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# MERIDIONAL MIGRATIONS OF THE INTERTROPICAL CONVERGENCE ZONE DURING THE LAST DEGLACIATION IN THE TIMOR SEA DETECTED BY EXTENSIVE RADIOCARBON DATING

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**ABSTRACT.** At the Intertropical Convergence Zone (ITCZ), the northern and southern Tradewinds converge, and this region is characterized by low atmospheric pressure and high precipitation. The climate in the Timor Sea is characterized by seasonal precipitation changes driven by meridional migrations of the ITCZ and the monsoonal front. The ITCZ shifts in response to changes in the thermal balance between the northern and southern hemispheres. Thus, reconstruction of paleo-precipitation in the Timor Sea is expected to reveal past changes in both regional and global climate, the latter through inference of the ITCZ position. To reconstruct paleo-precipitation in the Timor Sea, we performed extensive radiocarbon analysis on both planktonic foraminifera and total organic carbon (TOC), which is derived from terrestrial and marine sources. Increased precipitation enhances the fraction of relatively old, terrestrial carbon to the core site, which in turn increases the difference between the ages of TOC and planktonic foraminifera. Variations in radiocarbon ages reveal that during northern hemisphere cooling intervals such as Heinrich Stadial 1 and the Younger Dryas, the ITCZ was in a southern position, thus increasing precipitation in the Timor Sea. However, the Timor Sea was dryer during the Bølling–Allerød warming as the ITCZ shifted northward.

**KEYWORDS:** deglaciation, Intertropical Convergence Zone, radiocarbon AMS dating.

## INTRODUCTION

High-density radiocarbon ($^{14}C$) dating and improved age-depth modeling methods are advancing our understanding of recent paleoclimate variability (e.g., Hajdas et al. 2021). One important development is the increased number of high-precision measurements performed on a daily basis. For example, the single stage Accelerator Mass Spectrometer (AMS) installed at the Atmosphere and Ocean Research Institute (AORI), the University of Tokyo has already analyzed over 16,000 samples since 2013 (Yokoyama et al. 2019a; Yokoyama et al. 2022).

However, while analytical precision and throughput has greatly improved, the issue of material suitability is of paramount importance (e.g., Bronk Ramsey 2009). For example, organic carbon in marine sediments may be derived from multiple sources, complicating interpretation. In coastal settings, terrestrial material discharged from rivers may be relatively old while organic matter produced by plankton will generally be contemporaneous with deposition. The marine organic matter may be subject to a temporally and spatially uncertain reservoir age (e.g., Nakamura et al. 2012; Yokoyama et al. 2019b; Fukuyo et al. 2020; Heaton et al. 2020),

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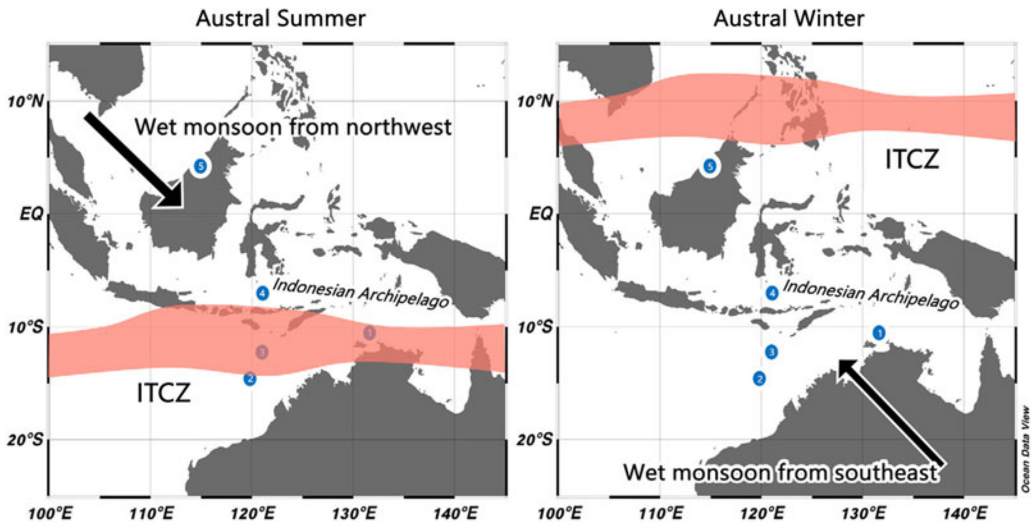


Figure 1 Seasonal climatic changes over the Indonesian Archipelago today during both the austral summer and winter. The shaded band indicates the approximate location of the ITCZ. Arrows indicate prominent monsoon wind direction. Blue dots correspond to the sites of cores (1) MD05-2970, (2) SO185-18506, (3) SO185-18479 all in the Timor Sea, (4) V33-80 offshore Flores Island and (5) the location of Snail Shell cave on Borneo Island. (Please see online version for color figures.)

while the residence time of terrestrial organic matter is similarly unknown (Carvalhais et al. 2014; Jiang et al. 2022).

