nature geoscience

ARTICLES

| DOI: 10.1038/NGEO520

Mid-Pliocene climate change amplified by a switch in Indonesian subsurface throughflow

Cyrus Karas[1]*, Dirk Nürnberg[1], Anil K. Gupta[2], Ralf Tiedemann[3], Kuppusamy Mohan[2] and Torsten Bickert[4]

The tectonically driven closure of tropical seaways during the Pliocene epoch (∼5–2 million years (Myr) ago) altered ocean circulation and affected the evolution of climate. Plate tectonic reconstructions show that the main reorganization of one such seaway, the Indonesian Gateway, occurred between 4 and 3 Myr ago. Model simulations have suggested that this would have triggered a switch in the source of waters feeding the Indonesian throughflow into the Indian Ocean, from the warm salty waters of the South Pacific Ocean to the cool and relatively fresh waters of the North Pacific Ocean. Here we use paired measurements of the δ^{18}O and Mg/Ca ratios of planktonic foraminifera to reconstruct the thermal structure of the eastern tropical Indian Ocean from 5.5 to 2 Myr ago. We find that sea surface conditions remained relatively stable throughout the interval, whereas subsurface waters freshened and cooled by about 4 °C between 3.5 and 2.95 Myr ago. We suggest that the restriction of the Indonesian Gateway led to the cooling and shoaling of the thermocline in the tropical Indian Ocean. We conclude that this tectonic reorganization contributed to the global shoaling of the thermocline recorded during the Pliocene epoch, possibly contributing to the development of the equatorial eastern Pacific cold tongue.

The role of the closures of the Central American seaway[1] and the Indonesian throughflow[2] (ITF) in the Pliocene global climatic reorganizations is intensively debated. It has been proposed that the closure of the Central American seaway affected tropical climate, and supplied heat and moisture to the high latitudes, though it remains debatable whether this pre-conditioned or delayed the Northern Hemisphere glaciation (NHG). However, the primary oceanographic and climatic responses to the seaway's closure terminated more than 1 Myr before NHG (refs 3–5). As such the mid-Pliocene climate transition[6] marks the gradual change from a climate with little or no ice in the Northern Hemisphere and ∼3 °C warmer global surface temperatures[7] to a climate state with extended continental ice sheets at high northern latitudes[8]. The onset of significant NHG (ref. 6) was accompanied by the initiation of strong winter monsoons in India[9] and a shift in African vegetation[10]. This time was also marked by enhanced sea surface temperature (SST) cooling in (sub)tropical upwelling regions and the development of a tropical Pacific west-to-east SST gradient, especially after 3 Myr ago[11–15]. These changes in (sub)tropical SST were taken as evidence for the termination of the early Pliocene 'permanent El Niño-like' climate conditions[16,17]. However, the major tropical reorganizations during the Pliocene, which also include significant shoaling of the thermocline in the equatorial eastern Pacific cold tongue[5,15,18], do not seem to have taken place synchronously. This makes it difficult to define and to allocate the driving mechanisms, especially if the response has different regional expressions, owing to different regional sensitivities[7]. Here, we examine whether the gradual constriction of the Indonesian Gateway from 4 to 3 Myr ago could be a viable process to reorganize the tropical Indian and Pacific oceanography and hence, tropical climate[2].

Testing the theory of Cane and Molnar

According to Cane and Molnar[2], the northward movement of New Guinea since 5 Myr ago switched the source of ITF surface waters from the warm and saline South Pacific to the cooler and fresher North Pacific. The postulated effects should have resulted in a distinct drop of SST (∼2 °C at 100 m water depth) in the tropical eastern Indian Ocean and a reorganization of the Pacific SST from an El Niño-like towards a La Niña-like pattern, which in turn both initiated droughts in eastern Africa and contributed to the NHG (refs 2, 19). To test this hypothesis[2], we generated combined planktonic foraminiferal Mg/Ca and δ^{18}O data from the tropical eastern Indian Ocean Deep Sea Drilling Project (DSDP) Site 214 (11°20.21′ S, 88°43.08′ E, 1,665 m water depth) spanning the time period from 5.5 to 2 Myr ago. Site 214 is at a key location, as the surface waters there record the conditions of the Indian–Pacific warm pool (Fig. 1a), whereas the subsurface waters belong to the cold and fresh Australasian Mediterranean water, which originates from the ITF area. Today, it can be traced at water depths of ∼300–450 m far into the Indian Ocean[20,21] (Fig. 1b, c). We selected surface-dwelling planktonic foraminifera *Globigerinoides ruber* and *Globigerinoides sacculifer*, deep mixed-layer species *Globoquadrina venezuelana* and deep-dwelling *Globorotalia crassaformis* to reconstruct oceanographic changes at different depth levels (Supplementary Information). In particular, *G. crassaformis* enabled us to monitor variations of the thermocline associated with the cold and fresh Australasian Mediterranean water (Fig. 1b, c; Supplementary Information). We combined δ^{18}O- and Mg/Ca-derived temperatures from surface-dwelling *G. ruber* and *G. sacculifer* and from deep-dwelling *G. crassaformis* to calculate δ^{18}O of sea water[22]. Ice-volume-corrected records ($\delta^{18}O_{\text{ivc-seawater}}$) that approximate local salinity

