Indonesian Throughflow Intensity and Sea Surface Temperature Anomaly since the Last Deglaciation: An Overview

M Hendrizan1,2, S Y Cahyarini2, N S Ningsih3, R Rachmayani3

1 Earth Sciences Study Program, Faculty of Earth Sciences and Technology, Bandung Institute of Technology, Labtek XI, Jl. Ganesha No.10, Bandung, Indonesia 40132,
2 Paleoclimate and Paleoenviornment Research Group, Research Center for Geotechnology, Indonesian Institute of Sciences, Jl. Sangkuriang Bandung Indonesia 40135
3 Research Group of Oceanography, Faculty of Earth Sciences and Technology, Bandung Institute of Technology, Labtek XI, Jl. Ganesha No.10, Bandung, Indonesia 40132

*Corresponding author: marf001@lipi.go.id, m_hendrizan@yahoo.com

Abstract. Indonesian Throughflow (ITF) is a low latitude pathway connecting the Pacific Ocean and the Indian Ocean via Indonesian Sea. It plays an important role in the thermohaline circulation, directly impacting the budget, mass, heat, and freshwater of the Pacific Ocean and the Indian Ocean, further impacting the global climate phenomena. Climate phenomena include sea surface temperature (SST) anomaly in the Pacific Ocean is known as El Niño Southern Oscillation (ENSO). ENSO has a global economic impact on countries adjacent to the Pacific. For example, Indonesia experiences drought during El Nino. Therefore, it is necessary to understand how oceanic circulation influences the Pacific Ocean and the Indian Ocean via Indonesian Throughflow (ITF). A Long time series of ocean data, including SST and salinity in the past, is required to better understand the variability of ITF intensity. This paper presents an overview of the previous study on the ITF intensity and its influences on climate since the last deglaciation to Holocene in the Makassar Strait

1. Introduction

The last deglaciation represented an important global climate in the transition between glacial and interglacial at 19-11 kyrs ago [1,2]. The last deglaciation was characterized northern hemisphere ice melted away, sea level rose ±120 m, sea surface temperature increased up to 5°C, and CO2 also increased up to 100 ppm per volume compared to today which was today started 1950 [2,3]. The main force of this climate transition was likely related to changes in obliquity and perihelion [1]. Numerous hypotheses to explain the last deglaciation that has existed, but the ultimate force of this shift remains unclear [1,4–6]. Some studies had suggested that Atlantic Meridional Overturning Circulation (AMOC) played a fundamental role in the Northern hemisphere ice sheet melting in the last deglaciation [4,7].

Today, sea surface temperature (SST) anomaly related to global warming is an important issue [8] due to variation of SST anomaly effects on various aspects, including changes in surface wind, rainfall, and seawater circulation in the Indo-Pacific warm pool region [9]. Regional SST anomaly in
the Pacific Ocean associates with El Niño Southern Ocean (ENSO). The impact of ENSO links to catastrophic floods in eastern Africa and severe drought in Indonesia [10]. Moreover, understanding SST anomaly in tropical regions will consider heat and fresh water transfer mechanisms in the Indonesian Sea. Indonesian Throughflow (ITF) is the only low latitude pathway connecting the Pacific Ocean and the Indian Ocean via Indonesian Sea (Figure 1)[9,11]. The ITF plays an important role in heat and freshwater budget and air-sea heat fluxes of Pacific and the Indian Ocean and may affect ENSO and monsoon [12–14]. The importance of ITF on the Pacific Ocean and Indian ocean is shown by strengthening ITF transport compensated for cooling in the Pacific Ocean and surface warming in the Indian Ocean during warming hiatus between the mid-1990s through mid-2000s [9]. However, few direct time series in Indonesian seas might be used directly to corroborate heat and fresh water transport between the Pacific and Indian Ocean to corresponding ITF profile changes [9]

![Figure 1](image_url). The map of a maritime continent in the Indonesian sea with a schematic of ITF in the Indonesian seas is explained in detail by (Sprintall et al., 2019).

