Palynological implications for the paleoclimate and paleoceanographic reconstruction of the East Sea since the early Pleistocene at IODP site U1430

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ABSTRACT

Palynomorphs, including pollen and dinoflagellate cysts from marine sediments, can provide a history of paleoclimate and paleoceanography. We present new palynological profiles based on a core from the Integrated Ocean Drilling Program Site U1430, which was drilled in the Ulleung Plateau East Sea. This core covers the past 2 Ma and spans the Mid-Pleistocene Transition (MPT, 1.2–0.8 Ma) and Mid-Brunhes Event (MBE, ~0.43 Ma). Terrestrial and marine palynomorph records indicate orbital-scale variations in paleoclimate and paleoceanography, reflecting changes in the interconnections between vegetation, climate, and the ocean. Before the MPT, the high pollen taxa ratio and abundant temperate pollen suggest a relatively warm temperature associated with astronomical forcing-induced insolation changes. At ca. 1.3 Ma, boreal coniferous pollen increased, suggesting intensification of the East Asian winter monsoon (EAWM). The long-term trend of boreal coniferous pollen concentration was similar to that of benthic δ18O. This orbital scale boreal conifer pollen assemblage variation indicates Quaternary EAWM evolution controlled by changes in global ice volume and climatic cooling. The marine palynological data reflect the ocean circulation history of the study area, where sea level fluctuations and tectonic activity played important roles around the marginal sea. The abundance of warm-water dinoflagellate species after ca. 1.9 Ma, including Tuberculodinium vancampoae, indicates Tsushima Warm Current intrusion related to the expansion of the Korea (Tsushima) Strait. Nematothecopsis labyrinthus and other cold-water species increased markedly during the MPT, suggesting a low sea surface temperature and weakened vertical mixing of the East Sea due to the cooled climate and sea ice during the MPT. The marked sea level fluctuation associated with the glacial–interglacial cycling after the MBE resulted in an assemblage composition shift from cold to warm water species. Tsuga and Betula thrived during mild winters, primarily influenced by winter insolation. These genera were particularly prosperous in the early Pleistocene, coinciding with a strong intrusion of the Tsushima Warm Current (TWC). Our findings should be considered in developing a comprehensive understanding of the paleoclimate and paleoceanographic history of northern East Asia across the major climate transitions of the Pleistocene.

1. Introduction

The East Sea (also known as the Japan Sea) is a semi-closed marginal sea that is ideal for reconstructing past environmental changes related to the ocean, vegetation, and climate, because it is influenced by the East Asian monsoon (EAM) and sea level fluctuations (Fig. 1). During the Quaternary period, the environment of the East Sea was shaped by tectonic activity in northeastern Asia, fluctuations in the eustatic sea level, and variability of the East Asian Monsoon (EAM). Ultimately, the EAM is tied to insolation forcing, which influences the seasonal land–sea temperature contrast, leading to the reversal of monsoon winds and altering regional precipitation patterns (Cheng et al., 2016; Beck et al.,...
Moreover, the EAM correlates with orbital-scale global climate changes related to variations in atmospheric CO$_2$ and ice sheet dynamics (Cai et al., 2012; Chalk et al., 2017; Clark et al., 2006; Clift and Plumb, 2008; Felder et al., 2022; Gallagher et al., 2015; Itaki, 2016; Li et al., 2014; Sun et al., 2019; Tada et al., 2015; Zheng et al., 2006). After the Northern Hemisphere Glaciation period, the Quaternary era exhibited a distinct glacial–interglacial climate cycle (Bailey et al., 2013; Bartoli et al., 2005; Naafs et al., 2013; Shackleton et al., 1984). During the Mid-Pleistocene Transition period (MPT, 1.2–0.8 Ma), the global climate cycle shifted from 41 to 100 kyr and the amplitude increased following the Mid-Brunhes Event (MBE, ~0.43 Ma; Barth et al., 2018; Clark et al., 2006; Cronin, 2009; Huang et al., 2018, 2019; Yin and Berger, 2010). Therefore, studying terrestrial and marine environmental responses to tectonic activity and monsoon climate changes across these significant climate transitions is crucial for a comprehensive understanding of paleoclimate and paleoceanography (see Fig. 1).

Pollen records from deep-sea sediments offer insights into regional vegetation and climate changes over extended time scales, and facilitate the interpretation of regional atmospheric circulation patterns in the context of global climate change (Sánchez Goñi et al., 2018). Decoding the paleo-environment using both terrestrial and marine proxies such as pollen and dinoflagellates from a single deep-sea sediment core allows direct comparisons between terrestrial and marine conditions, minimizing chronological uncertainties. Previous pollen studies in the East Sea have revealed vegetation and climate changes in relation to climate cycles (Hayashi et al., 2021, 2021a, 2021b; Ikehara and Oshima, 2009; Igarashi et al., 2018; Kim et al., 2019). However, these studies largely focused on specific and shorter time frames, limiting our understanding of longer-term environmental changes (Hayashi et al., 2021; Lee et al., 2022; Xin et al., 2020).

Located in the west-central East Sea, the Ulleung Plateau is adjacent to the montane forests of the eastern Korean Peninsula, North China, and Japanese Archipelago and is influenced by the EAM. EAM evolution studies are predominantly based on deposits from the Loess Plateau in China, suggesting a gradual intensification during the Pleistocene (Han et al., 2011; Sun et al., 2006, 2010). In contrast, aeolian dust sediments from Integrated Ocean Drilling Program (IODP) cores in the East Sea are used to reconstruct the aridity of Central Asia, where the dust originates (Anderson et al., 2020; Shen et al., 2017), and pollen and dust data offer insights into the strength of the East Asian Winter Monsoon. However, as pollen data reflect the regional characteristics of the East Sea and its adjacent forests, these two proxies may yield different results (Lee et al., 2022; Xin et al., 2020).