Planktonic foraminifera utilize seawater for calcification and are therefore also affected by the same reservoir effect as the contemporaneously produced marine organic matter, but as rainfall increases, river runoff from proximal rivers supplies an increasingly larger fraction of relatively older (due to above-mentioned residence time) terrestrial carbon to the sediments. This increases the offset of bulk organic matter from foraminiferal radiocarbon (Nakamura et al. 2016; Ishiwa et al. 2021). Hence, relative changes in the offset between radiocarbon of marine surface dissolved inorganic carbon (DIC) and bulk organic radiocarbon can be used as a proxy for precipitation variability on land. Here, we evaluate radiocarbon offsets offshore of Indonesia to infer past changes in local and global climate.

The regional climate in the Indonesian Archipelago is characterized by seasonal change in precipitation (Spooner et al. 2005) that is related to the position of the Intertropical Convergence Zone (ITCZ) because tropical convergence causes precipitation (Xie and Arkin 1997). The seasonal migration distance of the ITCZ over the Indonesian Archipelago is the largest on Earth today (van der Kaars et al. 2000). During the austral summer, the ITCZ migrates southward, resulting in high monsoonal precipitation over the Indonesian Archipelago (Hobbs 1998; Figure 1). The ITCZ returns to northerly position (10ºN to 15ºN) during the austral winter, resulting in lower precipitation driven by the dry southeast monsoon (Hobbs 1998). As the meridional position of the ITCZ reflects the thermal balance between the northern and the southern hemispheres (Chiang and Bitz 2005; Donohoe et al. 2013; Chiang et al. 2014), an understanding of past precipitation variations in the Indonesian Archipelago will also provide information on global climate change.

## MATERIALS AND METHODS

### Regional Setting and Sampling

The Indonesian Throughflow (ITF) transports surface and thermocline waters from the Pacific Ocean to the Indian Ocean. The ITF provides relatively cool and low salinity water to the Indian Ocean with its amount reaching 7.5 Sv (Sv = $10^6$ $m^3/s$) in the Timor Sea (Gordon et al. 2010). The ITF is the only pathway between the Pacific Ocean and the Indian Ocean because the water depth in the South China Sea and Arafura Sea is shallow (less than 20 m). The Indonesian Archipelago located in the Indo-Pacific Warm Pool. High sea surface temperature in this region invigorates atmosphere circulation, which in turn plays an important role in global climate (Chiang 2009).

Core MD05-2970 was recovered from the eastern Timor Sea (9º25′S, 130º60′E) at a water depth of 437 m below sea level in June 2005 during Cruise MD 148 of the *Marion Dufresne*. The 28.92-m-long core was subsampled at a 2.5-cm interval.

### Radiocarbon Dating

Radiocarbon analysis was performed on TOC (51 samples) and planktonic foraminifera (*G. ruber* and *T. sacculifer*; 8 samples) at the Atmosphere and Ocean Research Institute, The University of Tokyo, using a single stage AMS (Yokoyama et al. 2019a; Yokoyama et al. 2022). TOC samples (1 mg C) were graphitized following the procedures described in Yokoyama et al. (2022), which is an automated line using an elemental analyzer (Elementar, vario MICRO cube).

Samples for foraminfers were freeze dried then were passed through a >63 µm mesh to isolate the sand fraction containing mostly foraminifera. The >125 µm fraction was examined under a reflected light microscope and approximately 50–100 individuals of *T. sacculifer* were picked with the aim of obtaining at least 2 mg of calcite. If the number of *T. sacculifer* in the sample was too low to obtain the needed mass of calcite, specimens of *G. ruber* were also picked until 2 mg was obtained. Both foraminifera species are surface dwelling but *G. ruber* prefers a slighly shallower habitat. The foraminifera were treated by first evolving to $CO_2$ gas using $H_3PO_4$, and then the $CO_2$ gas was graphitized using $H_2$ as a reducing agent and Fe as a catalyst (Yokoyama et al. 2007).

