VARIABILITY OF SEA SURFACE TEMPERATURE AND SALINITY IN MAKASSAR STRAIT DURING THE LAST GLACIAL MAXIMUM

VARIABILITAS SUHU PERMUKAAN LAUT DAN SALINITAS DI SELAT MAKASSAR PADA PERIODE LAST GLACIAL MAXIMUM

Oktavira Dwi Demia Larasati[1,2*], Marfasran Hendrizan[2], Rima Rachmayani[1,3,4], Gandhi Napitupulu[3,4]

[1]Study Program of Earth Science, Faculty of Earth Science and Technology, Bandung Institute of Technology, Bandung, Indonesia
[2]Paleoclimate & Paleoenvironment Research Group, National Research and Innovation Agency (BRIN) Bandung, Indonesia
[3]Research Group of Oceanography, Faculty of Earth Science and Technology, Bandung Institute of Technology, Cirebon, Indonesia
[4]Study Program of Oceanography, Faculty of Earth Science and Technology, Bandung Institute of Technology, Bandung, Indonesia

*Corresponding author: oktaviradw@gmail.com

(Received 04 March 2024; in revised from 15 March 2024 accepted 27 November 2024)

DOI : 10.32693/bomg.39.2.2024.882

ABSTRACT: Indonesian Throughflow (ITF), which is part of the global thermohaline circulation, is known to play an important role in the heat exchange between the Pacific and Indian Oceans. The flow of the ITF is highly complex, it depends on temperature and salinity. This study presents a proxy study from 25,000–18,000 years ago from two sites that are connected by the Indonesian Throughflow in the Makassar Strait. Oceanographic characteristics, including Sea Surface Temperature (SST) and Sea Surface Salinity (SSS) were reconstructed and analyzed during the Last Glacial Maximum (LGM) period. A 295 cm marine sediment core coded SO217-18522 (1°24.106'N; 119°04.781'E, water depth 978 m) and SO217-18519 (0°34.329'N; 118°06.859'E, water depth 1658 m) from the SONNE 217 research cruise in 2011 was used as research material. Oxygen isotope $\delta^{18}O$ analysis, planktonic foraminiferal Mg/Ca geochemistry, and radiocarbon dating were used in this study. The SST reconstruction shows that the temperature during the LGM reach the minimum during ~20 ka BP and the SST value was significantly lower by ~2–3 °C compared to the Late Holocene value. The SST also shows significant cooler in marine sediment SO2017-8519 located in the southern site compared to the northern site. Salinity reconstructions during the LGM shows that SSS value was 0.82–1.13 psu higher than in the Holocene. The south–north gradients of SST and SSS in the Makassar Strait were larger over the 23.2–24.2 ka BP (SST gradient by 0.5–1 °C and SSS gradien by 1–1.7 psu) compared to the Late Holocene. The increase in SST and SSS gradients during the ~20 ka BP likely indicates a weakened intensity of the surface ITF relative to conditions during the Late Holocene.

Keywords: *Indonesian Throughflow, Last Glacial Maximum, Sea Surface Temperature, Sea Surface Salinity*

ABSTRAK*: Arus Lintas Indonesia (Arlindo) yang merupakan bagian dari sirkulasi arus termohalin global diketahui memainkan peran penting dalam pertukaran panas antara Samudra Pasifik dan Samudra Hindia. Aliran massa air Arlindo sangat kompleks dan bergantung pada suhu serta salinitas. Penelitian ini menyajikan studi proksi pada 25.000–18.000 thl dari dua lokasi yang dihubungkan oleh Arlindo di Selat Makassar. karakteristik oseanografi, termasuk Suhu Permukaan Laut dan Salinitas Permukaan Laut direkonstruksi dan dianalisis. Inti sedimen laut sepanjang 295 cm dengan kode SO217-18522 (1°24,106'LU; 119°04,781'BT, kedalaman air 978 m) dan SO217-18519 (0°34,329'LS; 118°06,859'BT, kedalaman air 1.658 m) hasil pelayaran riset*

SONNE 217 pada tahun 2011 digunakan sebagai bahan penelitian. Analisis oksigen isotop $\delta^{18}O$*, geokimia Mg/Ca foraminifera planktonik dan radiocarbon dating digunakan dalam penelitian ini. Rekonstruksi SPL menunjukkan bahwa suhu selama LGM mencapai minimal sekitar ~20 ribu thl dan secara signifikan lebih rendah sebesar ~2–3 °C dibandingkan dengan pada saat Holosen Akhir. SPL juga menunjukkan pendinginan yang signifikan pada sedimen laut SO2017-18519 yang terletak di selatan dibandingkan dengan di utara. Rekonstruksi salinitas selama LGM menunjukkan bahwa nilai salinitas permukaan laut lebih tinggi sebesar 0,82–1,13 psu dibandingkan saat Holosen akhir. Gradien selatan–utara SPL serta SSS di Selat Makassar menunjukkan gradien lebih besar pada periode 23,2–24,2 ribu thl (gradien SST sebesar 0,5–1 °C dan gradien SSS sebesar 1–1,7 psu) dan lebih tinggi dibandingkan saat Holosen akhir. Peningkatan gradien SST dan SSS selama 20 ribu thl kemungkinan menunjukkan melemahnya intensitas ITF permukaan relatif terhadap kondisi selama Holosen Akhir.*

Kata Kunci: *Arus Lintas Indonesia, Glasial Maksimum Terakhir, Suhu Permukaan Laut, Salinitas Permukaan Laut*

INTRODUCTION

Indonesian Throughflow (ITF) is the only connecting circulation between low latitude regions that carries upper thermocline water masses and surface water masses from the Pacific Ocean to the North Atlantic (Gordon, 1986). ITF, caused by the sea level difference between the Pacific and Indian Oceans (Wyrtki, 1961, 1987), transfers water mass and heat from the western equatorial Pacific to the Indian Ocean (Godfrey, 1996; Gordon et al., 2010; Sprintall et al., 2014; Vranes et al., 2002).

Under modern conditions, the strength of the ITF is known to modify the heat budget and freshwater and air-sea heat fluxes in the Pacific and Indian oceans seasonally, and influence the El Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) and monsoon. Climate models consistently project a weakening of the ITF in response to increasing greenhouse gases due to global warming (Ding et al., 2013; Feng et al., 2018; Sen Gupta et al., 2016). In this case, the study of the ITF variability and it's influence mechanisms in the Makassar Strait during the past periods of major climate change can provide important insights regarding the sensitivity of the ITF to various climate changes.

