Closing of the Indonesian seaway as a precursor to east African aridification around 3–4 million years ago

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Global climate change around 3–4 Myr ago is thought to have influenced the evolution of hominids, via the aridification of Africa, and may have been the precursor to Pleistocene glaciation about 2.75 Myr ago. Most explanations of these climatic events involve changes in circulation of the North Atlantic Ocean due to the closing of the Isthmus of Panama. Here we suggest, instead, that closure of the Indonesian seaway 3–4 Myr ago could be responsible for these climate changes, in particular the aridification of Africa. We use simple theory and results from an ocean circulation model to show that the northward displacement of New Guinea, about 5 Myr ago, may have switched the source of flow through Indonesia—from warm South Pacific to relatively cold North Pacific waters. This would have decreased sea surface temperatures in the Indian Ocean, leading to reduced rainfall over eastern Africa. We further suggest that the changes in the equatorial Pacific may have reduced atmospheric heat transport from the tropics to higher latitudes, stimulating global cooling and the eventual growth of ice sheets.

Eastern Africa used to be more humid than it is now, and Canada used to be devoid of ice sheets; New Guinea lay south of its present position, and the island of Halmahera (part of Indonesia; see Fig. 1) lay mostly below sea level. The collision of Australia with the Banda arc occurred about 3 Myr ago, when Timor began to emerge within what had been the eastward continuation of the Java trench[1,2] (Fig. 1) and volcanism along the arc ceased[3]. Here we are concerned with the flow of water through the archipelago of Indonesia: that is, the Indonesian throughflow. The more important events that affected this throughflow, however, occurred farther north, associated with New Guinea's northward movement towards the Equator.

Hydrographic measurements show that almost all water currently passing through the Indonesian seaway derives from the North Pacific Ocean[4,5] (Fig. 2). In the modern climate, heavy rainfall over the northern part of the western Pacific maintains fresher tropical waters north of the Equator than to the south. The configuration of landmasses, with more land to the north, forces this rainfall. Because this distribution of Asian landmass has changed little since Miocene time, we presume that the difference in salinity between western tropical Pacific waters north and south of the Equator has existed throughout this time. Being less saline than water at the same density in the southern Pacific, water in the northern Pacific is the colder, with a sharp temperature front at the Equator on surfaces of constant density (Fig. 2).

Warm southern Pacific water currently moves westward along the Equator, in the Southern Equatorial Current, along the north coast of New Guinea to the Halmahera eddy, just east of the island of Halmahera (Fig. 1), where it turns to flow eastward in the North Equatorial Countercurrent. We propose that when New Guinea lay farther south, and Halmahera was a smaller island, warm water from the South Pacific would have passed into the Indian Ocean, increasing sea surface temperatures (SSTs) there and precipitating a rainier climate in eastern Africa.

Closing of the Indonesian seaway

With a northward rate of about 70 km Myr^{-1} (ref. 6) relative to Eurasia and Sundaland (the area that includes Sulawesi, Borneo, Java and Sumatra)—areas that have moved little with respect to the Earth's spin axis in the past 20 Myr (ref. 7)—Australia and New Guinea lay 2°–3° south of their present positions at 3–5 Myr ago. Thus, a wide gap would have lain between New Guinea and Halmahera, which currently lies on the Pacific plate (or perhaps the Philippine Sea plate) and moves west relative to Sundaland.

Halmahera was a much smaller island 3–5 Myr ago than it is today. The western part of Halmahera consists of young volcanic rock. Ancient reefs on the eastern half of the island now lie at an elevation of 1,000 m (ref. 8), implying that its surface has risen by as much since about 5 Myr ago, consistent with an estimated ~60% east–west shortening of a once wider island[9]. Much, if not all, of Halmahera, which currently plays a major role in preventing water from the southern Pacific from joining the Indonesian throughflow[10], apparently has emerged since 5 Myr ago.

