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The Indonesian seas and their role in the coupled ocean–climate system

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The Indonesian seas represent the only pathway that connects different ocean basins in the tropics, and therefore play a pivotal role in the coupled ocean and climate system. Here, water flows from the Pacific to the Indian Ocean through a series of narrow straits. The throughflow is characterized by strong velocities at water depths of about 100 m, with more minor contributions from surface flow than previously thought. A synthesis of observational data and model simulations indicates that the temperature, salinity and velocity depth profiles of the Indonesian throughflow are determined by intense vertical mixing within the Indonesian seas. This mixing results in the net upwelling of thermocline water in the Indonesian seas, which in turn lowers sea surface temperatures in this region by about 0.5 °C, with implications for precipitation and air–sea heat flux. Moreover, the depth and velocity of the core of the Indonesian throughflow has varied with the El Niño/Southern Oscillation and Indian Ocean Dipole on interannual to decadal timescales. Specifically, the throughflow slows and shoals during El Niño events. Changes in the Indonesian throughflow alter surface and subsurface heat content and sea level in the Indian Ocean between 10 and 15° S. We conclude that inter-ocean exchange through the Indonesian seas serves as a feedback modulating the regional precipitation and wind patterns.

The tropical Indonesian seas play a central role in the climate system. They lie at the climatological centre of the atmospheric deep convection associated with the ascending branch of the Walker Circulation. They also provide an oceanic pathway for the Pacific and Indian inter-ocean exchange, known as the Indonesian throughflow (ITF). The ITF is the only tropical pathway in the global thermohaline circulation[1]. As such, the volume of heat and fresh water carried by the ITF is known to impact the state of the Pacific and Indian oceans as well as air–sea exchange[2–6], which modulates climate variability on a variety of timescales. Sea surface temperature (SST) anomalies over the Indonesian seas are associated with both the El Niño/Southern Oscillation (ENSO) in the Pacific and the Indian Ocean Dipole (IOD). Both modes of variability cause changes in the regional surface winds that alter precipitation and ocean circulation patterns within the entire Indo-Pacific region[7,8]. Indeed, proper representation of the coupled dynamics between the SST and wind over the Indonesian seas is required for a more realistic simulation of ENSO[9].

It was originally thought that the ITF occurs within the warm, near-surface layer with a strong annual variation driven by seasonally reversing monsoon winds[10]. However observations over the past decade reveal that the inter-ocean exchange occurs primarily as a strong velocity core at depths of about 100 m within the thermocline and exhibits large variability over a range of timescales[11,12]. Ongoing *in situ* measurements indicate that the vertical profile of the flow has changed significantly over the past decade. In particular there has been a prolonged shoaling and strengthening of the ITF subsurface core within the Makassar Strait inflow channel that occurred in concert with the more regular and stronger swings of ENSO phases since the mid-2000s[13]. On longer timescales, coupled models reveal that reduced Pacific trade winds will correspondingly reduce the strength and change the profile of the ITF. These changes have important implications to the air–sea coupled system, as it is the vertical profile of the ITF that is critical to the climatically relevant inter-basin heat transport[12].

In this Progress Article, we discuss observational evidence from the past few decades, supported by model simulations, that show how recent changes in the wind and buoyancy forcing have affected the vertical profile and properties of the flow through the Indonesian seas. Intense vertical mixing by vigorous tides and strong interactions between winds and the sea surface set the vertical stratification of the ITF flow[14]. Thermocline–wind coupling responds to and affects the further development of both ENSO and IOD[9,15]. We highlight how these changes have direct consequences for the ocean and climate system through their feedback on the large-scale SST, precipitation and wind patterns.

Ocean circulation within the Indonesian seas

Water masses entering the Indonesian seas from the Pacific Ocean pass between and around the islands of Indonesia, forming unique water masses that then enter and can be tracked within the Indian Ocean basin.

