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Paleo-Tsushima Water and its effect on surface water properties in the East Sea during the last glacial maximum: Revisited

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Abstract

The semi-enclosed deep marginal East Sea is known by limited sill flow and low sea-surface salinity during the last glacial maximum (LGM) when sea level was about 130 m lower than the present level. Although three straits (the Tsugaru, the Soya and the Tartar) with shallower than 130 m sills were completely closed, the Korea Strait with a maximum sill depth of 140 m seems to have persisted as a partial connection to the East Sea, allowing a sill flow. The volume transport at the Korea Strait during the LGM is estimated at approximately 0.3–1.1 $\times$ 10^{12} m^3/yr, by using bathymetry, seismic reflection profiles and current data. The low sea-surface salinity has been explained by the East China Sea Coast Water (ECSCW) and high precipitation. However, the existing geological observations indicate that precipitation was reduced in the glacial East Sea. The high-resolution numerical simulation results predict that evaporation (2.16 mm/day) exceeded precipitation (1.43 mm/day), further suggesting net evaporation (evaporation minus precipitation) rates (0.2 $\times$ 10^{12} m^3/yr) over the LGM East Sea. This signifies that the precipitation was not the factor lowering surface paleosalinity and that the paleo-Tsushima Water carried a huge amount of freshwater from the ECSCW than previously expected.

The calculated surplus evaporation (0.2 $\times$ 10^{12} m^3/yr) and sill flow (0.3–1.1 $\times$ 10^{12} m^3/yr) are not identical, but they could be oceanographically considered as similar. The comparison between both values implies that most of the throughflow ultimately escaped the East Sea through the evaporation process during the LGM. The regional sea level in the almost isolated East Sea might be largely maintained by a rough balance between incoming throughflow and outgoing evaporation during the LGM. The geographic restriction due to lowered sea level and lower surface salinity by limited vertical mixing in the glacial East Sea are analogous to modern oceanographic features in the Black Sea.
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1. Introduction

Glacial-caused global falling of sea level in the late Quaternary seems to be a generally synchronous event, and might have induced geographic and oceanographic changes especially in the small, semi-enclosed seas such as the East Sea, connected with the open ocean through shallow sill systems. The paleoenvironmental changes due to the late Quaternary sea-level drop have been presented in various areas of the world oceans (Wang and Wang, 1980; Ryan et al., 1997; Zhuo et al., 1998; Karaca et al., 1999; Petit-Maire et al., 2000; Aksu et al., 2002b; Siddall et al., 2004). Here we attempt to describe the implication of the sea-level drop to the water properties of the East Sea during the last glacial maximum (LGM).

The East Sea is a typical semi-enclosed marginal sea and is linked to the South Sea of Korea by the Korea/Tsushima Strait (about 140 m in sill depth), to the northwest Pacific Ocean by the Tsugaru Strait (130 m), and to the Sea of Okhotsk by the Soya (55 m) and Tartar (15 m) straits (Fig. 1). This sea has an area of approximately 1,000,000 km^2 and an average depth of 1680 m with a maximum depth of 3700 m. During the glacial periods of the late Quaternary, the East Sea must have experienced oceanographic alteration because the straits are shallow. Particularly during the LGM, the global drop of about 130 m in sea level might have led to a reduction of the surface area and closure of three shallow straits (the Tsugaru, the Soya and the Tartar) in the East Sea (Yasuda,

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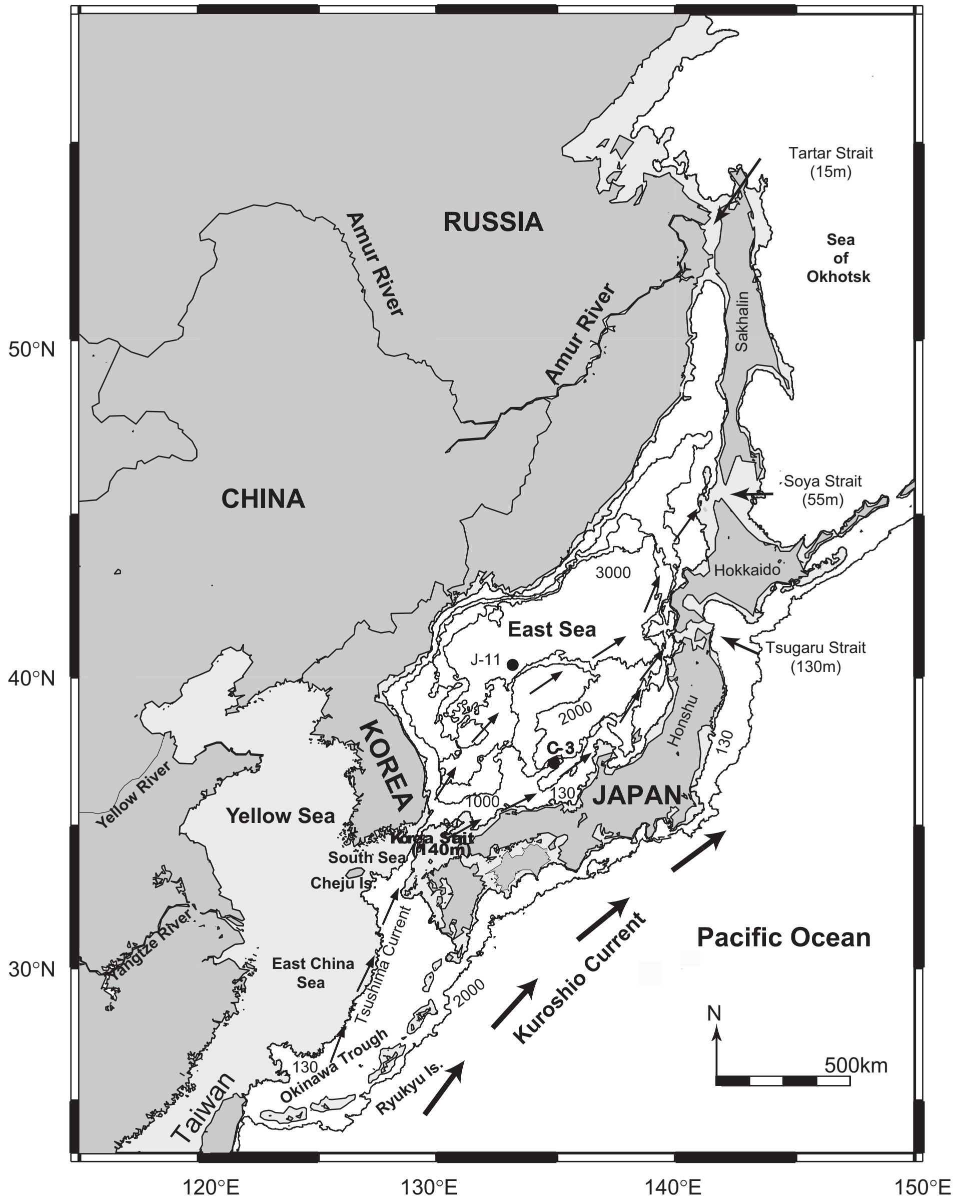