The Tsushima Warm Current (TWC) diverges into three branches and flows at different intensities along the west side of the Japanese Archipelago and the east side of the Korean Peninsula. Consequently, TWC indicator species may vary between the western Japanese Archipelago and the Ulleung Plateau. Previous studies have suggested that the inflow of the TWC into the East Sea started around 1.7 Ma, as indicated by an increase in subtropical fauna on the southwestern Japanese coast (Gallagher et al., 2015; Itaki, 2016; Kitamura & Komoto, 2006). However, studies using microfossils to investigate TWC intrusion near the Korean Peninsula are lacking.

In this study, we present a novel continuous palynological record from IODP Site U1430 located in the Ulleung Plateau, covering the past 2 million years, which includes the MPT and MBE. We discuss terrestrial vegetation changes in response to external forcings such as insolation, as well as the EAM as an internal forcing, based on pollen records. In addition, we newly report the TWC intrusion time period based on a warm water dinoflagellate assemblage from the Ulleung Plateau. Based on our novel findings, we established connections between vegetation, climate, and ocean changes without chronological uncertainties using terrestrial and marine palynomorphs. The results of this study contribute significantly to a comprehensive understanding of the paleoclimate and paleoceanographic history of northern East Asia, as well as vegetation responses to these changes in the region.
2. Regional setting

2.1. Physiographic and oceanographic setting

The East Sea is connected to the North Pacific Ocean, East China Sea, and Okhotsk Sea through four straits: the Korea (Tsushima) Strait (KS; maximum sill depth = ca. 230 m deep), Tsugaru Strait (TGS; 130 m deep), Soya Strait (55 m deep), and Tataraya Strait (TS; 12 m deep). It consists of three basins: the southwestern Ulleung Basin, southeastern Yamato Basin, and northern Japan Basin. These three basins are divided by the Korea Plateau, Yamato Ridge, and Oki Bank. The Korea Plateau is separated into the western Gangwon Plateau and eastern Ulleung Plateau (Fig. 1; Chough et al., 2000). The KS maintained high terrain up to the early Pleistocene. However, it gradually deepened and widened due to the stretching of the Okinawa Trough caused by a change in the convergence direction of the Philippine Sea (Gallagher et al., 2015; Itaki, 2016; Kitamura et al., 2001). The two currents flowing into the East Sea through the KS are the TWC and East China Sea Coastal Water (ECSCW)/Changjiang Diluted Water (CDW). The TWC, characterized by high sea surface temperature (SST) and sea surface salinity (SSS), is a branch of the Kuroshio Current originating in the Indo-Pacific Warm Pool. The ECSCW/CDW originates in the Yangtze River discharged from Eurasia during strong East Asian summer monsoon (EASM) periods, and forms a low-SSS ocean current with high nutrient content, which flows into the East Sea and causes density stratification (Chang et al., 2003, 2014; Kosugi et al., 2021; Usami et al., 2013; Zhao et al., 2022). The TGS maintained a deep and wide strait (>500 m; Itoh et al., 1997; Zhao et al., 2022), but became shallower (~130 m; Sato et al., 2012) due to regional uplift surrounding Japanese islands during the early Pleistocene; this resulted in restricted exchange of water masses between the North Pacific and East Sea. After the MBE, as the amplitude of glacio-eustatic sea-level fluctuations increased, the environment of the East Sea was altered markedly by TWC and ECSCW flowing through the KS with varying intensity (Gallagher et al., 2018; Huang et al., 2019; Saavedra-Pellitero et al., 2019; Tada, 1994).

2.2. Regional climate

The regions of East Asia, including the Korean Peninsula and Japanese Archipelago, are situated in a temperate zone that is primarily influenced by the EAM. Characterized by significant seasonality due to seasonal migration of the monsoon front, the EAM is divided into a winter and a summer monsoon (Nakagawa et al., 2006; Yi, 2011). The cold-dry winter monsoon is predominantly affected by the Siberian high air mass in the northwest, whereas the warm-humid summer monsoon is influenced by the oceanic Pacific air mass in the southeast. This seasonal temperature gradient between the two air masses results in northwesterly winds during winter and southeasterly winds in summer. During the past 30 years (1991–2020), the average annual temperature on the southern Korean Peninsula ranged from 7.1 °C to 16.9 °C. During this period, the average summer temperature varied between 18.5 °C and 25.7 °C, and winter temperatures ranged from −5.3 °C to 8.3 °C. The annual precipitation in this region ranged from 787 to 1989 mm, with summer precipitation varying from 431.5 to 1752.6 mm (Korea Meteorological Administration, 2022).

2.3. Potential vegetation

Temperature, topography, and precipitation is crucial factors influencing plant growth and distribution (Kong, 2000). For example, the vegetation of the Korean Peninsula is divided according to temperature variation with latitude and altitude into coniferous (subalpine zone), deciduous broadleaf (temperate zone), and evergreen forest (subtropical zone) forest types. The potential vegetation of the Korean Peninsula consists of subalpine coniferous and cold deciduous broadleaf forest (subalpine zone), mixed coniferous and deciduous broadleaf forest (temperate zone), and evergreen forest (subtropical zone) (Yi, 2011). Subalpine coniferous forest mainly includes fir (Abies), spruce (Picea), pine (Pinus-Haploxylon-type), and yew (Taxus). Hemlock (Tsuga) occurred on the Korean Peninsula before the Holocene, but is currently distributed only on Ulleung Island (Kong, 2000). Beyond the Korean Peninsula, hemlock is distributed in East Asian monsoon areas such as the coastal montane forests of China and south-central Japan (Wu et al., 2020; Yang et al., 2009). Deciduous broadleaf forests occur between 35° N and 43° N, except in subalpine areas, where the dominant taxa are birch (Betula) oak (Quercus), elm (Ulmus), lime (Tilia), Zelkova serrata, Styrex japonica, Carpinus tschonoskii, and hazel (Corylus). Subtropical evergreen forests are distributed along the southern coast and near coastal areas, and are dominated by Quercus acuta, Quercus glauca, Quercus myrsinifolia, Castanopsis cuspidate var. Sieboldii, and shrubs including Camellia japonica and llex integra (Yi, 2011). The vegetation of the Japanese Islands consists of subtropical evergreen forests, warm-temperate forests, temperate deciduous broadleaf forests, cool mixed forests, and cold evergreen forests (Takahara et al., 2010).