The region between the 'Bird's Head' of New Guinea and Sulawesi deforms as rapidly as any on Earth at present[11,12]. The Molucca Sea narrows at ~100 km Myr^{-1}; it also becomes shallower, as thick sediment in it becomes thrust atop itself[13]. Between the Bird's Head and Sulawesi, which converge at ~80 km Myr^{-1}, the various islands pile up one behind the other; this narrows and shallows the passages between the islands. But because relative motions among blocks have changed rapidly during the past 5 Myr, reconstructing the relative positions of the various islands of eastern Indonesia at ~5 Myr ago requires speculation that guarantees error, as indicated by differences among reconstructions[14–18]. Nonetheless, the combination of a wider gap between Seram and the Bird's Head, which converge at ~50 mm yr^{-1} (refs 11, 12), the recent rapid uplift of islands like Atauro along the eastern Banda arc[19], and the absence of Timor[1,2], implies that only a few million years ago, much of the shallow sea floor between New Guinea and Sulawesi was deeper, and gaps between islands were wider. Thus, not only was New Guinea farther south, but there was also a seaway between the Pacific and Indian oceans as wide and deep as the Makassar Strait, but located to the east and south of that feature.

Environmental change in eastern Africa

Climate in eastern Africa has evolved from moist and warm to arid and perhaps slightly cooler over the past ~3–4 Myr (ref. 20, Fig. 3).

Except for the Fort Ternan site near the Equator in Kenya[21], fossil fauna and flora suggest warm, moist environments, including rainforests, in eastern Africa before ~4 Myr ago[22–24]. In central Ethiopia, wooded habitats (at 4.4 Myr ago[25]), and even a rainforest environment, seem to have lingered until 3.4 Myr ago[26]. Similarly, in the Omo region of southern Ethiopia, a humid environment recorded by pollen at 4.1 Myr ago[26] lasted until 2.95 Myr ago, as implied by small mammals characteristic of that environment[27].

The tendency towards more arid environments apparently began earlier at lower latitudes. At Laetoli, Tanzania (Fig. 3), most fossil pollen dating from 3.7 Myr ago can be found in plants now living within 30 km of the region, suggesting little change in climate there

