The Indonesian Seas and their impact on the Coupled Ocean-Climate System

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Preface:

The Indonesian seas play a pivotal role in the coupled ocean and climate system as they provide the only tropical pathway connecting the global oceans. Recent observations show the Pacific input to the Indonesian seas throughflow is characterized by a strong velocity core near 100 m depth, rather than within the warm sea surface layer, as had earlier been assumed. Furthermore the depth of the velocity core has exhibited significant variability over the past decade. Here we show that intense vertical mixing within the Indonesian seas alters the temperature, salinity and velocity depth profiles of the Indonesian throughflow. The mixing induces net upwelling of thermocline water affecting the sea surface temperature and so impacting the tropical atmospheric circulation and precipitation patterns of the climate system. Despite considerable progress, there remain large gaps in our knowledge of the physical processes that contribute to variability in the coupled air-sea climate system within the Indonesian seas, which in turn also affects the marine ecosystem at the heart of the ecologically important Coral Triangle.

The tropical Indonesian seas play a central role in the climate system. They lie at the climatological center 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), conveying the only link in the global thermohaline circulation at tropical latitudes[1]. As such, the volume of heat and freshwater carried by the ITF are known to impact the state of the Pacific and Indian Oceans as well as the air-sea exchange[2-6], modulating climate variability on a variety of time scales. Sea surface temperature (SST) anomalies over the Indonesian seas are associated with both the Pacific El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), causing 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].

The ITF had originally been thought of as occurring within the warm, near surface layer with a strong annual signal driven by seasonally reversing monsoons[10]. However recent observations reveal the inter-ocean exchange primarily occurs as a strong velocity core at depth within the thermocline and exhibits large variability over a range of time scales[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 occurring in concert with the more regular and stronger swings of ENSO phases since the mid-2000s[13]. On longer time scales, 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, since it is the vertical profile of the ITF that is critical to the climatically relevant inter-basin heat transport[12].

In this article we discuss recent observational evidence supported by models that show how recent changes in the wind and buoyancy forcing affect the vertical profile and properties of the flow through the Indonesian seas. Intense vertical mixing through vigorous tides and strong air-sea interaction set the vertical stratification of the ITF flow[14], and is found to impact both ENSO and the IOD variability through thermocline and wind coupling[9,15]. We highlight how these changes have direct consequences for the ocean and climate system through their feedback onto the large-scale SST, precipitation and wind patterns.

Ocean Circulation within the Indonesian Seas

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]. Blockage of the ITF deepens the thermocline and reduces the warm pool-cold tongue SST gradient in the tropical Pacific, and shoals the mean thermocline in the Indian Ocean. Oceanic circulation changes when there is no ITF include 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 potentially decreasing the Indian Ocean inflow to the Atlantic. Although the magnitude of the changes depend on model sensitivities, this may alter the upper layer heat content, winds and the air-sea heat flux with subsequent consequences for the Indian Ocean monsoon and regional Indo-Pacific precipitation[3,16,17]. Coupled ocean-atmosphere simulations have an eastward shift in the deep convection and precipitation in response to the warmer Pacific SST and upper ocean heat content[18,19] when the ITF is absent.