Fig. 1. The East Sea is surrounded by the northeastern Asia and Japanese islands with four shallow straits of less than 140 m sills (the Korea, the Tsugaru, the Soya and the Tartar). The Tsushima warm Current enters the sea through the Korea Strait and exits mostly via the Tsugaru and Soya straits. This sea was nearly closed due to a glacio-eustatic drop in sea level and maintained a partial connection to the northern East China Sea via the Korea Strait during the LGM. The light gray area was exposed at that time. Solid circles indicate the core locations (C-3 and J-11) used in previous studies (Oba et al., 1991, 1995; Gorbarenko and Southon, 2000). Bathymetry is in meters.

1984; Oba et al., 1991; Ono and Naruse, 1997; Kim et al., 2000; Ono et al., 2004). Complete closure of the Korea Strait during the LGM is still debated, but the general opinion is that the deepest sill of the Korea Strait might have been in part inundated, allowing a continuous, but highly limited sill flow (Morley et al., 1986; Keigwin and Gorbarenko, 1992; Matsui et al., 1998; Tada, 1999; Park et al., 2000; Lee and Nam, 2003). Volume transport at the Korea Strait was reduced during the LGM. Despite the marked decrease in the influx, the East Sea is characterized by low sea-surface salinity (20–29‰; see Oba et al., 1995; Matsui et al., 1998; Tada, 1999; Gorbarenko and Southon, 2000; Itaki et al., 2004) associated with abnormally light δ^{18}O values of planktonic foraminifera during the LGM as shown in Fig. 2 (Oba et al., 1991; Tada, 1999; Gorbarenko and Southon, 2000).

There are three possible freshwater sources in the LGM East Sea: (1) freshwater input through the Korea Strait, (2) enhanced local precipitation and (3) river runoff from the surrounding land areas. The low surface paleosalinity event has been explained primarily by two factors: an increased freshwater supply from the East China Sea Coastal Water (ECSCW) (Oba et al., 1991; Tada, 1999; Tada et al., 1999; Gorbarenko and Southon, 2000); and