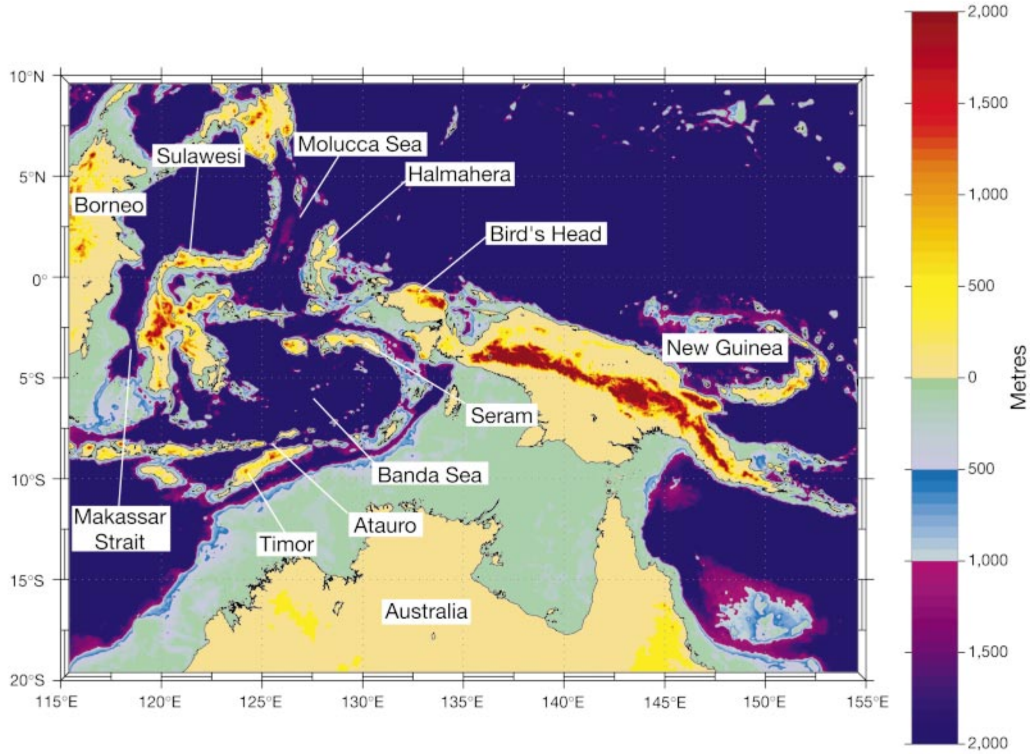

Figure 1 Map of the Indonesian-throughflow region. The main islands, crustal fragments, and other topographic features are labelled. Currently most Indonesian throughflow passes north of Sulawesi, then west of Sulawesi through the Makassar Strait, and finally across the Banda arc. The South Equatorial Current flows along the northern coast of New Guinea and then turns to the east at Halmahera in the Halmahera eddy. We suggest that at 3–5 Myr ago, Halmahera was a much smaller island with most of the area ~1,000 m deeper, New Guinea was 2°–3° farther south, and the mountains on the island were also much lower. In addition, Timor was under water, and the Java trench continued eastward and then northward into the Seram trough. Finally, the 'Bird's Head' lay 250–400 km east of its present position with respect to Borneo. Colour indicates elevation relative to mean sea level.

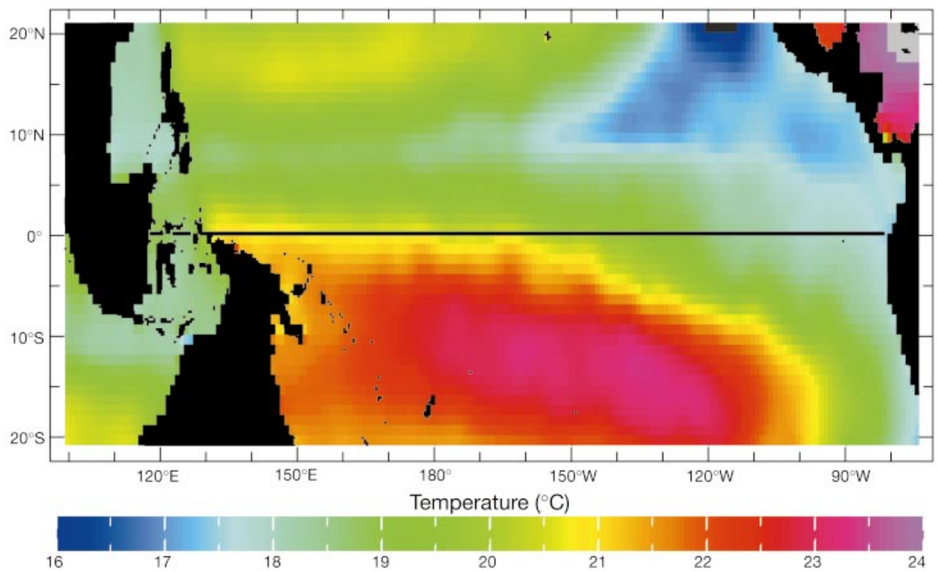

Figure 2 Map of the Pacific showing temperature at the $\sigma = 25.5$ (1,025.5 kg m^{-3}) isopycnal, in the thermocline. We note the strong front at the Equator in the west. It is apparent that water at this density in the Indonesian throughflow has a North Pacific source. Data from ref. 52.

since that time[21]. The aridification is best resolved in the Omo region (Fig. 3). Wesselman[27] showed that small mammals at 2.95 Myr ago included "species characteristic of the equatorial high forests of Central and West Africa," but by a little before 2.52 Myr ago only one species (in fact, a "forest-edge taxon") represented the tropical forest, and taxa typical of mesic woodlands dominated. The most marked shift in climate seems to have occurred between 2.4 and 2.5 Myr ago; by 2.34 Myr ago, riverine and forest taxa had diminished, and xeric species dominated[27]. Then, by just after 2.32 Myr ago, forest taxa were gone, for the fossil record contains only "dry savannas/open savanna woodland" and "arid semiarid steppe" taxa[27]. Farther north, in Ethiopia, evergreen bushland and montane forests at 3.3 and 2.9 Myr ago[28] gave way, a few tens of kilometres to the south, to grasslands by 2.5 Myr ago, though the climate there was not yet as arid as now[29].