Pathways. The inflow of ITF waters is drawn from the energetic Mindanao (mainly North Pacific water) and Halmahera (mainly South Pacific) Retroflections (Figure 1). In the primary inflow passage of Makassar Strait the ITF mostly consists of North Pacific thermocline and intermediate water[20]. Secondary ITF portals permit water to enter via 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. Although relatively shallow, these portals can provide a significant source of freshwater that influences the ITF stratification[13]. Smaller contributions of North Pacific surface water may directly enter the Banda Sea via the channels to the north that mark the eastern pathway of the ITF. The deeper channels east of Sulawesi primarily consist of saltier South Pacific water that infiltrates (isopycnally) into the lower thermocline of the Banda Sea and dominate the deeper layers 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 a clearly separated low salinity ITF surface core[23] from a 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, the Pacific temperature and salinity stratification is mixed and modified by the strong air-sea fluxes, monsoonal wind-induced upwelling, and extremely large tidal forces[14,25,26], to form the distinctly unique nearly isohaline ITF profile (Figure 2). The water masses appear 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 hot spots of mixing at various depths within the water column, with high diffusivity values of the order 1-10 $cm^2 s^{-1}$ 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] (Figure 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 $W m^{-2}$ and reduces the overlying deep convection by as much as 20%. Changes in the Indo-Pacific coupled wind/thermocline system in response to tidal mixing within the Indonesian archipelago influence the discharge and recharge of upper-ocean heat content of the Indo-Pacific region and so regulate the amplitude and variability of both ENSO and the IOD[15]. We do not as 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 to represent mixing within the Indonesian seas[30]. Yet it is likely 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, particularly from the modeling community, 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^3s^{-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 north-eastern passages that were not particularly well-resolved[22].

Pacific, Indian and local wind-forced variability across a broad range of time scales translates into a huge range of ITF variability. The seasonal variation is due to the influence of the reversing wind of the Asian-Australian monsoon, although the phasing of this seasonal signal 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 time scales, 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 Indian and Pacific 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 since 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 over all time scales[31,32,37].

Heat transport. It is the profile of the volume transport through each strait that is the key to the climatically important heat transfer. Interocean heat transfer through the Indonesian Seas had been thought to be surface intensified and warm[10], around 22°C-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 so during the rainy northwest monsoon when low-salinity buoyant 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 and the deeper subsurface maximum in Ombai Strait (~180 m) is subsequently colder (15.2°C) compared to 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].

Recent Changes in the Indonesian Seas Linked to the Climate System

Interannual Variability. Observational evidence points to a recent prolonged shoaling and strengthening of the ITF within Makassar Strait: the thermocline velocity maximum shifted from 140 m to 70 m depth and increased from 70 cm s^{-1} to 90 cm s^{-1} (Figure 4) resulting in a 47% increase in transport over the 50-150 m depth range[13]. The dramatic change in the transport profile began around 2007, occurring in concert with the return to more regular and stronger swings of the ENSO phases after the extended warm El Niño period from the 1990s to the mid 2000s. Model results showed that during the El Niño episodes, freshwater enters from the Sulu Sea and pools as buoyant surface water in the Sulawesi Sea, leading to a reduced 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. While 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]. Lombok Strait provides the most direct link from Makassar to the Indian Ocean, and the increased transport within the warm upper layer during these La Niña events would act to 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 time scales, changes in the Pacific tradewind system have had direct bearing on the strength and circulation patterns within the Indonesian seas and Indian Ocean. Weakening of the Walker Cell tradewinds in the 1970s[40] led to shoaling thermocline anomalies in the western Pacific that were transmitted by planetary wave processes along the eastern boundary of the Indonesian seas, similar to that which occur in response to ENSO induced wind shifts[39]. A corresponding surface warming, subsurface cooling and net decrease in the volume transport was observed where the ITF enters into the Indian Ocean[41]. A companion study of 20th century simulations from a suite of IPCC AR4 models showed 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 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 that are at odds with trends in the rest of the basin over the late 20th century[43,44]. Since the early 1990s, the Indian Ocean cooling trend has reversed[44] in response to a gradual intensification of the Pacific easterlies increasing the 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] from the early 1990s through the first decade of the 21st century.