Climate model projections predict a decrease in the ITF transport related to global warming but the cause of ITF dynamics remain elusive [15–17]. Data observation in the ITF’s main inflow in the Makassar Strait, which brings ±80% total volume ITF provides ±13.3-year timeseries (2004-2017), which shows wind and buoyancy are the main forces of the ITF transport during seasonal and interannual [9]. However, the time-series data in the Makassar Strait reveals that the upper and lower layers' ratio has changed, reached approximately 1:1 since 2016 [18]. Changes in the upper and lower layers of ITF transport in the Makassar Strait might be a subject for future detailed analysis of larger-scale ocean and climate systems [18]. On current status, decadal and centennial timescales are more concerned due to the weakening of deepwater contribution from tropical and South Pacific, which is suggested to reduce ITF transport at the end of the 21\textsuperscript{st} century [17].

Study of the ITF intensity in the geological period since the last deglaciation is expected to obtain more regional and larger-forcing in driving ITF variation for understanding air-sea climate system and heat and freshwater storage before being recirculated into global thermohaline circulation [9]. Marine sediment is one of the geological archives that store climate variability such as temperature and salinity in the long-term period from today until millions of years ago with decadal-orbital timescale.
In present study, Mg/Ca and δ^{18}O in marine sediment has been determined from foraminifera which is promising in determining temperature and salinity in paleoceanography and paleoclimatology. Several studies in the Indonesian seas has used a paired Mg/Ca and δ^{18}O to identify temperature and δ^{18}O sea water [7,19–23].

**Figure 2.** Changes in ostracod faunal composition and diversity within core BJ8-03-70GGC in the Makassar Strait with proxy records of deglacial-glacial climate indicate changes in intermediate water ventilation in the strait [24]. Warmer during Holocene thermal maximum (HTM) is consistent with warming Antarctic intermediate water warmer (Fig. 2G), strengthening ITF in the Makassar Strait (Fig. 2E), and increasing intermediate water ventilation in Northwest Pacific (Fig. 2D) [24].

On geological evidences, several studies suggested that changes in AMOC strength influence intensity of ITF during the last 50 kyrs ago [23,25] and may play major role in arid condition in mostly part of Indonesia such as Kalimantan, Sulawesi, Halmahera, and Java [7,20,23,26–31] and wet condition in Flores [32–34]. In addition, changes in the ITF intensity also influence marine productivity at Indonesian seas [24]. However, the main force of Indonesian throughflow (ITF) dynamics in the Indonesian sea is still unclear including several forces proposed such as glacio-eustatic sea level [35], northern hemisphere summer insolation [19], trade wind strength [20,21], and
ventilation of deep and intermediate water due to changes in AMOC strength [36]. Interestingly, similarity pattern between ITF intensity, bottom water temperature, and Antarctic intermediate water ventilation during Holocene (Figure 2) [23,24,37] show that possibility of intermediate and deep water changes can be the main force of ITF intensity since the last deglaciation in the Makassar.

2. Sensitivity of SST variability to intermediate water ventilation
West Pacific Warm Pool (WPWP) is the warmest pool with the highest mean sea surface temperature (>28°C) in the world [24]. The ITF plays a major role in transport 9-10 Sv (1 Sv = 10^6 m^3/s) water mass from WPWP into the eastern Indian Ocean before being recirculated to global thermohaline circulation in middle to high latitude [11,24]. The ITF transports warm, well ventilated and low salinity North Pacific water mass in the western pathway through Makassar Strait and maximum salinity South Pacific water mass in the eastern pathway via Halmahera Sea [38]. The main inflow of the ITF in the Makassar Strait brings ±80% total volume of ITF which occurs in the upper thermocline (upper 300 m water depth) [39]. Most of ITF volume in the Makassar Strait is distributed into Indian Ocean via Lombok Strait, Ombai Strait, and Timor Sea [9]. In addition, other water mass from South China Sea flows to Makassar Strait and Sulawesi Sea via Java Sea and Sulu Sea [11]. Modern ITF intensity based on 13.5-year timeseries in the Makassar Strait shows that the strengthening of ITF related to shoaling thermocline since 2007 [9]. Weakening ITF has existed since mid-2016 in the Makassar Strait [9]. It differs with model projection that shows the reduced ITF since 2006 [17]. This difference is likely controlled by interplay between SST anomaly in the Pacific Ocean and SST anomaly in the Indian Ocean [18,40].

