ECS (Fig. 4). A weak monsoon reduced the terrigenous organic matter flux leading to lower mass accumulation rates (Anderson et al., 2018) and to lower TOC (%) and $CaCO_3$ (%) (Black et al., 2018; Fig. 4). The weak EASM and KC acted in concert to reduce the total amount of organic carbon sinking to the bottom of the ECS during MIS 10, resulting in an oxic to suboxic water column, as indicated by the abundance of the oxic radiolarian species *C. davisiana* (Fig. 5; Matsuzaki et al., 2019) and the foraminiferal suboxic genus *Bulimina* and oxic genus *Quinqueloculina* (Fig. S3). During MIS 9, SST increased in the

ECS and EASM precipitation became enhanced (Clemens et al., 2018; Vats et al., 2020), leading to a higher CDW discharge (Vats et al., 2020) and to suboxic bottom water conditions that became dysoxic by the end of MIS 8 during termination T-III (biofacies Um; Figs. 3, 5). The prevalence of warm conditions is also supported by higher abundances of the shallow warm water radiolarian genus *Tetrapyle* (Matsuzaki et al., 2019) and planktic foraminifera *Globigerinoides ruber* (Vats et al., 2020). Thus, the relative strengthening of EASM and KC (e.g., during MIS 9) and relative weakening EASM and KC (e.g., during MIS 10 and 8) caused moderate organic export flux; and thus, prevalence of suboxic bottom water conditions in the ECS (Fig. 7).

The strengthening of the EASM and KC during MIS 7 maintained higher productivity in the ECS. By contrast, the KC was relatively weaker during MIS 6, as suggested by the declining trend of the KC indicator species *Globigerinodes ruber* (Vats et al., 2020) and lower sea-level (Spratt & Lisiecki, 2016), and SST varied within a range of ±1°C in the ECS (Clemens et al., 2018). Warm ECS condition, also supported by the presence of the planktic foraminifera *Globorotalia inflata* at the end of MIS 6 (Vats et al., 2020) may have been associated with changes in Northern Hemisphere insolation (Pahnke, 2003). These warmer conditions enhanced EASM precipitation, while the sea level low stand exposed most of the ECS continental shelf, leading to a shift of the Yellow/Yangtze River estuaries towards the OT (Ijiri et al., 2005; Kawahata & Ohshima, 2004; Tada et al., 2015; Xie et al., 1995; D. Zhao et al., 2017). The increased EASM precipitation and shift of the river mouths enhanced the input of terrigenous organic matter to the OT, as indicated by the prevalence of the suboxic to dysoxic biofacies Um (Figs. 3, 5). The relatively stable TOC (%) synchronous with a $CaCO_3$ (%) decline also confirms that the terrigenous organic export flux increased in relation to primary productivity. The development of oxygen depleted conditions in the OT bottom waters during MIS 6 was comparable to modern-day formation of hypoxia in river estuaries of the ECS. Thus, the relative strengthening of either KC or EASM (e.g., KC during MIS 7 and EASM during MIS 6 respectively) causes suboxic to dysoxic bottom water conditions (Fig. 7).

The enhanced pulsed phytodetritus input (biofacies Ct during MIS 5 onset; Figs. 3, 5) may have been linked to the strengthening of the KC and EASM during MIS 5 (Cheng et al., 2016; Clemens et al., 2018; Vats et al., 2020) in the ECS. Further strengthening of the KC and EASM induced rapid sinking of organic matter and consumption of dissolved oxygen from the entire water column during mid MIS 5; ultimately leading to dysoxic bottom water conditions in the ECS that continued during MIS 4. $CaCO_3$ (%), TOC (%), and $\delta^{13}C_{pf}$ (‰) values suggest higher productivity associated either with upwelling of the subsurface KC and/or increased influx from the CDW discharge (Vats et al., 2020; Matsuzaki et al., 2019). Thus, the stronger KC and EASM (e.g., during MIS 5) deposit massive organic matter and forms dysoxic bottom water conditions in the ECS (Fig. 7).

