East Asian monsoon history and paleoceanography of the Japan Sea over
the last 460,000 years

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Abstract The Japan Sea is directly influenced by the Asian monsoon, a system that transports moisture and heat across southeast Asia during the boreal summer, and is a major driver of the Earth’s ocean-atmospheric circulation. Foraminiferal and facies analyses of a 460 kyr record from IODP Expedition 346 Site U1427 in the Japan Sea reveal a record of nutrient flux and oxygenation that varied due to sea level and East Asian monsoon intensity. The East Asian summer monsoon (EASM) was most intense during MIS (Marine Isotope Stage) 5e, 7e, 9e and 11e when the Tsushima Warm Current flowed into an unrestricted well mixed normal salinity Japan Sea. Whereas East Asian winter monsoon (EAWM) conditions dominated MIS 2, 4, 6 and 8 when sea level minima restricted the Japan Sea resulting in low salinity and oxygen conditions in the absence of Tsushima flow. Reduced oxygen stratified, low salinity, higher productivity oceanic conditions characterise terminations TV, TIII, TII and TI when East China Sea Coastal Waters breached the Tsushima Strait. Chinese loess, cave and Lake Biwa (Japan) and U1427 proxy records suggests EASM intensification during low to high insolation transitions whereas the strongest EAWM prevailed during lowest insolation periods or high to low insolation transitions. Icesheet/CO₂ forcing lead to the strongest EAWM events in glacials and enhanced EASM in interglacials. Mismatches between proxy patterns suggests latitudinal and land/sea thermal contrasts played a role in East Asian monsoon variability suggesting a complex interplay between ice sheet dynamics, insolation and thermal gradients controls monsoonal intensity.

Keywords: Tsushima Warm Current, Pleistocene, Holocene, paleoceanography, East Asian summer monsoon, East Asian winter monsoon, foraminifera
1. Introduction

The semi-enclosed Japan Sea on the northwest margin of the Pacific (Figure 1) is an ideal region to investigate the interaction between the ocean, climate and sea level variability. The oceanography of the region is influenced by the Asian monsoon, a system that transports moisture and heat across southeast Asia during the boreal summer, and is a major driver of planetary atmospheric circulation (Cheng et al., 2016). The Japan Sea is primarily connected to the open ocean via two shallow straits (130-140 m deep) and because of this it has been strongly affected by the consequences of Pleistocene glacio-eustatic variability. Previous studies based on the analyses of microfossil, sedimentary and oxygen isotope proxies show highly variable oxygenation and salinity conditions over the last 160 kys was driven by ice volume, primarily varying with eccentricity influence and this affected East Asian summer monsoon (EASM) variability (Tada et al., 1995, 1999, 2018; Watanabe et al., 2007; Usami et al., 2013). The current well-mixed open ocean circulation mode of the present Japan Sea is similar to Marine Isotope Stage (MIS) 5e (Tada et al., 1999), yet during glacial maxima the Japan Sea was isolated. This change caused the surface salinity to decrease (as a result of an imbalance between precipitation and evaporation) and the resulting density stratification caused reduced oxygen bottom waters in MIS 2 and 6 (Oba et al., 1991; Tada, 1994; Tada et al., 1999; Usami et al., 2013). Periodic intrusions of relatively lower salinity, nutrient-rich waters into the Japan Sea from the East China Sea from MIS 3 to 5d was the result of an enhanced East Asian summer monsoon (EASM) which led to higher surface productivity and weaker oceanic circulation (Tada et al., 1999; Watanabe et al., 2007; Usami et al., 2013).

The oceanographic and climatic history of the Japan Sea prior to 160 kyrs is poorly constrained.

The glacial to interglacial mode described for the Japan Sea is interpreted to have likely started with the onset of the large amplitude climate cycles during the Middle Pleistocene Transition at ~0.8 Ma (Tada, 1994). Tsushima Warm Current inflow via an open Tsushima Strait has
intermittently occurred over the last few million years during highstands (Kitamura et al., 2001; Hoiles et al., 2012; Gallagher et al., 2015; Itaki, 2016). Longer-term climate records adjacent to Site U1427 from Lake Biwa (LB; Figure 1), central Japan (Nakagawa et al., 2008) and Chinese loess (Hao et al., 2012; Sun et al., 2015; Figure 1) records show that 100 kyr eccentricity and 41 kyr obliquity cycles dominate monsoon intensity and precipitation. The relationship between these terrestrial climate records and 460 kyr oceanographic history of the Japan Sea offers tantalizing glimpses into the complex interaction between sea level and monsoonal dynamics in the Japan Sea. Similarly, multiple proxies reveal a highly variable ventilation history over this period.

Integrated Ocean Drilling Program (IODP) Expedition 346 cored a series of sites in 2013 in the Japan Sea to obtain a continuous 5 Ma sedimentary record of Asian monsoon history (Tada et al., 2015a; Tada et al., 2018). The focus of this study is IODP Site U1427 (Tada et al., 2015b, 2018; Sagawa et al., 2018), adjacent to the western Japanese coastline underneath the main branch of the Tsushima Warm Current (Figure 1). We use sedimentary physical properties and facies, and benthic and planktic foraminiferal assemblage analyses of this section to reveal a high-resolution paleoceanographic history of the southern Japan Sea over the last 460 kyrs. The data reveal the strong relationship between sea level, monsoon and ocean variability over the last five glacial/interglacial cycles.

2. Oceanographic setting

The Japan Sea is a semi-closed marginal sea in the northwest Pacific. Its area exceeds 1,000,000 km² with an average depth of 1350 m (Oba et al., 1991; Tada, 1994; Tada et al., 1999). The sea is connected to the East China Sea through the Tsushima Strait (< 140 m), to the Pacific Ocean via the Tsugaru Strait (< 130 m), and to the Okhotsk Sea through the Soya (< 55 m) and
Mamiya (< 12 m) straits (Figure 1). The modern surface water of the Japan Sea is strongly influenced by the Tsushima Warm Current an offshoot of the Kuroshio Current (Figure 1; Gallagher et al., 2009; 2015). The warm saline Kuroshio Current mixes with the less saline nutrient-rich East China Sea Coastal Water (ECSCW) south of Japan (Figure 1; Qiu, 2001; Usami et al., 2013) before flowing into the Japan Sea via the Tsushima Strait as the Tsushima Warm Current (TWC; Figure 1). Today, the only oceanic water flowing into the Japan Sea is via the warm Tsushima Warm Current, with surface velocities ranging from 0.3 to 0.4 m/s⁻¹ and volumes from 1.1 to 2.6 Sverdrups in the Tsushima Strait flowing northward along the Coast of Honshu Island (Takikawa and Yoon, 2005). The majority of the current flows out through the Tsugaru Strait to the Pacific Ocean. Some of the current flows out through the Soya Strait to the Okhotsk Sea, the rest flows to the northern Japan Sea where it sinks to the bottom as it cools down to temperatures near 0°C (Suda, 1932; Moriyasu, 1972; Gamo and Horibe, 1983). This low temperature (0.1-0.3 °C), low salinity (34) and high dissolved oxygen concentration (>210 µmol/kg) homogenous water mass is the Japan Sea Proper Water (JSPW). JSPW dominates depths below 300 m (Oba et al., 1991; Tada et al., 1999; Ohta et al., 2015) and bathes the region around IODP Site U1427.