During the last deglaciation, ΔT increased and temperature thermocline oscillated within 20.5 to 22°C between 22-16 kyrs and SST increased abruptly began at 19 kyrs [19]. Long-term increase in ΔT during 23-16 kyrs was resulted from rising SST in the Makassar Strait due to the influence of boreal summer insolation [7,19]. However, the large differences of onset deglacial warming in the north Makassar Strait (17.9 ± 0.9 kyrs) and south Makassar Strait (20.4 ± 0.7) make it difficult to identify precise date for onset deglacial warming in the Makassar Strait [7]. The possibilities of regional and seasonal changes in monsoonal wind patterns are associated with the intermediate/deep water ventilation and the heat transfer in the Indonesian Seas [7] might control surface and thermocline in the Makassar Strait. Holocene studies show that a decrease in SST and TT since 11-2.5 kyrs is due to the dominance of east Asian winter monsoon [19]. Other study shows that the decrease in SST has started at the middle Holocene (6.5 kyrs) that is associated to reduced ITF at 7 kyrs [23]. Reduced SST at 6.5 kyrs is consistent with decreased in bottom water temperature due to changes in ventilation derived from Antarctic intermediate water in the Makassar Strait [24,37]. Moreover, comparing Holocene and last glacial ITF intensity and intermediate water changes in the Makassar Strait is important to understand the connection between intermediate water ventilation and SST in the Strait.

3. Impacts of ITF slowdown on Indonesian climate
Variation of the ITF intensity has a fundamental role in water mass transformation of the region [9]. The ITF transports water mass of warm water and fresh water from Pacific Ocean and mixes in the Indonesian sea which causes cool and fresh water properties in the Indian Ocean [9]. The ITF circulation in the Indonesian sea is influenced by wind-tidal mixing and underwater topographic differences [11,19,41]. The ITF is also controlled by climate condition on a seasonal to interannual timescale [13,18]. On a seasonal timescale, the ITF strengthens during southeast monsoon when surface and freshwater flow increases from Pacific Ocean [11,12]. The ITF weakens during northwest monsoon when freshwater water mass from Java Sea and South China Sea blocks surface water mass from Pacific Ocean [42]. The ITF strengthens during the La Niña period and the ITF weakens during El Niño [43]. On decadal timescale, the ITF strengthens during negative Pacific Decadal Oscillation (PDO) or cold phase in year of 2000s and the ITF weakens since 2016 during positive PDO.
strengthens [9]. At present status, few direct timeseries records are available in the Indonesian seas that might be used to corroborate PDO with changes in ITF profile [9].

During glacial period, the weakening of the ITF during the Younger Dryas and the Heinrich events identified in Makassar Strait and Timor Sea is related to reduced rainfall based on $\delta^{18}O_{sw}$ as proxy of salinity due to weakening of Asian monsoon forced by southward movement of the intertropical convergence zone (ITCZ) [23,25]. The records is consistent with glacial $\delta^{18}O_{sw}$ in the southern Makassar Strait which is influenced by reduced precipitation and runoff from Kalimantan and Sulawesi [19]. However, numerous studies suggest that the weakening of the Walker Circulation in response to a warming climate [40,44] which acts to diminish the size and the strength of the ITF on decadal and longer timescale [40]. Holocene precipitation from Kalimantan based on marine sediment $\delta^{13}CFA$ indicates that the reduced precipitation is around $\pm 7$ kyrs and the increased is in 2.5 kyrs [29]. Evidence of Holocene rainfall pattern looks similar to changes in the ITF intensity in the Makassar Strait [23]. The similarity between ITF intensity and rainfall pattern during Holocene could be related to the combination between boreal summer insolation and ocean-air interaction [29,45] that must be explored until the last deglaciation.