The palaeontological and palynological data can neither resolve short-term climate changes at most localities nor define unambiguous spatial differences in the pattern of increasing aridification. Nowhere in Africa, however, does there seem to have been an environmental change as large or as abrupt as that implied by the increase in ice-rafted debris in the North Atlantic and North Pacific at ~2.7 Myr ago, which presumably marks the onset of widespread glaciation in the Northern Hemisphere[30,31].

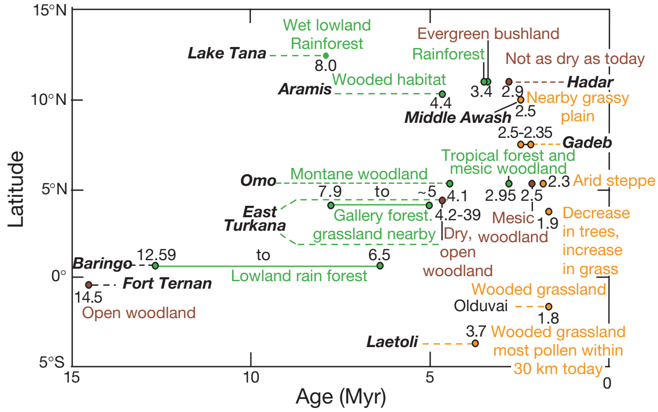

Figure 3 Palaeo-environments in eastern Africa as a function of time and latitude since 15 Myr ago. Green, humid environments; brown, more arid woodlands; and tan, more arid grasslands and deserts. Data sources as follows: Lake Tana[24], Hadar[26,28], Aramis[25], Middle Awash[29], Gadeb[53], Omo[26,27], East Turkana[21,23,54], Baringo[22]; Fort Ternan, Olduvai and Laetoli[21]. Numbers indicate ages in Myr.

Indonesian throughflow and east African aridity

Upon entering the Indian Ocean, waters of the modern Indonesian throughflow travel due west across the Indian Ocean to the east coast of Africa[32]. It is likely that such simple zonal flow has persisted for at least the past 10 Myr, because conservation of vorticity dictates the zonal path across the ocean, and the relatively constant latitude at which the water enters the Indian Ocean (~10° S) sets the vorticity of that water.

Rodgers *et al.*[33] used a general circulation model (GCM) of the ocean to calculate the difference between an approximation to present-day conditions and a case with the northern edge of New Guinea 3° south of its present position. It showed temperatures at 100 m depth across the central Indian Ocean to be 2 °C warmer for the more southerly position (Fig. 4). The difference reaches a maximum of 3 °C in a small region in the central Indian Ocean. Thus, a few million years ago, the central Indian Ocean may have been a few degrees warmer than it is today.

Observational studies of the modern climate have shown a link between east African rainfall and Indian Ocean SST, with warmer temperatures associated with more rain[34–36]. Several papers[34,35] offer explanations for the observed associations in which warm SST anomalies induce changes in the zonal (Walker-like) atmospheric circulation over the Indian Ocean, reducing the subsidence over east Africa and thus increasing rainfall there. The link between Indian Ocean SST and rain in east Africa was exhibited in the severe flooding that occurred during the 1997–98 El Niño event. Indeed, there is a well studied positive correlation between rainfall in eastern Africa and the warm (El Niño) phase of the El Niño/Southern Oscillation (ENSO) cycle[37], and an even stronger correlation between ENSO and Indian Ocean SST. Because Indian Ocean SST anomalies are so hard to separate from other ENSO changes, data alone are insufficient to decide if the Indian Ocean SST anomalies cause the African rainfall variations.