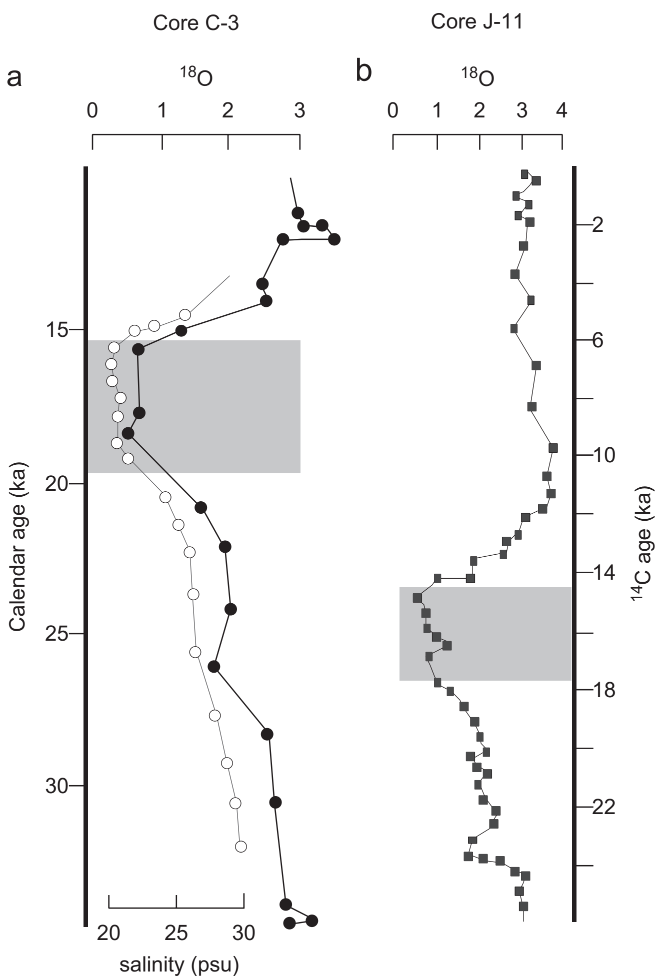

Fig. 2. Downcore variations in $\delta^{18}O$ of planktonic foraminifera and salinity. (a) Salinity (Tada, 1999) and $\delta^{18}O$ (Oba et al., 1995) are extracted from Core C-3 with calendar ages. Open circles are sea-surface salinity, displaying low values (down to 20‰) between 15 and 20 cal. ka BP. (b) $\delta^{18}O$ trends are derived from Core J-11 with ^{14}C age dates (Gorbarenko and Southon, 2000). The shaded areas show the time intervals of low sea-surface paleosalinity associated with light $\delta^{18}O$ with different chronological determinations.

from excess precipitation (Keigwin and Gorbarenko, 1992; Tada, 1995; Gorbarenko and Southon, 2000). It has been argued that precipitation may not be the factor decreasing surface salinity (Lee and Nam, 2003) because decreased temperatures during the glacial periods usually lead to reduction of global precipitation, compared with interglacial time (Kim et al., 2003, 2006). CLIMAP (1981) reconstructions show that the sea-surface temperature (SST) around the East Sea decreased by about 4–8 °C during the LGM. In addition, the lower SSTs have been inferred mainly based on $\delta^{18}O$ values of planktonic foraminifera (Oba et al., 1991; Tada, 1999; Gorbarenko and Southon, 2000). The cooled SSTs (less than 8 °C) in the East Sea were also suggested by the dominance of *N. pachyderma* during the LGM (Kim et al., 2000). Using the aeolian dust accumulation in sediment cores, Irino and Tada (2002) reconstructed stronger wind and reduced precipitation in the East Sea. Saito (1998) suggested that sediment supply by the Yellow River largely decreased due to low precipitation during the LGM. Comparatively, modern meteorological data (Yanagi, 2002) show that evaporation (3.27 mm/day) over the East Sea is higher than precipitation (2.96 mm/day). The colder, windier and drier conditions seem to have been maintained even in the glacial East Sea. Subsequently, the discussion concerning regional precipitation proposes that the effect of sill flow on the low paleosalinity in the LGM East Sea should be reevaluated. The effect of river runoff from the northeastern Asia and the Japanese islands has not been considered.

This study is primarily concerned about the major cause of the low sea-surface salinity in the East Sea during the LGM. The role of hydrological parameters (e.g. evaporation and precipitation) and throughflow at the Korea Strait that might play a role in reducing sea-surface salinity and in regulating regional sea-level conditions in the nearly isolated East Sea during the time of the lowest sea level in the late Quaternary will be addressed. To solve this problem, the relative importance of evaporation and precipitation is investigated with geologic records and climatic simulation. Volume transport at the Korea Strait is also estimated based on seismic reflection data, bathymetric mapping and the present current data. This study includes high-resolution numerical simulation results for the LGM condition of the East Sea. The simulation results are compared with the existing geological records to better understand the late Quaternary paleoceanography of the East Sea.

2. Background

The deep marginal East Sea is located between the Asian mainland and the Japanese islands and is connected with the Okhotsk Sea, the northwestern Pacific Ocean and the East China Sea (ECS) through the South Sea by four shallow straits (Fig. 1). This sea consists of a narrow shelf, steep slope and deep basin. The modern East Sea is vertically stratified in two water masses: surface layer and deep water. The SSTs range from 0 to 25 °C (Moriyasu, 1972). Temperatures (16–24 °C) and salinities (31.3–34.5‰) have been measured in the surface waters of the southern East Sea during the summer seasons (Kang et al., 1997). Low salinity values (down to 31.3‰) may be caused by freshwater influxes originating from the southeastern coast of Korea (e.g. the Nakdong River) and the Yangtze River (Delcroix and Murtugudde, 2002; Isobe et al., 2002). The surface water circulation is dominated by the warm Tsushima Current in the south and the cold Liman Current in the north. The warm Tsushima Current, a branch of the western boundary Kuroshio Current, enters the East Sea through the Korea Strait and then exits the sea mostly through the Tsugaru and Soya straits (Toba et al., 1982; Lim and An, 1985; Isobe, 1999). This current generally carries warm (26 °C in summer and 14 °C in winter) and saline water to the sea, with a mean velocity of about