Impact on the Pacific and Indian oceans. Model experiments that contrast open and closed ITF passages generally report warmer SST in the tropical Pacific and cooler SST in the southern Indian Ocean when ITF passages are closed[3]. Experiments in which the ITF is blocked show a deeper thermocline and a smaller SST gradient

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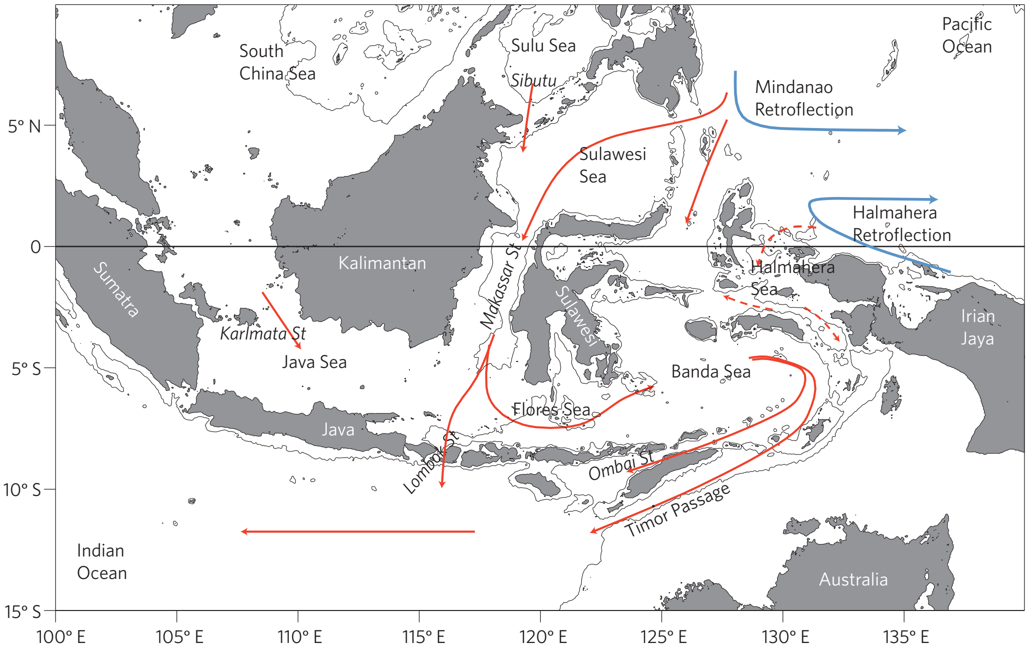

Figure 1 | Bathymetric and geographic features of the Indonesian seas. The mean pathway of the Indonesian throughflow is shown by red lines, and the contribution to the throughflow from the South Pacific is shown by the dashed lines. The pathways through the seas north of the Banda Sea are poorly resolved and uncertain.

between the warm pool and the cold tongue in the tropical Pacific, and a shallower mean depth of the thermocline in the Indian Ocean. The closed ITF simulations also show circulation changes, including less equatorward flow of subtropical waters from the South Pacific, and a weaker Indian Ocean South Equatorial Current with less flow into the Agulhas Current. Thus the Indian Ocean inflow to the Atlantic is potentially decreased. These circulation changes may alter the upper-layer heat content, winds and air–sea heat flux, with subsequent consequences for the Indian Ocean monsoon and regional Indo-Pacific precipitation[3,16,17], although the magnitude of the changes depends on the model sensitivity. Furthermore, coupled ocean–atmosphere simulations show an eastward shift in atmospheric deep convection and precipitation in response to the warmer Pacific SSTs and increased upper-ocean heat content[18,19] seen in simulations in which the ITF is absent.