Although the KC was generally weak during MIS 3-2, enhanced EASM (Vats et al., 2020) may have caused suboxic and intermittent dysoxic conditions in the ECS. The relatively stable trend of TOC values and $\delta^{13}C_{pf}$ values during MIS 3-2 indicates that primary productivity remained high, suggesting a higher influx of terrigenous organic matter and nutrients delivered by the CDW (Vats et al., 2020). However, during the LGM, the sea level fell by ~120 m, and EASM precipitation intensity weakened (Jiang & Lang, 2010; Sun et al., 2021). Together these conditions led to a substantial decline in marine productivity (lighter $\delta^{13}C_{pf}$ (‰) and low $CaCO_3$ (%); Fig. 4) and prevalence of oxic bottom water conditions in the ECS (Anderson et al., 2018; Kubota et al., 2010). Thus, the simultaneous weakening of KC and EASM (e.g., during LGM) cause oxic bottom water conditions in the ECS (Fig. 7). The interplay of biofacies Um and Hb during MIS 1 (Figs. 3, 5) suggests variable bottom water oxygenation, related either to the variability of EASM precipitation or the KC strength. Higher-resolution studies are required to further constrain the variability of ECS deep-water oxygenation on millennial to centennial-scales over the last two MIS stages.

5.4 Evolution of productivity and bottom water oxygenation in the ECS in relation to global climate trends

Benthic foraminiferal proxy data indicate marked variability in productivity, organic export flux and bottom water oxygenation over the last 400,000 years in the ECS. The oxic genus *Quinqueloculina* (%), and the productivity indicators $\delta^{13}C_{pf}$ exhibits ~100 kyr cyclicity (Fig. 6). Clemens et al. (2018) suggested that glacial-interglacial climate variability exerted an important control on local seawater properties (i.e., riverine influx). Thus, the 100 kyr cyclicity signal in *Quinqueloculina* (%) and the productivity indicator $\delta^{13}C_{pf}$ (Figs. 6a, 6d) is in phase with the 100 kyr cyclicity in local $\delta^{18}O_{sea\ water}$ suggesting EASM run-off (Clemens et al., 2018) in the ECS. The

Asian monsoon precipitation is modulated by global ice volume and greenhouse gases 100 kyr cyclicity during the middle to late Pleistocene (Clemens et al., 2021). Therefore, the long-term variations oxygenation of ECS bottom water was likely influenced by EASM related primary productivity changes linked to variations in nutrient input derived from terrestrial organic matter in the ECS; which may have been associated with greenhouse forcing or high-latitude ice sheet forcing during the late Pleistocene (Clemens et al., 2018, 2021).

Glacial-interglacial seas level changes additionally controlled the intensity of the KC intensity and the Tsushima warm current into the Japan Sea (Das et al., 2018, 2020; Gallagher et al., 2018; Saavedra-Pellitero et al., 2019). Spectral analysis of the oxic genus *Quinqueloculina* (%), suboxic genus *Bulimina* (%), dysoxic genus *Globobulimina* (%) and productivity indicator $\delta^{13}C_{pf}$ additionally reveals a prominent ~23 kyr cyclicity, likely related to KC-driven productivity changes in the ECS. Precession exerts a strong control on the KC inflow and the associated Tsushima Warm Current in the neighbouring Japan Sea (Vats et al., 2020, Das et al., 2021), which in turn strongly influences productivity and bottom water oxygenation in the ECS. The dominance of 23 kyr precession scale variance in benthic foraminiferal proxy records suggests that enhanced summer insolation forcing plays a more important role in controlling the bottom water oxygenation of the ECS.

The presence/absence of precession scale variability in EASM records across different proxies is highly debated. Precession scale variance dominates in speleothem $\delta^{18}O$ EASM records (Cheng et al., 2016); however, precipitation runoff records (U1429 $\delta^{18}O_{Seawater}$) from the ECS significantly lacks the precession band variance (Clemens et al., 2018). The most abundant suboxic genera *Bulimina* in the ECS, shows a similar coherency (0.68) with U1429 $\delta^{18}O_{Seawater}$ on 100 kyr band and KC Index (F4 loading) on 23 kyr band, suggesting that ECS productivity has 100 kyr cyclicity due to EASM and 23 kyr cyclicity due to KC (Table S1). This observation is further supported by a productivity indicator (U1429 $\delta^{13}C_{pf}$), which shows a similar cross-spectral signature (coherency=0.90) against U1429 $\delta^{18}O_{Seawater}$ on 100 kyr band and KC Index-F4 loading on 23 kyr band with almost similar phase values (Table S1). Since ECS marine productivity is linked with EASM and KC influencing the organic export flux to the bottom, impacting the benthic foraminiferal assemblage and bottom water oxygenation. Hence, it is inappropriate to disentangle the timing and phase of EASM from benthic foraminiferal records.