3. Materials and Methods

3.1. Study site

IODP Site U1430 is located on the Ulleung Plateau in the East Sea, at a water depth of 1072 m (37° 54.16′N, 131° 32.25′E). Site U1430 extends from the late Miocene to the Holocene. This study focuses on the upper 56 msb of this core, from the early Pleistocene to the Holocene. This section is dominated by silty clay, clayey silt, and biogenic ooze (Tada et al., 2015). The Quaternary sediments of the East Sea are characterized by alternating dark- and light-colored lamination bands; this color alternation is also observed in the Expedition 346 cores including Site U1430 (Tada et al., 2015, 2018). During Expedition 346, researchers established age models by correlating the dark and light layers of each core (U1422, U1423, U1424, U1425, U1426, and U1430; Irino et al., 2018; Sagawa et al., 2018; Tada et al., 2018). Additionally, Kim et al. (2020) identified the glacial period over the past 2 million years at site U1430, using cold-arid climate indicator species such as Picea, Abies, Pinus-Haploxylon-type, and Artemisia. The age model after 1.45 million years was established by correlating the proportion of boreal and xerophytic pollen taxa with the LR04 stacks, and following previous studies that investigated the correlation of physical properties for dark/light sediment sequence data (Irino et al., 2018; Sagawa et al., 2018; Tada et al., 2018). The period from 1.45 to 2 million years was determined by supplementing the biostratigraphic data (Kamikuri et al., 2017; Tada et al., 2015). In this study, we applied the chronological model established by these methods to site U1430 (Supplementary Table S1).

3.2. Palynological analysis

For palynomorph analysis, 91 samples were collected from IODP Site U1430 at approximately 20 cm to 1 m intervals from 0 to 56 m in consideration of sedimentation rates, corresponding to a resolution of ca. 20,000 years over the last 2 Ma. All dry samples were processed following a standard palynological pretreatment method (Moore et al., 1999). For each sample, 5 g was collected and two exotic tablets were added to each sample to calculate palynomorph concentrations. Samples were chemically treated with HCl (35%), HF (45%), and KOH (10%) in a fume hood at room temperature, and sieved using metal sieves with mesh sizes of 100 and 10 μm. Organic residues were mounted on glass slides using glycerin jelly. Palynomorphs were identified with an optical light microscope at 200 × and 400 × magnification referring to previous studies of dinoflagellates from the Western Pacific region (He et al., 2009; Marret and Zonneveld, 2003) and a pollen catalog for northern East Asia (Chang, 1986; Wang, 1995). A minimum of 300 grains of pollen and dinoflagellate cysts, respectively, were counted per slide until at least 250 Lycopodium spores were
obtained (Traverse, 2007).

3.3. Statistical analysis

Palynomorph diagrams were created using Tilia software (Grimm, 2011) and palynomorph assemblage zones were defined by constrained cluster analysis (CONISS). To verify and visualize the palaeoclimate and paleoceanography indices, principal component analysis (PCA) was conducted using R software (Oksanen et al., 2022) based on palynomorph data converted into percentages. Rodionov (2004) provided a statistical analysis method to recognize statistically significant regime shifts in time-series data. We applied this method to the terrestrial and marine palynomorph datasets for IODP Site U1430, and identified significant regime shifts. To identify the lag time between marine and terrestrial biotic responses to LR04 stacks, we performed cross-correlation using the R BINCOR package (Polanco-Martines et al., 2020). PCA analyses were implemented using the vegan v2.6-4 package in R (Oksanen et al., 2022). The relative paleo-temperature index based on pollen (Tp) was calculated according to the ratio between temperate-warm broadleaf pollen and temperate-cold conifer pollen taxa (Dumske et al., 2002; Hayashi et al., 2021; Igarashi and Oba, 2006; Igarashi et al., 2018; Kim et al., 2019; White et al., 1997; Whitlock and Bartlein, 1997; Yi, 2011)

4. Results

4.1. Palynomorph assemblages

4.1.1. Terrestrial palynomorph assemblages

Terrestrial palynomorphs identified within the top of 56 m at IODP

Fig. 2. Pollen diagram during the last 2 Ma (top 56 mbsf) at Site U1430. Pollen percentages are based on the sum of tree and herb pollen, excluding spores and freshwater algae. Taxaceae-Cephalotaxaceae-Cupressaceae (T-C-C). Three pollen assemblage zones were identified based on the CONISS dendrogram (Grimm, 2011). The grey shaded pattern denotes $3 \times$ amplification.

Fig. 3. Dinoflagellate diagram during the last 2 Ma (top 56 mbsf) at Site U1430. Four dinoflagellate assemblage zones were identified based on the CONISS dendrogram (Grimm, 2011). The grey shaded pattern denotes $3 \times$ amplification.
Site U1430 include coniferous pollen, broadleaf pollen, herbs, spores, and freshwater algae (Fig. 2 and Plate 1). The coniferous pollen species Picea, Abies, Tsuga, Pinus-Haploxylon-type, Pinus-Diploxylon-type dominated the entire section, ranging from 63 to 91%, likely with periodic fluctuation. The broadleaf pollen species Quercus subgenus Cyclobalanopsis, Tilia, Ulmus, Alnus, Salix, Ilex, Quercus subgenus Lepidobalanus, Carpinus, and Betula are common (5–35%). Three pollen assemblage zones are defined based on the CONISS dendrogram (Fig. 2). The P1 zone is dominated by Pinus-Diploxylon-type and Tsuga as cool-temperate conifer pollen, with Quercus subgenus Cyclobalanopsis as warm-temperate broadleaf pollen; deciduous broadleaf pollen was also common (Betula, Quercus subgenus Lepidobalanus, and Carpinus). The P2 zone is characterized by abundant conifer pollen from Picea, Abies, Tsuga, Pinus-Haploxylon-type, and Pinus-Diploxylon-type, with deciduous broadleaf tree pollen, including Quercus subgenus Cyclobalanopsis, and warm-temperate deciduous broadleaf tree pollen, including Tilia, Ulmus, Alnus, Salix, and Ilex. This zone demonstrates a decrease in Pinus-Diploxylon-type and Quercus subgenus Cyclobalanopsis compared to Zone P-I. Conversely, Artemisia represents approximately 10% of the total on average, indicating an increase compared to Zone P-I. Zone P3 is characterized by an abundance of coniferous pollen genera, such as Picea, Abies, Tsuga, Pinus-Haploxylon-type, and Pinus-Diploxylon-type, which show periodic fluctuations.