Pathways. The primary inflow passage for the ITF is the Makassar Strait. Some water exiting it enters the Pacific Ocean through the Lombok Strait, whereas the bulk flows east towards the Banda Sea before entering the Pacific Ocean through the Ombai Strait and Timor Passage. The inflow of ITF waters is drawn from the energetic Mindanao (mainly North Pacific water) and Halmahera (mainly South Pacific) retroflections (Fig. 1). In the Makassar Strait, the ITF consists mostly of North Pacific thermocline and intermediate water[20]. Secondary ITF portals permit water to enter through the western Pacific marginal seas, such as through the Sibutu Passage connecting the Sulawesi Sea to the Sulu Sea or from the South China Sea via Karimata Strait. These relatively shallow portals provide a source of fresh water that influences the stratification of the ITF[13]. Smaller contributions of North Pacific surface water may directly enter the Banda Sea via the channels to the north that serve as the eastern pathway of the ITF. The deeper channels east of Sulawesi consist primarily of saltier South Pacific water that infiltrates isopycnally into the lower thermocline of the Banda Sea. This salty water dominates the deeper layers of the ITF through density-driven overflows[20,21]. Shallower waters from the South Pacific enter through the passages that line the Halmahera Sea. The contribution of South Pacific waters to the ITF via these northeastern passages is not well resolved and represents one of the largest uncertainties of the ITF pathways[22]. The ITF enters into the Indian Ocean through gaps along the southern island chain running from Sumatra to Timor, but mostly via Lombok Strait and the deeper Ombai Strait and Timor Passage[12]. Observations show that the low-salinity ITF surface core[23] is clearly separated from the high-silica, low-salinity ITF intermediate depth core[24] that stretches from the outflow passages across nearly the entire Indian Ocean between 10° S and 15° S.

Mixing of water masses. During transit through the Indonesian seas, temperature and salinity stratified water from the Pacific is mixed and modified by strong air–sea fluxes, monsoonal wind-induced upwelling and extremely large tidal forces[14,25,26]. The mixing forms the unique, nearly isohaline ITF profile (Fig. 2). The water masses seem to be mostly transformed before entering the Banda Sea, with the mid-thermocline salinity maximum and intermediate depth salinity minimum clearly eroded in the Flores, Seram and Maluku seas. Strong diapycnal fluxes of fresher water are necessary to reproduce this transformation and are induced by the internal tides[27]. This baroclinic tidal mixing occurs preferentially above steep topography and within the narrow straits[14,28]. Recent estimates of dissipation and vertical diffusivity reveal surprising hotspots of mixing at various depths within the water column, with high diffusivity values of the order 1–10 $\mathrm{cm^2\ s^{-1}}$ in the thermocline and at the base of the mixed layer.

The enhanced and spatially heterogeneous internal tidal mixing in the Indonesian seas not only alters the ITF water mass properties, but also impacts the SST distribution that in turn modulates air–sea interaction, atmospheric convection and the monsoonal response[15,29] (Fig. 3). Coupled models show that when tidal mixing is included, the upwelling of deeper waters cools SST in the Indonesian seas by ~0.5 °C, increases ocean heat uptake by ~20 $\mathrm{W\ m^{-2}}$ and reduces the overlying deep convection by as much as 20%. In the Indo-Pacific coupled wind/thermocline system, tidal mixing within the Indonesian archipelago influences the discharge and recharge of upper-ocean heat content in the Indo-Pacific region. This in turn regulates the amplitude and variability of both ENSO and the IOD[15].