10–90 cm/s (Lee and Jung, 1977; Korea Hydrographic Office, 1982; Isobe et al., 1994; Teague et al., 2002). The most acceptable volume transport of the Tsushima Current is about 2 Sv (1 Sv = 10^6 m^3/sec) (Toba et al., 1982; Isobe, 1994, 1999) although its values measured range from 1.3 to 2.7 Sv (Yi, 1966; Toba et al., 1982; Lim and An, 1985; Isobe, 1994, 1997; Isobe et al., 2002; Teague et al., 2002; Chang et al., 2004). The Tsushima Current normally is faster in summer than in winter (Lee and Jung, 1977; Korea Hydrographic Office, 1982; Ichiye, 1984; Isobe et al., 1994). The nearly homogeneous deep water, known as the East Sea Proper Water (ESPW), is cold (0–1 °C) and well-oxygenated (5–6 ml/l) (Kim et al., 1996; Itaki et al., 2004; Kang et al., 2004). The deep water is subdivided into three water masses: the East Sea Central Water (ESCW), the East Sea Deep Water (ESDW) and the East Sea Bottom Water (ESBW) (Kang et al., 2004). The cold deep water seems to be formed in the northwestern East Sea because of strong cooling of surface water and sea ice formation during winter (Nitani, 1972; Gamo et al., 1986; Martine et al., 1992; Kawamura and Wu, 1998).

A strait with a shallow sill depth is a sensitive seaway because inflow and outflow passing through it are basically controlled by fluctuating sea levels. Global sea-level drop during the LGM (ranging from 23,000 to 19,000 cal. BP; see Mix et al., 2001) might considerably alter geographic and oceanographic conditions around the Korea Strait region, resulting in a reduction of cross-sectional area and sill flow. The Korea Strait is divided into two regions: (1) inner (down to 80 m) and mid-shelf (80–120 m) and (2) outer shelf (deeper than 120 m) including a trough as deep as about 230 m (Park and Yoo, 1988; Yoo and Park, 2000; Yoo et al., 2003). The inner shelf of the Korea Strait is characterized by thick (about 30 m), fine-grained muds corresponding to the highstand systems track (Park and Yoo, 1992; Yoo and Park, 2000). In contrast, the mid-shelf and outer shelf (except the trough region) are largely blanketed by thin (about 5 m), coarse sediments which are interpreted as the transgressive systems track (Park and Yoo, 1992; Yoo and Park, 2000). Although the inner and mid-shelf areas were subaerially exposed, the outer shelf was, to a considerable extent, below sea level during the LGM.

Despite the lower sea level during the LGM, a large surface area of the East Sea would be maintained. Only about 15% of the present surface area was exposed to air because the East Sea is quite steep and deep. It is generally agreed that all four straits around the East Sea have experienced such sea-level variations in the late Quaternary. The three straits with shallower sill depths, except the Korea Strait, are postulated to have been closed during the LGM (Yasuda, 1984; Oba et al., 1991; Ono and Naruse, 1997; Kim et al., 2000; Ono et al., 2004). Archaeologically, Kuzmin et al. (2002) revealed human exchange and migration from the northeastern Asia through Sakhalin to Hokkaido at least since 23,000 cal. BP. This indicates a land bridge across the Tartar and the Soya straits. The land route to Honshu since 30,000 BP has been also suggested (Oda, 1990; Motohashi, 1996), indicating the emergence of the Tsugaru Strait. Recently, the pre-exposure of the Tsugaru Strait has been investigated with a measurement of ^{10}Be concentration for underwater rock samples exposed during the sea-level lowstands of the last glacial period (Kim and Imamura, 2004). By contrast, the Korea Strait (about 200 km wide and 140 m in sill depth) might not be completely shut down (Fig. 3a), but it could remain partially submerged in the western part at that time (Matsui et al., 1998; Gorbarenko and Southon, 2000; Park et al., 2000; Lee and Nam, 2003; Yoo et al., 2003). The sea-level curve reconstructed in the Korea Strait region shows that the sea level was about 130 m lower than the present level during the lowest sea-level period of the late Quaternary between 25,000 and 15,000 years BP, suggesting the connection of the East Sea to the northern ECS (Park and Yoo, 1988; Park et al., 2000).

The coastline of East China might have moved to around Cheju Island due to a subaerial emergence of the shallow Yellow Sea. Freshwaters drained into the northern ECS during the LGM (Oba et al., 1991; Tada, 1999; Tada et al., 1999). Inflow of the Kuroshio Current into the ECS was largely restricted due to the formation of the land bridges around Taiwan and the Ryukyu islands during the LGM (Ujiie et al., 1991; Ahagon et al., 1993; Ujiie and Ujiie, 1999). This further limited the Tsushima Current influx, resulting in a relatively decreased influx of saline water into the East Sea at that time. The water passing through the Korea Strait during the LGM might not be entirely saline, but rather mixed with the Tsushima Current and freshwater (hereafter "the paleo-Tsushima Water"), diluting surface water. Subsequently, the lowered sea-surface salinity might create the density stratification between surface layer and deep water, severely limiting vertical mixing. As a result, anoxic conditions have been developed in the deep water of the East Sea during the LGM (Oba et al., 1991; Keigwin and Gorbarenko, 1992; Gorbarenko and Southon, 2000; Ishiwatari et al., 2001).

3. Volume transport via the Korea Strait during the LGM

A lowered sea level might considerably diminish the cross-sectional area of the Korea Strait, limiting the Tsushima Current influx into the East Sea during the LGM. The significantly reduced volume transport at the Korea Strait is estimated based on the cross-sectional passage obtained by bathymetry, seismic reflection profiles and the present-day current meter data. Sediment thickness was extracted from the seismic profiles, assuming that the seismic velocity for the latest Pleistocene–Holocene sediments is 1500 m/s (Cho, 1985; Kim and Suk, 1985).