---

[1]Leibniz Institute of Marine Sciences (IFM-GEOMAR), University of Kiel, Wischhofstrasse 1-3, D-24148 Kiel, Germany, [2]Department of Geology & Geophysics, Indian Institute of Technology, Kharagpur 721302, India, [3]Alfred Wegener Institute for Polar and Marine Research, Am Alten Hafen 26, D-27568 Bremerhaven, Germany, [4]Zentrum für Marine Umweltwissenschaften, Universität Bremen, D-28334 Bremen, Germany.
*e-mail: ckaras@ifm-geomar.de.

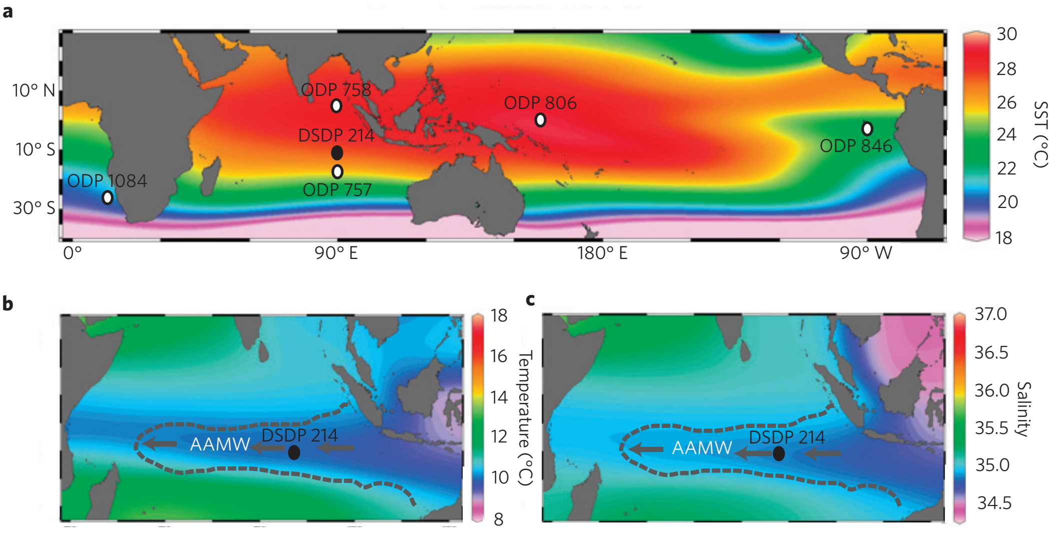

Figure 1 | Annual ocean temperatures and salinities at (sub)surface levels. a, Chart of annual ocean temperatures at 20 m water depth[23,41]. Palaeoceanographic proxy data were generated for DSDP Site 214. The locations of the sediment cores discussed in the text are indicated. ODP: Ocean Drilling Program. **b**,**c**, Annual temperatures (**b**) and salinities (**c**) at 400 m water depth[23,41] show the westward expansion of relatively cold and less-saline Australasian Mediterranean water (AAMW, dashed line) that originates from the ITF area[20,21].

were calculated from $\delta^{18}O_{seawater}$ by subtracting an estimation of the Pliocene global ice volume (Supplementary Information).

At tropical eastern Indian Ocean Site 214, the $\delta^{18}O$ and $SST_{Mg/Ca}$ records of the surface-dwelling foraminifera *G. ruber* and *G. sacculifer* (Supplementary Information) show similar trends between 5.5 and 2.0 Myr ago, indicating that the $\delta^{18}O$ signal to a large part reflects variations in $SST_{Mg/Ca}$ (Figs 2a b, 3a). The $SST_{Mg/Ca}$ records vary from 24 °C to 26.5 °C, showing a warming trend of ∼1.5 °C during the early Pliocene from 5.5 to 3.8 Myr ago and then a slight cooling of ∼1 °C during the Pliocene climate transition from 3.8 to 2.5 Myr ago. The deep mixed-layer Mg/Ca temperature record from *G. venezuelana* (spanning the time interval from 5.5 to 3.5 Myr ago) is 1–2 °C cooler than the $SST_{Mg/Ca}$ record, but clearly resembles the warming trend during the early Pliocene (Fig. 3a). The sea surface $\delta^{18}O$ signature and the pattern of $SST_{Mg/Ca}$ variability at Site 214 are very similar to that of west Pacific warm pool Site 806 (ref. 15). This indicates that the long-term $SST_{Mg/Ca}$ evolution between both sites developed almost identically between 5.5 and 2 Myr ago, although the absolute temperatures are different. $SST_{Mg/Ca}$ values in the tropical eastern Indian Ocean are consistently ∼3.5 °C cooler than in the west Pacific warm pool (Fig. 2a; Supplementary Information). This difference is similar to the modern SST offset of ∼2 °C between both core locations[23] (Fig. 1a). Our $SST_{Mg/Ca}$ record from Site 214 provides no evidence for pronounced surface cooling in the tropical eastern Indian Ocean between 4 and 3 Myr ago, which has been suggested as a response to the constriction of the Indonesian seaway[2]. The slight cooling trend at Site 214 of ∼1 °C from ∼3.8 to 2.5 Myr ago probably reflects global climate cooling, as similar trends are also registered at Site 806 and at eastern Indian Ocean Site 758 (ref. 24).