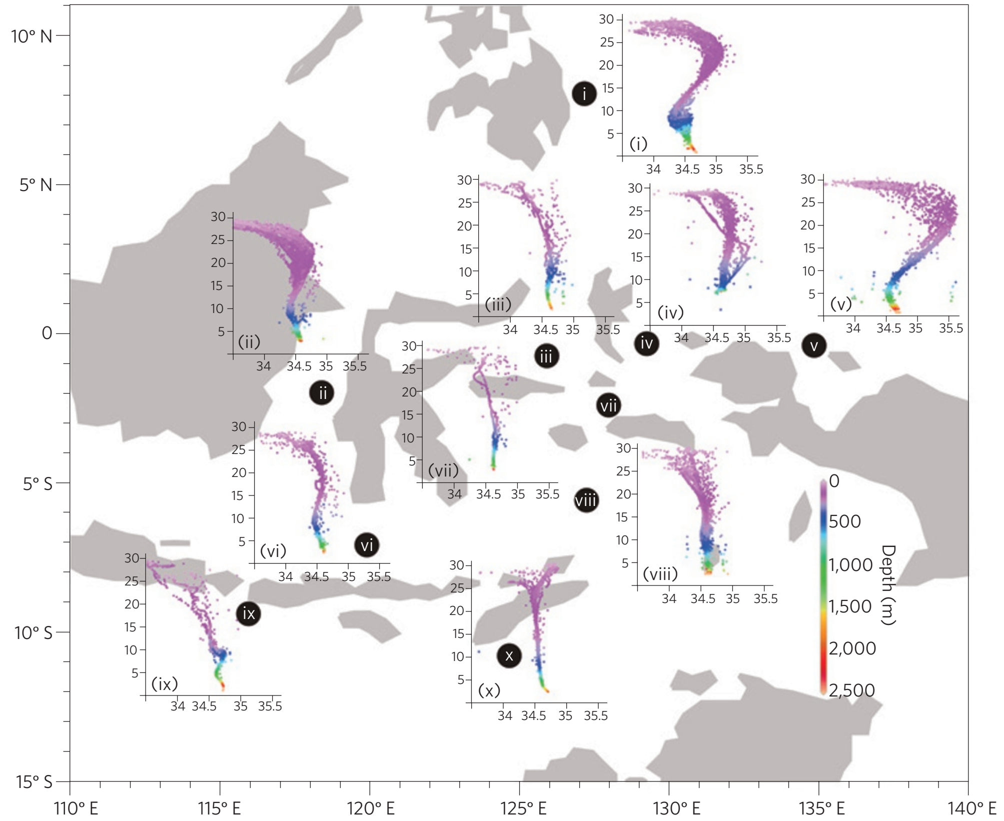

Figure 2 | Changes in temperature and salinity as the Pacific inflow water traverses the regional Indonesia seas. Each inset shows temperature (°C; *y* axis) and salinity (PSS-78; *x* axis) colour-coded by depth averaged over the region indicated by the corresponding numbered circles. The salinity maximum (pink) and minimum (blue-green) characteristics of the Pacific Ocean are mostly eroded in the Flores, Maluku and Seram seas before reaching the Banda Sea and outflow regions of Timor and Lombok. The data were derived from the World Ocean Data Base 2001 and additional regional CTD data (provided by A. Atmadipoera, Bogor Agricultural University, Indonesia).

We do not yet fully understand which mixing processes are responsible for the modification of the Pacific water masses. Climate model experiments suggest the pattern and magnitude of precipitation and air–sea heat exchange in the entire Indo-Pacific region is highly sensitive to the choice of model vertical diffusivity representing mixing within the Indonesian seas[30]. However, we expect that the same processes that form the ITF stratification also contribute to the relatively large vertical flux of nutrients that support the high primary productivity of the Indonesian seas. Quantitative knowledge of small-scale mixing processes is needed to properly model the regional circulation, to identify the influence on larger and longer scale variability, and to understand its role in the climate and marine ecosystems.

Volume transport. Because of the unique role that the ITF plays as the 'warm water pathway' for the global thermohaline circulation[1], there has always been a keen interest in knowing the total transport. Recent multi-year moorings in the major inflow and outflow passages suggest a total average ITF of about 15 Sv (1 Sv = 10^6 m^3 s^{-1}) into the Indian Ocean. Of this, about 2.6 Sv exited via Lombok Strait, 4.9 Sv via Ombai Strait and the remaining 7.5 Sv through Timor Passage[12]. Around 13 Sv was measured in the Makassar Strait inflow[13], suggesting the remaining 2 Sv is contributed via the northeastern passages that were not particularly well resolved[22].