The cross-sectional area at the Korea Strait is assessed at about 10 km wide and 10 m deep when sea level was the lowest during the LGM (see Fig. 3). To determine the accurate sill depth during the LGM, sediment thickness (less than 7 m) deposited since the LGM was estimated by

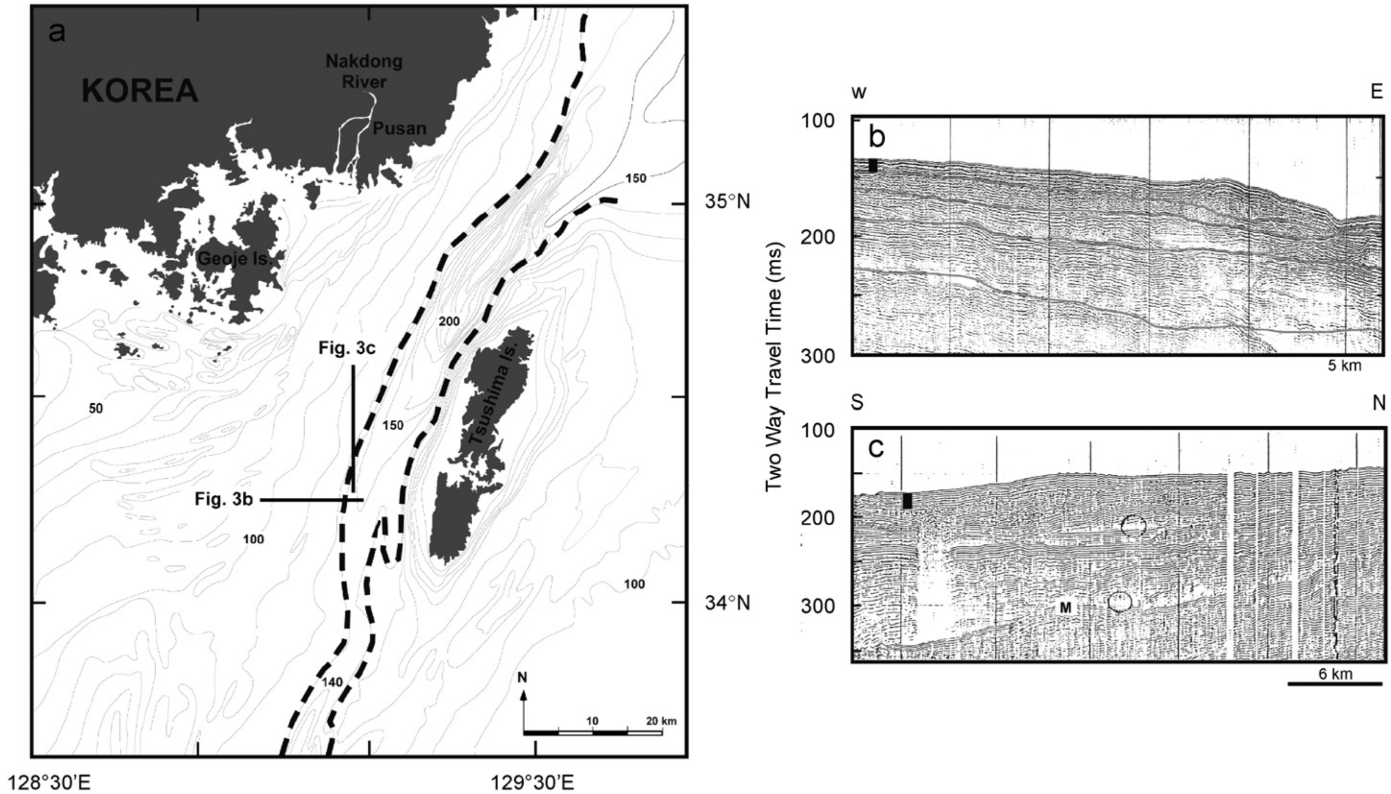

Fig. 3. The Korea Strait region with a general bathymetry. The paleo-strait is indicated by the area between two thick dotted lines (a). Sparker seismic reflection profiles (b and c) collected from the central western part of the Korea Strait shelf region. About 7 m of sediment layer (shown as a vertical bar) is interpreted to have accumulated since the LGM. The sediment thickness is estimated on the basis of the seismic velocity of about 1500 cm/s measured in Pleistocene sediments.

analyzing seismic reflection profiles (Fig. 3b, c). Similarly, previous studies (Park and Yoo, 1992; Yoo and Park, 2000) found that sediment sequence in the shelf margin (120–130 m deep) is less than 5 m in thickness. Molluscan shells selected at less than 1 m depth in sediment cores were dated by 15,000–21,000 ^{14}C ages (Yoo and Park, 2000; Yoo et al., 2003). This indicates that sediment accumulation around the shelf margin is presumably much less than 5 m. Thus, about 2 m of the sediment thickness was additionally subtracted, and then the corrected cross-section area (120,000 m^2) during the LGM is obtained by multiplying about 10 km wide and 12 m deep.