4.1.2. Marine palynomorph assemblages
We observed 24 species of dinoflagellate cysts belonging to 12 genera (Fig. 3 and Plate 1). Four dinoflagellate cyst assemblage zones are distinguished based on CONISS dendrogram (Fig. 3). The D1 zone is dominated by Filisphaera filifera, Habibacysta spp., and Spiniferites elongatus, Impagidinium striatum; Operculodinium centrocercum, Nematosphaeraeae labyrinthus, Pyxidinopsis reticulata, S. membranaceus, and S. mirabilis are also common. The D2 zone has abundant O. israelianum, Lingulodinium machaerophorum, L. filiform, Polysphaeridium zoharyi, Tuberculodinium vancampoae, N. labyrinthus, P. reticulata, S. membranaceus, and S. mirabilis. It is also characterized by a sharp increase in the proportions of O. israelianum, L. machaerophorum, and P. zoharyi, but a decline in the proportion of S. elongatus. The D3 zone is characterized by the highest proportions of N. labyrinthus in the entire section, and an increase in the proportion of S. elongatus. Operculodinium centrocercum, P. reticulata, S. membranaceus, Spiniferites ramosus, and S. mirabilis are common. The D4 zone has abundant O. centrocercum, P. reticulata, S. membranaceus, and S. mirabilis, and S. elongatus. O. israelianum, and L. machaerophorum are also common. In comparison with other zones, L. machaerophorum, P. zoharyi, S. elongatus, S. pacificus, and S. pachydermus represent periodic fluctuation.

4.2. Paleoenvironmental indicators
4.2.1. Climate indicators
We selected paleoclimate proxies based on previous reports of dinoflagellate cysts collected around the East Sea and North Pacific Ocean, to interpret the paleoceanography. Biectatodinium spp., F. filifera, Habibacysta spp., and S. elongatus are well-known cold-water indicator taxa; in particular, Biectatodinium spp. and S. elongatus live in cold water masses at high latitudes (Marret and Zonneveld, 2003; Matthiessen et al., 2018; Zonneveld et al., 2013; Zorzi et al., 2020). Opeculodinium israelianum, L. machaerophorum, L. filiform, P. zoharyi, and T. vancampoae are present in warm water masses in the East China Sea (Byun, 1995;Zonneveld et al., 2013). In particular, P. zoharyi and T. vancampoae live in high-salinity warm water, and are well-known indicators of the TWC (Byun, 1995; Kim et al., 2019; Li et al., 2017; Matsuoka et al., 1987). Operculodinium centrocercum can be abundant in cool environments and high-nutrient regions with reduced salinity due to river discharge, such as the South China Sea and Chinese coastal waters (Zonneveld et al., 2013; Zorzi et al., 2020). It was also the dominant species in the modern Okhotsk Sea (Bonnet et al., 2012) and the Gulf of Alaska during the late Pleistocene (Zorzi et al., 2020). Zonneveld and Pospelova (2015) reported that P. psilata might be characteristic of regions with freshwater input, based on reports from sites such as central western North America, the Black Sea, and the Maroma Sea. Therefore, it can be considered an euryhaline species. Pyxidinopsis psilata has not previously been reported in western Pacific areas, including the East Sea and East and South China Seas. However, this species was observed among the dinoflagellates at IODP Site U1430 (Fig. 3 and Plate 2). Pyxidinopsis psilata, which was newly reported in the western Pacific region, particularly in the East Sea, may contribute to global dinoflagellate datasets. Pyxidinopsis reticulata, S. membranaceus, and S. mirabilis are cosmopolitan species, but are most abundant in regions with low SSS as a result of river discharge near coastal areas (Zonneveld and Pospelova, 2015). Therefore, these species can be used as EGSCW indicators. Nematosphaeraeae labyrinthus is considered a cosmopolitan taxon, but it appears in higher proportions in high latitudes, including the North Atlantic, as well as in open ocean environments with low salinity and cold surface conditions (Radi and de Vernal; Zorzi et al., 2020). It is also reported in the Ulleung and Hupo Basins of the East Sea (Kim et al., 2019; Yi et al., 2012, 2020, 2022). This species is also known to thrive in environments characterized by lower upper water salinity due to increased river discharge or ice melting; it exhibits stenohaline behavior, making it a potential indicator species for low sea surface salinity (SSS). (Bonnet et al., 2012; Golovnina and Polyakova, 2005; Novichkova and Polyakova, 2007; Zonneveld et al., 2015). Impagidinium paradoxum can be dominant in central ocean regions with low upper water productivity and well-ventilated bottom waters; therefore, we used it as a proxy for ventilation (Zonneveld et al., 2013).
4.3. Principal component analysis