4. Potential of deep water contribution on changes in ITF intensity

Past reduction of the ITF intensity has impacted the global ocean circulation and climate variability since the last deglaciation [46]. Since the last 25 kyrs, thermocline temperature in the ITF region follows boreal summer insolation which is suggested as the main force of changes in ITF intensity in the Makassar Strait [19]. However, Indonesian seas experienced rapid sea level rise at ca. 19.6 kyrs lasting for ca. 800 years with 10 m magnitude [47]. In addition, there was rapid improvement in deepwater and intermediate ventilation from Antarctic Circumpolar water in Timor Sea at the beginning of Termination 1 (ca. 18 kyrs) [36]. Sea level change or deepwater and intermediate water ventilation could accomplish changes in ITF intensity in the Makassar Strait. Interestingly, cool and fresh water surface water are identified during Bölling/Alleröd (B/A) in the Makassar Strait associated to increase in ITF intensity [23]. The record in Mahakam Strait is consistent with increased in intermediate-deep water ventilation in Southeast Pacific (SEP) region indicated by oxygen (O$_2$) depleted [48].the weakening of the ITF in the Makassar Strait during the Younger Dryas (YD) and the Heinrich Event 1 (H1) [20,23] is also associated to the reduced intermediate-deep water ventilation with Oxygen (O$_2$) enrichment in the SEP [48]. Therefore, understanding intermediate water changes would be the key point for interpreting the main force of changes in ITF intensity in the Makassar Strait since the last deglaciation.

5. Conclusion

Understanding the relationship between ITF intensity and SST anomaly in the Makassar Strait suggest changes in intermediate water ventilation probably achieves SST anomaly in the Makassar Strait via ITF. The weakening of ITF intensity during warm climate in the past implied drying condition in most part of Indonesia due to weakening of Walker circulation. We suppose that changes in ITF intensity during global warming are forced by water mass transformation in the Pacific Ocean. Therefore, knowledge on ITF intensity in the inflow pathway would be subject for future detailed analysis to larger scale ocean and climate system. Study of the ITF intensity in geological period since the last deglaciation is expected to obtain more regional and larger-forcing in driving ITF variation for understanding air-sea climate system and storage of heat and freshwater before being recirculated into global thermohaline circulation.

References

[1] Clark P U, Shakun J D, Baker P A, Bartlein P J, Brewer S, Brook E, Carlson A E, Cheng H, Kaufman D S, Liu Z, Marchitto T M, Mix A C, Morrill C, Otto-bliiesner B L, Pahnke K, Russell J M, Whitlock C, Adkins J F, Blois J L, Clark J, Colman S M, Curry W B, Flower B P, He F, Johnson T C, Lynch-stieglitz J, Markgraf V, Memanous J, Mitrovica J X, Moreno P I
and Williams J W 2012 Global climate evolution during the last deglaciation PNAS 109

[2] Alley R B, Clark P U, Huybrechts P and Joughin I 2005 Ice-Sheet and Sea-Level Changes Science. 310

[3] Denton G H, Anderson R F, Toggweiler J R, Edwards R L, Schaefer J M and Putnam A E 2010 The Last Glacial Termination Science. 328 1652–6

[4] Shakun J D, Clark P U, He F, Marcott S a., Mix A C, Liu Z, Otto-Bliesner B, Schmittner A and Bard E 2012 Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation Nature 484 49–54

[5] Sarntthein M, Groottes P M, Holbourn A, Kuhnt W and Kühn H 2011 Tropical warming in the Timor Sea led glacial Antarctic warming and atmospheric CO2 rise by more than 500 yr Earth Planet. Sci. Lett. 302 337–48

[6] Stott L, Timmermann A and Thunell R 2007 Southern Hemisphere and deep-sea warming led deglacial atmospheric CO2 rise and tropical warming. Science 318 435–8

[7] Schröder J F, Kuhnt W, Holbourn A, Beil S and Zhang P 2018 Deglacial Warming and Hydroclimate Variability in the Central Indonesian Archipelago Paleoceanogr. Paleoclimatology 974–93

[8] England M H, Mcgregor S, Spence P, Meehl G A, Timmermann A, Cai W, Gupta A Sen, Mcphaden M J, Purich A and Santosoto A 2014 the Pacific and the ongoing warming hiatus Nat. Clim. Chang. 4 222–7