One of the most important periods among other geological periods is the Last Glacial Maximum (LGM). LGM is generally known as a period of global cooling and significant sea level changes. During this period, Sunda Shelf including Java Sea, Gulf of Thailand, South China Sea (SCS) and Sahul Shelf was exposed as sea levels dropped down to 120 meters (Peltier & Fairbanks, 2006) compared to modern conditions. During this period, the path of the ITF was only through the Makassar Strait and Timor Sea, therefore it is very interesting to study the Sea Surface Temperature (SST), Sea Surface Salinity (SSS) and ITF variability during this time periods.

In the past 30 thousand years (30 ka BP), a previous study demonstrated that the south–north thermocline temperature gradient reached its maximum value during the time intervals of 27–24.2 ka BP and 19–13.4 ka BP, respectively. These two intervals of enhanced S–N thermocline hydrological gradient indicated a weaker ITF (Fan et al., 2018).

In this study, two marine sediment cores SO217-18522 (1°24.106'N; 119°04.781'E, water depth 978 m) and SO217-18519 (0°34.329'N; 118°06.859'E, water depth 1658 m) were collected from the Sulawesi Sea region (representing north of Makassar Strait) and the Makassar Strait (representing south of Makassar Strait), respectively, during the SONNE 217 research cruise in 2011. The water masses in the surface and thermocline layer at both locations are linked by the ITF from the Pacific Ocean to the Indian Ocean. The SST and SSS obtained from proxies at both sites were then compared, enabling an assessment of the variability of the past ITF conditions during the LGM.

METHODS

This study uses two marine sediment cores obtained from the SONNE 217 research cruise in 2011, namely SO217-18519, and SO217-18522 (Figure 1). The marine sediment cores were taken in the Makassar Strait as these locations are the main pathways of the ITF (~80% of water masses from the Pacific Ocean to the Indian Ocean enter through the Makassar Strait and Sulawesi Sea).

Age Model

The absolute age dating (quantitative age) of the marine sediment cores SO217-18522 and SO217-

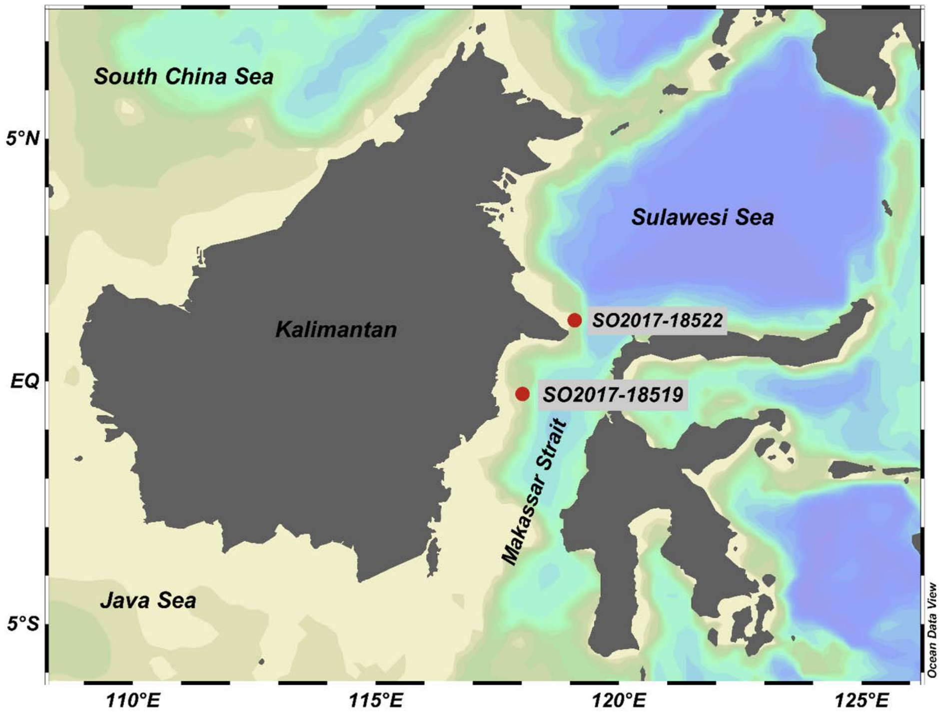

Figure 1. Study area (sediment sampling locations shown by red circles)

18519 was determined using Accelerator Mass Spectrometry (AMS)^{14}C measurements. These AMS^{14}C measurements followed the methodology outlined in previous studies (Fraser et al., 2014; Hendrizan et al., 2017). The age dating for the marine sediment cores SO2017-18522 and SO217-18519 was based on eight AMS^{14}C data point published by Schröder et al.(2018).

Stable Oxygen Isotopes δ^{18}O Analysis

The stable isotope proxies that are frequently used in this research are the δ^{18}O. The term δ used in this notation reflects the ratio of ^{18}O/^{16}O compared to a standard: PeeDee Belemnite (PDB). The variation of δ^{18}O is expressed in permille (‰).

The δ^{18}O isotope analysis of planktonic foraminifera was measured at 2–5 cm intervals, equivalent to a time resolution of hundreds of years to thousands of years (Hendrizan et al., 2017; Schröder et al., 2016). Each sample contains 40 shells of planktonic foraminifera *Globigerinoides ruber* (fraction size 315–250 µm) for δ^{18}O analysis. Stable isotope measurements were performed using a Finnigan MAT 253 instrument located in the Leibniz Laboratory at Kiel University.

Temperature Reconstruction derived from Mg/Ca Measurements

The Mg/Ca analysis was conducted using planktonic foraminifera *Globigerinoides ruber* obtained from marine sediment cores SO217-18522 and SO217-18519. For this analysis, about 30 specimens were picked from the 315–250 µm sieve with sample intervals of 4–10 cm. The Mg/Ca analysis was carried out at the Institute of Geosciences, University of Kiel, Germany, using ICP-OES (Spectro Ciros SOP 34 CCD, Spectro Analytical Instruments, Germany). Each Mg/Ca data was then normalized using a value of 3.82 mmol/mol Mg/Ca (Greaves et al., 2008). After monitoring the data quality of the measurement results, the Mg/Ca ratio was converted into calcification temperature using the *Globigerinoides ruber* calibration (Anand et al., 2003) as formulated in Equation 1:

$$Mg/Ca = 0{,}38\,(\pm 0{,}009) \times exp\,(0{,}090((\pm 0{,}003) \times T\,) \quad (1)$$

where Mg/Ca is the Mg/Ca measurement result (‰); T is the temperature (°C).