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 likely have similar impacts on the Indian Ocean thermocline structure and sea level as observed when analogous conditions prevailed during the late 20th century. 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 elusive, 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 around 88% of the ITF water 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 the Pacific and Indian Oceans and beyond. The contribution of the South Pacific water masses through the northeastern passages of the Indonesian seas has been poorly measured in the past. Understanding the governing physics that partition the North and South Pacific source waters through the various inflow passages over a range of time scales is important since they transport water masses with different physical and biogeochemical characteristics. In particular, direct measurements of mixing of these different source waters within the Indonesian seas are needed, with a 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 modeling studies to shed light on the likely mechanisms, the horizontal and vertical scales of the mixing, and the locations of dissipation. In addition, focused process studies designed to measure the influence of mixing on the marine ecosystem (specifically the nutrient and biogeochemical fluxes) are required since the Indonesian seas lie within the heart of the Coral Triangle, a recognizable center of marine biodiversity and a priority of high-level conservation efforts. Finally, the recent unexpected changes observed in the Makassar Strait velocity profile and the feedback to regional climate variability highlight the need for sustained measurements of the velocity and property characteristics in all the major ITF passages. Understanding the variation in the Indonesian seas is crucial, not only for its role in the coupled air-sea climate system, but also for the impact on regional ecosystems and the local economies of this populous region with a heavy reliance on the maritime environment resources.

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Figure Captions

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.

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) color-coded by depth (m; see colorbar) averaged over the region indicated by the dark gray dot. The salinity maximum (pink) and the salinity minimum (blue-green) characteristic 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).

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 (upper panel), and the SINTEX-F model with (middle) and without (lower) tidal mixing parameterization[14]. High OLR values imply increased cloudiness and likely increased precipitation. Differences in **b,** SST (°C) and **c,** rainfall (mm) between coupled simulations with and without tidal parameterization. Negative values indicate cooler SST and reduced rainfall

when tidal mixing is included. Overall, the tidal effect cools the mean SST and reduces mean precipitation by about 20%.

Figure 4: Time series of the depth of the maximum along-channel velocity (m s^{-1}) within Makassar Strait[13]. Colors 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.

References

1. Gordon, A.L. Interocean exchange of thermocline water. *J. Geophys. Res.* **91**, 5037-5046 (1986).
2. Godfrey, J.S. The effect of the Indonesian Throughflow on ocean circulation and heat exchange with the atmosphere: A review. *J. Geophys. Res.* **101**, 12217-12237 (1996).
3. Lee, T., Fukumori, I., Menemenlis, D., Xing, Z. & Fu, L.L. Effects of the Indonesian Throughflow on the Pacific and Indian Oceans. *J. Phys. Oceanogr*. **32**, 1404-1429 (2002).
4. Vranes, K., Gordon, A.L. & Ffield, A. The heat transport of the Indonesian throughflow and implications for the Indian Ocean Heat Budget. *Deep-Sea Res*. **49**, 1391-1410 (2002).
5. Potemra, J.T., & Schneider, N. Influence of low-frequency Indonesian throughflow transport on temperatures in the Indian Ocean in a coupled model. *J. Clim.* **20**, 1439–1452 (2007).
6. McCreary, J.P. *et al.* Interactions between the Indonesian Throughflow and circulations in the Indian and Pacific Oceans. *Progr. Oceanogr.* **75**, 70-114 (2007).
7. Song, Q., Gordon, A.L. & Visbeck, M. Spreading of the Indonesian Throughflow in the Indian Ocean. *J. Phys. Oceanogr.* **34**, 772-792 (2004).
8. Meyers, G., McIntosh, P., Pigot, L & Pook, M. The years of El Niño, La Niña, and interactions with the tropical Indian Ocean. *J. Clim.* **20**, 2872–2880 (2007).