Pacific, Indian and local wind-forced variability across a broad range of timescales translates into a strongly variable ITF volume. The seasonal variation is due to the influence of the reversing wind directions of the Asian-Australian monsoon. The phasing of this seasonal signal, however, varies from strait to strait and over different depth levels[11–13] and is further modulated by the intraseasonal Madden-Julian Oscillation[31,32].

On annual and longer timescales, the westward Pacific tradewinds that form the lower limb of the Walker Circulation pile up water in the western tropical Pacific, setting up a sea-level gradient between the Pacific and Indian basins that drives the ITF[33]. During El Niño conditions when the Pacific tradewinds weaken or reverse, the Makassar ITF transport is weaker and the thermocline shallower[34,35]. However, the relationship to Pacific ENSO variability at the exit portals of the ITF into the Indian Ocean is less clear, because transport in these straits is also subject to Indian Ocean variability[12,36]. The oceanic response to wind forcing is often accomplished through wave processes that propagate along the equatorial and coastal wave guides within the Indonesian archipelago, and impact the water properties, thermocline and sea level on all timescales[31,32,37].

Heat transport. The profile of the volume transport through each strait is the key to the climatically important heat transfer. Inter-ocean heat transfer through the Indonesian Seas had been thought to be surface intensified and warm[10], around 22–24 °C. However, the Makassar Strait transport profile was recently shown to have a subsurface maximum[4], so the transport-weighted temperature is only ~13 °C. This is particularly true during the rainy northwest monsoon, when buoyant, low-salinity water from the South China Sea inhibits southward flow in the Makassar Strait surface layer[38]. The increase of the South China Sea throughflow during El Niño also induces a cooler ITF[13]. Subsurface maxima transport profiles are similarly evident in the outflow passages: the deeper subsurface

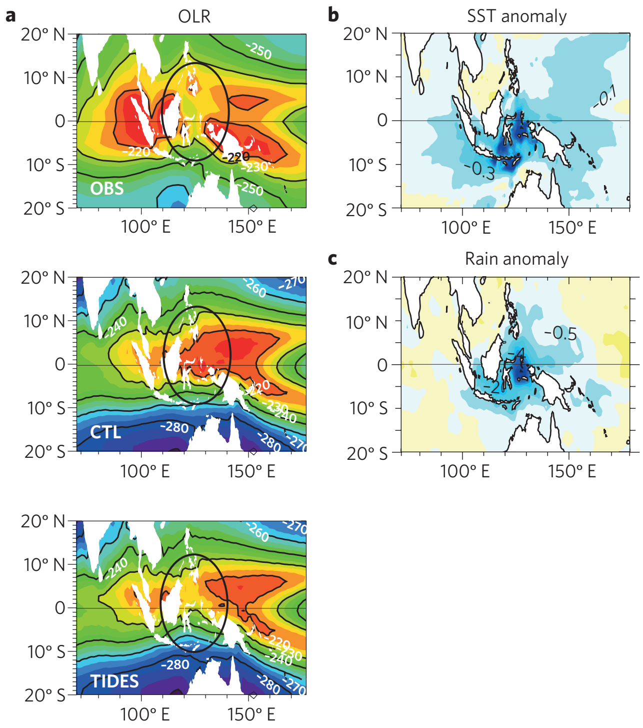

Figure 3 | Changes in tropical Indo-Pacific mean climate from models with and without tidal mixing parameterizations. a, Annual average outgoing long-wave radiation (OLR; Watts per m^2) from the NOAA NCEP Climate Prediction Center (OBS; upper panel) and the SINTEX-F model without (CTL; middle) and with (TIDES; lower) tidal mixing parameterization[14]. High OLR values imply increased cloudiness and probably increased precipitation. The oval outline indicates where a ~20% reduction in deep convection occurs when tidal mixing is included in the model, more aligned with the OLR observations within the Indonesian seas. **b**,**c**, Differences in SST (°C; **b**) and rainfall (mm; **c**) between coupled simulations with and without tidal parameterization. Negative values (blues) indicate cooler SST and reduced rainfall when tidal mixing is included. Overall, the tidal effect cools the mean SST by ~2 °C and reduces mean precipitation by about 20%.