Salinity Reconstruction From $\delta^{18}O_{sw}$

The reconstruction of $\delta^{18}O_{sw}$ was calculated from the equation derived by Bemis et al. (1998) based on the Mg/Ca and δ^{18}O data pairs of *Globigerinoides ruber* with the following formulation (Equation 2):

$$\delta^{18}O_{sw} = 0{,}27 + (T - 16{,}5 + 4{,}8 \times \delta^{18}O\,)/4.8 \quad (2)$$

Where $\delta^{18}O_{sw}$ is the seawater stable oxygen isotope (‰), T is the temperature (°C); and $\delta^{18}O$ is calcite/*Globigerinoides ruber* stable oxygen isotope (‰).

In this case, the results of the calculation of $\delta^{18}O_{sw}$ cannot be used directly as a proxy for seawater salinity, but still need to be completed by calculating the effect of ice volume. The calculation of the ice volume correction is obtained based on the reconstruction of past sea level changes from the global ocean $\delta^{18}O_{sw}$ data (Sarnthein et al., 2011). Salinity were calculated based on Equation 3 (Fairbanks et al., 1997).

$$\delta^{18}O_{sw} = 0{,}273\,(S) - 9{,}14 \quad (3)$$

where $\delta^{18}O_{sw}$ is the seawater stable isotope (‰), S is the salinity (PSU)

RESULTS

Depth and Age of Sediment Cores

The absolute age dating (quantitative age) of marine sediment cores from the Makassar Strait in this analysis uses data from Schröder et al., (2018), performing the AMS^{14}C measurement. Interpolation curves were generated from AMS^{14}C tie points using the Stineman function (a function in Kaleidagraph). The AMS^{14}C measurement data for these two marine sediment cores, derived from planktonic foraminifera, indicate that the sediment ages of cores SO217-18522 and SO217-18519 range from 25 ka BP (thousand years ago/ka before present) (Figure 2). These cores provide a more complete climate record, spanning from the LGM (25–18 ka BP) to the Late Holocene (5–0 ka BP).

Stable Isotopes δ18O Variability

The $\delta^{18}O$ values of *Globigerinoides ruber* in marine sediment cores SO217-18522 and SO217-18519 exhibit a highly consistent trend with a glacial–interglacial contrast of ~2‰ (Figure 3) in the Makassar Strait.

During the Late Holocene period, which lasted approximately ~5–0 ka BP, both marine sediment cores in southern and northern site shows the $\delta^{18}O$ of *Globigerinoides ruber* an average value of around -2.9‰. and -2.8‰, respectively. The average value of the $\delta^{18}O$ in northern site (SO2017-18522) during the Late Holocene is 2.9‰ with a maximum $\delta^{18}O$ of -2.76‰ around ~0.6 ka BP and minimum $\delta^{18}O$ of -3.21‰ around ~0.3 ka BP. The average value of $\delta^{18}O$ in southern site (SO2017-18519) is -2.9‰ with a maximum $\delta^{18}O$ of -2.78‰ around ~2.3 ka BP ka BP and minimum $\delta^{18}O$ of -3.17‰ around ~1.4 ka BP.

The $\delta^{18}O$ of *Globigerinoides ruber* in northern site (SO217-18522) indicates that the oldest sediment layer, corresponding to the LGM or 25–18 ka BP, shows $\delta^{18}O$ values ranging from -0.7 to -1.3‰ with an average of -1‰. The $\delta^{18}O$ of *Globigerinoides ruber* in southern site

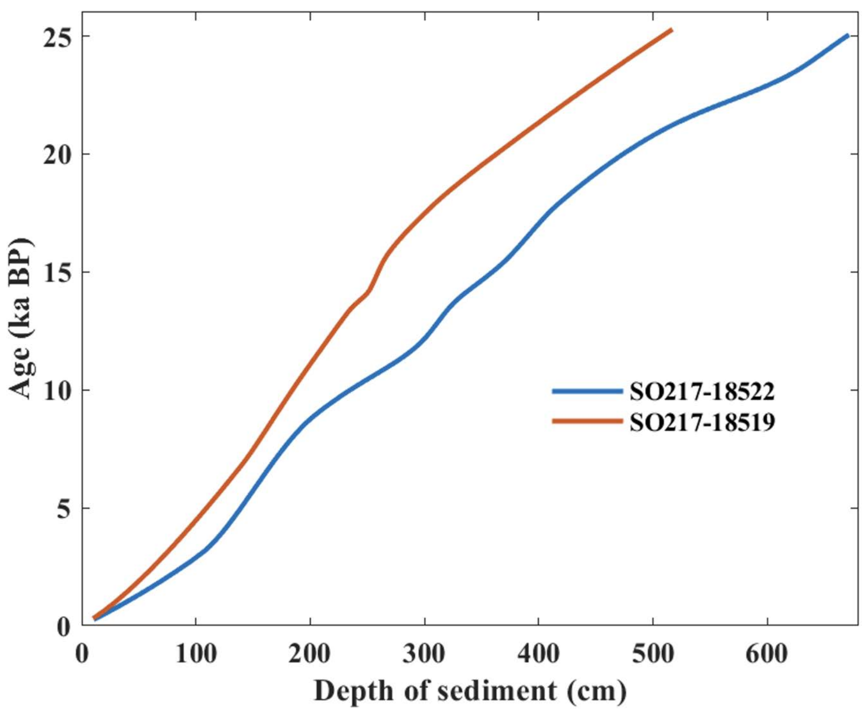

Figure 2. Age Model of marine sediment cores SO217-18522 and SO217-18519 (Schröder et al., 2018)

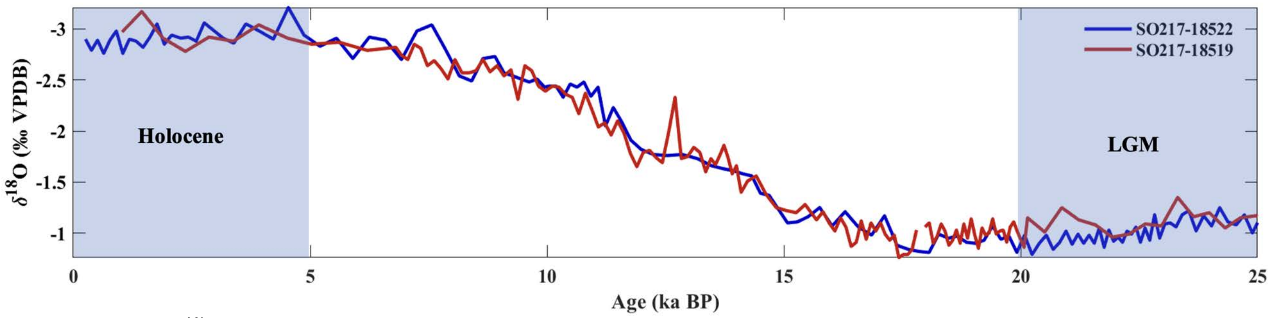

Figure 3. The $\delta^{18}O$ in Marine Sediment Cores SO217-18522 and SO217-18519 from the Last Glacial Maximum (LGM) to the Late Holocene

(SO217-18519) shows $\delta^{18}O$ values ranging from -0.8 to 1.28 ‰ with an average of 1‰.