3. Site location and Methods

IODP Expedition 346 Site U1427 was cored in the Yamato Basin at 35°57.92’N, 134°26.06’E (Figure 1) at 337 meters water depth recovering nearly 550m of continuous sediment core below sea floor. This work focuses on detailed analyses of the top 180 m of this core (Figure 2). The lithology of the facies (Figure 2) was compiled from detailed shipboard core descriptions with interpretations of standard IODP shipboard physical property measurements (Tada et al., 2015a) and additional %carbonate data. Natural Gamma Radiation (NGR) logging was carried out on wholeround core though the section. Postcruise
U, Th and K elemental concentrations were extracted from the shipboard NGR spectral measurements using a least-squares method (see de Vleeschouwer et al., 2017). A colour reflectance spectrometer (Ocean Optics sensor) measured L* lightness, a* redness (positive) versus greenness (negative), and b* yellowness (positive) versus blueness (negative) of the strata. Carbonate content analyses using the volumetric technique of Wallace et al. (2002) was carried out on one hundred and sixty five samples (Figure 2). b* is illustrated (Figure 2) as it was found to be related to relative carbonate content (Tada et al., 2015b). The age model used in this work (Figure 2; Table 1) is from Sagawa et al. (2018) who constructed a detailed calibration using radiolarian biostratigraphy, tephrochronology and benthic foraminiferal isotope correlations to the LR2004 stack (Lisiecki and Raymo, 2005).

The sediment size is mainly silt (Figure 2), subdivided it into three main facies types: calcareous silt (with relatively high %carbonate (>5%) and b* and low NGR values), clayey silt (with high NGR values and low %carbonate (<5%) and b*) and silt (low NGR values and low %carbonate). When a sand component was recognised during visual core description, the facies were designated “sandy”. One hundred and sixty-three samples were processed for foraminifera by standard microfossil techniques for paleoenvironmental analyses (with emphasis on sea surface conditions and paleoproductivity proxies). The samples were split (using a micro-splitter) into several fractions. Quantitative benthic and planktic assemblage data were compiled from the ≥150μm fraction. The foraminiferal data are expressed as a percentage of the total fauna (eg. %plankton and %miliolids) or as a percentage of the calcareous benthic or planktic assemblage. Foraminiferal concentrations are expressed as numbers of foraminifera per gram of dry sediment (Figure 3).

Conditions within and on the seafloor are interpreted using facies and benthic foraminiferal assemblage data. Sea surface conditions are determined using planktic foraminiferal assemblage data (Figure 4, 5) and comparisons with modern regional analogues (Kuroyanagi
and Kawahata, 2004; Domitsu and Oda, 2005). Benthic foraminifera (Figure 6, 7) are sensitive indicators of bottom water conditions as they show variability related to dissolved oxygen and nutrient availability world wide (Kaiho, 1994; Jorissen, 1999; Gooday, 2003; Jorissen et al., 2007). Specific benthic foraminifer assemblage comparisons (in this work, Table 2) to modern analogues off Japan (Fontanier et al., 2014) and in the Okhotsk Sea (Bubenshchikova et al., 2008, 2015) allow fossil assemblages to be interpreted in their regional context (cf. Usami et al., 2013) accounting for the relative isolation of the Japan Sea compared to more open ocean settings. The diversity indices used (Figure 3) are the Fisher α index (Murray, 1991; 2006) and the Shannon–Weaver index $H(S)$ (Shannon and Weaver, 1949; Murray, 2006). $H(S)$ takes into account the number of taxa in a sample and their equitability of distribution within that sample. The Shannon–Weaver index is calculated as follows:

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

Where $H(S)$ = index of species diversity, $S$ = the number of species, $p_i$ = proportion of total samples belonging to the $i$th species. Our data are compared to global faunal data, where $H(S)$ values > 2 and Fisher α values >5 typify open marine shelfal and deep sea environments (Murray, 2006; the vertical lines on Figure 3) whereas values less than this are from more restricted marine and marginal marine environments. Bioturbation intensity is also strongly related to sea bed oxygenation (Watanabe et al., 2007). In this work the terms anoxic = 0.1 O$_2$ ml/l, dysoxic = 0.1-0.3 O$_2$ ml/l, suboxic = 0.3-1.5 O$_2$ ml/l and oxic = >1.5 O$_2$ ml/l (sensu Kaiho, 1994).

4. Results
4.1 Facies and physical properties

The sediment facies at IODP Site U1427 are strongly cyclic (Figure 2).

From the base to the top we observe:

a. The lowest strata (below 156 m, MIS 11/12) are sandy clayey silt overlain by clayey silt and a unit of laminated silt. Colour reflectance $b^*$ increases up section while brightness ($L^*$) and NGR values decrease associated with relatively high $\%K$, Th/U and Th/K ratios.

b. From ~156-84 m (MIS 11 to MIS 8) the two cycles are composed of calcareous silt (with high $b^*$, low brightness, $L^*$) at the base, grading upward to a calcareous clayey silt and a silt unit. Brightness ($L^*$), NGR values, $\%K$, Th/U and Th/K ratios increase and $b^*$ values decrease into the mud-rich facies and reverse in the silt. Sections with sandy facies are present from ~158-150 m and ~108-98 m. Bioturbation intensity is generally high, although there is a laminated interval at the start of MIS 11 and occasional homogenous clayey silt and silt units near the end of MIS 10 and MIS 8.

c. The sedimentary facies in the interval above ~84 m (MIS 7 to MIS 6) shows metre-scale variability. Calcareous silt (with high $b^*$ and low NGR values with low $\%K$, Th/U and Th/K ratios) alternate clayey silt (with low $b^*$, high $L^*$ and NGR values and high $\%K$, Th/U and Th/K ratios) and silt units. Sandy facies are present in MIS 7 and common in MIS 6. Intensely bioturbated horizons are present at ~70 m and 50 m. d. The upper cycle above ~50 m is a sandy calcareous silt that grades to a calcareous muddy silt (MIS 5 to 4) overlain by a 15 m interval (MIS 3) of meter scale silt/calcareous silt alternations. The uppermost 10 m (MIS 2 to MIS 1) is sandy silt that grades up section to clayey silt that is overlain by calcareous silt. NGR, $L^*$ and $b^*$ values in the upper 50 m show similar patterns to facies variations to the underlying cycles. The facies in the upper cycle is relatively homogenous with one interval of intense bioturbation at ~30 m.

4.2 Sedimentation Rates
Linear sedimentation rates increase from MIS 12 to Termination V and from MIS 10 to Terminations IV (Figure 3). Thereafter values range from 20 to 40 cm/kyr with occasional maxima near the start of MIS 8 and just prior to Termination II. Values decrease from MIS 5 to present.