In contrast to the conditions at the sea surface, the Mg/Ca temperature record from the deep-dwelling *G. crassaformis* suggests a distinct cooling of the subsurface level of ∼4 °C between ∼3.5 and 2.95 Myr ago, with an abrupt component from ∼3.3 to 3 Myr ago (Fig. 3a). This pattern is also reflected by the $\delta^{18}O_{G.\ crassaformis}$ record (Fig. 2c). Most notable is the rapid ∼1‰ increase in $\delta^{18}O_{G.\ crassaformis}$ from ∼3.5 to 2.95 Myr ago. Evidently, the most intense hydrographic changes in the tropical eastern Indian Ocean occurred during the mid-Pliocene transition at ∼3.5–2.95 Myr ago within the subsurface level rather than at the surface. The decoupled evolution of subsurface and surface water masses caused an increasing temperature and $\delta^{18}O$ gradient between shallow and deep-dwelling species after ∼3.5 Myr ago and point to a shoaling and cooling of the thermocline[25,26] in the tropical eastern Indian Ocean. Similar to the modern situation, we assume that the Pliocene ITF was characterized by changes in the subsurface flow rather than at the surface[27,28]. This is supported by our $\delta^{18}O_{ivc\text{-}seawater}$ reconstructions, which point to a gradual change of the source of ITF waters[2] during ∼3.5–2.95 Myr ago. The deep-dwelling *G. crassaformis* $\delta^{18}O_{ivc\text{-}seawater}$ record (Fig. 3d) reveals an overall freshening trend from ∼4.3 to 2.5 Myr ago, indicated by a $\delta^{18}O_{ivc\text{-}seawater}$ change from ∼0.4‰ to ∼−1.2‰, interrupted by sudden and stepwise changes towards more saline conditions at ∼3.3–3.15 Myr ago. These rapid subsurface changes might have been due to a reduction in ITF, as the throughflow waters would have been replaced by warmer and saltier Indian Ocean waters. Alternatively, the ITF source might have switched back to more warm and saline South Pacific waters (Fig. 3a, d). Rapid and gradual freshening of subsurface waters started again at ∼3.15 Myr ago, with a $\delta^{18}O_{ivc\text{-}seawater}$ amplitude of ∼1‰ until ∼2.95 Myr ago (Fig. 3d). The shallow-dwelling *G. ruber* and *G. sacculifer* $\delta^{18}O_{ivc\text{-}seawater}$ records (Fig. 3d) also exhibit a long-term continuous freshening from ∼5.2 Myr to ∼2 Myr, although with a much smaller $\delta^{18}O_{ivc\text{-}seawater}$ amplitude.

We attribute the gradual freshening from ∼4.3 to 2.5 Myr ago and the related cooling (∼4 °C) of subsurface waters—with the most prominent changes at ∼3.5–2.95 Myr—to the gradual constriction of the Indonesian seaway and the related switch in the source of subsurface ITF waters[2]. The long- and short-term variability in subsurface salinity after 2.95 Myr, however may partly reflect oceanic changes in response to global climate variability. Sea surface conditions of the tropical eastern Indian Ocean and of the equatorial west Pacific, instead, developed almost identically (Figs 2a, b, 3d). In this respect, our data do not support Cane and Molnar's[2] prediction of a surface cooling in the tropical eastern Indian Ocean synchronous to a relative sea surface warming in the equatorial west Pacific and the initiation of the west Pacific warm pool. Our interpretation of the freshening and cooling of tropical eastern Indian subsurface waters during ∼3.5–2.95 Myr ago is supported by ε_{Nd} data from eastern Indian Ocean Site 757 (ref. 29) (located south of Site 214), which were interpreted as a switch from southern to northern Pacific source waters in the ITF.