Sea Surface Temperature Reconstruction From Mg/Ca Measurements

The SST reconstruction derived from Mg/Ca analysis of *Globigerinoides ruber* in marine sediment cores SO217-18522 and SO217-18519 exhibit a highly consistent trend with a glacial-interglacial contrast of ~2–3°C (Figure 4) in the Makassar Strait. Mg/Ca ratios measured in both marine sediment cores SO217-18522 and SO217-18519 at the LGM and Late Holocene period are not significantly different. The detailed Mg/Ca trend can be observed in Figure 4.

During the Late Holocene period, which lasted approximately ~5–0 ka BP, both marine sediment cores in southern and northern site shows an average concentration of around 4.72 mmol/mol and 4.73 mmol/mol, respectively. Increasing trend of Mg/Ca is equivalent to a increase in SST of approximately ~2 °C. The average value of SST in northern site (SO2017-18522) during the Late Holocene is 27.98 °C with a maximum SST of 28.79 °C around ~1.4 ka BP and minimum SST of 26.65 °C around ~0.3 ka BP. The average value of SST in southern site (SO2017-18519) is 27.98 °C with a maximum SST of 28.57 °C around ~3.9 ka BP ka BP and minimum SST of 27.66 °C around ~2.3 ka BP.

During the LGM period, which lasted approximately ~25-18 ka BP, both marine sediment cores SO217-18522 and SO2017-18519 shows a decreasing trend with an average concentration of around 3.78 mmol/mol and 3.62 mmol/mol, respectively. Decreasing trend of Mg/Ca is equivalent to a decrease in SST of approximately ~2 °C. The average value of SST in northern site (SO2017-18522) during the LGM is 25.48 °C with a minimum SST of 24.57 °C around ~19.9 ka BP. The average value of SST in southern site (SO2017-18519) is 25.06 °C with a minimum SST of 24.57 °C around ~20.1 ka BP.

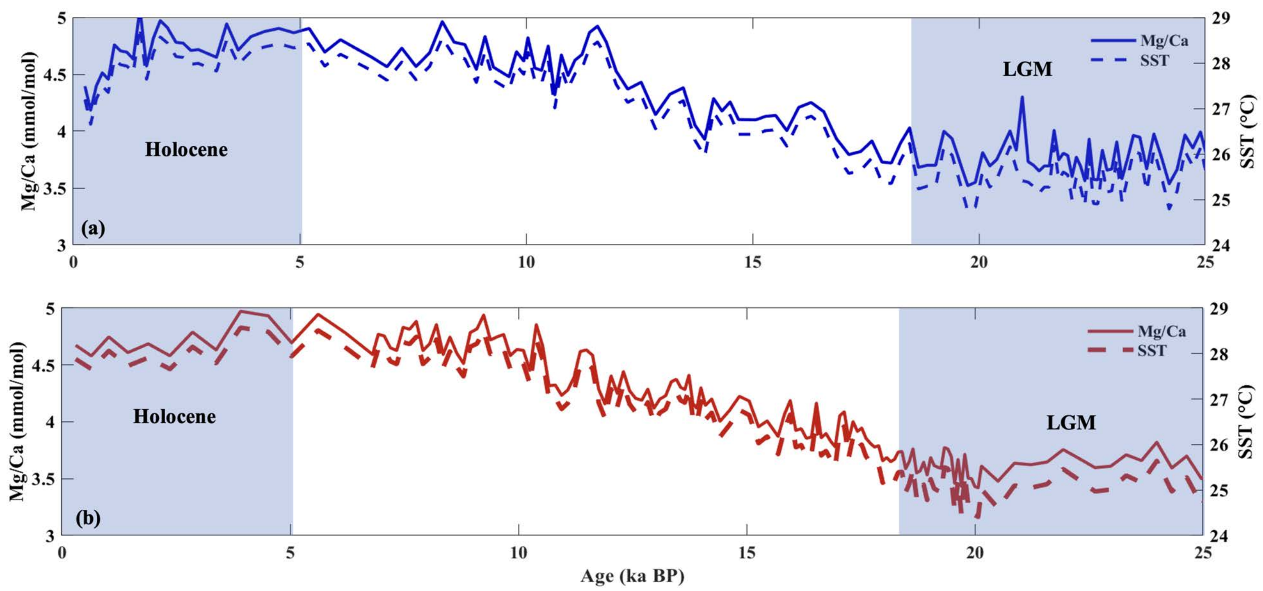

Figure 4. Mg/Ca Ratio of Marine Sediment Cores (a) SO217-18522 and (b) SO217-18519 from the Last Glacial Maximum (LGM) to the Late Holocene

$\delta^{18}O/\delta^{18}O_{sw}$ and Sea Surface Salinity

The corrected $\delta^{18}O_{sw}$ record, based on the Mg/Ca and $\delta^{18}O$ data pairs, shows that SSS values increase at the LGM for both marine sediment cores SO2017-18522 and SO2017-18519. The $\delta^{18}O_{sw}$ and salinity reconstruction in both marine sediment cores SO217-18522 and SO217-18519 at 25–18 ka BP shows the difference between the northern and southern sites. The marine sediment core SO2017-18522 located in the north exhibits higher $\delta^{18}O_{sw}$ and salinity values compared to the marine sediment core SO2017-18519 in the southern site. The detailed $\delta^{18}O_{sw}$ and salinity reconstruction trend can be observed in Figure 5.

During the Late Holocene period, which lasted approximately ~5–0 ka BP, both marine sediment cores in southern and northern site shows the average value of $\delta^{18}O_{sw}$ is around -0.01‰ and 0.7‰, respectively. The average value of SSS in northern site (SO2017-18522) during the Late Holocene is 33.39 psu with a minimum SST of 32.63 psu around ~4.5 ka BP. The average value of SSS in southern site (SO2017-18519) is 33.37 psu with a minimum SSS of 32.31 psu around ~1.4 ka BP and maximum SSS of 33.80 psu around ~4.5 ka BP.