### 4.3 Foraminiferal assemblages

Foraminiferal abundance is low in U1427 with an average 300 foraminifera/g of sediment with a maximum of ~2700 during MIS 3 (Figure 3). Abundance varies, intervals where foraminifera are absent or rare include MIS 12/base MIS 11, end of MIS 10/base MIS 9, end of MIS 7/base MIS 6, end of MIS 6/base MIS 5 and MIS 2 (Figure 3). Foraminiferal concentration maxima >1000 foraminifera/g of sediment are present in MIS 6, MIS 5e, MIS 5d and from MIS 4 to 3. In other intervals, foraminiferal abundance varies from 50 to 500 foraminifera/g. Maxima numbers of benthic foraminifera generally correspond to the abundance maxima described above, however, they are relatively common in MIS 11, near the start of MIS 9 and MIS 7. The relative abundance of planktic foraminifera varies markedly, ranging from 10% to 100% with an average of ~55% (Figure 3). With a mean value of 250 planktics/g of sediment, planktic foraminifera dominate the total foraminiferal concentration described above. Where foraminifera are present prior to MIS 5 the pattern of low and high planktic values follow b* values with common benthic foraminifera during periods with higher b* and %carbonate. The trend is similar from MIS 5, MIS 2 and MIS 1, however, the b* variation from MIS 4 to MIS 3 does not follow the %planktic pattern. Benthic foraminiferal diversity is generally low with Fisher α values typically < 5 and $H(S) < 2$. Peaks of $H(S)$ (> 2) and Fisher α (> 5) benthic diversity occur during the interglacial maxima of MIS 11, MIS 9e, MIS 8, MIS 7, MIS 5e and MIS 1 where the assemblages are generally well preserved. Other peaks of diversity are present in MIS 6 and MIS 3 corresponding to maxima in foraminiferal concentration values. In general the lowest diversity assemblages characterize glacial phases of MIS 10, MIS 8, MIS 6 and MIS
Planktic foraminifera

Three species of planktic foraminifera dominate (Figure 4, 5): *Globigerina bulloides* (the thick-walled form of Domitsu and Oda, 2005, Figure 4a), *Neogloboquadryina pachyderma* sinistral (Figure 4d,e) and *Globigerina quinqueloba* (Figure 4c). Other common species include: Tsushima Warm Current planktics (*sensu* Gallagher et al., 2015); *Globigerinoides ruber*, *Globorotalia tumida* (Figure 4h,i) and *Pulleniatina obliquiloculata* (Figure 4j), *Neogloboquadryina incompta* (Figure 4f,g) and the colder water species *Globigerina umbilicata* (Figure 4j).

Prior to 180 ka *Globigerina bulloides* are abundant at the base and top of MIS 11, near the top of MIS 10 and within MIS 8. *Globigerina bulloides* abundance fluctuate markedly after 180 ka with maxima near the top of MIS 6 and during MIS 1. With the exception of MIS 4 *G. bulloides* is also common from MIS 5e to MIS 2. The abundance of *G. quinqueloba* is variable, this species is rare from MIS 11 to 10 and MIS 5e to MIS 1 with maxima at ~180 and ~80 ka. *Globigerina quinqueloba* is common between ~310 and 160 ka reaching a maximum from MIS 7 and MIS 6. *Neogloboquadryina pachyderma* abundance in general shows the opposite pattern to the *G. bulloides* distribution (Figure 5), except in periods when Tsushima Warm Current species dominate (especially *N. incompta*) at ~405 ka, 315 ka and at present and where *G. quinqueloba* are most common. Although relatively rare, *Globigerina umbilicata* peak in MIS 8, MIS 6 and increase upward in abundance from MIS 3 to MIS 1.

Benthic foraminifera

Three calcareous foraminifera taxa dominate 50 to 90% of the benthic assemblages (Figure 6,
Islandiella norcrossi (Figure 6a), Trifarina angulosa (Figure 6b, also referred to as Angulogerina ikebei; Usami et al., 2013) and striate Uvigerina spp. The striate Uvigerina are also known as U. akitaensis (Figure 6e) and spinose striate forms are equivalent to U. cf. graciliformis, (Figure 6d, cf. Fontanier et al., 2014). Other relatively common taxa include (Figure 6): Cibicidoides spp. (C. pachyderma, C. refulgens and C. lobatulus, Figure 6h, j), Elphidium spp. (especially Elphidium excavatum, Figure 6j,k), miliolids (Quinqueloculina spp. and Triloculinella spp.), Pullenia bulloides (Figure 6l,m) and Globocassidulina subglobosa (Figure 6c).

Islandiella norcrossi is the dominant species in the section making up >40-50% of the benthic rotaliid assemblage. It is most abundant from MIS 10 to the base of MIS 7 and rarest above this level in MIS 7, MIS 6 and MIS 2. Uvigerina spp. abundance fluctuate markedly. Spinose/striate Uvigerina spp. peak in MIS 11 with variable maxima and minima from MIS 9 to MIS 7 reaching a maximum at the base of MIS 6. The distribution of spinose/striate Uvigerina is highly variable from MIS 5e to MIS 1 with a minimum during MIS 2. Uvigerina akitaensis abundance is generally low however, this taxon shows maxima at the base of MIS 11, top of MIS 8, base of MIS 6 and from MIS 4 to MIS 3.

The interval from the start of MIS 9 to the end of MIS 6 is characterized by short-lived peaks of less common benthic foraminiferal taxa. Taxa such as Gobobulimina pacifica (Figure 6f) and Fursenkoina bradyi peak at ~170 ka, ~160 ka and ~120 ka. Periodic maxima of neritic taxa (Figure 8) are present above interglacial maxima (MIS 9 to MIS 7) or just prior to glacial maxima (top of MIS 10 and MIS 6).
5. Discussion

5.1 Sedimentary facies and relative sea level

Sediment in the region near Site U1427 is dominated by sand facies shallower than 200 m water depth (the shelf edge), silt below 200 m and clay below 500 m (Ohta et al., 2015). Assuming relative wave base has not changed significantly in the last 460 kyr then glacial to interglacial sea levels are likely to have varied from ~337 (today’s depth) to ~210 m (last glacial maximum depth) (cf. Spratt and Lisiecki, 2016; Figure 6) accounting for the predominantly silty facies. These paleodepths are supported by the presence generally high (> 50%) %planktic values in the sequence (Figure 3) typical of upper slope depths > 200 m (van Hinsbergen et al., 2005). There is a strong relationship between facies and sea level. Calcareous silt dominated highstands, Clayey silt prevailed during the glacial maxima lowstands and silt during the terminations.

The clayey and sandy facies in lowstands reflects a closer proximity to the shelf edge and source of siliciclastics from regional fluvial systems, in the absence of inflow through the Tsushima Strait with the isolation of the Japan Sea (Tada, 2004). The lack of calcareous facies during these times may be due to a combination of dilution by siliciclastics (especially during periods with high sedimentation rates during Terminations V and IV and prior to TII, Figure 3) and/or decreased sea surface productivity (Tada et al., 1999; 2007). The predominance of clay (with high NGR values) during the glacials is likely related to eolian dust influx associated Chinese loess deposition (de Menocal et al., 1992). Intervals with increased Th/K and Th/U values in Site U1427 are interpreted to be related to increased aridity and dust influx (cf. Christensen et al., 2017; Groeneveld et al., 2017). Analyses of IODP 346 Site U1422 to the north of Site U1427 (Figure 1) showed that maxima in %K values in the Japan Sea are likely to be related to enhanced East Asian winter monsoon conditions and arid conditions over the
last 3.6 million years (Zheng et al., 2018). The higher values of all these proxies at Site U1427 therefore reflect the generally drier stronger winter monsoonal conditions prevailed during glacial compared to interglacial periods (Figures 2 and 9). Silt deposition during the later stages of the glacial periods and the deglaciations is likely related to the rapid flooding of the Tsushima Strait causing increased inflow of East China Sea coastal waters (ECSCW) into the Japan Sea and increased seabed current activity. The lack of sandy facies during these times may relate to reduced fluvial activity due to arid conditions (cf. Dersch and Stein, 1994). The transition to highstand conditions during interglacials decreased clayey facies due to the increasing dominance of the ECSCW and/or the Tsushima Warm Current higher energy flow through the Tsushima Strait. Similar warm sea surface temperatures to today, due to Tsushima Warm Current inflow, increased marine carbonate (calcareous microfossil) productivity during the highest sea level periods depositing calcareous silt. The sand and occasional maxima in neritic microfossils in highstand calcareous facies may have been transported via down slope mass wasting from the edge of the shelf and possibly via a “submarine valley”/canyon nearby (Ohta et al., 2015).