[9] Sprintall J, Gordon A L, Wijffels S E, Feng M, Hu S, Koch-Larrouy A, Phillips H, Nugroho D, Napitu A, Pujiana K, Susanto R D, Sloyan B, Peña-Molino B, Yuan D, Riam D H P, Siswanto S, Kuswardani A, Arifin Z, Wahyudi A J, Zhou H, Nagai T, Ansong J K, Bourdalle-Badié R, Chanut J, Lyard F, Arbic B K, Ramdhani A and Setiawan A 2019 Detecting Change in the Indonesian Seas Front. Mar. Sci. 6 1–24

[10] Sprintall J, Potemra J T, Hautala S L, Bray N A and Pandoe W W 2003 Temperature and salinity variability in the exit passages of the Indonesian Throughflow Deep. Res. Part II Top. Stud. Oceanogr. 50 2183–204

[11] Gordon A L 2005 Oceanography of the Indonesian Seas Oceanography 18 14–27

[12] Gordon A L, Susanto R D and Vranes K 2003 Cool Indonesian throughflow as a consequence of restricted surface layer flow Nature 425 824–8

[13] Hu S and Sprintall J 2016 Interannual variability of the Indonesian Throughflow: The salinity effect J. Geophys. Res. Ocean. 121 6762–78

[14] Cahyarinî S Y, Pfeiffer M, Nurhati I S, Aldrian E, Dullo W-C and Hetzinger S 2014 Twentieth century sea surface temperature and salinity variations at Timor inferred from paired coral d18O and Sr/Ca measurements J. Geophys. Res. Ocean. 119 4593–604

[15] Sen Gupta A, Mcgregor S, 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 Geophys. Res. Lett. 43 1669–78

[16] Hu D, Wu L, Cai W, Sen Gupta A, Ganachaud A, Qiu B, Gordon A L, Lin X, Chen Z, Hu S, Wang G, Wang Q, Sprintall J, Qu T, Kashino Y, Wang F and Kessler W S 2015 Pacific western boundary currents and their roles in climate Nature 522 299–308

[17] Feng M, Zhang X, Sloyan B and Chamberlain M 2017 Contribution of the deep ocean to the centennial changes of the Indonesian Throughflow Geophys. Res. Lett. 44 2859–67

[18] Gordon A L, Napitu A, Huber B A, Gruenburg L K, Pujiana K, Agustiadi T, Kuswardani A and Mbay N 2019 Makassar Strait Throughflow Seasonal and Interannual Variability : An Overview Journal of Geophysical Research : Oceans 3724–36

[19] 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 Glob. Planet. Change 169 214–23

[20] 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 Sci. Rep. 8 1–8.

[21] 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 Glob. Planet. Change 111 111–7

[22] Schroder 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. 154 143–56

[23] Hendrizan M, Kuhnt W and Holbourn A 2017 Variability of Indonesian Throughflow and Borneo Runoff During the Last 14 kyr Paleoeceanography 32 1054–69

[24] Iwatani H, Yasuhara M, Rosenthal Y and Linsley B K 2018 Intermediate-water dynamics and ocean ventilation effects on the Indonesian Throughflow during the past 15,000 years: Ostracod evidence Geology 46 567–70

[25] Zuraida R, Holbourn A, Nurnberg D and Kuhnt W 2009 Evidence for Indonesian Throughflow slowdown during Heinrich events 3–5 Paleoeceanography 24 1–15

[26] Gustiyanlini L 2018 Paleoclimate reconstructions by multiproxy approaches in Halmahera Sea since the late Pleistocene-Holocene

[27] Carolin S A, Cobb K M, Adkins J F, Clark B, Conroy J L, Lejau S, Malang J and Tuen A A 2013 Varied Response of Western Pacific Hydrology to Climate Forcing over the Last Glacial Period Science. 340 1564–6

[28] Partin J W, Quinn T M, Shen C-C, Okumura Y, Cardenas M B, Siringan F P, Banner J L, Lin K, Hu H-M and Taylor F W 2015 Gradual onset and recovery of the Younger Dryas abrupt climate event in the tropics Nat. Commun. 6 8061

[29] Dubois N, Oppo D W, Galy V V., Mohtadi M, Van Der Kaars S, Tierney J E, Rosenthal Y, Eglinton T I, Glücke A and Linsley B K 2014 Indonesian vegetation response to changes in rainfall seasonality over the past 25,000 years Nat. Geosci. 7 513–7