6 Conclusions

Multivariate analysis of benthic foraminiferal assemblages allows retracing of the history and variability in ECS bottom water oxygenation over the last 400 kyr, suggesting four different phases of bottom water oxygenation. Bottom water was generally suboxic between mid MIS 11 and the end of MIS 8, except for transient intervals of suboxic to dysoxic conditions during MIS 8. The ECS bottom water subsequently became suboxic to dysoxic during MIS 7 and 6, reflecting a general increase in productivity, then remained dysoxic during MIS 5 and 4. Bottom water oxygenation exhibited major changes between oxic to dysoxic conditions from MIS 3 to 1. The dominant biofacies in the ECS over the last 400 kyr are biofacies Mc representing suboxic condition, biofacies Um representing suboxic to dysoxic condition and biofacies Co representing dysoxic conditions. The oxic benthic foraminifera and marine productivity proxy $\delta^{13}C_{pf}$ respond to the global ice volume change and greenhouse gas that modulated 100 kyr East Asian Monsoon precipitation cycle. The oxic, suboxic, and dysoxic foraminiferal genera and $\delta^{13}C_{pf}$ respond to 23 kyr precessional variability related to KC strength. This study suggests that bottom water oxygenation in the ECS is directly influenced by the terrigenous supply of organic matter and primary marine productivity on 100 and 23 kyr cycles.

Open Research

Benthic foraminiferal percentage abundance data for the last 400 kyr from Site U1429 generated for this study. Major benthic foraminiferal abundance data, Biofacies abundance data and oxic-suboxic-dysoxic benthic foraminiferal species abundance data archived at Mendeley Data (http://dx.doi.org/10.17632/gcsgc2byps.2; Vats et al., 2021).

Acknowledgments

The authors are grateful to IODP for providing core samples to RKS (Request No. #4201 and 13522). RKS, NV and DKP acknowledge the financial support given by the ESSO-National Centre for Polar and Ocean Research, Ministry of Earth Sciences, India, to carry this research. RKS acknowledges SERB (CRG/2020/000396) for support. NV acknowledges CSIR, New Delhi, for providing CSIR-JRF and CSIR-SRF (09/1059(0013)/2017-EMR-I). MD acknowledges DST, New Delhi, for providing INSPIRE Fellowship (IF150105). AKG thanks DST, New Delhi, for the J.C. Bose Fellowship (SR/S2/JCB-80/2011). Funding was provided by the Australian IODP Office and the Australian Research Council (ARC) Basins Genesis Hub (IH130200012) to SJG. The authors declare no conflicts of interest. We are grateful to Editor Ursula Röhl, Associate Editor and two anonymous reviewers for their constructive suggestions that significantly improved the manuscript.

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Tables:

Table 1. *Benthic Foraminiferal Biofacies, Factor Scores and their preferred Environments at Site U1429.*