PCA was used to investigate trends in pollen and dinoflagellate cyst records (Fig. 4a). Based on pollen data, principal components (PC) 1 (axis 1) and 2 (axis 2) accounted for 22% and 16% of the total variance, respectively. Temperate conifer species as Pinus-Diploxylon-type and Juniperus, and warm temperate evergreen tree pollen Quercus subgenus Cyclobalanopsis appear to represent warm climate conditions (Fig. 4a, yellow shading). Xerophytic herb pollen, Artemisia, and cold-dry conifer species such as Pinus-Haploxylon-type, Abies, Picea, Larix, and Ephedra indicate relatively cold-dry climate conditions (Fig. 4a, blue shading). The families Taxaceae, Cephalotaxaceae, and Cupressaceae (T-C-C) and Tilia, Betula, and Tsuga species appear to represent temperate-humid climate conditions (Fig. 4a, green shading). Pollen from boreal conifer taxa such as Picea, Abies, and Pinus-Haploxylon-type were associated with positive values on axis 1 and showed correlations with boreal conifer pollen (Fig. 4a, blue shading). The value of axis 2 was negatively correlated with the changes in Betula and Tsuga proportions (Fig. 4a, green shading). Therefore, we suggest that PC 2 represents humidity changes in the pollen record at site U1430 spanning the MPT (Fig. 4a, green shading). Based on the dinoflagellate cyst assemblage, PC 2 and 1 accounted for 25% and 13% of the total variance, respectively. The presence of N. labyrinthus and S. elongatus could reflect cold and low-saline water mass conditions (Fig. 4a, blue shading). Lingulodinium machaerophorum and O. israelianum may indicate warm, high-saline water mass conditions (Fig. 4a, orange shading). PC 1 was positively correlated with changes in the N. labyrinthus proportion and negatively correlated with changes in Impagidinium spp. (Fig. 4b). We infer that variation in PC 1 could represent vertical mixing of the East Sea, ranging from a relative stratification mode (positive values) to a ventilation mode (negative values), considering the habitat conditions of dinoflagellate indices.

5. Discussion

5.1. Paleoclimate changes based on terrestrial palynomorph records during the last 2 Ma

5.1.1. Fluctuations in the pollen record at site U1430 spanning the MPT and MBE

Temperature is an important factor in plant growth and distribution. Vegetation patterns depend on the annual temperature during the plant growing season (Igarashi and Oba, 2006; Yi, 2011). Previous palynological studies have used Tp ratios to reconstruct changes in relative paleo-temperature (Demske et al., 2002; Hayashi et al., 2021; Igarashi and Oba, 2006; Igarashi et al., 2018; Kim et al., 2019; White et al., 1997; Whitlock and Bartlein, 1997; Yi, 2011). According to this definition, we reconstructed relative temperature changes during the last 2 Ma based on Tp ratios (broadleaf/conifer Tp). Site U1430 is predominantly characterized by conifer pollen, which represents 63–91% of all pollen grains (mean, 73%). Conversely, broadleaf pollen is rare to moderate at site U1430, but can still provide valuable information about past environmental changes in vegetation (Igarashi and Oba, 2006; Igarashi et al., 2018; Kim et al., 2019; Yi et al., 2008). Although broadleaf pollen is not dominant at Site U1430, we utilized the paleo-temperature index to reconstruct relative paleo-temperature changes over the past 2 Ma, taking into account the Tp ratio and the ratio of warm/cold broadleaf pollen. Three pollen zones were recognized based on the CONISS dendrogram (Grimm, 2011) and regime shift analysis (Rodionov, 2004). The occurrence pattern of paleoclimate indicators, which is associated with relative temperatures, shows fluctuation at ca. 1.5 and 0.4 Ma following insolation changes (Fig. 5). High Tp and broadleaf pollen ratio values before ca. 1.5 Ma (P1) indicate a warm climate with an expansion of temperate broadleaf forests, including Quercus subgenus Cyclobalanopsis. In addition, the Tp ratio before the MPT shows a trend following the mid-latitude Northern Hemisphere mean annual insolation (Fig. 5, light blue shading and Supplementary Figure S1a). This might be related to the climate/vegetation changes that occurred mainly in response to astronomical forcing-induced insolation before the MPT when ice and CO$_2$ variability were relatively low (Sun et al., 2019).

During the MPT (ca. 1.5–0.6 Ma; P2), the levels of Quercus subgenus Cyclobalanopsis and temperate broadleaf pollen decreased, and the Tp ratio generally shows a diminishing trend (indicating an increase in conifer pollen) that does not correlate closely with the trend of mean annual insolation compared to the period before the MPT (Fig. 5 and Supplementary Figure S1b). However, the ratio of broadleaf pollen clearly varies with insolation. These results suggest that, although the overall climate cooled during the MPT, vegetation dynamics were controlled by temperature changes driven by insolation. Our findings may be consistent with previous results suggesting a decreased sensitivity of monsoon climate/vegetation changes to insolation forcing due to the Northern Hemisphere gradually becoming glaciated and the associated increase in ice sheet volume during the MPT (Sun et al., 2019).

After the MBE (ca. 0.4 Ma; P3), the amplitude of the
glacial–interglacial climate cycle increased significantly due to CO$_2$ and ice volume dynamics (Chalk et al., 2017; Clark et al., 2006; Felder et al., 2022; Sun et al., 2019). The Tp ratio clearly demonstrates a positive relationship with the LR04 stacks rather than with insolation (Fig. 5, light orange shading and Supplementary Figure S1c), whereas the broadleaf pollen ratio trends align with insolation variation, as seen in zones P1 and P2. Terrestrial vegetation responses are typically controlled by insolation (Hayashi et al., 2021; Yin & Berger, 2010), whereas coniferous pollen, primarily transported by wind, may reflect fluctuations in the EAM (Igarashi et al., 2018; Kim et al., 2019). After the MBE, there was an increase in conifer pollen, which accounted for a significant proportion of the Tp ratio. Therefore, the Tp ratio after ca. 0.4 Ma appears to represent not only shifts in the EAWM and EASM according to the glacial–interglacial periods but also paleo-temperatures associated with insolation. Sun et al. (2019) suggested that the MPT transition likely reflects decreased sensitivity of monsoon climates to insolation forcing as the Northern Hemisphere became increasingly glaciated through the MPT, according to climate model simulations.
Therefore, the Tp ratio after the MPT likely indicates EAM variation following orbital-scale global climate changes associated with variation in atmospheric CO\textsubscript{2} and ice sheet dynamics.