During the LGM period, approximately The $\delta^{18}O_{sw}$ values in marine sediment core SO217-18522 vary between -0.1‰ and 0.6‰ with an average of 0.1‰. The $\delta^{18}O_{sw}$ values in sediment core SO217-18519 vary between -0.08‰ and 0.4‰ with an average of 0.2‰. The mean sea surface salinity value derived from the Mg/Ca and $\delta^{18}O$ data pairs in sediment core SO217-18522 is 34.61 psu and 34.19 psu in sediment core SO217-18519.

DISCUSSIONS

Trend SST and SSS in the Makassar Strait on the LGM indicates cooling SST and increasing SSS from 25 to 18 ka BP for both marine sediment cores SO2017-18522 and SO2017-18519 (Figure 6). The reconstructed SST and SSS results are consistent with other published marine sediment records in Makassar Strait (Visser et al., 2003; Fan et al., 2013, 2018; Schröder et al., 2018).

The trend of Mg/Ca values from 25 – 18 ka BP indicates a decrease in both sediment cores from the northern (SO217-18522) and southern (SO217-18519) sites with small fluctuations during the LGM period (Figure 6). Based on the trend analysis, the Mg/Ca value for the sediment core at the northern site (SO217-18522) is -0.00061 mmol/mol, while the sediment core at the southern site (SO217-18519) shows a value of -0.004 mmol/mol during the LGM. The Mg/Ca trend during this period is lower in the sediment core located in the south (SO217-18519) compared to the northern site (SO217-18522). These Mg/Ca values for the northern site (SO217-18522) align with similar trends observed in previous studies (Fan et al., 2018), which suggests that the decrease in Mg/Ca values during the LGM is consistent across different locations.

SST value in both marine sediment cores shows significantly cooler in the southern region (SO217-18519) compared to the northern region (SO217-18522) (Figure 5). During the LGM period both two

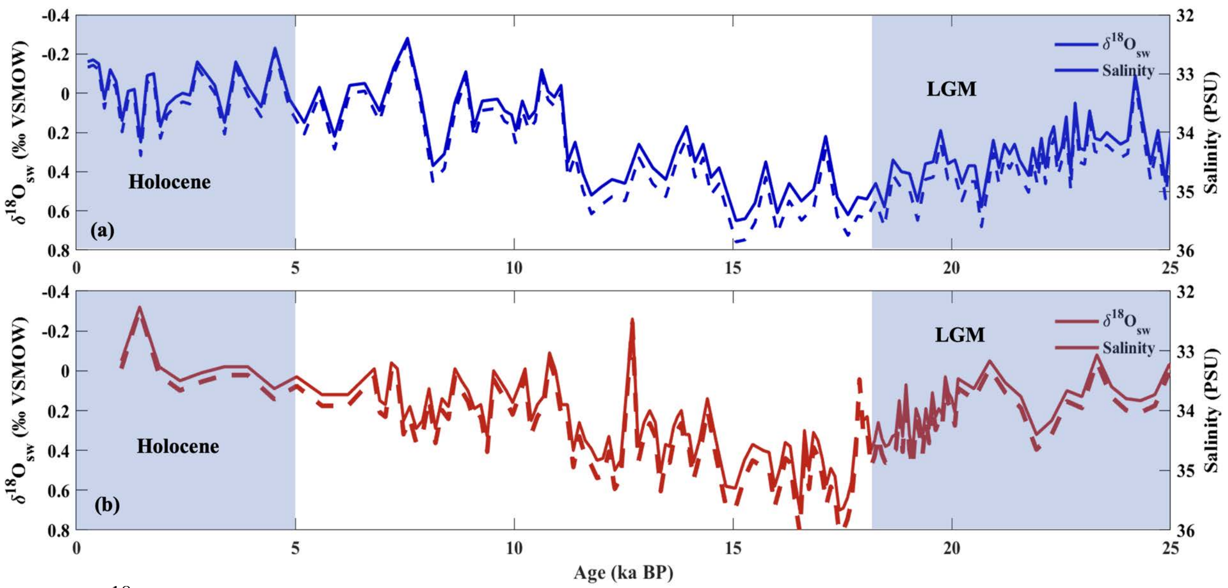

Figure 5. $\delta^{18}O_{sw}$ and Salinity of Marine Sediment Cores (a) SO217-18522 and (b) SO217-18519 from the Last Glacial Maximum (LGM) to the Late Holocene

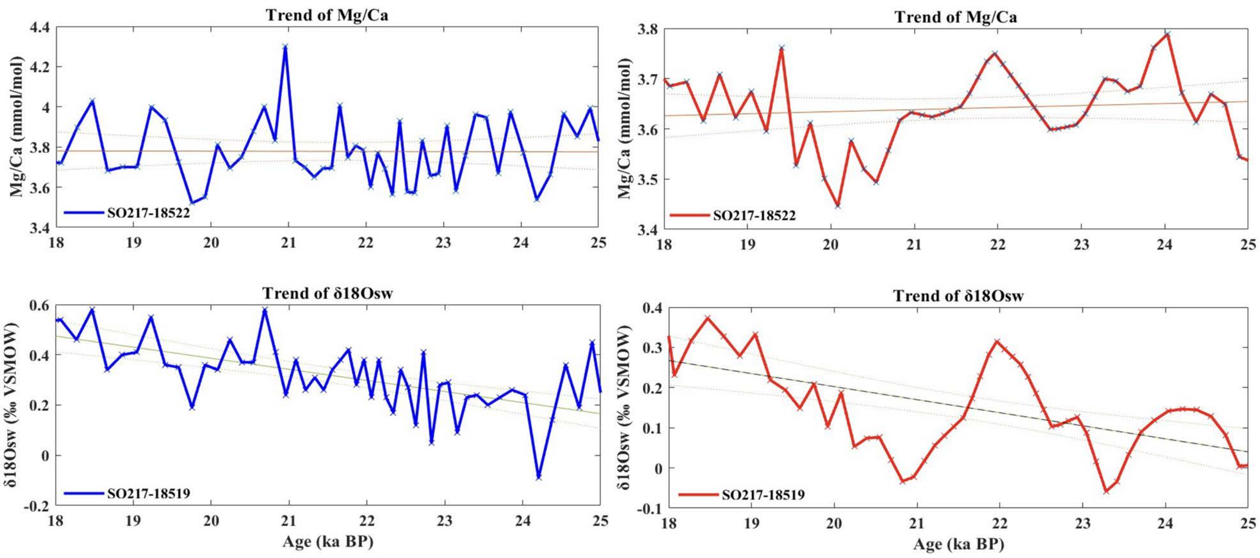

Figure 6. Trend of SST and SSS of Marine Sediment Cores SO217-18522 and SO217-18519 during the Last Glacial Maximum (LGM)

cores reach the minimum SST during ~19.8–20.2 ka BP. The results are consistent with two other sediment cores in the Makassar Strait, which indicate a maximum decrease of SST around ~23–18 ka BP (Fan et al., 2018; Lis., 2019). This decrease is shows that peak of the LGM period in both cores SO2017-18522 and SO2017-18519 in the Makassar Strait reached its maximum at ~19.8 ka BP.