Biofacies	**Factor Scores**	**Environment**	**Age (ka)**
1. **Biofacies Gv (**Factor 1^{-ve})		High energy conditions, pulsed food supply, oxic to slightly suboxic bottom water conditions	23-14
Gavelinopsis sp.	-0.64		
Oridorsalis umbonatus	-0.49		
Gyrodinoides cibaoensis	-0.46		
Quinqueloculina seminulum	-0.36		
2. **Biofacies Co** (Factor 2^{+ve})		High productivity, high food supply, highly dysoxic bottom water conditions	206, 93-41, and 27-17
Chilostomella oolina	0.81		
Fursenkoina rotundata	0.52		
Globobulimina pacifica	0.36		
3. **Biofacies Hb** (Factor 4^{-ve})		Moderate to high influx of organic carbon, suboxic bottom water conditions	302-295, 39-30, and 15-0
Hyalinea balthica	-0.46		
Bulimina mexicana	-0.44		
Hoeglundina elegans	-0.36		
Valvulineria sadonica	-0.32		
4. **Biofacies Ct** (Factor 3^{+ve})		Enhanced but pulsed flux of phytodetritus, suboxic conditions with intermittent dysoxic conditions	331, 278-262, 153, 114-107, and 60-57
Cassidulina teretis	0.74		
Epistominella exigua	0.53		
Cassidulina laevigata	0.47		
Bolivina robusta	0.47		
Globocassidulina subglobosa	0.42		
5. **Biofacies Um** (Factor 5^{-ve})		High productivity, high influx of organic matter, suboxic to slightly dysoxic bottom water conditions	390-386, 282-218, 188-138, and 29-1
Uvigerina mediterranea	-0.55		
Uvigerina pygmaea	-0.49		
Uvigerina peregrina	-0.47		
6. **Biofacies Mc** (Factor 1^{+ve})		Suboxic bottom water conditions, moderate organic carbon flux	396-283, 248-242, 212-193, 158, 135-122, 74 and 61
Martinotiella communis	0.44		
Gaudryina sp.	0.41		
Amphicoryna scalaris	0.33		
Uvigerina auberiana	0.33		
Melonis barleeanum	0.32		
Bulimina aculeata	0.32		

Table 2. *List of Oxic, Suboxic, and Dysoxic species recorded at Site U1429.*

Type:	**Microhabitat**	**Species:**
Oxic Species	Epifaunal	*Cibicidoides mundulus* (Kaiho, 1994; Pérez-Asensio et al., 2017)
	Epifaunal	*Cibicidoides wuellerstorfi* (Moumita Das et al., 2017; De & Gupta, 2010; Kaiho, 1994)
	Epifaunal	*Epistominella exigua* (Bhaumik et al., 2007; De & Gupta, 2010)
	Epifaunal	*Gavelinopsis* sp. (Akimoto & Hasegawa, 1989; Takata et al., 2018)
	Epifaunal	*Globocassidulina subglobosa* (Araújo et al., 2018; Kaiho, 1994; Kaminski, 2012; R. K. Singh et al., 2021; Verma et al., 2013)
	Epifaunal	*Quinqueloculina seminulum* (Moumita Das et al., 2017; Hayward et al., 1997; Kaminski, 2012; Laprida et al., 2007)
	Epifaunal	*Sigmoilopsis schlumbergeri* (Kaminski, 2012; Mackensen et al., 1995; Saravanan et al., 2019)
Suboxic Species	Shallow infaunal	*Amphicoryna scalaris* (García-Sanz et al., 2018; Kaminski, 2012)
	Intermediate to deep infaunal	*Bulimina aculeata* (Moumita Das et al., 2017; Kaiho, 1994; Kaminski, 2012)
	Deep infaunal	*Bulimina marginata* (Moumita Das et al., 2017; Kaminski, 2012; Saravanan et al., 2019)
	Infaunal	*Bulimina mexicana* (Grunert et al., 2018)
	Shallow infaunal	*Cassidulina laevigata* (Bubenshchikova et al., 2010; Schmiedl et al., 1997)
	Infaunal	*Cassidulina teretis* (Cronin et al., 2019; Mackensen & Hald, 1988)
	Shallow to deep infaunal	*Gaudryina* sp. (Rostami et al., 2020)
	Epifaunal	*Gyroidinoides cibaoensis* (Bhaumik et al., 2007; Moumita Das et al., 2017; De & Gupta, 2010)
	Epifaunal	*Hoeglundina elegans* (Gupta & Thomas, 1999; Kaiho, 1994, 1999; Sarkar & Gupta, 2014)
	Shallow infaunal	*Hyalinea balthica* (Charrieau et al., 2018; Moumita Das et al., 2017; Kaminski, 2012)
	Intermediate infaunal	*Melonis barleeanum* (Fontanier et al., 2002, 2005; Kaminski, 2012; Schmiedl et al., 2000)
	Infaunal	*Martinottiella communis* (Culver & Buzas, 1987; Jian et al., 1999; Kender & Kaminski, 2017)
	Infaunal	*Nonionina communis* (Diz & Francés, 2008; Fontanier et al., 2002)
	Shallow infaunal to epifaunal	*Oridorsalis umbonatus* (Bubenshchikova et al., 2010; Moumita Das et al., 2017)
	Infaunal	*Pullenia bulloides* (Moumita Das et al., 2017; Gupta & Thomas, 1999; Rathburn & Corliss, 1994)
	Infaunal	*Pullenia quinqueloba* (Moumita Das et al., 2017; Kaminski, 2012; N. Wang et al., 2018)
	Shallow infaunal	*Uvigerina auberiana* (Bubenshchikova et al., 2010; Gorbarenko et al., 2004; Kuhnt et al., 1999; Schmiedl et al., 1997)
	Shallow infaunal	*Uvigerina mediterranea* (Manisha Das et al., 2018; Schmiedl et al., 2000)
	Shallow infaunal	*Uvigerina peregrina* (Manisha Das et al., 2018; Lutze, 1979; Schmiedl et al., 1997; Schmiedl & Leuschner, 2005)
	Shallow infaunal	*Uvigerina pygmaea* (Manisha Das et al., 2018; Kastens & Mascle, 1990; Lutze, 1979)
	Intermediate infaunal	*Valvulineria sadonica* (Bubenshchikova et al., 2010)
Dysoxic Species	Infaunal	*Bolivina robusta* (Haller et al., 2018; Kaiho, 1994; B. Zhao et al., 2018)
	Deep infaunal	*Chilostomella oolina* (Kaiho, 1994; McGann & Conrad, 2018; N. Wang et al., 2018)
	Infaunal	*Fursenkoina rotundata* (Moumita Das et al., 2017; Kaiho, 1994; Patarroyo & Martínez, 2015)
	Deep infaunal	*Globobulimina pacifica* (Moumita Das et al., 2017; McGann & Conrad, 2018)