An atmospheric GCM forced by SSTs[36] shows that warmer temperatures in the eastern Pacific, by themselves, slightly reduce calculated rainfall over Africa. A warmer central Indian Ocean alone, however, yields calculated rainfall over eastern Africa that is even greater than the full ENSO response, and an increase in temperature of only 0.5 °C can induce the observed high rainfall in Africa during El Niño years in the GCM calculations[36,38]. Goddard and Graham[36] showed that a change in the circulation of the atmosphere acting on the mean moisture field provides the main

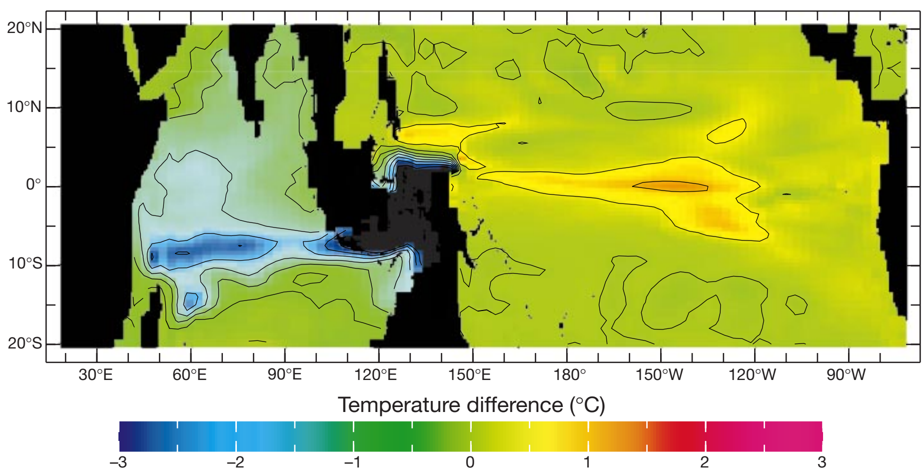

Figure 4 The difference in temperatures at 100 m depth between the two ocean GCM runs of ref. 33. The sole difference between conditions for the runs is that in one the northern tip of New Guinea–Halmahera is at 2° N, and in the other it is at 3° S. We suggest that the pattern shown—the difference of the former minus the latter—approximates the difference between that at present minus that at 4 Myr ago.

mechanism by which rainfall increases in the GCM calculations. This model result is corroborated by their study of reanalysis data, and is essentially the same mechanism suggested in earlier observational studies[34,35]. The atmospheric GCM studies[36,38] leave little doubt that Indian Ocean SSTs are the controlling causal factor affecting variations in rainfall over east Africa.

Indonesian throughflow and the position of New Guinea

The results of numerical-model experiments[33] (Fig. 4)—which we use as evidence that the Indian Ocean would warm as the western Pacific barrier 'island' of Australia–New Guinea moved northward—may be thought to depend too strongly on the peculiarities of the model, or the modern wind field used in these experiments. We present here a more general result. Because most of the Indonesian throughflow occurs in the upper part of the water column[5], and because SSTs influence the atmosphere most, we consider the upper ocean through the thermocline. It is therefore appropriate to use a theory for baroclinic flow, with parameter settings for the gravest baroclinic (largest vertical wavelength) mode. Because east–west variations in flow span long distances (long wavelengths), islands can be treated as one-dimensional features for which only their northern and southern limits matter[39]. This simplification allows the production of analytical theories for such flow; such theories have been worked out independently by two groups[40,41], and yield identical results for the problem we consider. Insofar as the theories are valid, only two aspects of the complex geometry of the region matter for the Indonesian throughflow; the northern latitude (b) of the Halmahera–New Guinea–Australia barrier on the Pacific Ocean side; and the southern latitude (g) of the collection of islands comprising Java, Sulawesi, Borneo, and all of Asia that form a barrier on the Indian Ocean side.