5.2 Sea surface conditions

Modern planktic foraminiferal assemblages reflect sea surface temperature and relative nutrient conditions in the Japan Sea (Kuroyanagi and Kawahata, 2004; Domitsu and Oda, 2005). The assemblages are dominated by warmer water Neogloboquadrina incompta (<20°C, Tsushima waters and high chlorophyll-α concentrations; Kuroyanagi and Kawahata, 2004) and colder water N. pachyderma (<12°C, typically ~5°C) with lesser amounts of Globigerina bulloidies and G. quinqueloba, taxa with wide temperature tolerances (Bé and Hutson, 1977; Koroyanagi and Kawahata, 2004). Presently Globigerina bulloidies (thick-walled form) and G. quinqueloba are abundant in nutrient rich low salinity water in the Tsushima Strait (Domitsu
and Oda, 2005) associated with an inflow of freshwater (ECSCW) from the Yangtze River. *Globigerina quinqueloba* is also common in sediment of the coastal region of western Japan associated with fluvial freshwater input (Domitsu and Oda, 2005). *Globigerina quinqueloba* shows a strong correlation to high chlorophyll-α concentrations and *G. bulloides* (thin-walled) is associated with upwelling in the Japan Sea near the Tsugaru and Tsushima Straits (Kuroyanagi and Kawahata, 2004). The modern distribution of *Globigerina umbilicata* is not well known as it is rare in the Japan Sea, however, it is typical of cold low salinity Last Glacial Maximum water in the region (Ujiié et al., 1983).

Previous analyses of glacial/interglacial planktic foraminiferal distribution (Domitsu and Oda, 2005; Usami et al., 2013; Ortakand et al., 2015) indicates that the present assemblage distribution typifies only brief interglacial warmer Tsushima Warm Current “anomalies” in the predominantly cold oceanic conditions in the Japan Sea over the last 160 kyrs. The high concentration of subpolar to polar *Neogloboquadryina pachyderma* at Site U1427 suggests cold (<12 °C, ~5°C average) oceanic conditions prevailed in all but the glacial/interglacial maxima over the last 460 kyrs.

The presence of abundant *Globigerina bulloides* (with rarer *G. umbilicata*) during glacial maxima MIS 2, MIS 6 and MIS 10 (Figure 5) suggest cold lower salinity nutrient rich surface water conditions. A similar assemblage in core MD01-2407 to the north of Site U1427 is interpreted to represent the mixing of high nutrient surface water caused by enhanced winter cooling due to the intensification of the winter monsoon (Usami et al., 2013). Alternatively, *Globigerina bulloides* (thick-walled) ingressions during MIS 5, MIS 8, MIS 9, MIS 11 and terminations TV, TIV, TII and TI are likely to be related to the inflow of fresh water and
nutrients from the China Sea (ECSCW) via the Tsushima Strait during summer monsoon conditions.

Maxima of *Globigerina quinqueloba* may also be related to fresh water inflow from the China Sea (possibly during summer monsoon conditions during MIS 11), however, their abundance in other intervals is most likely to be related to proximal fluvial runoff from the adjacent Japanese coastal region during the winter and/or summer monsoon. The switch from *G. bulloides* dominance (MIS 11/ MIS 10) to upward increasing *G. quinqueloba* from MIS 9 to MIS 6 suggests a marked increase in chlorophyll-$\alpha$ in the surface waters. The planktic assemblage from MIS 9 to MIS 6 is similar to the modern biota from the coastal region off western Japan (Domitsu and Oda, 2005) suggesting increased proximal fluvial freshwater influence on the salinity variability in the absence of ECSCW input. The *G. quinqueloba* maximum from MIS 5 to MIS 4 is interpreted to reflect Japan Sea Coastal Water (JPCW) input.

Brief ingressions of surface water dwelling subtropical oligotrophic *G. ruber* (Peeters et al., 2002) and the warmer water deeper dwelling *Neogloboquadrina incompta* (associated with high chlorophyll-$\alpha$ concentrations; Kuroyanagi and Kawahata, 2004) signify “modern” Tsushima Warm Current conditions prevailed during MIS 1, MIS 5e, MIS 9 and in particular during the “exceptionally” warm interglacial period MIS 11 (Droxler et al., 2003). Other intervals lack faunal evidence for strong Tsushima Warm Current influence, suggesting that optimal conditions for this current to reach the Japan Sea were only facilitated by the highest interglacial sea levels in the Tsushima Strait. In contrast, the lack of any fauna (planktic or benthic) during glacial maxima MIS 12, MIS 10 and intermittently during MIS 6, suggests periods of reduced oceanic productivity during the lowest sea levels (see section below).

5.3 Sea bed conditions
The majority of the benthic foraminiferal assemblages in U1427 are less diverse than other shelf regions and deep ocean environments worldwide (where $H(S) >> 5$ and Fisher $\alpha >> 5$; Murray, 2006). The diversity values are comparable to more restricted environments such as normal marine estuary or lagoonal settings (Murray, 2006). Overall, the relatively low assemblage diversity is likely related to the high latitude and restricted nature of the Japan Sea. Nevertheless, diversity maxima during the warmest interglacial phases show that more open marine shelf/deep sea environments prevailed during sea level highstands. Conversely, very low diversity values signify periods when the Japan Sea was restricted during sea level lowstands. The dominant benthic foraminifera at Site U1427 (Figure 6, 7) are also common in the Japan and the Okhotsk Sea (Usami et al., 2013; Bubenshchikova et al., 2008, 2015, Table 2). Islandiella norcrossi are found at depths from 150 to 1500 m in suboxic to oxic organic rich sediment with moderate to high seasonal surface productivity and relatively high stable sea bed salinity (Hasegawa, 1979; Inoue, 1989; Usami et al., 2013; Bubenshchikova et al., 2015). Trifarina angulosa are present from 200 to 2000 m in suboxic to oxic conditions in organic poor sediments (Hasegawa, 1979; Ujiié et al., 1983; Inoue, 1989; Usami et al., 2013; Bubenshchikova et al., 2008, 2015, Table 2). Uvigerina spp. typically are associated with sustained organic flux and/or dysoxic conditions at the seafloor and within the uppermost few centimeters of the sediment (Gooday, 1993; Jorissen et al., 1995, 2007; Jorissen, 1999). Uvigerina akitaensis inhabits organic rich sediments associated with high surface productivity and dysoxic to anoxic conditions (Fontainier et al., 2014; Bubenshchikova et al., 2015, Table 2) at depths greater than 200 m in the Japan Sea (Hasegawa, 1979; Matoba and Fukasawa, 1992). Spinose striate Uvigerina species such as U. cf. graciliformis inhabit slightly more oxic conditions with a lower organic flux than U. akitaensis (Fontainier et al., 2014; Bubenshchikova et al., 2008, 2015) at depths greater than 100 m (Ujiié et al., 1983). Globocassidulina subglobosa, Cibicidoides pachyderma and Pullenia bulloides are
cosmopolitan taxa common in oxic conditions associated with low surface productivity and strong bottom currents (Poli et al., 2012) at depths greater than 200 m (Hasegawa, 1979; van Hinsbergen et al., 2005). Taxa typical of dysoxic conditions (sensu Fontainier et al., 2014 and Kaiho, 1994) are rare and include (Figure 6, 7, Table 2): Brizalina spp., Glandulina laevigata (Figure 6g), Fursenkoina bradyi and Gobobulimina pacifica (Figure 6f). Neritic species of the miliolids Quinqueloculina spp. and Triloculinella spp., Elphidium spp., Cibicidoides lobatulus and C. refulgens (Hasegawa, 1979; Akimoto and Hasegawa, 1989; van Hinsbergen et al., 2005) are typically oxic taxa (Kaiho, 1994). Overall, the dominant benthic assemblages at Site U1427 suggest that site remained bathed in suboxic to oxic conditions above the dysoxic zone (Tada et al., 2007) for most of the last 460 kyrs. However, there were considerable variations in nutrient flux and intervals with lower oxygen conditions.