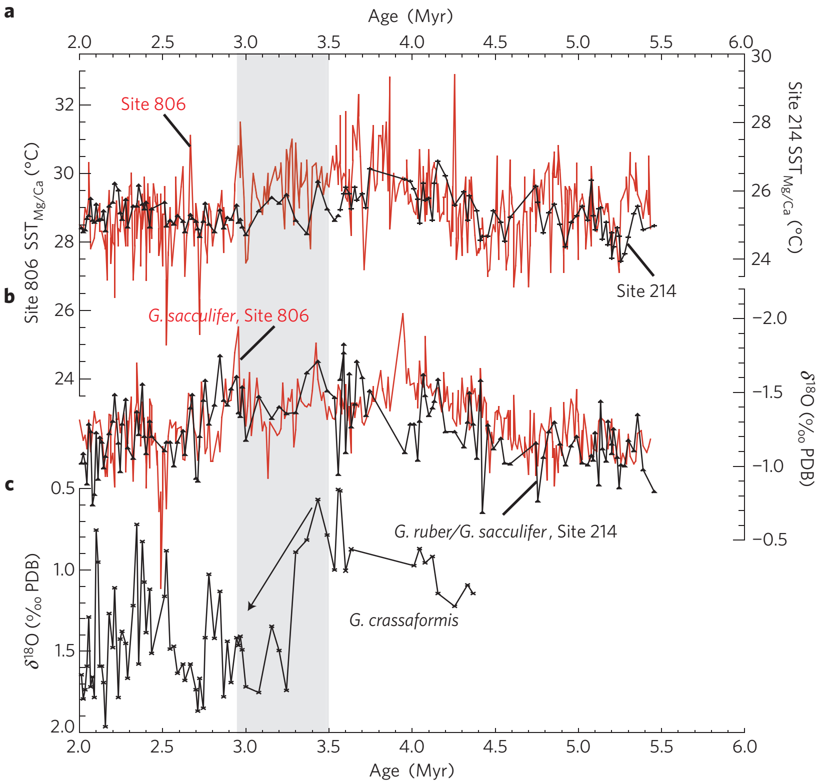

Figure 2 | Pliocene proxy records from Site 214 and Site 806. a, SST$_{Mg/Ca}$ derived from *G. ruber* (black triangles) and *G. sacculifer* (black crosses) from Site 214 and SST$_{Mg/Ca}$ *G. sacculifer* (red) from Site 806 (ref. 15). **b**, δ^{18}O records from Site 214 (black triangles) and Site 806 (ref. 15) (red; stratigraphy of Site 806 (ref. 15) was changed on the basis of extra $\delta^{18}O_{benthic}$ data; Supplementary Information). Site 214 $\delta^{18}O_{G.\ ruber}$ values were adjusted to the $\delta^{18}O_{G.\ sacculifer}$ record by adding 0.25‰ (Supplementary Information). **c**, Site 214 $\delta^{18}O_{G.\ crassaformis}$ record. Note the different temperature scales for Site 214 and Site 806.

The timing of subsurface events largely coincides with eastern African climate proxy data, which indicate a change from formerly wet to dry conditions between ∼4 and 3 Myr ago[10]. It might indeed be speculated that the prominent temperature drop in the tropical eastern Indian Ocean subsurface waters affected the surface temperature in the west Indian Ocean through equatorial and/or coastal upwelling off Somalia, which is partly fed by thermocline waters being supplied by the Indonesian throughflow[30,31]. A SST drop in the west Indian Ocean triggered by upwelling of cooler tropical eastern Indian Ocean subsurface waters might have caused a reduction in evaporation and thus less precipitation over eastern Africa and, as a consequence, a change in hominid evolution[2,10]. During this time, the gradual slight freshening of surface waters in the tropical eastern Indian Ocean may have resulted from enhanced precipitation in line with the strengthening of the Monsoon system (after ∼3.6 Myr ago)[9,32] rather than being a result of changing throughflow at the surface. This is corroborated by the good agreement between the surface $\delta^{18}O_{ivc\text{-}seawater}$ records from Site 806 (*G. sacculifer* SST$_{Mg/Ca}$ and δ^{18}O data from ref. 15) and Site 214, in particular during the critical time period 3.5–2.95 Myr ago (Fig. 3d).

Pliocene global cooling and the Indonesian Gateway

The distinct change in the tropical eastern Indian Ocean thermocline structure during the mid-Pliocene (∼3.5–2.95 Myr ago) occurs within a long-term sequence of palaeoceanographic events (∼4.8–3 Myr ago)[5,11–15,18], leading to the cooling and shoaling of the thermocline and the appearance of cold surface waters in various ocean regions[16]. In the tropical eastern Pacific this process had already started at ∼4.8 Myr and has been related to the gradual closing of the Central American seaway[5,18], which might have preconditioned the cooling of the equatorial eastern Pacific cold tongue[12]. As a consequence, this process marked the start of the gradual termination of permanent El Niño-like conditions. Alternatively, Philander and Fedorov[16] related the termination of permanent El Niño-like conditions to global cooling inducing overall thermocline shoaling.