maximum in Ombai Strait (~180 m) is subsequently colder (15.2 °C) than the Lombok (21.5 °C)[12]. Timor Passage heat transfer is relatively warm (17.8 °C) because it is more surface intensified. The much warmer temperatures of the outflow passages can be largely reconciled with the cooler estimates from the inflow via Makassar Strait by accounting for the local surface heat fluxes within the internal Indonesian seas that warm the ITF during its passage[39].

Climate-driven changes in the Indonesian seas

The circulation and properties within the Indonesian seas are impacted by interannual to decadal modes of variability in the coupled air–sea climate system.

Interannual variability. Observational evidence points to a recent prolonged shoaling and strengthening of the ITF within Makassar Strait. Since 2007, the thermocline velocity maximum shifted from 140 to 70 m depth and the velocity increased from 70 to 90 cm s^{-1} (Fig. 4). This has resulted in a 47% increase in transport over the 50–150 m depth range[13]. The dramatic change in the transport profile occurred in concert with the return to more regular and stronger swings between El Niño and La Niña conditions after the extended warm El Niño period from the 1990s to the mid-2000s. Model results showed that during the El Niño episodes, fresh water enters from the Sulu Sea and pools as buoyant surface water in the Sulawesi Sea. This reduces the surface layer contribution to the Makassar throughflow[13]. In contrast, during La Niña, the Sulu Sea exchange is small and the freshwater pool dissipates, causing a shoaling and strengthening of the upper thermocline layer of the Makassar Strait ITF such as observed in 2008–2009. Although it is still unclear how the Makassar Strait transport is partitioned through the main ITF exit passages, and to what extent its vertical profile is maintained, proxy transports derived from remotely sensed sea-level data show a concurrent change in the Lombok Strait outflow over the same period[36]. The Lombok Strait provides the most direct link from Makassar to the Indian Ocean, and increased transport within the warm upper layer during La Niña events would warm the tropical Indian Ocean SST and so regulate the Indian Ocean stratification and surface heat fluxes[16,17].

Decadal and secular trends. On multi-decadal timescales, changes in the Pacific tradewind system have had direct bearing on the strength and circulation patterns within the Indonesian seas and Indian Ocean. A weakening of the tradewinds that form part of the Pacific Walker Cell in the 1970s[40] led to shoaling thermocline anomalies in the western Pacific. The anomalies were transmitted by planetary wave processes along the eastern boundary of the Indonesian seas, similar to those that occur in response to ENSO-induced wind shifts[39]. Corresponding surface warming, subsurface cooling and net decrease in the volume transport was observed where the ITF enters the Indian Ocean[41]. A companion study of twentieth-century simulations from a suite of models from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4) showed that subsurface cooling in the tropical Indian Ocean was consistent with shoaling of the thermocline and increased vertical stratification[42]. Although the coarse grid spacing of these climate models did not fully resolve the narrow Indonesian passages, a majority of the models confirmed this trend was linked to the observed weakening of the Pacific tradewinds and was transmitted by the ITF[42]. The ITF profile changes resulted in the decreasing heat content and falling sea level in an isolated zonal band of the Indian Ocean; the trends in this band over the late twentieth century are at odds with those in the rest of the basin[43,44]. Since the early 1990s, the Indian Ocean cooling trend has reversed[44] in response to a gradual intensification of the Pacific easterlies, which increased sea level in the western tropical Pacific[44,45]. As a consequence, models and proxy-derived transports have indicated a significant increase in the ITF[36,44,46–48] since the early 1990s.