The minimal low diversity benthic fauna (with less than five benthic foraminifera/g sediment, Figure 3), absence of bioturbation and presence of laminations suggests periodic oxygen minimum zone conditions and/or reduced oceanic productivity during glacial maxima. Some of these horizons (MIS 8, MIS 6 and MIS 2) are equivalent to the glacial maxima dark layers deposited in the deeper water core MD01-2407 north of Site U1427 (Figure 1), reflecting stratified shallow (<237 meters paleodepth) low oxygen events across the Japan Sea (Tada, 1994; 2018; Kido et al., 2007; Watanabe et al., 2007; Usami et al., 2013). Similar to Okhostok Sea (Bubenschchikova et al., 2015), reduced oxygen and stratified oceanic conditions prevailed during terminations TV, TIII, TII and TI. These conditions weakened in the later stages of each deglaciation and became much weaker during interglacial periods representing the well-mixed aerobic interglacial “mode” of the Japan Sea (Tada, 1994; Watanabe et al., 2007; Usami et al., 2013). Intense fluctuating OMZ conditions during MIS 7-MIS 6 and MIS 4-MIS 3 were followed by oxic and low organic flux conditions (MIS 6 and MIS 3/2) suggesting that enhanced oceanic mixing and oxygenation typified the onset of glacial conditions. The
presence of increased neritic taxa during MIS 10 and MIS 6 (Figure 8) may be related to the proximity of the shelf during glacial maxima and possibly transported down slope. Peaks in neritic taxa during TI, MIS 9 and MIS 7 may also represent increased down slope transportation of foraminiferal tests due to highstand upper slope instability and/or increased oceanic current activity with the rapid flooding of the Tsushima Strait. The neritic maxima in MIS 8, late MIS 7/MIS 6 and MIS 4/ MIS 3 may relate to downslope sediment transport due to falling sea level.

6. East Asian monsoon variability over the last 460 kyrs

6.1 Chinese loess, cave and Lake Biwa records

Asian monsoon variability is modulated by precession (~23 ky) and/or obliquity (~41 ky) insolation (Figure 9; Nakagawa et al., 2008; Sun et al., 2015; Cheng et al., 2016) when stronger winter monsoon conditions are interpreted to have prevailed during glacial periods (Zheng et al., 2018) and an enhanced summer monsoon during interglacial maxima (Fujine et al., 2009; Usami et al., 2013). In the Japan Sea, freshwater discharge from the Yangtze River via the Tsushima Strait lowers the salinity and increases the nutrient flux of the Japan Sea during enhanced summer monsoon conditions in MIS 1 and MIS 5 (Tada, 2004). In contrast, enhanced ventilation and sea ice (ice rafted debris in the northern part of the Japan Sea, the asterisks on Figure 9) typically occurs in the Japan Sea during the winter monsoon conditions during glacial maxima and occasionally during MIS 5 (Tada, 2004; Ikehara and Itaki, 2007).

We extend the 160 kyr record of MD01-2407 (Figure 1) to 460 kyrs and compare our data (Figure 9) with Japanese Lake Biwa palynological (Nakagawa et al., 2008), Chinese speleothem (Cheng et al., 2016) and Chinese loess (Hao et al., 2012; Sun et al., 2015) data. The lightest cave oxygen and loess carbon isotope values are interpreted to typify periods of East Asian summer monsoon intensification (the dark green vertical bars; Figure 9) associated with
the lowest temperature variability and highest precipitation estimates in Lake Biwa. The concurrent patterns in these proxies suggest that the strongest East Asian summer monsoon conditions prevailed across the region following terminations TV to TII, during MIS 8/MIS 7e interglacial warm periods (Figure 9) and with the exception of MIS 11e prevailed during the transition from insolation maxima to minima. A weaker East Asian summer monsoon is interpreted during interglacial maxima in MIS 9, MIS 5 and MIS 1 (light green vertical bars; Figure 9) in the Chinese loess and speleothem records associated with insolation maxima, when floral proxies at Lake Biwa do not show a strong temperature or precipitation signal. These differences suggest a variable East summer monsoon strength, which may reflect latitudinal switches in the monsoon front from Japan to China. More intense East Asian winter monsoon conditions are interpreted during periods when relatively more enriched cave oxygen and loess carbon isotope values coincide with highest temperature variability and lowest rainfall estimates at Lake Biwa (dark orange vertical bars; Figure 9). These coincide with transitions from low to high insolation or insolation minima in MIS 8, MIS 6, MIS 4 and MIS 2 (Figure 10). The cave and loess signals for the East Asian winter monsoon are not as strong during periods of low insolation variability from MIS 11 to MIS 10, coinciding with a period of relative low precipitation and high temperature variability in Lake Biwa (light orange vertical bars; Figure 9).

6.2 The Japan Sea record of the Asian Monsoon

At Site U1427 patterns in the b* (related to %carbonate) and L* (brightness) which reflects TOC (cf. Sagawa et al., 2018) are partially controlled by sea level variability (Figure 9). Where reduced b* and increased L* typifying glacial maxima. Whereas increased b* and lower L* prevail in interglacials. However, the lithological characteristics at Site U1427 are related to East Asian Monsoon intensity. For example, higher %K (cf. Zheng et al., 2018), lighter (L*) silts and clayey silts with lower b* values coincide with periods of more intense
East Asian winter monsoon (MIS 10, MIS 8, MIS 6, MIS 4 and MIS 2, Figure 9, 10) conditions, whereas generally lower %K, darker (L*) and relatively high b* silts were deposited during times of increased East Asian summer monsoon (MIS 11c, MIS 9e, start of MIS 8, MIS 7e, start of MIS 6 and MIS 5e, Figure 9, 10). The terminations corresponds to the transitions between enhanced winter and summer monsoon conditions (Figure 10). In addition to insolation forcing the monsoonal patterns in Figure 9 also reflect glacial/interglacial (ice volume, CO₂) forcing of the monsoonal system (Sun et al., 2015; Cheng et al., 2016). One to two periods of the strongest EAWM prevail in glacial phases (with an enhanced Northern Hemisphere Icesheet) whereas up to three periods of enhanced EASM typify interglacial phases (during glacial retreat). The latitudinal variability in the intensity of the EASM and EAWM between the Chinese and Japanese monsoon records (the light orange and green intervals) also reflect variations in thermal contrast between land (Asian continent) and sea (Japan) and an overall latitudinal thermal gradient (Sun et al., 2015). The matches and mismatches in patterns between these multiproxy records suggest a complex interplay between ice sheet dynamics, insolation and thermal gradient control the nature and intensity of the East Asian monsoon.