Radiocarbon ages were calibrated to calendar years using MatCal (Lougheed and Obrochta 2016), the Marine20 calibration curve (Heaton et al. 2020) for foraminifera age dating and the Intcal20 calibration curve (Reimer et al. 2020) for TOC age dating. Following previous work, a local reservoir effect was not applied because the surface ocean was stratified (Sarnthein et al. 2011; Kuhnt et al. 2015). However, the assumption of a constant marine reservoir age is problematic before 18 ka. Calibrated ages older than 18 ka are considered maximum ages (Sarnthein et al. 2011). Although the TOC samples contain a mixture marine and terrestrial carbon, the IntCal20 calibration curve is used for the assumption of dominance of terrestrial carbon in the sediment. The IntCal20 curve produces older ages than the Marine20 curve (Heaton et al. 2020). Therefore, the use of the Marine20 to calibrate TOC samples would decrease the TOC age and thus also the difference between the TOC and foraminifera age (hereafter $\Delta_{\text{TOC-foram}}$). This is because TOC ages are older than foraminifera ages. Changing the calibration curve affects neither the timing nor direction of changes in $\Delta_{\text{TOC-foram}}$. Age modeling was performed in a deterministic $10^5$ iteration Monte Carlo routine, *undatable*, that considers depth uncertainty and a Gaussian accumulation rate uncertainty between adjacent dates (Lougheed and Obrochta 2019). Sedimentation uncertainty scaling was set to 0.1 and

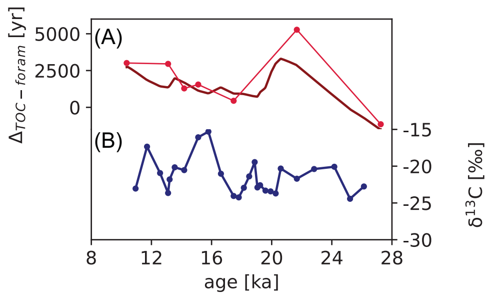


Figure 2 Display of (A) the age difference between the TOC and foraminifera age from the same horizon in core MD05-2970 (thin red line with dots) and from the age models (brown thinker line). (B) $\delta^{13}C$ values of TOC samples measured by accelerator mass spectrometry.

bootstrapping was set to 30%. Separate foraminifera and TOC age models were created using the above parameters.

## RESULTS

The obtained age models for both planktonic and TOC radiocarbon dating and the calibrated calendar year ranges are shown in Appendix A and B. The minimum and maximum calendar ages of foraminifera range between 10.2 ka and 27.4 ka with an average sedimentation rate 17 cm/kyr. The minimum and maximum calendar ages of TOC dating range between 5.0 ka and 29.6 ka. The model based $\Delta_{\text{TOC-foram}}$ exhibits minima values of ~0 year offsets at around 18 ka, and is negative before 24 ka (Figure 2A). Offset increase to ~3000 years in the intervening intervals. $\Delta_{\text{TOC-foram}}$ calculated from paired measurements from the same horizon exhibits a similar pattern as the model-based offset (Figure 2A). $\delta^{13}C$ of TOC samples ranges between –25 and –15‰. $\delta^{13}C$ values of TOC are relatively low from 28 ka to 17 ka, are relatively high from 16 ka to 11 ka. As all samples analyzed are taken at a 2.5 cm interval, each sample represents 300 years at the points of the highest sedimentation rate. Hereafter, we will discuss millennial scale climate change using $\Delta_{\text{TOC-foram}}$.

## DISCUSSION

### Age Models and Variations in$\Delta_{\text{TOC-foram}}$

As the mentioned $\Delta_{\text{TOC-foram}}$ is consistent with the $\Delta_{\text{TOC-foram}}$ calculated from paired measurements (Figure 2A), we consider only the higher-resolution, modeled offsets in this section. Planktonic foraminifera tests are formed in seawater and therefore solely from marine DIC. However, total organic carbon in sediments is a mixture of terrigenous and marine organic material, with the terrigenous material subject to multiple carbon pathways and residence times. Thus, we generally consider the planktonic foraminifer age depth model to be more reliable and use it as the basis for the following discussion.