Ujiie and Ujiie (1999) suggested that the Kuroshio Current system had moved further southward during the LGM. This might weaken the intrusion of the Kuroshio Current into the north ECS and hence affect the Tsushima Current. For this reason, the current velocity at the LGM Korea Strait appears to have decreased although surface currents in open oceans are usually faster in the glacial than in the interglacial due mainly to the stronger winds (Crowley and North, 1991). Although sands (up to 90%) predominate, gravelly sediments (grain sizes of 2–16 mm) commonly are present on the mid and outer shelf in the Korea Strait region (ranging from 80 to 170 m in water depths), a route for the paleo-Tsushima Water (Park and Yoo, 1992; Yoo and Park, 2000; Yoo et al., 2003). The coarse-grained deposits predominantly are oriented northeast, indicating flow direction and intensity of the paleo-Tsushima Water toward the East Sea. These sediments are interpreted to have deposited between 21 and 15 ^{14}C ka BP which corresponds to a period of lowest sea level (Yoo and Park, 1997, 2000; Park et al., 2000). According to the diagram relating current velocity to grain size (Sundborg, 1956), most grains of 10 mm do not move until water velocity reaches ~100 cm/s. Moreover, sediment particles (about 2–5 mm in diameter) are usually not in motion at a flow velocity of about 50 cm/s. In consideration of the abundant sands with some gravelly particles, the lower values (10–30 cm/s) of the modern current speeds for this study are adopted to assume the paleo-current velocities for the LGM because it is not possible to directly measure the glacial current velocities. The volume transport at the Korea Strait during the LGM is evaluated as approximately $(0.3\text{–}1.1) \times 10^{12}$ m^3/a, by multiplying 120,000 m^2 by (10–30) cm/s.

Previous studies also suggested that the water mass flowing through the Korea Strait diminished by more than 95% during the LGM (Tada, 1995; Matsui et al., 1998). This means that only about 5% (3.0×10^{12} m^3/a) of the present transport volume entered the East Sea at that time period. This sill flow during the LGM is assessed, based on the suggested volume transport (2 Sv) passing through the

Korea Strait. The comparison between two calculated values of $(0.3–1.1) \times 10^{12}\,m^3/a$ and $3.0 \times 10^{12}\,m^3/a$ shows that these estimates for the volume transport at the strait during the LGM seem to be reasonable.

4. Effect of surface evaporation and throughflow on low paleosalinity

The paleo-hydrological values (evaporation and precipitation) for the LGM are taken from a high-resolution numerical simulation by Kim et al. (2006) who used NCAR CCM3 at spectral truncation of T170, corresponding to a grid cell size of roughly 75 km. The simulation results reveal that evaporation (3.43 mm/day) exceeds precipitation (2.85 mm/day) in the present East Sea. Additionally, excessive evaporation (2.16 mm/day) over precipitation (1.43 mm/day) is calculated for the LGM East Sea. The net evaporation rates in the LGM East Sea are evaluated at $0.2 \times 10^{12}\,m^3/a$, using evaporation minus precipitation (0.73 mm/day) and the surface area $(0.85 \times 10^6\,km^2)$.

Both numerical model results and geological records show that evaporation was higher than precipitation in the East Sea during the LGM. This attests that precipitation may not be the factor lowering the sea-surface salinity in the LGM East Sea. The excessive surface evaporation during the LGM indicates that more throughflow via the Korea Strait is required to sufficiently offset the evaporation effect during the LGM than previously suggested. This further supports that the freshwater entered the East Sea was sustained by the ECSCW derived from the Yellow and Yangtze Rivers.

According to the studies of the planktonic foraminiferal assemblage, the Kuroshio Current might not have flowed into the ECS due to the land bridge during the LGM (Ujiie et al.,1991; Ujiie and Ujiie, 1999; Li et al., 2001; Ujiie et al., 2003). The isolation of the ECS from the Pacific Ocean is supported by a significantly reduced abundance of *Pulleniatina obliquiloculata* and an increase in the frequency of the coastal water species (e.g. *Globigerina bulloides*). On the other hand, the limited propagation of the Kuroshio Current over the Okinawa Trough region has been proposed based on the existence of *N. dutertrei* during the LGM (Xu and Oda, 1999; Ijiri et al., 2005). Recent palynological studies reported the occurrence of *Phyllocladus* in the northern ECS sediment deposited between 25 and 8 ka BP (Kawahata and Ohshima, 2004). This pollen genus originating from the tropical areas seems to have been transported to the ECS by the Kuroshio Current during the last Glacial period. Whether the ECS was completely isolated or not, the ECSCW prevailed in the ECS region due to the land bridge formation and southward shift of the Kuroshio Current pathway, especially over the Okinawa Trough during the LGM. The dominance of the ECSCW over the Okinawa Trough region is also supported by the positive correlation between $\delta^{18}O$ and $\delta^{13}C$ signals of planktonic foraminifera (*Globigerinoides ruber*) during the LGM, implying freshwater supply from the Yellow and the Yangtze Rivers (Ijiri et al., 2005). This work thus indicates that the ECSCW extended to the East Sea through the Korea Strait, and then decreased surface salinity during the LGM. The ECSCW expansion to the East Sea is further evidenced by the occurrence of *Paralia sulcata* in the East Sea because *P. sulcata* is a useful diatom species for less saline river water (Koizumi, 1989; Tada et al., 1999).