Over the last 460 kyrs nutrient flux, salinity and relative oxygenation has varied markedly (Figure 9, 10) at Site U1427. Much of this variability is related to sea level fluctuations during glacial maxima such as dysoxia and low oceanic productivity causing foraminiferal faunal minima during MIS 12, MIS 10, MIS 6 and MIS 2, and Tsushima Warm Current planktic assemblage and diverse benthic foraminiferal influxes during interglacial maxima. However, planktic foraminiferal assemblage variability also seems to be modulated by the relative intensity of the East Asian winter and summer monsoons.

The distribution of the common planktic species *Globigerina bulloides* and *G. quinqueloba* at Site U1427 is related to salinity (relative influence of EACSW and JSCW) and
sea surface nutrient flux. Peaks of these taxa commonly coincide with enhanced monsoonal conditions (Figure 9), suggesting regular surface plankton blooms particularly during the EASM. Similar patterns in the relative abundance *Globigerina bulloides* are used as upwelling and nutrient flux indicators signifying Indian monsoon intensification in the Arabian Sea (Kroon et al., 1991). *Globigerina bulloides* maxima occur in MIS 11, MIS 9/MIS 8 (part) and MIS 5 due to increased fresh water influx from the East China Sea (EACSW) during enhanced East Asian summer monsoon conditions when sea levels were high enough to breach the Tsushima Strait. However, when this strait was restricted by lower sea level (during MIS 8, MIS 7 and MIS 6) maxima of *G. quinqueloba* reflect fresh water influx from Japan (JSCW) during the East Asian summer monsoon (Figure 8). The pattern of peaks of *Globigerina* spp. during the winter monsoon is not as distinct as the summer, occasionally maxima coincide with enhanced EAWM during MIS 10, MIS 7, MIS 6 and MIS 2.

### 7. Conclusions

The semi-enclosed Japan Sea is ideal region to investigate the interaction between the ocean, climate and sea level variability. The typical interglacial/glacial mode for the deep water (>1000 m) Japan Sea is well documented for the last ~160 kyrs (Tada et al., 1999; Usami et al., 2013) where freshwater discharge from the Yangtze River via the Tsushima Strait lowered the salinity and increased the nutrient flux of the Japan Sea during the summer monsoon in MIS 1 and MIS 5. Enhanced ventilation and northern sea ice (ice rafted debris) occurred in the Japan Sea in winter monsoon conditions during glacial maxima and MIS 5. Foraminiferal and sediment facies analyses from the relatively shallow (325 m depth) IODP Expedition 346 Site U1427 in the Japan Sea reveals a ~460 kyr record of highly variable nutrient flux and sea bottom ventilation that is related to relative sea level variability, the depth of the Tsushima Strait and East Asian monsoon intensity.
At this shallow site, sea level variations have a large impact on processes and the origin of sedimentary- and bio-facies. Calcareous silt dominates interglacials when depths were either higher than or 50 m below present. Clayey silt prevails in glacial maxima and silt during terminations. The lack of calcareous facies during glacial maxima may have been caused by dilution by siliciclastic sediment input and/or reduced oceanic surface productivity. Silt deposition during terminations is likely related to the rapid flooding of the Tsushima Strait causing increased inflow of East China Sea Coastal Water into the Japan Sea and increased current activity.

Previous analyses of glacial/interglacial planktic foraminiferal distribution suggests that modern assemblages typify interglacial warmer Tsushima Warm Current “anomalies” in the predominantly cold Japan Sea over the last 160 ka. At Site U1427 brief ingressions of surface water dwelling subtropical oligotrophic *Globigerinoides ruber* and the warmer water deeper dwelling *Neogloboquadryina incompta* suggest “modern” Tsushima Warm Current conditions prevailed during MIS 1, MIS 5e, MIS 9 and were especially strong during MIS 11. Other intervals lack Tsushima Warm Current planktic foraminifera, suggesting that optimal conditions for this current to reach the Japan Sea were only facilitated by the highest interglacial sea levels in the Tsushima Strait. The subpolar to polar *Neogloboquadryina pachyderma* is the most common planktic species in the section suggesting cold (~5°C average) oceanic conditions prevailed in all but the glacial/interglacial maxima over the last 460 kyrs.

The lack of planktic and benthic foraminifera, absence of bioturbation and presence of laminations suggests periodic reduced oxygen conditions during many glacial maxima, suggesting enhanced oceanic stratification during some periods of lowest sea level (*cf.* Tada et al., 2007). Similar to Okhostok Sea (Bubenschchikova et al., 2015) stratified lower oxygen conditions characterise terminations TV, TIII, TII and TI (Figure 10). These conditions
weakened during interglacial periods when the Japan Sea transitioned to a well-mixed aerobic interglacial “mode” (Figure 10, Tada, 1994; Watanabe et al., 2007; Usami et al., 2013). Fluctuating OMZ conditions followed by oxic low organic flux conditions during the onset of glacial periods suggest enhanced oceanic mixing and oxygenation was associated with the isolation of the Japan Sea during the lowest sea levels.

While the facies and foraminiferal variability at Site U1427 is controlled by relative sea level the biofacies patterns also reflect East Asian monsoon variability. The middle to late Pleistocene history of the East Asian winter and summer monsoons has been interpreted from palynofloral records in Lake Biwa, Japan (Nakagawa et al., 2008), Chinese speleothem (Cheng et al., 2016) and loess (Hao et al., 2012; Sun et al., 2015) data (Figure 9). The lightest cave oxygen and loess carbon isotope values typify East Asian summer monsoon intensification with the lowest temperature variability and highest precipitation at Lake Biwa. These data suggest enhanced East Asian monsoon conditions following terminations TV to TII, during MIS 8/MIS 7 that prevailed during the transition from insolation maxima to minima. Intense East Asian winter monsoon conditions coincide with transitions from low to high insolation or insolation minima in MIS 8, MIS 7, MIS 6, MIS 4 and MIS 2. When compared to foraminiferal and sedimentary facies data at Site U1427 (Figure 9) patterns the lighter silts and clayey silts with lower %carbonate values coincide with periods of more intense East Asian winter monsoon during MIS 8, MIS 6, MIS 4 and MIS 2 (Figure 10). In contrast, the darker calcareous silts were deposited during times of increased East Asian summer monsoon during MIS 11c, MIS 9e, MIS 8, MIS 7e, MIS 6 and MIS 5e (Figure 10). Peaks of Globigerina bulloides and G. quinqueloba commonly coincide with enhanced monsoonal conditions (Figure 9), suggesting regular surface plankton nutrient enrichment and influx of fresh water from the East China Sea during the East Asian summer monsoon when sea levels were high enough to breach the Tsushima Strait. However, when the Tsushima Strait was restricted by lower sea level,
maxima of \textit{Globigerina quinqueloba} reflect a switch to a Japanese source of fresh water influx from Japan during the summer monsoon.