After the MBE, boreal and temperate conifer pollen grains were abundant during glacial and interglacial periods, respectively; the association between EAM variability and conifer pollen assemblages is discussed in further detail in Section 5.1.3. Yin and Berger (2010) simulated the post-MBE warmer interglacial associated with increased global mean temperature during Northern Hemisphere winters, as induced by insolation and greenhouse gas concentrations. Huang et al. (2018) reported distinct ostracod faunal composition changes between the pre- and post-MBE periods at IODP Site U1427, and amplified glacial–interglacial cycling. Significant increases in Quercus subgenus Cyclobalanopsis was visible during the interglacial period after the MBE at IODP Site U1430 (Fig. 5f), and our results are in line with those of previous studies reporting that the interglacial period after the MBE was warmer (Matsuzaki et al., 2018; Yin and Berger, 2010).

Cryptomeria, a moisture-loving pollen taxon, is currently indigenous...
on Ulleung Island in the Korean Peninsula, and is distributed along the western coast of the Japanese Archipelago due to the high humidity that occurs in this area as a result of the EASM (Igarashi et al., 2018). Cryptomeria was distributed in the southern part of the Korean Peninsula until the early Pleistocene, after which it became extinct (Kong, 1995, 2000). Therefore, Cryptomeria during the early to late Pleistocene may have originated from the western coast of the Japanese Archipelago via the EASM. Despite its rarity, Cryptomeria was present intermittently during the interglacial period and is more frequently represented after ca. 1.5 Ma in this study section (Fig. 5f). This result indicated that the EASM markedly affected the East Sea due to the subsequently intensified EAM after ca. 1.5 Ma.
5.1.2. Boreal conifer and xerophytic pollen records indicate EAWM variability

Softwood conifers such as Picea, Abies, and Pinus-Haploxylon-type, which are distributed in the subalpine zone of northern East Asia, are resilient to cold, dry climate conditions and serve as effective indicators of such conditions (Chen et al., 2017; Chung et al., 2006; Li et al., 2015; Yasuda et al., 2004; Yi et al., 2003; Zheng et al., 2014). Moreover, coniferous pollen grains, equipped with two air sacs, can be transported by wind over long distances compared to other arboreal pollen grains, making them suitable as EAM indicators (Igarashi et al., 2018; Kim et al., 2019; Xin et al., 2020). However, pollen records from the deep ocean reflect vegetation on adjacent landmasses, such that pollen from Site U1430 could represent vegetation from the Korean Peninsula, Japanese Archipelago, and inland China (Sánchez Goñi et al., 2018).

However, because Site U1430 is influenced by the EAM and the third TWC branch, the vegetation it reflects may vary regionally based on climate and ocean circulation. Given the direction of the East Sea current circulation, it is highly unlikely that pollen released from rivers in the Japanese Archipelago would reach the Ulleung Plateau (Fig. 1; Jun et al., 2020; Yi, 2011). Therefore, the pollen record from Site U1430 is more likely to reflect the vegetation of the Korean Peninsula rather than the Japanese Archipelago from a water transportation perspective. Nevertheless, pollen transported by streams to the ocean could be morphologically transformed through processes such as oxidation or breakage (Traverse, 2005).

At Site U1430, oxidized and broken grains were rare and were excluded from the count as noted in Materials and Methods.

Considering the wind direction of the EAM affecting the Ulleung Plateau, a strong EAWM/EASM is more likely to reflect northwestern/southeastern vegetation due to northwesterly/southeasterly winds, respectively. Moreover, the boreal conifer pollen record at Site U1430 exhibits a distinct positive correlation with δ¹⁸O values, suggesting clear transportation by the EAWM during the glacial period (Supplementary Figure; Kim et al., 2020). Therefore, boreal conifer pollen from Site U1430 serves as a potential EAWM indicator in this study, as it is likely to have been transported to the Ulleung Plateau under the influence of the EAWM from northwestern vegetation rather than southwestern vegetation in the Japanese Archipelago.

Values on PCA axis 1 were positively correlated with changes in boreal conifer concentration, reflecting the variability of the EAWM (Fig. 6b and c). Artemisia, a genus of xerophytic herbs, was also positively correlated with boreal conifer pollen concentration and LR04 stacks (Kim et al., 2020). These pollen data and the value on PCA axis 1 also demonstrate a positive correlation with LR04 stacks. Therefore, we confirm the glacial period in this study based on the high value of PCA axis 1 and EAWM pollen data.

Boreal conifer pollen concentrations remained below 9000 n/g during the early Pleistocene (Fig. 6c). However, regime shift detection results show the shift from a low boreal conifer pollen concentration (below 9000 n/g) to a high concentration (above 9073 n/g) after ca. 1.3 Ma, which suggests climate cooling and an enhanced EAWM after ca. 1.3 Ma (Fig. 6c). Strengthening of the EAWM during the Mid-Pleistocene (Sun et al., 2020) reported a distinct positive correlation of the EAWM at 1.6 Ma (Fig. 6e), and the significant increase in less grain size in the CLP since 1.25 Ma also suggests strengthening of the EAWM during the Mid-Pleistocene (Sun et al., 2020). The median dust record from Site U1425 from Site U1430 shows an increase in Gobi clay in the East Sea by 0.6 Ma due to westerly jet (WJ) and EAWM strengthening due to increasing Siberian high activity after the intensification of Northern Hemisphere glaciation (INHG). After 0.6 Ma, the aeolian dust record was dominated by Taklimakan and Gobi dust transported by the WJ rather than Gobi clay by the EAWM (Fig. 6e and f; Lee et al., 2022). By contrast, boreal conifer data from Site U1430 show consistently high values after 1.3 Ma, and our findings imply a consistently enhanced EAWM after 1.3 Ma. Site U1430 pollen data and core U1425 dust data provide insight into the strength of the EAWM. However, the pollen data reflects the specific characteristics of the East Sea terrain, which includes nearby forests, and may therefore differ from the dust data. Consequently, incorporating pine pollen data from the East Sea can contribute significantly to investigations of regional atmospheric circulation patterns, such as EAWM fluctuations across North-east Asia.