The trend of SSS values from 25 – 18 ka BP indicates an increase in both sediment cores from the northern (SO217-18522) and southern (SO217-18519) sites during the LGM period (Figure 6). Based on the trend analysis, the sediment core at the northern site (SO217-18522) shows an increase of 0.42 ‰, while sediment core in southern site (SO217-18519) shows an increase of 0.19 ‰ during the LGM. The SSS trend during this period is higher in the sediment core located in the north (SO217-18522) compared to the southern site (SO217-18519), indicating a more significant rise in the northern part.

The highest SSS values in the northern site, along the ITF pathway during the LGM, show a similar trend to SSS values observed in previous studies (locations MD98-2178 and MD98-2161; Fan et al., 2018). The difference in SSS between the southern and northern parts of the Makassar Strait during the LGM period is believed to be related to differences in freshwater input from the Kalimantan region (Hendrizan et al., 2020). This freshwater input leads to lower SSS values in the southern site compared to the northern site.

Indonesian Throughflow Intensity

The south–north SST and SSS gradient represents the amount of warm and salty water mass transported through the Makassar Strait (Pang et al., 2021; Fan et al., 2018). The south–north SST and SSS gradients in the Makassar Strait, relatively increased from the Last Glacial Maximum (LGM) to the Late Holocene period, with a significant peak between 23.8–20.6 ka BP (Figure 7). Fan et al. (2018) suggest that, over multi-millennial timescales, greater temperature gradients likely indicate a reduction in ITF transport compared to Holocene conditions.

Figure 7 shows that the south–north gradients of SST and SSS across the Makassar Strait were higher during the LGM compared to the Late Holocene, with a notable peak between 24.2 and 23.2 ka BP. Under modern conditions, ITF intensity is weaker, especially during the west monsoon (seasonal), El Niño (interannual), and positive Pacific Decadal Oscillation (PDO) phases, as indicated by lower SST, higher SSS, and a shallower thermocline in the Makassar Strait (Gordon et al., 2012; 2019; Susanto et al., 2012).

Assuming similar conditions during the glacial period to those of the modern era, a possible explanation for the increased trend of South–North SST gradient in the Makassar Strait could be related to a weakened ITF. Weakened ITF would results in less warm and saline Pacific water reaching the southern end of the Makassar Strait, which, in turn, enhances the temperature gradients between the southern and northern areas, as reflected by cores SO217-18522 and SO217-18519.

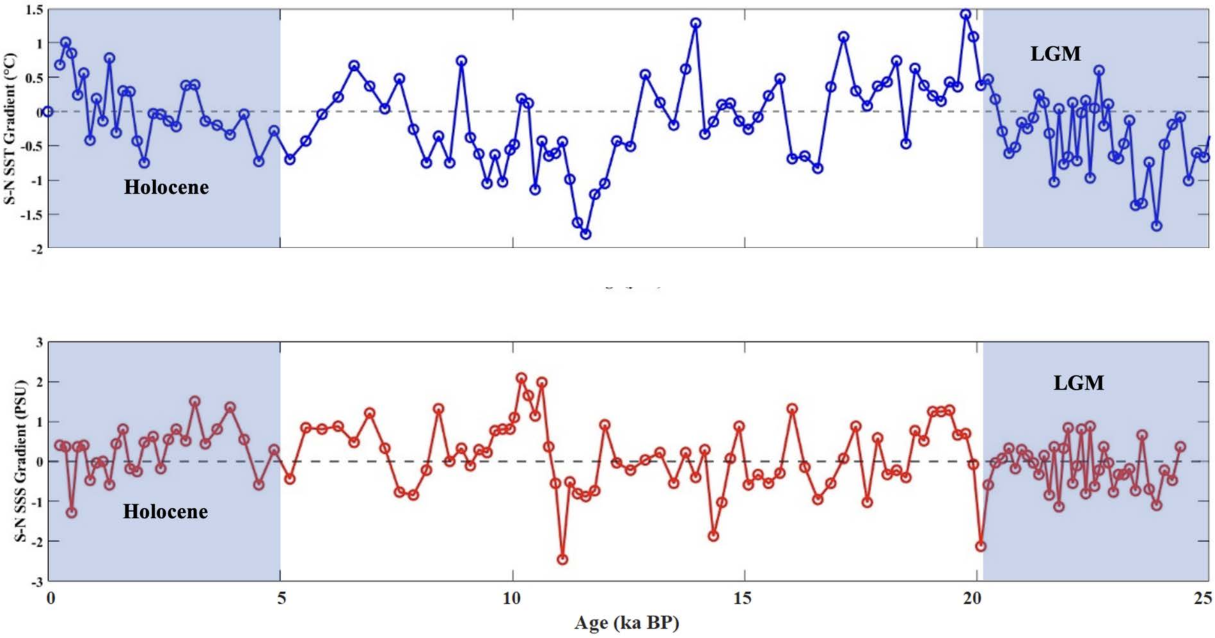

Figure 7. South–North SST and SSS gradients of marine sediment cores SO217-18522 and SO217-18519 from the LGM to the Late Holocene

During long periods over the past hundreds to thousands of years that show reduced ITF intensity, a deeper mixed layer and thicker thermocline should have occurred, similar to the modern seasonal ITF pattern (Xu et al., 2008). In this scenario, ITF transport is reduced and generally occurs in the mixed layer. This results in a larger SST gradient between the southern and northern ends of the Makassar Strait (Fan et al., 2018). Using this framework, our data suggests a decrease in throughflow during the LGM relative to the Late Holocene. Our results show that ITF transport was also reduced in the mixed layer, increasing the SST gradient between the southern and northern ends of the Makassar Strait (Fan et al., 2018). Our data suggest a decrease in ITF transport during the LGM compared to the Late Holocene. We observe that ITF transport was reduced in the mixed layer, as indicated by the greater south–north gradient of SST and SSS. This negative gradient reflects weakened ITF transport during the LGM, with less warm, saline water reaching the southern Makassar Strait. The result is a more stratified water column, with cooler, fresher water remaining in the south, thus increasing the SST and SSS gradient.