River runoff from the surrounding land areas has been little studied because the ECSCW has been regarded as an important freshwater source for the LGM East Sea. Presently, the Amur River flows to the northern part of the East Sea along the Russian coast near the Tartar Strait (Nijssen et al., 2001). Southward transport of freshwater from the Amur River has been measured about $2600\,m^3/s$ at a channel around the Tartar Strait (Yakunin, 1975). Simulation results reported that freshwater discharges by the Amur River were increased by about 80% during the LGM (Kim et al., 2003). This increased river runoff suggests that the Amur River could, to some extent, contribute to the increase in freshwater in the East Sea. It is not possible to quantitatively estimate how much the paleo-Tsushima Water carried freshwater and how much the river runoff discharged in the East Sea during the LGM.

Accordingly, the excessive surface evaporation indicates that the paleo-Tsushima Water carried huge amounts of freshwater originated from the ECSCW than previously expected. The extensive invasion of the ECSCW to the East Sea reflects at least the partial opening of the Korea Strait during the LGM (Morley et al., 1986; Koizumi, 1989; Oba et al., 1995; Tada et al., 1999; Park et al., 2000; Lee and Nam, 2003).

5. Regional control on sea-level condition

The comparison between the surplus evaporation $(0.2 \times 10^{12}\,m^3/a)$ and volume transport $(0.3–1.1 \times 10^{12}\,m^3/a)$ shows that two values are not quantitatively identical (Fig. 4). However, the two values could be considered as similar from an oceanographic point of view. This comparison implies that most of the throughflow eventually escaped the East Sea via evaporation during the LGM. It, furthermore, may be inferred that the sea level in the LGM East Sea might be primarily maintained by the incoming paleo-Tsushima Water and the outgoing evaporation.

It is hard to tell whether there was an outflow from the East Sea to the northern ECS through the paleo-Korea Strait. Because the sill depth was only about 12 m, it may have been difficult for outflow to exist. There is no geological evidence on the countercurrent in the strait region at that time period even though the inflow of the paleo-Tsushima Water into the East Sea has been reported (Park and Yoo, 1992; Yoo et al., 1996; Yoo and Park, 1997). Tide influence on the East Sea as well as the northern ECS seems to have been negligible because of the

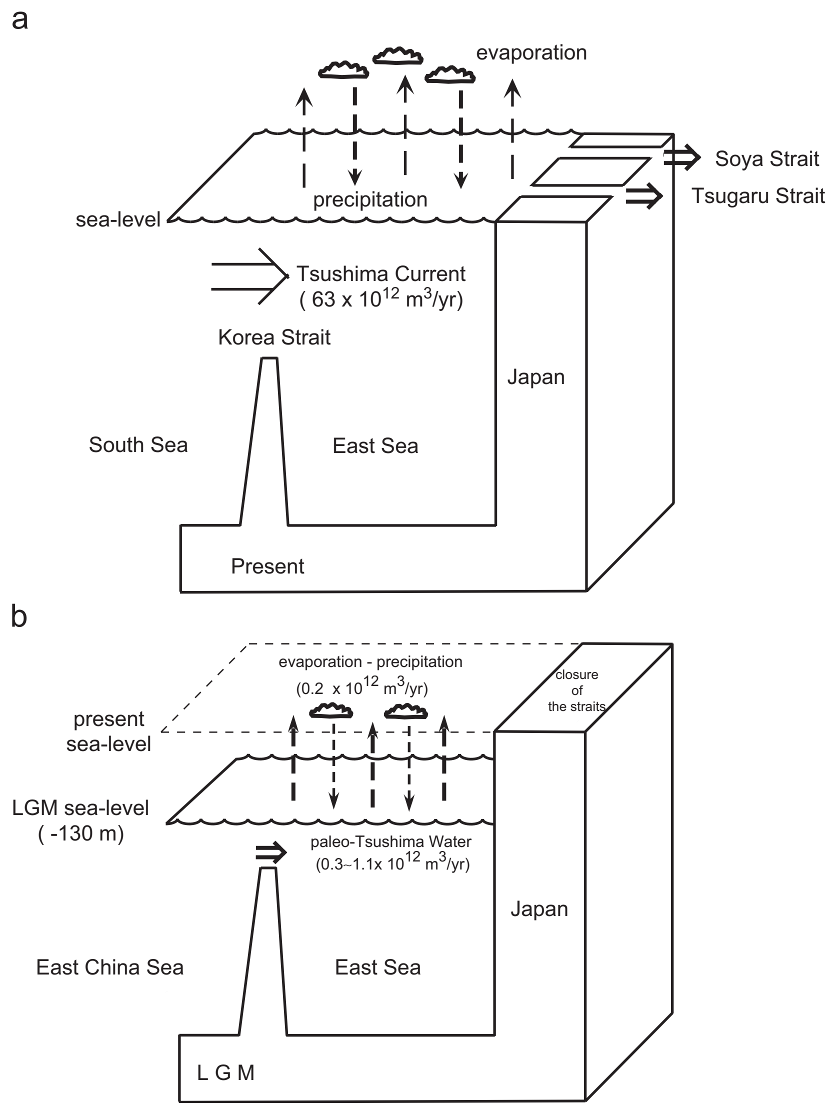

Fig. 4. Simplified diagrams illustrate that the Tsushima Current flows into the East Sea through the Korea Strait and flows out through the Tsugaru and Soya Straits (a). The sill flow significantly decreased due to the reduced cross-sectional passage when sea level was the lowest during the LGM (b). The throughflow ultimately escaped the sea mostly through excessive surface evaporation, maintaining a rough balance between them. This further indicates that regional factors might play an important role in sea level conditions in nearly isolated East Sea during the LGM.

land bridge formation between the Taiwan and the Ryukyu Islands. As a result, regionally excessive evaporation may serve as the most important factor regulating sea-level conditions in the nearly isolated East Sea during the LGM.