9. Annamalai, H., Kida, S. & Hafner, J. Potential impact of the tropical Indian Ocean - Indonesian Seas on El Niño characteristics. *J. Clim.* **23**, 3933–3952 (2010).
10. Wyrtki, K. Physical Oceanography of the Southeast Asian Waters, Scripps Institution of Oceanography NAGA Report 2, 195 pp. (1961).
11. Gordon, A. L., Susanto, R.D., Ffield A., Huber, B.A., Pranowo, W. & Wirasantosa, S. Makassar Strait Throughflow, 2004 to 2006. *Geophys. Res. Lett.* **35**, L24605 (2008).
12. Sprintall, J., Wijffels, S.E., Molcard, R. & Jaya, I. Direct estimates of the Indonesian Throughflow entering the Indian Ocean. *J. Geophys. Res*. **114**, C07001 (2009).
13. Gordon, A.L., Huber, B.A., Metzger, E.J., Susanto, R.D., Hurlburt, H.E., & Adi, T.R. South China Sea Throughflow impact on the Indonesian Throughflow. *Geophys. Res. Lett.* **39**, L11602 (2012).
14. Koch-Larrouy, A., Madec, G., Bouruet-Aubertot, P., Gerkema, T., Bessieres, L., & Molcard, R. On the transformation of Pacific Water into Indonesian Throughflow Water by internal tidal mixing. *Geophys. Res. Lett.* **34**, L04604 (2007).
15. Koch-Larrouy, A., Lengaigne, M., Terray, P., Madec, G. & Masson, S. Tidal mixing in the Indonesian Seas and its effect on the tropical climate system. *Climate Dyn,* **34**, 891 – 904 (2010).
16. Wajsowicz, R. Air-sea interaction over the Indian Ocean due to variations in the Indonesian Throughflow. *Clim. Dynamics* **18**, 437-453 (2002).

17. Song Q. & Gordon, A.L. Significance of the vertical profile of the Indonesian Throughflow transport on the Indian Ocean. *Geophys. Res. Lett.* **31**, L16307 (2004).

18. Santoso A., Cai, W., England, M.H. & Phipps, S.J. The role of the Indonesian Throughflow on ENSO dynamics in a coupled climate model. *J. Clim*. **24**, 585-601 (2011).

19. Schneider, N., The Indonesian throughflow and the global climate system. *J. Clim.* **11**, 676-689 (1998).

20. Gordon, A.L & Fine, R. Pathways of water between the Pacific and Indian Oceans in the Indonesian seas. *Nature* **379**, 146-149 (1996).

21. van Aken, H.M., Brodjonegoro, I.S. & Jaya, I. The deepwater motion through the Lifamatola Passage and its contribution to the Indonesian Throughflow. *Deep-Sea Res.* **53**, 1203-1216 (2009).

22. Gordon, A.L. *et al.* The Indonesian Throughflow during 2004-2006 as observed by the INSTANT program. *Dyn. Atmosph. Oceans* **50**, 115-128 (2010).

23. Gordon, A. L. *et al.* Advection and diffusion of Indonesian Throughflow water within the Indian Ocean South Equatorial Current. *Geophys. Res. Lett.* **24,** 2573-2576 (1997).

24. Talley, L. D., & Sprintall, J. Deep expression of the Indonesian Throughflow: Indonesian Intermediate Water in the South Equatorial Current. *J. Geophys. Res*. **110**, C10009 (2005).

25. Ffield, A., & Gordon, A.L. Tidal mixing signatures in the Indonesian Seas. *J. Phys. Oceanogr*. **26**, 1924-1937 (1996).

26. Koch-Larrouy A., Madec, G., Iudicone, D., Molcard, R. & Atmadipoera, A. Physical processes contributing in the water mass transformation of the Indonesian ThroughFlow. *Ocean Dyn.* **58**, 275-288 (2008).

27. Koch-Larrouy A., Madec, G., Blanke, B. & Molcard, R. Quantification of the water paths and exchanges in the Indonesian archipelago. *Ocean Dyn*. **58**, 289-309 (2008).

28. Ffield, A. & Robertson, R. Indonesian Seas finestructure variability. *Oceanogr.* **18**, 108-111 (2005).

29. Kida, S., & Wijffels, S.E. The impact of the Indonesian throughflow and tidal mixing on the summertime sea surface temperature in the western Indonesian seas. *J. Geophys. Res*. **117**, C09007 (2012).