The negative $\Delta_{\text{TOC-foram}}$ before 24 ka is consistent with previous work suggesting a non-stationary reservoir age at this time (Sarnthein et al. 2011). The $\Delta R$ in the Timor Sea appears to have been relatively constant near 0, yet it was significantly larger prior to 18 ka, likely more than 1000 years, possibly due to ocean circulation changes and lack of stratification (Sarnthein et al. 2011). Thus, we

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avoid making paleoclimatic interpretations prior to 18 ka, In particular, the negative values prior to ~24 ka suggest a substantial increase in reservoir age, a major decrease in terrestrial organic matter residence time, or a combination of both.

The interpretation that ΔR was constant after 18 ka suggests that $\Delta_{TOC\text{-}foram}$ change after this time is unrelated to ocean circulation changes. While variations in ocean productivity could affect $\Delta_{TOC\text{-}foram}$, the relatively constant $\delta^{13}C$ of TOC samples suggests that stable productivity and little. vegetation changes across the Indonesian Archipelago (Dubois et al. 2014). $\delta^{13}C$ values obtained by AMS may reflect fractionation in the ion source, as opposed to IRMS measurements. This could cause higher variability in our data, but as the values are relatively constant, we believe the interpretation of the $\delta^{13}C$ values is relatively straightforward. Thus, we interpret variations in $\Delta_{TOC\text{-}foram}$ as reflecting changes in the residence time of terrestrial organic carbon.

We further suggest that varying precipitation amount drives changes in TOC residence time (e.g., Carvalhais et al. 2014; Jiang et al. 2022; Appendix C). Turnover times of terrestrial carbon is mainly influenced by precipitation over the Indonesian Archipelago (Carvalhais et al. 2014), with higher precipitation being associated with shorter turnover times. The soil is easily eroded and transported to the Timor Sea resulting in the younger TOC of material sampled from the ocean floor. On the other hand, turnover times of terrestrial carbon become longer when the precipitation is low because soil less effectively eroded. Therefore, we expect an antiphased relationship between $\Delta_{TOC\text{-}foram}$ and precipitation amount. Although terrigenous material input to the Sunda Trench is limited today (Omura et al. 2017), terrestrial carbon contents of coastal sediment cores are ~20% (Zhou et al. 2019). Organic carbon in the sediments recovered from the Bengal Fan at a water depth of 240 m was stored for more than 1000 years (French et al. 2018). Considering that our sediment core was recovered from a depth of 437 m, it is reasonable to interpret that terrestrial carbon input likely influenced $\Delta_{TOC\text{-}foram}$ variability at this site.

### The Meridional Shift of the ITCZ During the Deglaciation

During the last deglaciation (18–11.7 ka), the thermal balance between the northern and southern hemispheres changed dramatically causing a dynamic meridional migration of the ITCZ (e.g., Yokoyama et al. 2011; De Deckker et al. 2014) A portion of migration was driven by partial collapse of northern hemisphere ice sheets (Chiang and Bitz 2005; Yokoyama and Purcell 2021). The northern hemisphere cooled because of the weakened Atlantic Meridional Overturning Circulation (AMOC), allowing more heat to be related by the southern hemisphere during Heinrich Stadial 1 (HS1; 18.0–15.0 ka) and the Younger Dryas (YD; 12.9–11.7 ka; McManus et al. 2004; Chiang and Bitz 2005; Obrochta et al. 2014). A resulting teleconnection is movement of the ITCZ (and its associated precipitation band) southward over the Indonesian Archipelago (Yokoyama et al. 2006; Safaierad et al. 2020). In contrast, a vigorous AMOC during the Bølling–Allerød warming interval (B/A; 15.0–12.9 ka; McManus et al. 2004) reduced the thermal balance between the hemispheres, warmed the northern hemisphere, and shifted the ITCZ northward away from the Indonesian Archipelago. Thus, precipitation over the southern margin of the Indonesian Archipelago decreased during B/A (Kuhnt et al. 2015).