Following the approach summarized in the Methods section, and to be presented in more detail elsewhere, we obtain an estimate of the amplitude of the Indonesian throughflow, θ, for a unit mass flux (a δ-function) impinging on the western boundary of the Pacific at latitude c. Because Sundaland was essentially in place before 10–20 Myr ago, and the southern limit of Java has moved little during this period, we fix g at 10° S. With such a value, sufficiently large as to be unimportant if it changed by a few degrees, θ depends strongly on b, and in particular on which hemisphere the northern tip of Australia–New Guinea (with or without Halmahera) lies (Fig. 5). When b is south of the Equator, the Indonesian passage is effectively blocked for incident flux north of the Equator; only ~2% of Northern Hemisphere ($c > 0$) water passes through, but ~32% of the flux south of the Equator ($c < 0$) passes through. The situation reverses when b moves north of the Equator; only ~2% of South Pacific westward flux ($c < 0$) enters the Indian Ocean, but ~25% of northern waters ($c > 0$) form the Indonesian throughflow. As either b or c passes near the Equator (within one radius of deformation, which is ~3° of latitude for the gravest baroclinic mode) there is a rapid transition from one regime to the other (Fig. 5).

This solution has a simple physical interpretation, because in the low-frequency limit, large-scale motions in the open ocean can be described by waves—westward-propagating Rossby waves, and equatorially trapped, eastward-propagating, Kelvin waves. Whereas westward propagation can occur at all latitudes, the eastward return propagation occurs only near the Equator. When the westward-propagating jet meets a western boundary, like that of the Australia–New Guinea island, it becomes a current trapped to the boundary. The Coriolis effect forces the boundary current to propagate towards the Equator. If the northern extent of the island lies south of the Equator ($b < 0$), then when the current reaches the northern end, most of the boundary current turns west past the island. If the island reaches into the Northern Hemisphere ($b > 0$), however, the boundary current turns eastward and propagates as an equatorial Kelvin wave. Correspondingly, when a jet north of the island reaches the western island (Sundaland–Eurasia), it becomes a western boundary current travelling to the Equator, where it turns east as Kelvin waves. If $b > 0$, reflection of the Kelvin waves from the west side of the Australia–New Guinea island traps most of the flow in the Indonesian seas, creating an Indonesian throughflow. If instead $b < 0$, the Kelvin waves will propagate eastward unobstructed, transporting a large fraction of the jet back to the Pacific rather than letting it pass into the Indian Ocean.

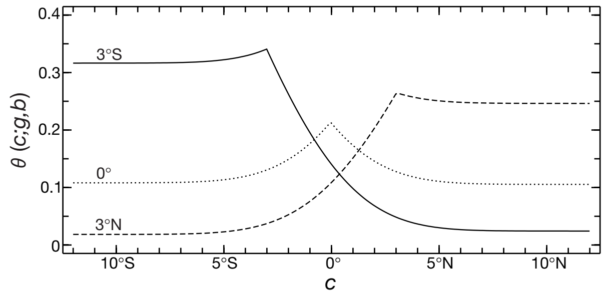

Figure 5 Plots of the Indonesian throughflow $\theta(c;g,b)$ for a δ-function zonal flow incident on the western boundary of the Pacific at latitude c. The plots are for three values of b, the latitude of the northern tip of the western Pacific boundary now ending at Halmahera: b = 3° S, 0° and 3° N. In all cases, the latitude of the Indian Ocean boundary formed by Java to Timor is g = 10° S. Calculations are according to the analytic theory described in Methods.

The function $\theta(c; g, b)$ plotted in Fig. 5 is a Green's function; for a general mass flux $u(y)$ at the western boundary of the Pacific, the magnitude of the Indonesian throughflow is given by $\int_{-\infty}^{\infty}\theta(y; g, b)u(y)\mathrm{d}y$. The incident mass flux $u(y)$ depends on the wind stress over the Pacific, as well as on global thermohaline forcing. Although little data constrain what these forcing functions were several million years ago, because of the simple structure of θ we may conclude that the movement of b from south to north must have changed the dominant source of the Indonesian throughflow from the South Pacific to the North Pacific. With b = 3° S, virtually all of the water flowing into the Indian Ocean would have been from the south, whereas with b = 3° N, almost all of the water would be derived from the north. In the modern ocean, where $b \approx 3°$ N, compelling evidence shows that the Indonesian throughflow comprises mostly northern water[4,5]. The total transport would change little as b progressed from 3° S to 3° N, probably decreasing slightly. These statements should hold unless $u(y)$ were so skewed that the total flux from one hemisphere were at least 10 times the other, but it is hard to imagine how this extreme state could arise in a configuration so much like that of the present day.