30. Jochum, M., & Potemra, J.T. Sensitivity of tropical rainfall to Banda Sea diffusivity in the Community Climate System Model. *J. Clim.* **21**, 6445–6454 (2008).

31. Drushka, K., Sprintall, J., & Gille, S.T. Vertical structure of Kelvin waves in the Indonesian Throughflow exit passages. *J. Phys. Oceanogr.* **40,** 1965-1987 (2010).

32. Pujiana, K., Gordon, A.L. & Sprintall, J. Intraseasonal Kelvin waves in Makassar Strait. *J. Geophys. Res*. **118**, 2023-2034 (2013).

33. Wyrtki, K. Indonesian Throughflow and the associated pressure gradient. *J. Geophys. Res.* **92**, 12941-12946 (1987).

34. Gordon A. L., Susanto, R.D. & Ffield, A. Throughflow within Makassar Strait. *Geophys. Res. Lett.* **26**, 3325-3328 (1999).

35. Ffield, A., Vranes, K., Gordon, A.L., Susanto, R.D. & Garzoli, S.L. Temperature variability within Makassar Strait. *Geophys. Res. Lett*. **27**, 237-240 (2000).

36. Sprintall, J. & Révelard, A. The Indonesian Throughflow response to Indo-Pacific climate variability. *J. Geophys. Res.* **119**, 1161-1175 (2014).

37. Wijffels, S.E. & Meyers, G. An intersection of oceanic wave guides: variability in the Indonesian Throughflow region*. J. Phys. Oceanogr.* **34**, 1232-1253 (2004).

38. Gordon, A.L., Susanto, R.D. & Vranes, K. Cool Indonesian Throughflow as a consequence of restricted surface layer flow. *Nature* **425,** 824-828 (2003).

39. Wijffels, S. E., Meyers, G.M. & Godfrey, J.S. A 20-Yr average of the Indonesian Throughflow: Regional currents and the interbasin exchange. *J. Phys. Oceanogr*. **38**, 1965-1978 (2008).

40. Vecchi, G.A., Soden, B.J., Wittenberg, A.T., Held, I.M., Leetma, A. & Harrison, M.J. Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing. *Nature* **441**, 73-76 (2006).

41. Wainwright, L., Meyers, G., Wijffels, S. & L. Pigot, Change in the Indonesian Throughflow with the climatic shift of 1976/77. *J. Geophys. Res.* **35**, L03604 (2008).

42. Alory, G., Wijffels, S. & Meyers, G. Observed temperature trends in the Indian Ocean over 1960–1999 and associated mechanisms. *Geophys. Res. Lett.* **34**, L02606 (2007).

43. Han, W. *et al.* Patterns of Indian Ocean sea-level change in a warming climate. *Nature Geosc.* **3**, 546-550 (2010).

44. Schwartzkopf, F.U. & Böning, C.W. Contribution of Pacific wind stress to multi-decadal variations in upper-ocean heat content and sea level in the tropical south Indian Ocean. *Geophys. Res. Lett.* **38**, L12602 (2011).

45. Lee, T. & McPhaden, M.J. Decadal phase changes in large-scale sea level and winds in the Indo-Pacific region at the end of the 20th century. *Geophys. Res. Lett*. **35**, L01605 (2008).

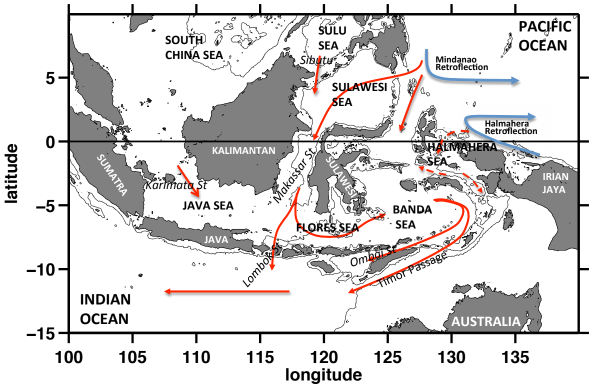
46. Lee, T. *et al.* Consistency and fidelity of Indonesian-throughflow total volume transport estimated by 14 ocean data assimilation products. *Dyn. Atmos. Oceans.* **50**, 201-223 (2010).