Figure Captions:

Figure 1. Location of IODP Site U1429 (31°37.04’N, 128°59.85’E, 732 mbsl) in the East China Sea (Blue star). Location of the Sanbao cave in China (Filled black circle). Black arrows indicate surface current directions. Magenta arrows indicate the East Asian Summer Monsoon (EASM) direction. CDW– Changjiang Diluted Water, NPIW– North Pacific Intermediate Water, TWC– Tsushima Warm Current, NPSG– North Pacific Subtropical Gyre, TSS– Tsushima Strait, TGS– Tsugaru Strait. Surface currents marked after D. Zhao et al. (2017) and EASM direction marked after N. Li et al. (2021). This map was made with GeoMapApp (http://www.geomapapp.org) using the GMRT data set (Ryan et al., 2009).

Figure 2. Light microscope photographs of the dominant benthic foraminifera (32 species) present at Site U1429. Plate (a): 1. *Amphicoryna scalaris* (side view) 2. *Bolivina robusta* (side view) 3. *Bulimina aculeata* (side view) 4. *Bulimina marginata* (side view) 5. *Bulimina mexicana* (side view) 6. *Cassidulina laevigata* (umbilical view) 7. *Cassidulina laevigata* (spiral view) 8. *Cassidulina teretis* (umbilical view) 9. *Cassidulina teretis* (spiral view) 10. *Chilostomella oolina* (side view) 11. *Cibicidoides mundulus* (spiral view) 12. *Cibicidoides mundulus* (umbilical view) 13. *Cibicidoides wuellerstorfi* (spiral view) 14. *Cibicidoides wuellerstorfi* (umbilical view) 15. *Epistominella exigua* (spiral view) 16. *Epistominella exigua* (umbilical view) 17. *Fursenkoina rotundata* (side view) 18. *Fursenkoina rotundata* (apertural view) 19. *Gaudryina* sp. (side view) 20. *Gavelinopsis* sp. (spiral view) 21. *Gavelinopsis* sp. (umbilical view) 22. *Globobulimina pacifica* (side view) 23. *Globocassidulina subglobosa* (apertural view) 24. *Gyroidinoides cibaoensis* (spiral view) 25. *Gyroidinoides cibaoensis* (umbilical view); Plate (b): 1. *Hoeglundina elegans* (spiral view) 2. *Hoeglundina elegans* (umbilical view) 3. *Hyalinea balthica* (spiral view) 4. *Martinottiella communis* (side view) 5. *Melonis barleenaum* (spiral view) 6. *Nonionina communis* (side view) 7. *Oridorsalis umbonatus* (spiral view) 8. *Oridorsalis umbonatus* (umbilical view) 9. *Pullenia bulloides* (side view) 10. *Pullenia quinqueloba* (side view) 11. *Quinqueloculina seminulum* (side view) 12. *Sigmoilopsis schlumbergeri* (side view) 13. *Uvigerina auberiana* (side view) 14. *Uvigerina mediterranea* (side view) 15. *Uvigerina peregrina* (side view) 16. *Uvigerina pygmaea* (side view) 17. *Valvulineria sadonica* (umbilical view) 18. *Valvulineria sadonica* (spiral view) [All Scale bars = 100 μm].