In the tropical eastern Indian Ocean (Site 214), the cooling and freshening of subsurface waters took place at ∼3.5–2.95 Myr and seems to be quasi-synchronous to the northward tectonic drift of New Guinea and the postulated change in the source of ITF waters towards a cool and fresh North Pacific source[2]. At the same time, the benthic δ^{18}O values were globally low and small in amplitude[33] (Fig. 3c), indicating low ice volume and little variability. The benthic Mg/Ca values imply low and hardly changing deep-ocean temperatures[34]. Accordingly, we argue that the relative abrupt cooling of Indian Ocean subsurface waters is not the result of 'cooling from below' due to global cooling that strengthened the NHG (ref. 16). Instead, we suggest that the tectonically triggered changes amplified global climate change by contributing to a shoaling/cooling of the thermocline in various ocean areas.

At ∼3.2 Myr, the previously uniform SST$_{Mg/Ca}$ evolution at Site 214 and within the Benguela upwelling cell (Site 1084 alkenone-derived SST (SST$_{alkenone}$) data from ref. 11; age model revised by Etourneau *et al.*, manuscript in preparation; Fig. 3a) started to deviate, suggesting that the relative cooling of the Benguela upwelling system might have been preconditioned by the continuously cooled tropical eastern Indian Ocean thermocline, the temperature signal of which would have been transported westward towards Site 1084. Today, the Benguela Current system transports ∼25 Sverdrup of water, 15 Sv of which can be related to Indian Ocean thermocline water[35]. Ventilation of the Indian Ocean thermocline is driven by the Australasian Mediterranean water, which mixes with Indian Ocean central water before being transported in the South Atlantic Ocean by the Agulhas Current[21,36].