47. Feng, M., Böning, C.W., Biastoch, A., Behrens, E., Weller, E., & Masumoto, Y. The reversal of the multi-decadal trends of the equatorial Pacific easterly winds, and the Indonesian Throughflow and Leeuwin Current transports. *Geophys. Res. Lett.* **38**, L11604 (2011).

48. England, M. H. *et al*. Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. *Nature Clim. Change* **4**, 222-227 (2014).

49. Tokinaga, H. *et al*. Regional patterns of tropical Indo-Pacific Climate change: Evidence of the Walker Circulation weakening. *J. Clim*. **25**, 1689-1710 (2012).

50. Sen Gupta, A., Ganachaud, A., McGregor, S., Brown, J.N. & Muir, L. Drivers of the projected changes to the Pacific Ocean equatorial circulation. *Geophys. Res. Lett.* **39**, L09605 (2012).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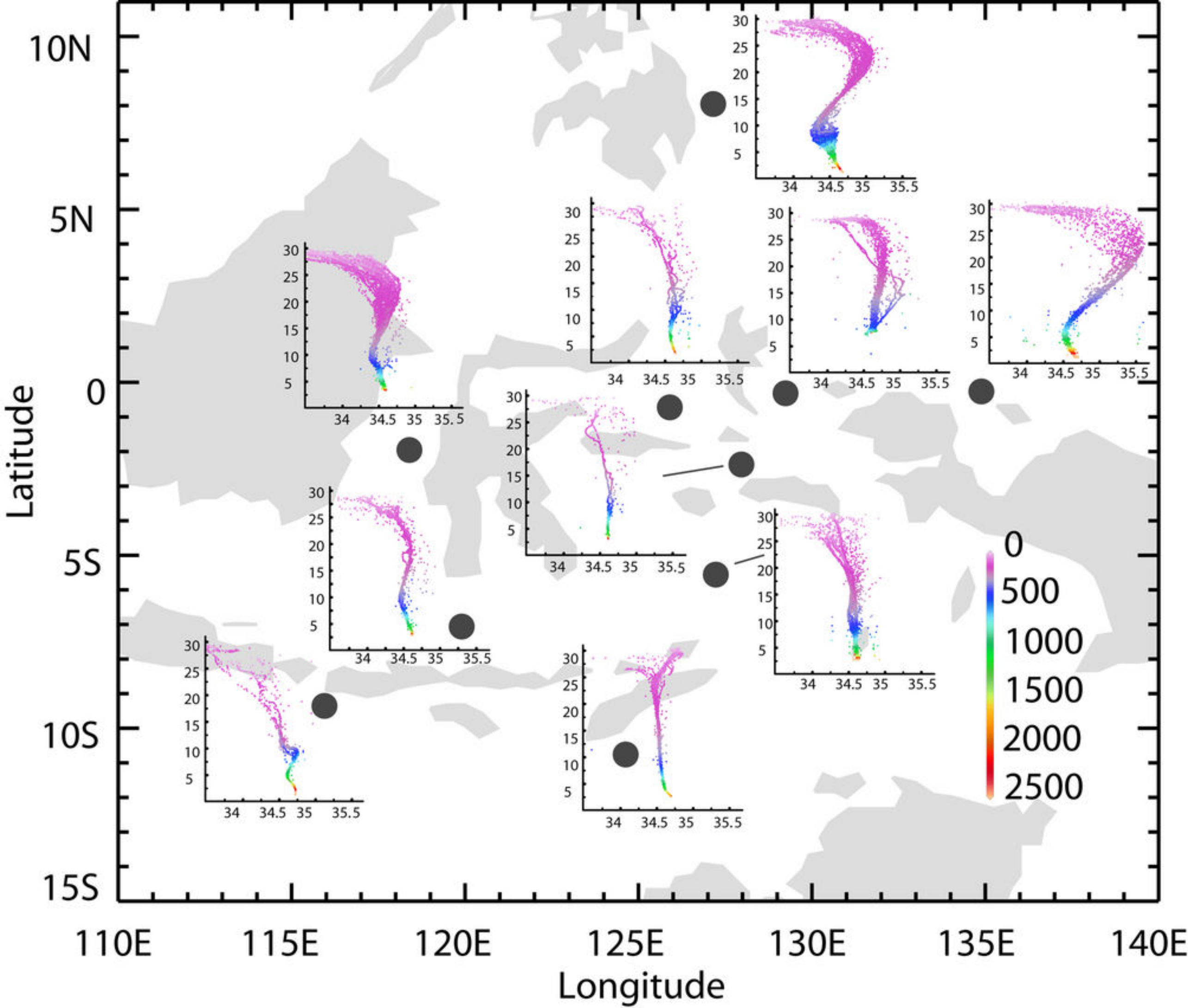
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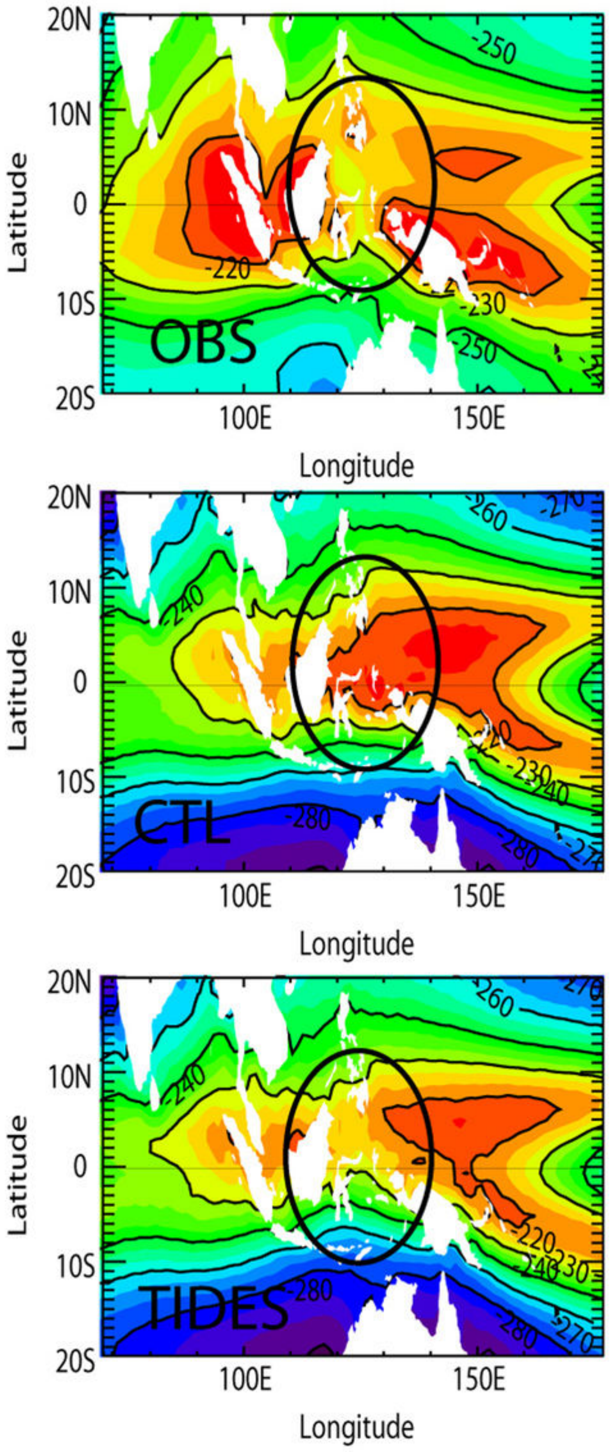
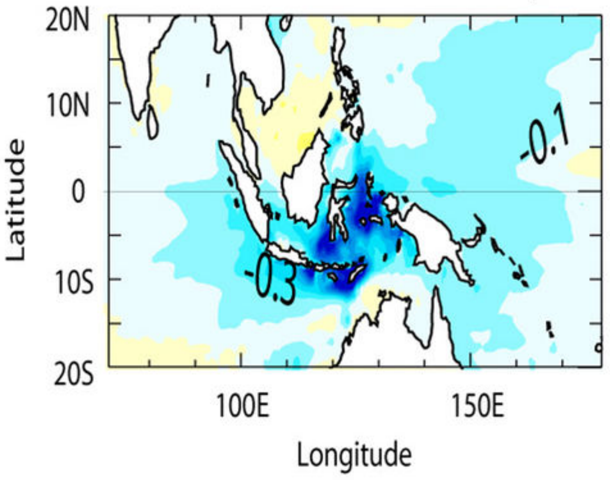
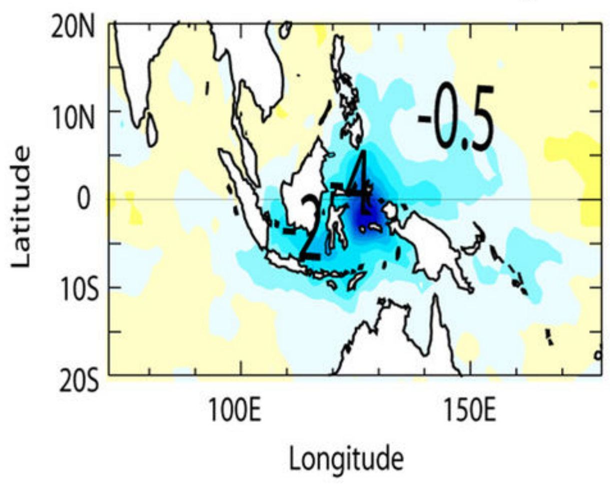
35.5
0
500
1000
1500
2000
2500