As New Guinea–Australia moved northward, the colder waters from the north replaced the warmer southern water in the Indonesian throughflow, cooling the thermocline in the Indian Ocean. Consequently, SSTs cooled throughout the Indian Ocean, especially in upwelling regions, such as the Somali Current north of the Equator along the African coast. We presume that the atmospheric response was like that in the modern climate, and so would reduce rainfall over eastern Africa. While we cannot assert categorically that this is true, it is the most plausible possibility: the proposed physical mechanism applies to present-day conditions, and the geometry of the Indian Ocean was very much as it is today. The northward movement of New Guinea–Australia would have caused the drying of east Africa by switching the source waters for the Indonesian throughflow from the warm south Pacific to the cold north, thereby cooling the Indian Ocean and reducing rainfall in east Africa.

New Guinea's movement and global climate change

The onset of widespread glaciation in the Northern Hemisphere is notable, not only for how it affected temperature and precipitation over large areas, but also for its abrupt beginning at ~2.75 Myr ago[30,31]. Yet the oxygen-isotope content of benthic microorganisms, the dominant proxy for high-latitude temperature, show a gradual increase in $\delta^{18}O$ beginning at ~4 Myr ago[42], with the most obvious change since then being an increase in the amplitude of variations. The absence of an abrupt change in the $\delta^{18}O$ record accords with a relatively slow geologic process affecting high-latitude climate gradually, not abruptly. (Glaciation may have set in abruptly when the decreasing temperature crossed the threshold for freezing water.) The closure of the Indonesian seaway provides such a gradual change at the right time. Given our prejudice for the tropical Pacific as a key to global climate change[43], we consider, necessarily only qualitatively, how the northward movement of New Guinea might affect global climate by changing the tropical Pacific.

In agreement with observations[44], our analytic solution (Fig. 5) indicates that with the present configuration the water turned eastward along the Equator in the Pacific comes from the south. Conversely, with the opening south of the Equator the source would be the colder water to the north, which agrees with GCM calculations[33] showing that the thermocline thins more in the western than in the eastern Pacific, and that the greatest surface cooling occurs over the central equatorial Pacific (Fig. 4). In these calculations, the gentler slope of the thermocline is maintained by specifying present-day easterly winds. With New Guinea both farther south and apparently lower, for the present-day high elevations of New Guinea reportedly formed since ~5 Myr ago[45,46], atmospheric convection over the western Pacific should have been weaker at ~3–5 Myr ago than now. The resulting weaker Walker circulation implies weaker easterlies over the equatorial Pacific, which would relax the slope of the thermocline further, warming the east and cooling the west[47]. Changes in both the distributions of microorganisms living near the thermocline and oxygen isotopes of surface-dwelling (planktonic) foraminifers corroborate such a change in the western equatorial Pacific since 3–4 Myr ago[48]. In a state much like a permanent El Niño, the ocean and especially the atmosphere would transport more heat from the tropics to higher latitudes. If the global anomaly pattern before 3 Myr ago resembled what currently occurs during El Niño, the absence of large continental ice sheets in Canada before 3 Myr ago follows from the greater heat transport to Canada[49].