In relation to the short-term (e.g. seasonal) intensity of the Indonesian Throughflow (ITF), SST gradients between the southern and northern ends of the Makassar Strait exhibit variations. These variations likely reflect seasonal changes in wind patterns and surface currents that modulate the ITF strength. But in an equilibrium state on the scale of hundreds to thousands of years, the increase in SST and SSS gradients over the past 20 ka BP likely indicates weakened ITF transport relative to the situation during the Holocene (Fan et al., 2018; Lis, 2019).

The observed decrease in the south–north SST gradient during the LGM period suggests a potential link to changes in large-scale ocean-atmosphere circulation patterns, particularly El Niño-Southern Oscillation (ENSO), the dominant mode of interannual climate variability in the tropical Pacific. The prolonged El Niño-like conditions occurs during the LGM and reduced the pressure gradient difference between the western Pacific and the eastern Indian Ocean. Previous studies (Dang et al., 2015; Fan et al., 2018, 2013; Zhang et al., 2018) suggest that during "El Niño-like" conditions, weakened trade winds and enhanced westerlies in the Indo-Pacific region can lead to drier conditions in Indonesia, particularly in Kalimantan and Sulawesi. This reduced rainfall, coupled with altered surface currents and ocean-atmosphere interactions, likely contributed to the increased SST gradient in the Makassar Strait. Understanding the complex interplay between ENSO, ITF variability, and SST gradients in this region is crucial for assessing the potential impacts of climate change on the marine ecosystem. Future research should focus on quantifying the relative contributions of these mechanisms and predicting how they may respond to changes in global climate patterns.

CONCLUSSIONS

Variability of the ITF during the LGM period is largely reflected in the SST and SSS reconstruction results from the two marine sediment cores SO217-18522 and SO217-18519. During this period, oxygen isotope analysis and Mg/Ca geochemistry of the planktonic foraminifera *Globigerinoides ruber* showed changes in SST and SSS in the Makassar Strait. Trends in SST and SSS shows that SST decreased and SSS increased during the LGM period. The south–north gradients of SST and SSS in the Makassar Strait increased (reflected by the negative S–N SST values) since this period relative to the Late Holocene conditions and was higher at ~20 ka BP, indicating a weakening of the ITF transport in the mixed layer. These results agree with previous research findings which showing that the Indonesian Throughflow weakened during the glacial period with a peak at 20 ka BP in this sites.

ACKNOWLEDGEMENTS

The authors would like to thank the Center for Climate and Atmospheric Research, National Research and Innovation Agency (BRIN), and related parties who have provided advice and support in this research. The authors also express gratitude to the Indonesian Endowment Fund for Education (LPDP) (grant number: 202206110209603) for the financial assistance.

REFERENCES

Anand, P., Elderfield, H., and Conte, M.H., 2003. Calibration of Mg/Ca thermometry in planktonic foraminifera from a sediment trap time series. *Paleoceanography*, 18. https://doi.org/10.1029/2002PA000846.

Bemis, B.E., Spero, H.J., Bijma, J., and Lea, D.W., 1998. Reevaluation of the oxygen isotopic composition of planktonic foraminifera: Experimental results and revised paleotemperature equations. *Paleoceanography*, 13: 150–160. https://doi.org/10.1029/98PA00070.

Dang, H., Jian, Z., Kissel, C., and Bassinot, F., 2015. Precessional changes in the western equatorial Pacific Hydroclimate: A 240 kyr marine record from the Halmahera Sea, East Indonesia. *Geochemistry, Geophysics, Geosystems*, 16: 148–164. https://doi.org/10.1002/2014GC005550.

Ding, X., Bassinot, F., Guichard, F., and Fang, N.Q., 2013. Indonesian Throughflow and monsoon activity records in the Timor Sea since the last glacial maximum. *Marine Micropaleontology*, 101: 115–126. https://doi.org/10.1016/J.MARMICRO.2013.02.003.

Fairbanks, R.G., Evans, M.N., Rubenstone, J.L., Mortlock, R.A., Broad, K., Moore, M.D., and Charles, C.D., 1997. Evaluating climate indices and their geochemical proxies measured in corals. *Coral Reefs*, 16: S93–S100. https://doi.org/10.1007/S003380050245/METRICS.

Fan, W., Jian, Z., Bassinot, F., and Chu, Z., 2013. Holocene centennial-scale changes of the Indonesian and South China Sea throughflows: Evidences from the Makassar Strait. *Global and Planetary Change*, 111: 111–117. https://doi.org/10.1016/J.GLOPLACHA.2013.08.017.

Fan, W., Jian, Z., Chu, Z., Dang, H., Wang, Y., Bassinot, F., Han, X., and Bian, Y., 2018. Variability of the Indonesian Throughflow in the Makassar Strait over the Last 30 ka. *Scientific Reports*, 8: 1–8. https://doi.org/10.1038/s41598-018-24055-1.

Feng, M., Zhang, N., Liu, Q., and Wijffels, S., 2018. The Indonesian throughflow, its variability and centennial change. *Geoscience Letters*, 5: 1–10. https://doi.org/10.1186/S40562-018-0102-2.

Fraser, N., Kuhnt, W., Holbourn, A., Bolliet, T., Andersen, N., Blanz, T., and Beaufort, L., 2014. Precipitation variability within the West Pacific Warm Pool over the past 120 ka: Evidence from the Davao Gulf, southern Philippines. *Paleoceanography,* 29: 1094–1110. https://doi.org/10.1002/2013PA002599.

Godfrey, J.S., 1996. The effect of the Indonesian throughflow on ocean circulation and heat exchange with the atmosphere: A review. *Journal of Geophysical Research: Oceans*, 101: 12217–12237. https://doi.org/10.1029/95JC03860.

Gordon, A.L., 1986. Interocean exchange of thermocline water. *Journal of Geophysical*

Research: Oceans, 91: 5037–5046. https://doi.org/10.1029/JC091IC04P05037.

Gordon, A.L., Sprintall, J., Van Aken, H.M., Susanto, R.D., Wijffels, S., Molcard, R., Ffield, A., Pranowo, W., and Wirasantosa, S., 2010. The Indonesian throughflow during 2004–2006 as observed by the INSTANT program. *Dynamics of Atmospheres and Oceans*, 50: 115–128. https://doi.org/10.1016/J.DYNATMOCE.2009.12.002.