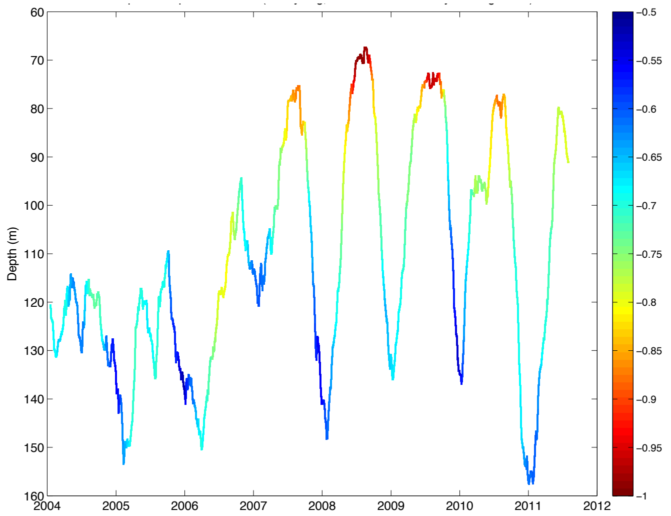
a) OLR



b) SST anomaly



c) Rain anomaly


Depth (m)
60
70
80
90
100
110
120
130
140
150
160
2004
2005
2006
2007
2008
2009
2010
2011
2012
-0.5
-0.55
-0.6
-0.65
-0.7
-0.75
-0.8
-0.85
-0.9
-0.95
-1