Ephedra, a drought-resistant shrub distributed in arid and semi-arid regions, is commonly used as a desert indicator species in northwestern inland China (González-Juárez et al., 2020; Su and Zhang, 2016). In addition, Ephedra is a wind-pollination, which is typically dispersed by wind (Bolinder, 2017; Rydin and Bolinder, 2015).

Ephedra found in the East Sea usually indicates the cold-dry glacial period and is thought to originate from inland China (Gallagher et al., 2015; Igarashi et al., 2018). Alternatively, it is also possible that Ephedra may have been transported by wind to southwestern China during the warm period was transported via the Kuroshio extension and TWC into the East Sea (Kawahata and Oshihma, 2002). However, in this study, Site U1430 exhibits a high abundance of Ephedra after 0.4 Ma, coinciding with a period of strong WJs as indicated by dust data (Fig. 6e and g; Lee et al., 2022). Thus, it is likely that Ephedra was transported by WJs into the East Sea from arid inland regions during the glacial period.

5.2. Paleoceanographic changes inferred from dinoflagellate cyst records

Before ca. 1.9 Ma (D1), an abundance of Bitectatodinium spp. and S. elongatus, which are cold-water species, indicates a sustained low SST due to cold climatic conditions after the NHG period. Furthermore, the positive value of axis 1 implies poor circulation of the East Sea, which might be associated with the intrusion of weak ECSWC based on low-salinity dinoflagellates, including N. labyrinthus (Fig. 7). Based on the redox proxies from authigenic U (αU) and U/Al records, Das et al. (2021) reported relatively anoxic conditions for Site U1430 before ca. 2 Ma, in line with our results for PCA axis 1 (Fig. 7b). Oxygen-rich water flowing into the East Sea through the northeastern strait (TGS) from the North Pacific was restricted due to gradual uplift of the northeastern strait from the early Pliocene to ca. 1.7 Ma (Itaki, 2016; Sato et al., 2012; Zhao et al., 2022). Additionally, the eustatic sea-level fall after the NHG period might have caused suppressed vertical mixing following the isolation of the East Sea (Miller et al., 2005).

After ca. 1.9 Ma (D2), the abundance of TWCC indices, including Tuberculodinium vanampcowa and warm-water dinoflagellate species, indicates intrusion of the strong TWC into the East Sea. The KS, through which the TWC and ECSWC flow, is located in the southern part of the East Sea. The KS maintained high terrain up to the Miocene, and TWC flowed weakly into the East Sea due to the narrow and shallow KS up to the early Pleistocene. Subsequently, the KS gradually deepened due to the stretching of the Okinawa Trough during ca. 1.5–2.0 Ma (Gungor et al., 2012; Park et al., 1998), and a strong TWC flowed into the East Sea after ca. 2 Ma (Gallagher et al., 2009, 2015; Itaki, 2016; Kitamura and Kimoto, 2006; Lee et al., 2001). Hence, we suggest that the strong TWC flowed into the East Sea after ca. 1.9 Ma, and the intrusion of the TWC resulted in relatively ventilated conditions (Fig. 7g). Furthermore, abundant ECSWC indexes indicate that the ECSWC might also have alternately flowed into the East Sea along with the TWC during this period. When the ECSWC was dominant, PCA axis 1 showed a positive value, indicating a relatively stratified condition (Fig. 7b, g). Changes in SSS in the East China Sea occur due to significant river discharge influenced by EASM precipitation (Ichikawa and Beardsley, 2002). The CDW is created when fresh water from the Changjiang mixes with seawater around the estuary, and then flows eastward into the East Sea, thereby contributing to its low SSS (Ichikawa and Beardsley, 2002; Sobel et al., 2002; Kubota et al., 2019). Zhao et al. (2022) reported that the relatively fresh TWC, with enhanced dilution from Yangtze River water under enhanced EASM rainfall, weakened vertical mixing of the East Sea, resulting in relatively anoxic conditions during the interglacial.
period before the MPT. Therefore, we suggest that the change from relative stratification to ventilated conditions in the East Sea after ca. 1.9 Ma was affected by the changes in inflows of the TWC and ECSCW.

During the MPT (ca. 1.5–0.6 Ma; D3), N. labyrinthus was maintained in high proportions, cold-water species were abundant, and axis 1 had a positive value. Therefore, this result implies low salinity of surface water and stratification of the East Sea during this period. There are two potential scenarios leading to a reduction in SSS in the East Sea. The first involves an increased inflow of ECSCW/CDW due to an intensified EASM. However, our study shows a decline in ECSW index values (Fig. 7), alongside a decrease in theTp ratio and an increase in boreal conifer pollen during the MPT (D3). These results suggest relatively cold climate conditions under the intensified EAWM. Thus, it appears unlikely that the SSS decrease during this period resulted from surface water freshening due to heavy EASM-driven precipitation. The second scenario involves the freshening of surface water by melting sea ice due to a southward shift of the subpolar front (indicating a weakened TWC). As noted above, N. labyrinthus has been reported in areas where ice melt may lower upper water salinity (Golovchina and Polyakova, 2005; Novichkova and Polyakova, 2007). Therefore, the dominance of cold-water species and N. labyrinthus during D3 may suggest that sea ice formed during the cold climate conditions of the MPT and moved southward, leading to reductions in SST and SSS, and increased stratification of the East Sea (Fig. 7).