During HS1, decreased $\Delta_{TOC\text{-}foram}$ suggests high precipitation over the Timor Sea and adjacent landmasses and implies a southward shift of the ITCZ resulting in wet conditions over the

Timor Sea (Figure 3A). As the northern hemisphere cooled during HS1 due to weakened AMOC (Figure 3G; McManus et al. 2004), the ITCZ likely shifted southward due to the changing thermal balance between both hemispheres (Chiang and Bitz 2005; Donohoe et al. 2013; Chiang et al. 2014). This is consistent with a relatively low $\Delta_{TOC\text{-}foram}$ that implies wet conditions during HS1. Wet conditions over the Timor Sea and adjacent landmasses are also consistent with paleoclimatic records from the Indonesian Archipelago region (Kuhnt et al. 2015).

The K/Ca ratio of cores SO185-18506 and SO185-18479 recovered from the western Timor Sea is high during HS1 indicating high terrigenous input to the western Timor Sea caused by the increased precipitation amount (Figure 3B, C; Kuhnt et al. 2015). Both the $^{232}$Th flux and the residual flux (non-biogenic components) of core V33-80 recovered from offshore Flores Island increased due to enhanced precipitation runoff into the Flores Sea from the surrounding landmass (Figure 3D; Muller et al. 2012). Terrigenous input of core ST08, retrieved from offshore and to the southwest of Sumba Island, also exhibited an increase as a result of higher precipitation (Ardi et al. 2020). The southward ITCZ and the associated wet northwest monsoon are causes of increased precipitation in the Flores Sea region (Muller et al. 2012), consistent with low $\Delta_{TOC\text{-}foram}$. This is consistent with the speleothem $\delta^{18}$O record from northern Borneo Island, which shows a trend toward more positive values during HS1. This reflects dry conditions in that region due to a southward shift of the ITCZ away from Borneo Island (Figure 3E; Partin et al. 2007). Therefore, the precipitation band associated with the ITCZ was located between northern Borneo Island and the Timor Sea during HS1.

Although dry conditions are revealed by grain size analysis and terrigenous input proxy variability of core GeoB 10053-7 recovered from south of Java Island, it is also consistent with the southward displacement of the ITCZ during HS1 (Mohtadi et al. 2011). The precipitation band associated with the ITCZ was located further south of the Java Sea. Modeling results are also consistent with this inferred southward position of the ITCZ during HS1 (Du et al. 2023). In contrast, no major changes in annual rainfall were observed in northwestern Australia (De Deckker et al. 2014), suggesting that the degree of the southward migration of the ITCZ and the associated precipitation change was insufficiently large to change the local climate in this region. Although the effects of HS1 have not been identified in the Australian region (De Deckker et al. 2014), the northern hemisphere cooling during HS1 may have pushed the ITCZ southward because the one of significant factors of the ITCZ movement is thermal balance between both hemispheres.

The $\Delta_{TOC\text{-}foram}$ increase was substantial during the B/A interval implying that the ITCZ shifted northward with a prominent dry southeast monsoon. The southern hemisphere, especially around Antarctica, cooled (as seen through the Antarctic Cold Reversal; ACR; Lemieux-Dudon et al. 2010) during the northern hemisphere warming (B/A). The shifting thermal balance would have pushed the ITCZ northward. However, the $\Delta_{TOC\text{-}foram}$ did not remain high during the B/A interval because of the exposure of the Sunda Shelf (at ~14 ka) which forced a shift of the atmospheric circulation over the Indonesian Archipelago (Du et al. 2021). The low $^{232}$Th flux and residual flux in the Flores Sea (Muller et al. 2012), and the low K/Ca ratio in the western Timor Sea (Kuhnt et al. 2015), are all consistent with decreased precipitation during the B/A (Figure 3A, B, C, D). In contrast, increased precipitation during the B/A was recorded in the Borneo speleothem (Figure 3E; Partin et al. 2007). All these records are consistent with the northward shift of the ITCZ because of AMOC recovery (Figure 3G) and associated vigorous thermal exchange between both hemispheres as recorded in the Atlantic Ocean