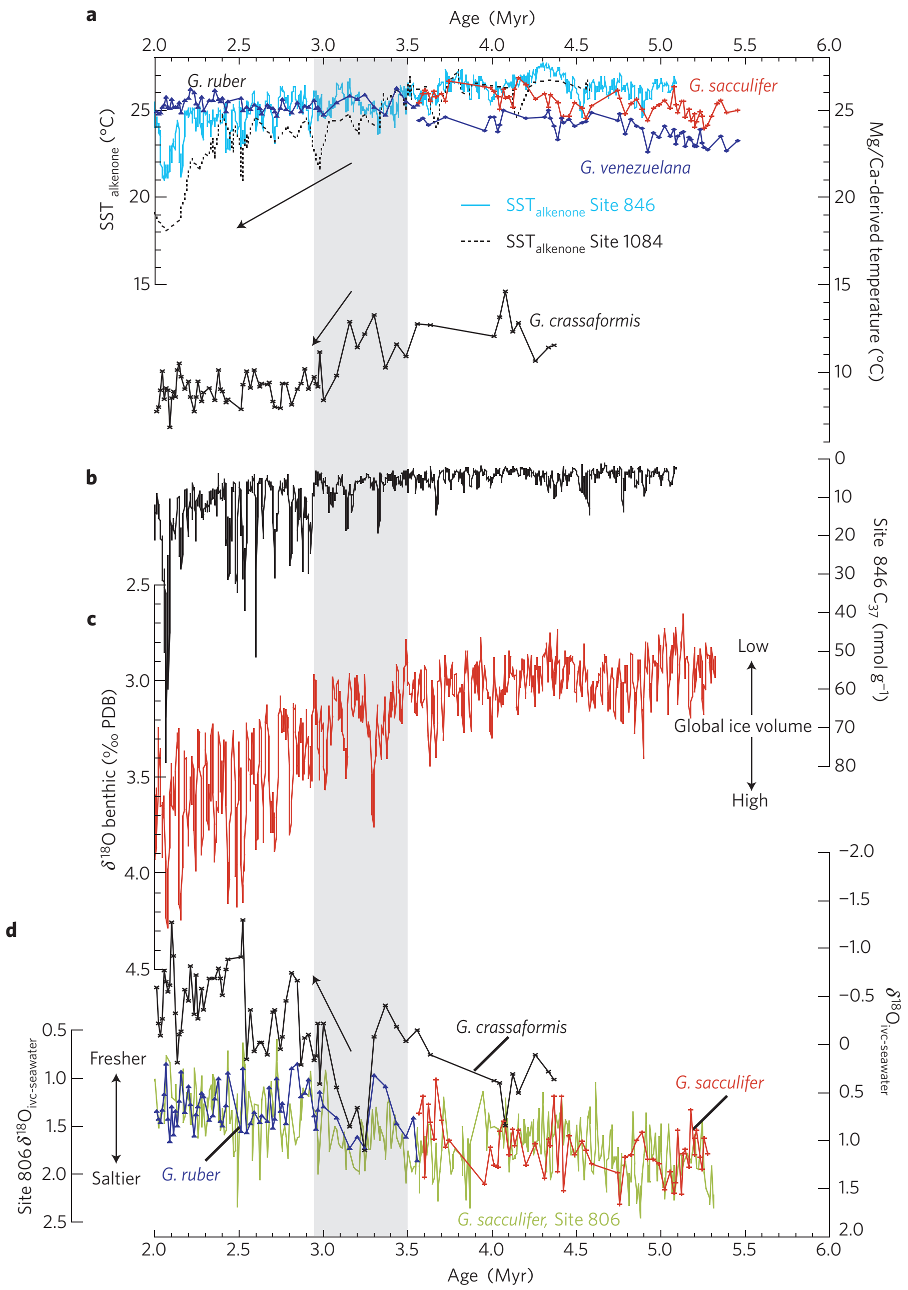

Figure 3 | Pliocene (sub)surface changes in the tropical eastern Indian Ocean in relation to other ocean areas. a, Mg/Ca-derived temperatures of *G. ruber* (blue triangles), *G. sacculifer* (red crosses), *G. venezuelana* (blue diamonds) and *G. crassaformis* (black crosses) from Site 214; $\mathrm{SST_{alkenone}}$ records from Site 846 (light blue) and Site 1084 (dashed; Etourneau *et al.*, manuscript in preparation)[11,12]. **b**, C_{37} alkenone concentrations of Site 846 (ref. 12). **c**, The LR04 global benthic δ^{18}O stack[33]. **d**, Site 214 $\delta^{18}\mathrm{O_{ivc\text{-}seawater}}$ records from *G. ruber* (blue triangles), *G. sacculifer* (red crosses) and *G. crassaformis* (black crosses) and Site 806 $\delta^{18}\mathrm{O_{ivc\text{-}seawater}}$ *G. sacculifer* record (green; $\mathrm{SST_{Mg/Ca}}$ and δ^{18}O values from ref. 15), (see Supplementary Information). The arrows indicate trends.

The pronounced cooling in the Benguela upwelling cell observed after ∼2.4 Myr ago (Fig. 3a), however, was probably related to the occurrence of more intense glacials[11,33].

When constant and low subsurface temperatures indicate prevailing North Pacific source waters passing through the Indonesian Gateway since ∼2.95 Myr ago, we observe a significantly increasing number of high productivity/upwelling events occurring in the equatorial eastern Pacific (Site 846) indicated by C_{37} alkenones and accompanied by distinct drops in $\mathrm{SST_{alkenone}}$ (ref. 12) (Fig. 3a, b). Both the high productivity/upwelling events and the increasing gradient in ocean surface temperatures between the tropical eastern Indian Ocean and the equatorial eastern Pacific evolving after 2.95 Myr ago are taken as evidence for the manifestation of the equatorial eastern Pacific cold tongue, presumably amplified by strengthened wind stress in line with the intensification of NHG (refs 16, 37). A viable mechanism linking the ITF dynamics to eastern Pacific upwelling might come through the equatorial undercurrent. A plate-tectonics modelling study[19] suggests that the northward drift of New Guinea would change the source of the equatorial undercurrent in the Pacific towards a stronger Southern Ocean component. In fact, upwelled waters in the equatorial eastern Pacific cold tongue today originate from the lower levels of the equatorial undercurrent, which is fed by cold subantarctic mode water[38]. The subantarctic mode water serves as the main contributor of nutrients fuelling the eastern Pacific thermocline from below and enhancing primary productivity[39]. As this relationship probably held throughout the Pliocene[11,13], we suspect that after 2.95 Myr ago a larger portion of Subantarctic mode water transported through 'ocean tunnels' to equatorial regions[40] amplified the shoaling of the eastern Pacific thermocline, the cooling of upwelled water and the increase in productivity (Fig. 3a, b).

Our reconstructions of tropical eastern Indian Ocean surface and subsurface temperatures and $\delta^{18}O_{\text{ivc-seawater}}$ shed new light on the hydrographic changes in the Indonesian Gateway and its implications for the mid-Pliocene climate transition. Our results support the hypothesis of Cane and Molnar[2] that the constriction of the Indonesian seaway (4–3 Myr ago) led to a major reorganization in the ITF. Although their assumption of a change in the surface throughflow and the proposed drop in tropical eastern Indian Ocean SST is not registered, our data reveal a pronounced cooling of ∼4 °C at the subsurface level from ∼3.5 to 2.95 Myr. This points to a switch in ITF source waters from initially South Pacific to North Pacific subsurface waters. After 2.95 Myr ago, constantly low subsurface temperatures and fresher conditions suggest a prevailing throughflow of North Pacific source waters through the Indonesian Gateway. The associated changes in the thermocline might have preconditioned the cooling of the Benguela upwelling system at ∼3.2 Myr ago and contributed to the global cooling of the thermocline. We suggest that the plate-tectonic constellation in the ITF area after 2.95 Myr ago enabled a larger portion of subantarctic mode water to be transported through 'ocean tunnels' into the equatorial undercurrent[40], thereby supporting the final formation of the equatorial eastern Pacific cold tongue.