It is worth remembering that these decadal changes are embedded within much longer-term secular trends of the climate system. Most anthropogenic climate change simulations predict a weakening of the Walker Circulation in response to a warming world[49] and so project a decrease in the ITF transport[50]. This would be likely to have similar impacts on the Indian Ocean thermocline structure and sea level as observed when analogous conditions prevailed during the late twentieth century — namely surface warming and subsurface cooling. What remains unclear is how these changes in the Indian Ocean might impact the downstream Agulhas Current system and perhaps even the Atlantic Meridional Overturning Circulation[1]. The connectivity between the ITF and the Agulhas system has remained fairly difficult to determine, at least in terms of direct observations. This is primarily because the fingerprint of the fresh ITF signature becomes more ambiguous in the western Indian Ocean where it mixes with the hypersaline Red Sea water masses[7,24]. Model results using Lagrangian trajectory experiments to trace particles from the Indonesian seas suggest that around 88% of the water carried by the ITF exits the Indian Ocean via the Agulhas Current after a 50-year period[6].

Unravelling the ITF

Large uncertainties remain in our current understanding of many aspects of the circulation in the Indonesian seas and its impact on

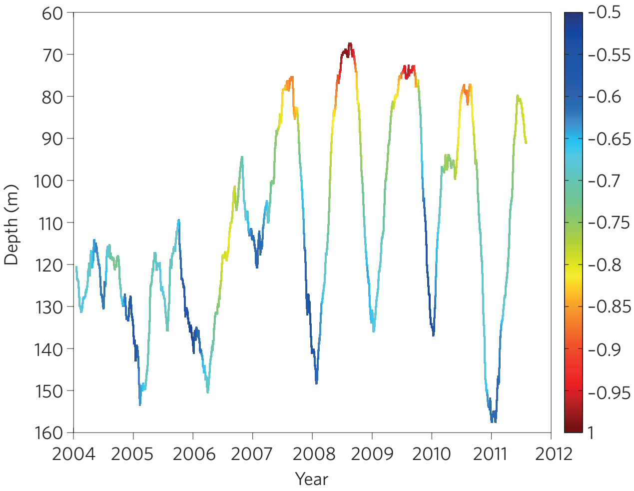

Figure 4 | Time series of the depth of the maximum along-channel velocity (m s^{-1}) within the Makassar Strait[13]. Colours indicate the 3-day averaged velocity that has been smoothed with a 90-day running mean, with negative values denoting southward flow. The throughflow is weakest in boreal winter and strongest in boreal summer. During 2007, the velocity maximum shoaled and increased speed, reaching a peak in maximum speed in 2008 and 2009.

the Pacific and Indian oceans and beyond. In particular, although the sources and paths of North Pacific water through the Makassar Strait and into the Indian Ocean is fairly well constrained, the contribution of South Pacific water masses that enter through the northeastern passages is relatively unknown. Even less is known about the mixing and partitioning of these water masses. Given their very different biogeochemical signatures, and the intense marine conservation efforts in this region, understanding the mixing processes that set the nutrient content of the surface and thermocline waters is of considerable importance. Direct measurements of mixing of North and South Pacific source waters within the Indonesian seas would address this question. Measurements should focus on quantifying the level of energy available for mixing and identifying where and when the mixing occurs. This latter effort will involve an iterative process between the observational and modelling studies to shed light on the likely mechanisms, the horizontal and vertical scales of the mixing, and the locations of dissipation. Further focused process studies should measure the influence of mixing on the marine ecosystem (specifically the nutrient and biogeochemical fluxes) in the biodiversity centre known as the Coral Triangle, which spans much of the area where the ITF occurs. Finally, the unexpected changes observed in the Makassar Strait velocity profile over the past few decades, and the observed feedback with regional climate variability, highlight the need for sustained measurements of the velocity and property characteristics in all the main ITF passages. Such measurements will help to inform our understanding of how variations in the Indonesian Seas affect and respond to the coupled air–sea climate system, and may ultimately be used to assess changes in the economically important regional ecosystems.

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Additional information

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Competing financial interests

The authors declare no competing financial interests.