Das et al. (2021) suggested that southward sea ice movement in the melting zone induced cooling of the SST and lower SSS over the East Sea based on ice-raftered debris records at IODP Site U1423. Additionally, based on benthic foraminiferal taxa proportions (e.g., *Uvigerina*) at IODP Site U1426 during this period, Das et al. (2020) suggested that this faunaal composition is associated with highly stressed and suboxic to dysoxic conditions. Zhao et al. (2022) confirmed a relatively anoxic environment in this region based on high aU stack values during the MPT. These previous studies support our findings that the East Sea might have been stratified due to suppressed vertical mixing based on dinoflagellate indices, indicating low SST and SSS at the Site U1430. On the other hand, TWC indices of foraminifera and bivalve fauna from the western margin of the Japanese Archipelago, which were affected by the first branch of the TWC, were abundant during ca. 1.8–1 Ma (Gallagher et al., 2015; Itaki, 2016; Kitamura and Kimoto, 2006), while dinoflagellate cyst TWC indices at IODP Site U1430, which were affected by the third branch of the TWC, were rare after ca. 1.5 Ma. The third branch of the TWC flows north along the eastern margin of the Korean Peninsula and deflects eastward to cross the Ulleung Plateau (Fig. 1), forming the subpolar front (Hase et al., 1999). Therefore, the difference in TWC faunas between U1430 and the western margin of the Japanese Archipelago implies that the subpolar front moved southward, and was affected by the low SSS and SST water mass flowing southward during this period.

After the MPT (~0.6 Ma; D4), eutrophic-cool temperature environment species (ECSCW indicators) were abundant, and the cold-water species and TWC indicator species alternately appeared, although not continuously. Additionally, axis 1 moved toward a negative value after the MBE, and N. labyrinthus was rare. These results imply that the East Sea became ventilated or stratified due to intrusion or prevention of the current through the KS following the increase in sea level fluctuations occurring after the MBE.

### 5.3. Vegetation changes in response to climatic and marine environment changes

Hemlock (*Tsuga*) naturally grows in cool, humid climates ranging from coastal areas to subalpine zones (Brisbin, 1970; Li et al., 2023). Although hemlock currently inhabits Ulleung Island, it was also found on the Korean Peninsula prior to the Holocene (Kong, 2000). Birch (*Betula*) thrives in snow-covered alpine regions, exhibiting tolerance to winter humidity (Binney et al., 2009; Qian et al., 2019). In this study, the broadleaf ratio aligns with Northern Hemisphere mean annual insolation (Fig. 5), whereas the occurrence patterns of *Tsuga* and *Betula* are linked to Northern Hemisphere winter insolation (Fig. 8). According to these results, the expansion of hemlock and birch forests would likely have been influenced by mild winter climate conditions associated with high levels of winter insolation. Both *Tsuga* and *Betula* are found in high proportions during transition periods, specifically from glacial (cold) to interglacial (warm) periods. Moreover, the occurrence patterns of these taxa over the last 2 million years predominantly manifest during the early, rather than late, Pleistocene (Fig. 8) (see Fig. 9).

Dinoflagellate assemblage indicators in the TWC also represent a high proportion during the early Pleistocene (Fig. 7). In addition, *Tsuga*, *Betula*, and dinoflagellate peaks (TWC indicators) are well correlated with high winter insolation levels (Fig. 8). These results suggest that
Factors such as mild winter conditions with high winter insolation, coupled with the inflow of the TWC, could have influenced the abundance of *Tsuga* and *Betula*. Previous studies suggested that moisture-loving conifer tree taxa, such as Taxodiaceae and *Tsuga*, expanded in coastal areas of the Korean Peninsula and Japanese Archipelago due to heavy snowfall driven by TWC inflows during the early Pleistocene (Igarashi et al., 2018; Kim et al., 2019). Similarly, mild winter climate conditions brought on by high levels of winter insolation and evaporation due to TWC intrusion may have led to heavy snowfall, supplying soil moisture. Therefore, these environmental conditions would have been conducive for the growth of winter humidity-tolerant taxa such as *Tsuga* and *Betula*.

6. Conclusion

Palynological profiles for the past 2 Ma in the Ulleung Plateau of the East Sea reflect orbital-scale climate changes, EAM fluctuations, and ocean circulation of the East Sea. The vegetation response is controlled by insolation, and the ratio of hardwoods to conifers (the Tp ratio) and broadleaf pollen ratio can indicate a relatively paleo-temperature. The high Tp and broadleaf pollen ratio before the MPT showed a positive correlation with insolation, which implies a relatively warm climate.
The lower Tp ratio value throughout the MPT might be related to glaciation and cooling of the Northern Hemisphere. The proportion of conifers increased after the MBE; boreal (temperate) conifers dominated during the glacial (interglacial) period. In addition, the Tp ratio and occurrence pattern of conifers after the MBE clearly show a positive correlation with the δ18O curve. Therefore, pollen records from IODP Site U1430 could imply temperature changes due to astronomical forcing-induced insolation before the MPT. Alternatively, they could represent suppressed vertical mixing of the East Sea due to the low SSS and ᵃ¹⁸O which is associated with low-salinity conditions due to sea ice melting, and cold-water species were abundant after 1.5 Ma. This finding suggests that the Quaternary EAWM evolution was controlled by changes in global ice volume and climatic cooling. An abundance of warm-water species after ca. 1.9 Ma indicates intensified intrusion of the TWC after the expansion of the KS. During this period, the average SST of the East Sea might have been relatively high due to the inflow of the TWC, and intrusion of the high-salinity TWC may have promoted vertical mixing of the East Sea. Nematosphaeropsis labiatus, which is associated with low-salinity conditions due to sea ice melting, and cold-water species were abundant after 1.5 Ma. This finding suggests suppressed vertical mixing of the East Sea due to the low SSS and SST associated with sea ice during the cool climate of the MPT, as shown by the low Tp ratio. After the MBE, an alternation of dinoflagellate assemblages between cold and warm water masses marks changed occurring due to sea level fluctuations associated with a globally amplified glacial-interglacial cycle. Tsuga and Betula, taxa tolerant of winter humidity, were abundant during mild winter periods characterized by high winter insolation throughout the past 2 million years. They were especially prevalent in the early Pleistocene due to the strong intrusion of the TWC may have led to heavy snowfall, supplying soil moisture. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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