Received 20 October 2008; accepted 17 April 2009;

References

1. Haug, G. H., Tiedemann, R., Zahn, R. & Ravelo, A. C. Role of Panama uplift on oceanic freshwater balance. *Geology* **29**, 207–210 (2001).
2. Cane, M. & Molnar, P. Closing of the Indonesian seaway as a precursor to east African aridification around 3–4 million years ago. *Nature* **411**, 157–162 (2001).
3. Haug, G. H., Sigman, D. M., Tiedemann, R., Pedersen, T. F. & Sarnthein, M. Onset of permanent stratification in the subarctic Pacific. *Nature* **401**, 779–782 (1999).
4. Driscoll, N. W. & Haug, G. H. A short circuit in the ocean's thermohaline circulation: A cause for northern hemisphere glaciation? *Science* **282**, 436–438 (1998).
5. Steph, S., Tiedemann, R., Groeneveld, J., Sturm, A. & Nürnberg, D. in *Proc. ODP, Sci. Results* Vol. 202 (eds Tiedemann, R., Mix, A. C., Richter, C. & Ruddiman, W. F.) 1–51 (College Station, 2006).
6. Mudelsee, M. & Raymo, M. E. Slow dynamics of the northern hemisphere glaciation. *Paleoceanography* **20**, PA4022 (2005).
7. Ravelo, A. C., Andreasen, D. H., Lyle, M., Lyle, A. O. & Wara, M. W. Regional climate shifts caused by gradual global cooling in the Pliocene epoch. *Nature* **429**, 263–267 (2004).
8. Shackleton, & N. J., *et al.* Oxygen isotope calibration of the onset of ice-rafting and history of glaciation in the North Atlantic region. *Nature* **307**, 620–623 (1984).
9. Gupta, A. K. & Thomas, E. Initiation of northern hemisphere glaciation and strengthening of the northeast Indian monsoon: Ocean drilling program site 758, eastern equatorial Indian ocean. *Geology* **31**, 47–50 (2003).
10. deMenocal, P. B. Plio-Pleistocene African climate. *Science* **270**, 53–59 (1995).
11. Marlow, J. R., Lange, C. B., Wefer, G. & Rosell-Melé, A. Upwelling intensification as part of the Pliocene-Pleistocene climate transition. *Science* **290**, 2288–2291 (2000).
12. Lawrence, K. T., Liu, Z. & Herbert, T. D. Evolution of the eastern tropical Pacific through Plio-Pleistocene glaciation. *Science* **312**, 79–83 (2006).
13. Dekens, P. S., Ravelo, A. C. & McCarthy, M. D. Warm upwelling regions in the Pliocene warm period. *Paleoceanography* **22**, PA3211 (2007).
14. Ravelo, A. C., Billups, K., Dekens, P. S., Herbert, T. D. & Lawrence, K. T. in *Deep-Time Perspectives on Climate Change: Marrying the Signal from Computer Models and Biological Proxies* (eds Williams, M., Haywood, A. M., Gregory, J. & Schmidt, D.) (The Geol. Soc. of London & The Micropal. Soc., 2007).
15. Wara, M. W., Ravelo, A. C. & Delaney, M. L. Permanent El Niño-Like conditions during the Pliocene warm period. *Science* **309**, 758–761 (2005).
16. Philander, S. G. & Fedorov, A. V. Role of tropics in changing the response to Milankovich forcing some three million years ago. *Paleoceanography* **18**, 1045 (2003).
17. Fedorov, A. V. *et al.* The Pliocene paradox (Mechanisms for a permanent El Niño). *Science* **312**, 1485–1489 (2006).
18. Chaisson, W. & Ravelo, A. C. Pliocene development of the east–west hydrographic gradient in the equatorial pacific. *Paleoceanography* **15**, 497–505 (2000).
19. Rodgers, K. B., Latif, M. & Legutke, S. Sensitivity of equatorial Pacific and Indian Ocean watermasses to the position of the Indonesian throughflow. *Geophys. Res. Lett* **27**, 2941–2944 (2000).
20. Tomczak, M. & Godfrey, J. S. *Regional Oceanography: An Introduction* (Pergamon, 1994).
21. You, Y. & Tomczak, M. Thermocline circulation and ventilation in the Indian Ocean derived from water mass analysis. *Deep-Sea Res. 1* **40**, 13–56 (1993).
22. Shackleton, N. J. Attainment of isotopic equilibrium between ocean water and the benthonic foraminifera genus Uvigerina: Isotopic changes in the ocean during the last glacial. *Colloq. Int. Cent. Natl. Rech. Sci.* **219**, 203–209 (1974).