Figure 3. Benthic foraminiferal biofacies at Site U1429 plotted against interpolated ages (a-g), (a, b) Green shading and diamond indicate biofacies Mc (%), (a, c) Blue shading and diamond indicate biofacies Um (%), (a, d) Orange shading and diamond indicate biofacies Ct (%), (a, e) Purple shading and diamond indicate biofacies Hb (%), (a, f) Pink shading and diamond indicate biofacies Co (%), (a, g) Light green shading and diamond indicate biofacies Gv (%). Biofacies: Mc- *Martinottiella communis*, Um- *Uvigerina mediterranea*, Ct- *Cassidulinia teretis*, Hb- *Hyalinea balthica*, Co- *Chilostomella oolina*, Gv- *Gavelinopsis sp.* Dark grey bars indicate MIS stages. Dark blue lines mark the termination events T-I, T-II, T-III, and T-IV.

Figure 4. Plot of (a) Oxic species abundance (%), (b) Suboxic species abundance (%), (c) Dysoxic species abundance (%), (d) $CaCO_3$ (%) and (e) TOC (%) (Black et al., 2018); (f) Planktic foraminiferal $\delta^{13}C_{pf}$ (‰) and (g) Benthic foraminiferal $\delta^{18}O_{bf}$ (Clemens et al., 2018) plotted against age at Site U1429. Dark blue lines mark the termination events T-I, T-II, T-III, and T-IV. The colored bold curves are smooth curve fit using Stineman function to the data and the output has a geometric weight applied to the current point and ± 10% of the data range, applied using KaleidaGraph software. Dark grey bars indicate MIS stages.

Figure 5. (a) Benthic foraminiferal biofacies, (b) Dysoxic species abundance (%), (c) Benthic foraminiferal diversity as Shannon Index (H), (d) Oxic radiolarian species *C. davisiana* (%) (Matsuzaki et al., 2019), (e) KC Index- Factor 4 loading (Vats et al., 2020), (f) $\delta^{13}C_{pf}$ (‰) (Clemens et al., 2018) at Site U1429, and (g) Composite Chinese cave $\delta^{18}O$ (‰) as Asian Monsoon indicator (Cheng et al., 2016) and (h) Late Pleistocene Sea level stack (Spratt & Lisiecki, 2016). Dark blue lines mark termination events T-I, T-II, T-III, and T-IV. The colored bold curves are smooth curve fit using Stineman function to the data and the output has a geometric weight applied to the current point and ± 10% of the data range, applied using KaleidaGraph software. Dark grey bars indicate MIS stages. Biofacies: Mc- *Martinottiella communis*, Um- *Uvigerina mediterranea*, Ct- *Cassidulinia teretis*, Hb- *Hyalinea balthica*, Co- *Chilostomella oolina*, Gv- *Gavelinopsis sp.*

Figure 6. Spectral analysis of (a) oxic genus *Quinqueloculina* (%), (b) suboxic genus *Bulimina* (%), (c) dysoxic genus *Globobulimina* (%), and (d) $\delta^{13}C_{pf}$ (‰) at Site U1429 for the period 400 to 0 ka revealing significant periodicities at 90% significance level.

Figure 7. Schematic representation of forcing mechanisms controlling bottom water oxygenation

over the last ~400 ka in the ECS. Dashed line represents the Sea-Level (SL) during MIS stages marked after Matsuzaki et al. (2019). Biofacies: Mc- *Martinottiella communis*, Um- *Uvigerina mediterranea*, Ct- *Cassidulinia teretis*, Hb- *Hyalinea balthica*, Co- *Chilostomella oolina*, Gv- *Gavelinopsis sp.*