Gordon, A. L., Huber, B. A., Metzger, E. J., Susanto, R. D., Hurlburt, H. E., and Adi, T. R. 2012. South China Sea throughflow impact on the Indonesian throughflow. *Geophysical Research Letters*, *39*(11).

Gordon, A. L., Napitu, A., Huber, B. A., Gruenburg, L. K., Pujiana, K., Agustiadi and Setiawan, A. 2019. Makassar Strait throughflow seasonal and interannual variability: An overview. *Journal of Geophysical Research: Oceans*, 124(6): 3724-3736.

Greaves, M., Caillon, N., Rebaubier, H., Bartoli, G., Bohaty, S., Cacho, I., Clarke, L., Cooper, M., Daunt, C., Delaney, M., DeMenocal, P., Dutton, A., Eggins, S., Elderfield, H., Garbe-Schoenberg, D., Goddard, E., Green, D., Groeneveld, J., Hastings, D., Hathorne, E., Kimoto, K., Klinkhammer, G., Labeyrie, L., Lea, D.W., Marchitto, T., Martínez-Botí, M.A., Mortyn, P.G., Ni, Y., Nuernberg, D., Paradis, G., Quinn, T., Rosenthal, Y., Russel, A., Sagawa, T., Sosdian, S., Stott, L., Tachikawa, K., Tappa, E., Thunell, R., and Wilson, P.A., 2008. Interlaboratory comparison study of calibration standards for foraminiferal Mg/Ca thermometry. *Geochemistry, Geophysics, Geosystems*, 9. https://doi.org/10.1029/2008GC001974.

Hendrizan, M., Kuhnt, W., and Holbourn, A., 2017. Variability of Indonesian Throughflow and Borneo Runoff During the Last 14 kyr. *Paleoceanography*, 32: 1054–1069. https://doi.org/10.1002/2016PA003030.

Hendrizan, M., Ningsih, N.S., Cahyarini, S.Y., Mutiara, M.R., Setiadi, B., Anwar, I.P., Utami, D.A., and Agusta, V.C., 2020. Centennial-Millennial Climate Variability in the Makassar Strait during Early Holocene until the End of the Last Deglaciation. *Int. Journals Ocean,* 14: 197–220.

Lis, M., 2019. Glacial-Interglacial Changes in the Thermocline Structure of the Makassar Strait: Implications for Changes in the Indonesian Throughflow. Master's thesis. University of South Carolina.

Pang, X., Bassinot, F., and Sepulcre, S., 2021. Indonesian Throughflow variability over the last two glacial-interglacial cycles: Evidence from the eastern Indian Ocean, *Quat. Sci. Rev*, 256. 10.1016/j.quascirev.2021.106839.

Peltier, W.R., and Fairbanks, R.G., 2006. Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record. *Quat Sci Rev*, 2: 3322–3337. https://doi.org/10.1016/J.QUASCIREV.2006.04.010.

Sarnthein, M., Grootes, P.M., Holbourn, A., Kuhnt, W., and Kühn, H., 2011. Tropical warming in the Timor Sea led deglacial Antarctic warming and atmospheric CO2 rise by more than 500 yr. *Earth Planetary Science Letters*, 302: 337–348. https://doi.org/10.1016/J.EPSL.2010.12.021.

Schröder, J.F., Holbourn, A., Kuhnt, W., and Küssner, K., 2016. Variations in sea surface hydrology in the southern Makassar Strait over the past 26 kyr. *Quat Sci Rev*, 154: 143–156. https://doi.org/10.1016/J.QUASCIREV.2016.10.018.

Schröder, J.F., Kuhnt, W., Holbourn, A., Beil, S., Zhang, P., Hendrizan, M., and Xu, J., 2018. Deglacial Warming and Hydroclimate Variability in the Central Indonesian Archipelago. *Paleoceanography, Paleoclimatology*, 33: 974–993. https://doi.org/10.1029/2018PA003323.

Sen Gupta, A., McGregor, S., Van Sebille, E., Ganachaud, A., Brown, J.N., and Santoso, A., 2016. Future changes to the Indonesian Throughflow and Pacific circulation: The differing role of wind and deep circulation changes. *Geophysical Research Letters*, 43: 1669–1678. https://doi.org/10.1002/2016GL067757.

Sprintall, J., Gordon, A.L., Koch-Larrouy, A., Lee, T., Potemra, J.T., Pujiana, K., and Wijffels, S.E., 2014. The Indonesian seas and their role in the coupled ocean–climate system. *Nature Geoscience*, 7(7): 487–492. https://doi.org/10.1038/ngeo2188.

Susanto, R. D., Ffield, A., Gordon, A. L., and Adi, T. R. 2012. Variability of Indonesian throughflow within Makassar strait, 2004–2009. *Journal of Geophysical Research: Oceans*, 117(C9).

Visser, K., Thunell, R., and Stott, L. 2003: Magnitude and timing of temperature change in the Indo-Pacific warm pool during deglaciation. *Nature*, 421:3667–3670. https://doi.org/10.1038/nature01331.1.

Vranes, K., Gordon, A.L., and Ffield, A., 2002. The heat transport of the Indonesian Throughflow and implications for the Indian Ocean heat budget. *Deep Sea Research Part II: Topical Studies in Oceanography*, 49: 1391–1410. https://doi.org/10.1016/S0967-0645(01)00150-3.

Wyrtki, K., 1961. The thermohaline circulation in relation to the general circulation in the oceans. *Deep Sea Research*, 8: 39–64. https://doi.org/10.1016/0146-6313(61)90014-4.

Wyrtki, K., 1987. Indonesian Throughflow and the associated pressure gradient. *Journal of Geophysical Research: Oceans*, 92: 12941–12946.https://doi.org/10.1029jc092ic12p12941.

Xu, J., Holbourn, A., Kuhnt, W., Jian, Z., and Kawamura, H., 2008. Changes in the thermocline structure of the Indonesian outflow during Terminations I and II. *Earth Planet Sci Lett*, 273: 152–162. https://doi.org/10.1016/J.EPSL.2008.06.029.

Zhang, P., Xu, J., Schröder, J.F., Holbourn, A., Kuhnt, W., Kochhann, K.G.D., Ke, F., Wang, Z., and Wu, H., 2018. Variability of the Indonesian Throughflow thermal profile over the last 25-kyr: A perspective from the southern Makassar Strait. *Global and Planetary Change*, 169:214–223. https://doi.org/10.1016/j.gloplacha.2018.08.003.