We have suggested that the aridification of east Africa at ~4 Myr ago was caused by the northward movement of New Guinea–Australia and the emergence of much of Halmahera. This suggestion could be tested with sediment cores from the Indian Ocean, particularly with cores from 10° S, where we expect temperatures to have decreased. The possibility that the concomitant changes in the tropical Pacific played a major role in bringing about the onset of glaciation, if yet more speculative, could also be tested with equatorial Pacific sediment cores, and with data from regions known to have strong ENSO teleconnections in today's climate. □

Methods

We use the linear shallow-water equations on an equatorial β-plane to approximate the baroclinic flow near the Equator[50]. In the approximate form appropriate to low-frequency motions (including the steady state)[51], the equations permit three classes of free motions, which must be described mathematically by orthogonal functions: (1) Rossby waves with long zonal wavelengths and standing meridional structures, which carry energy westward; (2) equatorial Kelvin waves, with the meridional structure $u(y) = h(y) = \psi_0(y) = \pi^{-1/4}\exp(-y^2/2)$, where u is the eastward velocity and h is the perturbation pressure or, equivalently, the perturbation height. All quantities are rendered dimensionless in the canonical way for equatorial motions[50,51]. (3) Western boundary currents, trapped along that boundary.

The low-frequency, long-wavelength Kelvin and Rossby modes obey a geostrophic balance between the meridional pressure gradient and the Coriolis force:

$$yu + \frac{\partial h}{\partial y} = 0 \qquad (1)$$

Flows incident on the western boundary are composed of modes that carry energy westward: the long-wavelength Rossby waves. The reflection must carry energy eastward, and hence the reflected motion must consist of Kelvin waves. For a boundary devoid of passages, all mass flux incident on the boundary returns in Kelvin waves[51], which determines the amplitude of the Kelvin mode. Western boundary currents connect the fluid circuits between the incident Rossby motions and the reflected Kelvin mode.

The western Pacific boundary has openings, allowing some of the fluid to be transmitted through to the Indian Ocean. By using geostrophy, equation (1), the condition that no Kelvin wave can be transmitted west of the boundary (namely, equation (4)), and the fact that all motions must be of types (1)–(3), the reflected and transmitted components of the flow may be determined[40,41].

The mass flux αT reflected and carried eastward by Kelvin waves, when a zonal current $u(y)$ and its geostrophically balanced pressure field $h(y)$ are incident on the western boundary of the Pacific, is given by:

$$\alpha T = -\frac{\alpha h(b) + \alpha b\int_{-\infty}^{b} u(y)\mathrm{d}y + \Gamma(g)\int_{-\infty}^{\infty} u(y)\mathrm{d}y}{\Gamma(g) + \Gamma(-b)} \qquad (2)$$

(which corrects a typographical error in equation (41) of ref. 41) where T is the amplitude of the reflected Kelvin waves, $\alpha = \int_{-\infty}^{\infty}\psi_0(y)\mathrm{d}y = \sqrt{2}\pi^{1/4}$ is the (dimensionless) mass flux in a Kelvin wave of unit amplitude, g is the latitude of the southern boundary of Eurasia–Sundaland, and b is the latitude of the northern boundary of Australia–New Guinea (with and without Halmahera). Latitudes are rendered dimensionless using the radius of deformation for the gravest baroclinic mode (333 km). Also in equation (2),

$$\Gamma(a) = \psi_0(a) - a\int_{a}^{\infty}\psi_0(y)\mathrm{d}y \qquad (3)$$

The minus sign in equation (2) accounts for the change of sign upon reflection.

If the incident mass flux u is a δ-function at latitude c, $u(y) = \delta(y-c)$, then by geostrophy, equation (1), $h(y) = h\_$ for $y < c$, and $h(y) = h\_ - c$ for $y > c$, where $h\_$ is a constant determined by the condition that $u(h)$ be orthogonal to the Kelvin wave:

$$\int_{-\infty}^{\infty}(u + h)\psi_0\mathrm{d}y = 0 \qquad (4)$$

which yields $\alpha h\_ = -\Gamma(c)$, Substituting the expressions for u and h into equation (2) we obtain:

$$\alpha T = -\frac{\Gamma(g) - \Gamma(c) + \alpha\max(0, b - c)}{\Gamma(g) + \Gamma(-b)} \qquad (5)$$

The Indonesian throughflow due to a westward jet of unit amplitude, which equals incident minus reflected flux $\theta = 1 + \alpha T$, is plotted in Fig. 5.

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