Insolation forcing is a strong control on the monsoonal intensity in loess, cave and lake records in the region. However, the fact that the strongest EAWM events prevail in glacial phases whereas several enhanced EASM periods typify interglacial phases suggests glacial/interglacial (ice volume, CO\textsubscript{2}) forcing of the monsoonal system. Apparent mismatches between the Chinese and Japanese East Asian monsoonal intensity between proxies suggests latitudinal and land/sea thermal contrasts also have role to play in East Asian monsoon variability. This suggest a complex interplay between ice sheet dynamics, insolation and thermal gradient controls the nature and intensity of the East Asian monsoon.

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Figure 1. Location of IODP Expedition 346 Site U1427. The path of the Tsushima and Kuroshio Current and Extension around Japan are shown. Tsushima Warm Current nomenclature (TWC-1 to 3) is from Tada et al. (2015a). Base map adapted from General Bathymetric Chart of the Oceans (GEBCO) www.gebco.net. LB - Lake Biwa, MS - Mamiya Strait, TSS - Tsushima Strait, SS - Soya Strait, TSG - Tsuguru Strait. The inset map shows the centre (H) of the Siberian High and the dashed red line the area with 1,028 hPa of mean sea level pressure (adapted from Hao et al., 2012). The yellow dashed line is the northern limit of the summer monsoon front (Sun et al., 2015). YMG - Yimiguan and LC - Luochuan loess sections (Hao et al., 2012); GL - Gulang, JY - Jingyuan loess sections (Sun et al., 2015); DG - Dongge, SB - Sanbao, HL - Hulu cave sections (Cheng et al., 2016).
Figure 2. Lithostratigraphy of the upper 180 m of Site U1427 with down hole physical properties. The age-depth curve shows Marine Isotope Stages, benthic foraminiferal isotope data and tephrochronology (Table 1) from Sagawa et al. (2018). NGR cpm = natural gamma ray counts per minute.
Figure 3. An age plot of the lithostratigraphy, foraminiferal concentration and %planktics (expressed as percentage of the total foraminiferal fauna) in the upper 460 kyr of Site U1427. Benth.F = benthic foraminifera and Plank.F = planktic foraminifera. The yellow horizons are interglacial maxima in the LR2004 stack (Lisiecki and Raymo, 2005). The labelling uses the Railsback et al. (2014) nomenclature. The gray horizons are barren of foraminifera. The key to the log lithology and symbols is in Figure 2. The linear sedimentation rate (Sed.Rate) curve is from Sagawa et al. (2018). The benthic assemblage diversity uses the Fisher α index and Shannon-Weaver indices, $H(S) > 2$ and Fisher α > 5 typify open marine shelf and deep sea environments.
Figure 4. Planktic foraminifera in Pleistocene strata of IODP Site U1427. The scale bar is 100 μm. (a) *Globigerina bulloides* (d’Orbigny, 1826: thick-walled form *sensu* Domitsu and Oda, 2005), log level 167.02 m. (b) *Globigerina umbilicata* Orr and Zaitzeff, 1971, 167.02 m. (c) *Globigerina quinqueloba* Natland, 1938, log level 61.27 m. (d) and (e) *Neogloboquadrina pachyderma* (Ehrenberg, 1861), log level 11.92 m. (f) and (g) *Neogloboquadrina incompta* (Cifelli, 1961), log level 0.04 m. (h) and (i) *Globorotalia tumida* (Brady, 1877), log level 145.57 m. (j) *Pulleniatina obliquiloculata* (Parker and Jones, 1862), log level 44 m.
Figure 5. An age plot of the key planktic species in the upper 460 kyr of Site U1427. G. = Globigerina, N. = Neogloboquadrina and (s) = sinistral. ECSCW = East China Sea Coastal Waters, JSCW = Japan Sea Coastal Waters, SST = Sea Surface Temperatures and TWC Plank. = Tsushima Warm Current Planktic species. %values are expressed as a percentage of the total planktic fauna.
Figure 6. Benthic foraminifera in Pleistocene strata of IODP Site U1427. The scale bar is 100 μm. (a) Islandiella norcrossi (Cushman, 1933), log level 8.86 m. (b) Trifarina angulosa (Williamson, 1858), 167.02 m. (c) Globocassidulina subglobosa (Brady, 1861), log level 10.92 m. (d) Spinose-striate Uvigerina cf. graciliformis (sensu Fontanier et al., 2014), log level 61.27 m. (e) Uvigerina akitaensis Asano, 1950, log level 44 m. (f) Globobulimina pacifica Cushman, 1927, log level 167.02 m. (g) Glandulina laevigata (d’Orbigny, 1826), log level 167.02 m. (h) and (i) Cibicidoides lobatulus (Walker and Jacob, 1878), log level 2.98 m. (j) and (k) Elphidium excavatum (Terquem, 1875), log level 2.98 m. (l) and (m) Pullenia bulloides (d’Orbigny, 1846), log level 11.92 m. (n) and (o) Lenticulina inornata, log level 10.92 m.
**Figure 7.** An age plot of common benthic species in the upper 460 kyrs of Site U1427. *I.* = Islandiella, *T.* = Trifarina, *Globocass.* = Globocassidulina subglobosa, *U.* = Uvigerina, spin/str = spinosa striate Uvigerina spp. Note: var. org. flux = variable organic flux and OMZ = oxygen minimum zone. All benthic data in this figure are expressed as a percentage of total benthic calcareous foraminiferal data.
Figure 8. An age plot of common benthic taxa in the upper 460 kyrs of Site U1427 plotted with the sea level curve of Spratt and Lisiecki (2016). Cib. = Cibicidoides. The benthic data for Cibicidoides, Elphidium, P. bulloides and %Neritic taxa in this figure are expressed as a percentage of total calcareous benthic foraminiferal data (the list of taxa included in this column is in the text). The %Miliolids are expressed as a percentage of the total benthic fauna.
Figure 9. The relationship between the stratigraphy of Site U1427 and (a) Eccentricity and (b) insolation in watts per metre$^2$ (at 36°N and 50°N) created using Analyseries 2.0.4 software (Paillard et al., 1996) using the Laskar et al. (2004) solution; (c) The Chinese stalagmite record of the Asian monsoon (Cheng et al., 2016); (d and f) Chinese loess record of GT32% (%32 mm particle content) and frequency-dependent magnetic susceptibility data from the Yimaguan and Louchuan sections (Hao et al., 2012); (e) the carbon isotope values of inorganic carbonates of
Chinese loess is shown in per mill (Sun et al., 2015). (g) and (h) Temperature and precipitation variability at Lake Biwa inferred from palynological data, the green horizontal lines are modern values (Nakegawa et al., 2008). Tvar°C denotes the temperature difference between winter and summer whereas Pmax is the maximum estimated precipitation. When Pmax is elevated and Tvar reduced strong summer monsoonal conditions are interpreted (Nakagawa et al., 2008), when the pattern reverses a stronger winter monsoon prevailed; (m) the LR2004 stack (Lisiecki and Raymo, 2005) the asterisks are horizons of ice rafted debris documented by Ikehara and Itaki (2007) in the northern part of the Japan Sea. The colored vertical bars denote where proxies suggest enhanced EASM (green, red arrow) and stronger EAWM (orange, blue arrow). We have annotated periods with stronger EAWM and EASM by darker colors, as these are time when the majority of the patterns of the proxies align. The lighter shade are weaker yet distinct EAWM and EASM periods. Note: the location of the proxy records above is in Figure 1. The %K, brightness (L*) and b* for Site U1427 is plotted in age also showing percentage of Globigerina spp. in the total planktic assemblage. The black curve is %Globigerina quinqueloba, the remaining species (white) are primarily Globigerina bulloides with minor G. umbilicata. The lowermost curve are global sea level estimates with error ranges (Spratt and Lisiecki, 2016).
Figure 10. Variations in oceanography and the position and intensity of the East Asian Monsoon during (a) low to high insolation transitions and insolation minima, (b) Terminations and (c) high to low insolation transitions. *MIS 11c coincides with an insolation maxima during an eccentricity low (Figure 9). The thicker blue arrows signify enhanced EAWM and thicker yellow arrows a stronger EASM. The thin blue line (ECSCW) is the path of fresh water from the China Sea during terminations and interglacial maxima. The temporal variations in the Kuroshio Current position and strength are adapted from Gallagher et al. (2015). The base map is from General Bathymetric Chart of the Oceans (GEBCO) www.gebco.net where modern bathymetry represents interglacial maxima (see also Figure 1). This is recalibrated to ~100 m below present for glacial phases and ~25 m below present during the terminations. The paleoshorelines during these sea level phases are adapted from Hayashi et al. (2017). prod. = productivity.
Table 1. The age depth model used in Figure 2 from Sagawa et al. (2018).