23. Locarnini, R. A. *et al.* in *NOAA Atlas NESDIS 61* (ed. Levitus, S.) (World Ocean Atlas 2005, Vol. 1: Temperature, US Gov. Printing Office, 2006).
24. Dekens, P. S., Ravelo, A. C. & Wara, M. W. *AGU, Fall Meeting 2006 abstr.* PP12A-07 (American Geophysical Union, 2006).
25. Ravelo, A. C. & Fairbanks, R. G. Oxygen isotopic composition of multiple species of planktonic foraminifera: Recorders of the modern photic zone temperature gradient. *Paleoceanography* **7**, 815–832 (1992).
26. Ravelo, A. C. & Andreasen, D. H. in *Reconstructing Ocean History—A Window into the Future* (eds Abrantes, F. & Mix, A.) 217–244 (Plenum Press, 1999).
27. Gordon, A. L. & Fine, R. A. Pathways of water between the Pacific and Indian Oceans in the Indonesian seas. *Nature* **379**, 146–149 (1996).
28. Gordon, A. L., Susanto, R. D. & Ffield, A. Throughflow within Makassar straight. *Geophys. Res. Lett.* **26**, 3325–3328 (1999).
29. Martin, E. E. & Scher, H. A Nd isotopic study of southern sourced waters and Indonesian throughflow at intermediate depths in the Cenozoic Indian Ocean. *Geochem. Geophys. Geosyst.* **7**, Q09N02 (2006).
30. Bruce, J. G., Quadfasel, D. R. & Swallow, J. C. Somali eddy formation during the commencement of the southwest monsoon, 1978. *J. Geophys. Res.* **85**, 6654–6660 (1980).
31. Schott, F. A., Dengler, M. & Schoenefeld, R. The shallow overturning circulation of the Indian Ocean. *Prog. Oceanogr.* **53**, 57–103 (2002).
32. Zheng, H., Powell, C. McA., Rea, D. K., Wang, J. & Wang, P. Late Miocene and mid-Pliocene enhancement of the East Asian monsoon as viewed from the land and sea. *Global Planet. Change* **41**, 147–155 (2004).
33. Lisiecki, L. E. & Raymo, M. E. A Pliocene-Pleistocene stack of 57 globally distributed benthic δ^{18}O records. *Paleoceanography* **20**, PA1003 (2005).
34. Billups, K. & Schrag, D. P. Paleotemperatures and ice volume of the past 27 Myr revisited with paired Mg/Ca and 18O/16O measurements on benthic foraminifera. *Paleoceanography* **17**, PA000567 (2002).
35. Gordon, A. L., Weiss, R. L., Smethie, W. M. Jr & Warner, M. J. Thermocline and intermediate water communication between the South Atlantic and Indian Ocean. *J. Geophy. Res.* **97**, 7223–7240 (1992).
36. Gordon, A. L. Interocean exchange of thermocline water. *J. Geophys. Res.* **91**, 5037–5046 (1986).
37. Timmermann, A., Justino, F. B., Jin, F.-F. & Goosse, H. Surface temperature control in the North and tropical Pacific during the last glacial maximum. *Clim. Dyn.* **23**, 353–370 (2004).
38. Toggweiler, J. R., Dixon, K. & Broecker, W. S. The Peru upwelling and the ventilation of the South Pacific thermocline. *J. Geophys. Res.* **96**, 20467–20497 (1991).
39. Sarmiento, J. L., Gruber, N., Brzezinski, M. A. & Dunne, J. P. High-latitude controls of thermocline nutrients and low latitude biological productivity. *Nature* **427**, 56–60 (2003).
40. Liu, Z. & Yang, H. Extratropical control of tropical climate, the atmospheric bridge and oceanic tunnel. *Geophys. Res. Lett.* **30**, 1230 (2003).
41. Schlitzer, R. *Ocean Data View*<http://odv.awi.de> (2007).

Acknowledgements

Samples for this study were provided by the IODP. Financial support for this research was provided by the German Science Foundation (DFG) within project Nu60/17-1. We thank J. Etourneau, S. Steph, D. Garbe-Schönberg, J. Groeneveld, M. Regenberg, N. Gehre and K. Kiesling for valuable comments and technical support. K.M. was supported by an IIT Kharagpur fellowship.

Additional information

Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Raw data are available electronically at World Data Center for Paleoclimatology, NOAA/NGDC, (http://www.ngdc.noaa.gov/paleo/data.html). Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to C.K.