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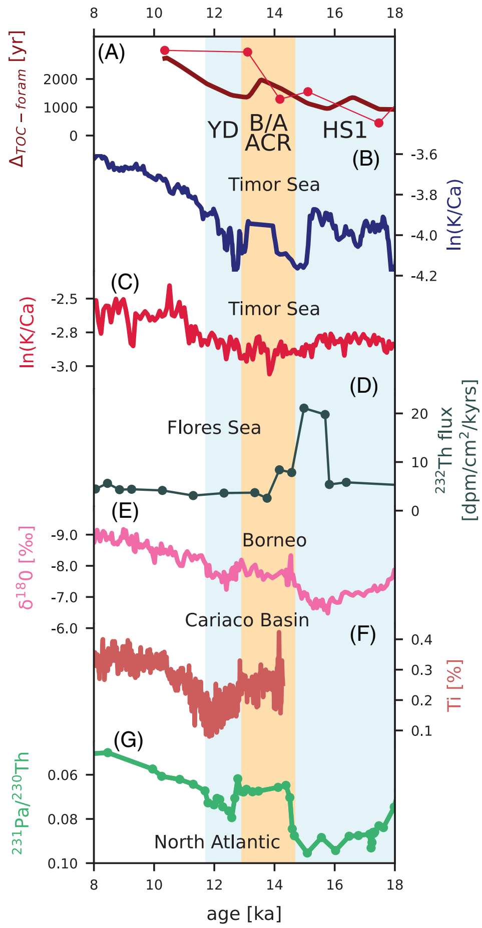


Figure 3 The age difference between the TOC and foraminifera age from the same horizon of core MD05-2970 (thin red line with dots) and that from the age models (brown thicker line). (B) core SO185-18506 (ln(K/Ca)) indicating changes in terrigenous flux in the Timor Sea (Kuhnt et al. 2015). (C) core SO185-18479 (ln(K/Ca)) indicating changes in terrigenous flux from the Timor Sea (Kuhnt et al. 2015). (D) core V33-80 $^{232}$Th flux indicating changes in terrigenous flux in the Flores Sea (Muller et al. 2012). (E) Snail Shell cave δ$^{18}$O indicating precipitation changes over Borneo Island (Muller et al. 2012). (F) Titanium content of the sediment core recovered from ODP Site 1002 indicating changes in terrigenous flux in the Cariaco Basin (Haug et al. 2001). (G) core OCE326-GGC5 $^{231}$Pa/$^{230}$Th indicating the strength of the Atlantic Meridional Overturning Circulation from the western subtropical Atlantic Ocean (McManus et al. 2004). Shaded areas correspond to Heinrich Stadial 1 (18–14.7 ka), the Bølling–Allerød warming interval (14.7–12.9 ka) and the Younger Dryas (12.9–11.7 ka).

(McManus et al. 2004). The relatively high titanium input to the Cariaco Basin (Haug et al. 2001) off the coast of Venezuela, also supports a northward movement of the ITCZ during the B/A over the western Atlantic indicating that the ITCZ moved similarly in both the eastern and the western Pacific in this interval (Figure 3F).

AMOC was reduced and the meridional thermal exchange was inhibited during the YD (Matsumoto and Yokoyama 2013). Although AMOC remained stronger during the YD than during HS1 (Figure 3G; McManus et al. 2004), our $\Delta_{\text{TOC-foram}}$ was low and the K/Ti ratio in the Timor Sea increased during the YD interval suggesting precipitation had increased because of the southward shift of the ITCZ which is similarly observed during HS1 (Figure 3A, B, C; Kuhnt et al. 2015). The positive shift of the speleothem $\delta^{18}$O record from Borneo Island and the low terrestrial material input to the Ciriaco Basin, both imply a precipitation decrease. This supports the interpretation that the ITCZ was in a southward location globally during the YD (Figure 3E, F; Haug et al. 2001; Partin et al. 2007). On the other hand, the $^{232}$Th flux and residual flux in the Flores Sea remained steady during the YD (Figure 3D; Muller et al. 2012), possibly because either a reduced meridional movement of the ITCZ as a result of AMOC production, or perhaps chronological uncertainty hinders interpretation of the record.

## CONCLUSION

By performing extensive radiocarbon dating of both the TOC and planktonic foraminifera in a coastal marine core, it was possible to reconstruct precipitation changes driven by the ITCZ movement in the Timor Sea region. During HS1 and the YD, the Timor Sea region was wet because of the southerly position of the ITCZ. Conversely, the northward shift of the ITCZ resulted in dry conditions in the Timor Sea during the B/A. The ITCZ movement during the last deglaciation was consistent with the thermal balance/shift between both hemispheres that was mainly controlled by AMOC strength. As precipitation is a key factor of climate change, precipitation reconstruction using the extensive radiocarbon dating may be a useful tool to determine paleoclimate changes in different regions over the Indonesian Archipelago.

## SUPPLEMENTARY MATERIAL

To view supplementary material for this article, please visit https://doi.org/10.1017/RDC.2024.13

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