[30] Wicaksono S A, Russell J M, Holbourn A and Kuhnt W 2017 Hydrological and vegetation shifts in the Wallacean region of central Indonesia since the Last Glacial Maximum Quat. Sci. Rev. 157 152–63

[31] Konecky B, Russell J and Bijaksana S 2016 Glacial aridity in central Indonesia coeval with intensified monsoon circulation Earth Planet. Sci. Lett. 437 15–24

[32] Ayliffe L K, Gagan M K, Zhao J, Drysdale R N, Hellstrom J C, Hantoro W S, Griffiths M L, Scott-Gagan H, Pierre E S, Cowley J A and Suwargadi B W 2013 Rapid interhemispheric climate links via the Australasian monsoon during the last deglaciation Nat. Commun. 4 1–6

[33] Muller J, McManus J F, Oppo D W and Francois R 2012 time of Heinrich event 1 Strengthening of the Northeast Monsoon over the Flores Sea, Indonesia, Geology 40 635–8

[34] Griffiths M L, Drysdale R N, Gagan M K, Zhao J, Ayliffe L K, Hellstrom J C, Hantoro W S, Frisia S, Feng Y, Cartwright I, Pierre E S, Fischer M J and Suwargadi B W 2009 Increasing Australian – Indonesian monsoon rainfall linked to early Holocene sea-level rise Nat. Geosci. 2 636–9

[35] Petrick B, Martinez-Garcia A, Auer G, Reuning L, Auderset A, Deik H, Takayanagi H, De Vleeschouwer D, Iryu Y and Haug H G H 2019 Glacial Indonesian Throughflow weakening across the Mid-Pleistocene Climatic Transition Sci. Rep. 9 1–13

[36] Holbourn A, Kuhnt W and Xu J 2011 Indonesian Throughflow variability during the last 140 ka: The timor sea outflow Geol. Soc. Spec. Publ. 355 283–303

[37] Rosenthal Y, Linsley B K and Oppo D W 2013 Pacific Ocean Heat Content During the Past 10,000 Years Science (80-. ). 342 617–21

[38] Gordon A L and Fine R A 1996 Pathways of water between the Pacific and Indian oceans in the Indonesian seas Nature 379 146–9

[39] Tillinger D and Gordon A L 2009 Fifty years of the Indonesian throughflow J. Clim. 22 6342–55

[40] Sprintall J and Revélard A 2014 Journal of Geophysical Research : Oceans J. Geophys. Res.
Ocean. 119 1161–75

[41] Gordon A L, Giulivi C F and Ilahude A G 2003 Deep topographic barriers within the Indonesian seas Deep. Res. II 50
[42] Qu T, Du Y, Strachan J, Meyers G and Slingo J 2005 Sea surface temperature and its variability in the Indonesian region Oceanography 18 50–61
[43] Susanto R D, Field A, Gordon A L and Adi T R 2012 Variability of Indonesian throughflow within Makassar Strait, 2004 – 2009 117 2004–9
[44] Tokinaga H, Xie S-P P, Deser C, Kosaka Y and Okumura Y M 2012 Slowdown of the Walker circulation driven by tropical Indo-Pacific warming Nat. Res. Lett. 491 439–43
[45] Tierney J E, D. W. Oppo, LeGrande A N, Huang Y, Rosenthal Y and Linsley B K 2012 The influence of Indian Ocean atmospheric circulation on Warm Pool hydroclimate during the Holocene epoch J. Geophys. Res. 117 1–9
[46] Praetorius S K, Condron A, Mix A C, Walczak M H, Mckay J L and Du J 2020 The role of Northeast Pacific meltwater events in deglacial climate change Sci. Adv. 6 1–17
[47] Hanebuth T, Stattegger K and Bojanowski A 2009 Termination of the Last Glacial Maximum sea-level lowstand : The Sunda-Shelf data revisited Glob. Planet. Change 66 76–84
[48] Haddam N A, Michel E, Siani G, Licari L and Dewilde F 2020 Ventilation and expansion of intermediate and deep waters in the Southeast Pacific during the last termination Paleoceanogr. Paleoclimatology 35