6. Comparison between the LGM East Sea and the present Black Sea

The Black Sea is a small semi-closed sea which links to the Sea of Marmara through the Bosporus Strait (about 3 km wide and 50 m sill depth) and further to the Mediterranean Sea via the Dardanelles Strait. This sea occupies an area of 422,000 km^2 with a maximum depth of about 2200 m. The Black Sea is a large anoxic marine basin due to significantly limited mixing between much less saline (down to 20‰) surface layer water (down to 100 to 150 m deep) and highly saline (38–39‰) deeper water (Latif et al., 1992; Ozsoy and Unluata, 1997; Aksu et al., 2002a). Oceanographic conditions in the Black Sea are primarily regulated by changes in the inflowing Mediterranean water and outflowing Black Sea water through the narrow and shallow Bosporus Strait. The cold and less salty surface (20–30 m thick) water flows out of the Black Sea via the Bosporus Strait toward the Mediterranean Sea, whereas warm and saline Mediterranean water flows into the Black Sea below the surface outflow (Ozsoy et al., 1995; Polat and Tugrul, 1996). Presently, about 300 km^3/a of water flows out of the Black Sea to the Mediterranean Sea through the Bosporus Strait. This outflow is a result of surplus precipitation and high river discharge, which exceed evaporation in the Black Sea area (Ozsoy et al., 1995; Aksu et al., 2002b). During the last glacial maximum, globally lowered sea level led to closure of the Bosporus Strait, ceasing the Mediterranean inflow. The Black Sea then became a freshwater lake at least in the upper layer (Degens and Ross, 1974; Ryan et al., 1997; Karaca et al., 1999; Aksu, et al., 2002b).

Both the present Black Sea and the glacial East Sea are characterized by similar oceanographic features because they are connected with the neighboring marine environments by narrow, channel-like straits, the Bosporus Strait and the Korea Strait, respectively. One of the striking characteristics in both seas is a low sea-surface salinity of down to about 20‰, approximately half as saline as the normal ocean (34–35‰). The low surface salinity in the Black Sea is due to the river runoff and excessive precipitation (Ozsoy et al., 1995; Aksu et al., 2002b). On the other hand, precipitation was not a factor in the paleo-East Sea. The paleo-Tsushima Water influx together with the Amur River discharge might have contributed to the reduction in the surface salinity during the LGM. The low surface salinity results in the strong stratification and inhibits vertical mixing between surface layer and deep water. Thus, anoxic conditions could have been established in deep sediments in the LGM East Sea as in the modern Black Sea (Degens and Ross, 1974; Oba et al., 1991; Jones and Gagnon, 1994; Gorbarenko and Southon, 2000; Ishiwatari et al., 2001; Aksu et al., 2002b).

The local effects (e.g. river runoff, precipitation, evaporation) may have a critical factor on sea level for each sea. In the Black Sea, unusually high river discharges along with excessive precipitation not only dilute the surface layer, but increase the water level, about 30 cm higher than that of the adjacent Marmara Sea (Besiktepe et al., 1994). In contrast, excessive evaporation prevailed over the East Sea, and seems to have been roughly balanced with the throughflow, regulating the sea level during the LGM. Consequently, the comparison between both seas strongly indicates that regional conditions could serve as an important parameter regulating surface water properties and sea level in an almost isolated sea.

7. Conclusions

Sea-level fall during the LGM altered geographic and oceanographic conditions, resulting in exposure of shallow-water areas, reduction of sill flow with a relatively increased freshwater, freshening of surface water, and restriction of vertical mixing in the East Sea. About 15% of surface area might have been subaerially exposed and three straits shallower than 130 m in sill depths were closed, blocking water exchanges through them in the LGM East Sea. By contrast, the Korea Strait was partially open and allowed the reduced sill flow ($0.3–1.1 \times 10^{12}\,m^3/a$) which might be mixed with the ECSCW and seawater (“the paleo-Tsushima Water”) during the time of the lowest sea level.

The model results show that the evaporation exceeded the precipitation by $0.2 \times 10^{12}\,m^3/a$ in the East Sea during the LGM, and are well-correlated with existing geological records. This means that the precipitation was not the factor decreasing sea-surface salinity. Moreover, the excessive evaporation indicates that the paleo-Tsushima Water transported substantial amounts of freshwater to lower the surface salinity.

The comparison between surface evaporation and volume transport suggests that most of the throughflow ultimately escaped the East Sea through evaporation during the LGM. This may imply that regional sea level might be largely maintained by a rough balance between incoming paleo-Tsushima Water and outgoing evaporation in the latest Quaternary.

The modern Black Sea can be considered as an analog of the glacial East Sea. The two seas are characterized by limited connection through a narrow and shallow strait to an adjoining marine environment, and by low sea-surface salinity. Sea-level variations are primarily influenced by local effects in the modern Black Sea and in the glacial East Sea. The former is controlled by high river runoff and surplus precipitation, leading to outflow from the Black Sea to the Mediterranean Sea. The later glacial sea is regulated by excessive evaporation, roughly balanced with the amount of throughflow.

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