Table. U1427 age depth model

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<tr>
<td>76.67</td>
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<td>84.67</td>
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<td>Ata-Th</td>
<td>Lisiecki and Raymo (2005)</td>
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<tr>
<td>88.51</td>
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<tr>
<td>97.68</td>
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<td>Lisiecki and Raymo (2005)</td>
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<tr>
<td>108.55</td>
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<td>subtropical microfossil</td>
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<td>121.27</td>
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<td>Lisiecki and Raymo (2005)</td>
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<td>126.74</td>
<td>339.2</td>
<td>tephra (tied to U1429)</td>
<td>Kkt</td>
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<td>131.00</td>
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<td>benthic δ18O</td>
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<td>153.05</td>
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<td>Lisiecki and Raymo (2005)</td>
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<td>167.2</td>
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<td>b*</td>
<td>MIS 12a</td>
<td>Lisiecki and Raymo (2005)</td>
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<td>Lisiecki and Raymo (2005)</td>
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<tr>
<td>198.94</td>
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<td>subtropical microfossil</td>
<td>MIS 13c</td>
<td>Lisiecki and Raymo (2005)</td>
</tr>
</tbody>
</table>
Table 2. The environmental distribution of key benthic foraminifera taxa in Figure 7 and 8. The main interpretations are from Bubenschchikova et al. (2008, 2015) and Fontainier et al. (2014). Other information is from references cited in text, especially: Kaiho (1994) and Usami et al. (2013).

<table>
<thead>
<tr>
<th>Benthic Taxon</th>
<th>Oxygen level</th>
<th>Depth</th>
<th>Habitat</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Islandiella norcrossi</td>
<td>suboxic-oxic</td>
<td>150-1500 m</td>
<td>Shallow infauna</td>
<td>moderate to high and seasonal surface productivity and organic matter flux in seasonally ice free areas of northern high latitudes, inhabits moderately organic (0.4-2.0%) sediment shows opportunistic response on input of the phytodetritus in meso-oligotrophic areas</td>
</tr>
<tr>
<td>Trifarina angulosa/ikebei</td>
<td>suboxic-oxic</td>
<td>200-2000 m</td>
<td>Shallow infauna</td>
<td>organic-poor (0.1-0.8%) coarse sediments and well-oxygenated bottom waters, low organic matter flux</td>
</tr>
<tr>
<td>Globocassidulina subglobosa</td>
<td>oxic</td>
<td>&gt;200 m</td>
<td>Shallow infauna</td>
<td></td>
</tr>
<tr>
<td>Striate spinose Uvigerina spp.</td>
<td>suboxic-oxic</td>
<td>200-1000 m</td>
<td>Shallow infauna</td>
<td>found living above oxygen-depleted water masses (&gt;45 mmol/L)</td>
</tr>
<tr>
<td>Uvigerina cf. U. graciliformis</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Species</td>
<td>Environment</td>
<td>Depth</td>
<td>Zone</td>
<td>Habitat</td>
</tr>
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<td>------------------------</td>
<td>-------------</td>
<td>-------</td>
<td>-------------</td>
<td>-------------------------------------------------------------------------</td>
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<tr>
<td><em>Uvigerina akitaensis</em></td>
<td>anoxic-dysoxic</td>
<td>200-1000 m</td>
<td>Shallow infauna</td>
<td>high suspended particles and sustained organic matter flux, inhabits a wide range of organic-enriched (0.3-5%) sediments, common in the OMZ on Japanese margin within oxygen-depleted water mass</td>
</tr>
<tr>
<td><em>Globobulimina pacifica</em></td>
<td>anoxic-dysoxic</td>
<td>200-1000 m</td>
<td>Deep infaunal OMZ</td>
<td>found living above oxygen-depleted water masses (&gt;45 mmol/L)</td>
</tr>
<tr>
<td><em>Glandulina laevigata</em></td>
<td>anoxic-dysoxic</td>
<td>200-1000 m</td>
<td>Deep infaunal OMZ</td>
<td></td>
</tr>
<tr>
<td><em>Brizalina spp.</em></td>
<td>dysoxic</td>
<td>200-1000 m</td>
<td>Shallow-intermediate infaunal OMZ</td>
<td></td>
</tr>
<tr>
<td><em>Fursenkoina bradyi</em></td>
<td>anoxic-dysoxic</td>
<td>200-1000 m</td>
<td>Deep infaunal OMZ</td>
<td></td>
</tr>
<tr>
<td><em>Cibicidoides pachyderma</em></td>
<td>oxic</td>
<td>&gt;100 m</td>
<td>Epifauna</td>
<td></td>
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<tr>
<td><em>Cibicidoides lobatulus</em></td>
<td>oxic</td>
<td>0-200 m</td>
<td>Epifauna</td>
<td></td>
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<tr>
<td><em>Cibicidoides refulgens</em></td>
<td>oxic</td>
<td>0-200 m</td>
<td>Epifauna</td>
<td></td>
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<tr>
<td><em>Elphidium excavatum</em></td>
<td>oxic</td>
<td>0-100 m</td>
<td>Infaunal</td>
<td></td>
</tr>
<tr>
<td>Millioliids (Quinqueloculina/Triloculina spp.)</td>
<td>oxic</td>
<td>$&gt;0$ m</td>
<td>Epifauna</td>
<td></td>
</tr>
<tr>
<td>---------------------------------------------</td>
<td>------</td>
<td>--------</td>
<td>---------</td>
<td></td>
</tr>
<tr>
<td><em>Pullenia bulloides</em></td>
<td>oxic</td>
<td>$&gt;200$ m</td>
<td>Shallow infauna</td>
<td>well-oxygenated bottom and pore waters, inhabits moderately organic-enriched (0.4-2.0%) sediments</td>
</tr>
</tbody>
</table>