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

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16 **Progress Article for Nature Geosciences**

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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 latitudes¹. 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 exchange²⁻⁶, 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 ENSO⁹.

The ITF had originally been thought of as occurring within the warm, near surface layer with a strong annual signal driven by seasonally reversing monsoons¹⁰. 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-2000s¹³. 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 transport¹².

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

flow¹⁴, 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 closed³. 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) Retroflexions (Figure 1). In the primary inflow passage of Makassar Strait the ITF mostly consists of North Pacific

88 thermocline and intermediate water²⁰. Secondary ITF portals permit water to enter via the
89 western Pacific marginal seas, such as through the Sibutu Passage connecting the
90 Sulawesi Sea to the Sulu Sea or from the South China Sea via Karimata Strait. Although
91 relatively shallow, these portals can provide a significant source of freshwater that
92 influences the ITF stratification¹³. Smaller contributions of North Pacific surface water
93 may directly enter the Banda Sea via the channels to the north that mark the eastern
94 pathway of the ITF. The deeper channels east of Sulawesi primarily consist of saltier
95 South Pacific water that infiltrates (isopycnally) into the lower thermocline of the Banda
96 Sea and dominate the deeper layers through density-driven overflows^{20,21}. Shallower
97 waters from the South Pacific enter through the passages that line the Halmahera Sea.
98 The contribution of South Pacific waters to the ITF via these northeastern passages is not
99 well resolved and represents one of the largest uncertainties of the ITF pathways²². The
100 ITF enters into the Indian Ocean through gaps along the southern island chain running
101 from Sumatra to Timor, but mostly via Lombok Strait and the deeper Ombai Strait and
102 Timor Passage¹². Observations show a clearly separated low salinity ITF surface core²³
103 from a high silica, low salinity ITF intermediate depth core²⁴ that stretches from the
104 outflow passages across nearly the entire Indian Ocean between 10°S and 15°S.

105 **Mixing of Water Masses.** During transit through the Indonesian seas, the Pacific
106 temperature and salinity stratification is mixed and modified by the strong air-sea fluxes,
107 monsoonal wind-induced upwelling, and extremely large tidal forces^{14,25,26}, to form the
108 distinctly unique nearly isohaline ITF profile (Figure 2). The water masses appear mostly
109 transformed before entering the Banda Sea with the mid-thermocline salinity maximum
110 and intermediate depth salinity minimum clearly eroded in the Flores, Seram and Maluku

111 Seas. Strong diapycnal fluxes of fresher water are necessary to reproduce this
112 transformation and are induced by the internal tides²⁷. This baroclinic tidal mixing
113 occurs preferentially above steep topography and within the narrow straits^{14,28}. Recent
114 estimates of dissipation and vertical diffusivity reveal surprising hot spots of mixing at
115 various depths within the water column, with high diffusivity values of the order 1-10
116 $\text{cm}^2 \text{s}^{-1}$ in the thermocline and at the base of the mixed layer.

117 The enhanced and spatially heterogeneous internal tidal mixing in the Indonesian
118 seas not only alters the ITF water mass properties, but also impacts the SST distribution
119 that in turn modulates air-sea interaction, atmospheric convection and the monsoonal
120 response^{15,29} (Figure 3). Coupled models show that when tidal mixing is included, the
121 upwelling of deeper waters cools SST in the Indonesian seas by $\sim 0.5^\circ\text{C}$, increases ocean
122 heat uptake by $\sim 20 \text{ W m}^{-2}$ and reduces the overlying deep convection by as much as 20%.
123 Changes in the Indo-Pacific coupled wind/thermocline system in response to tidal mixing
124 within the Indonesian archipelago influence the discharge and recharge of upper-ocean
125 heat content of the Indo-Pacific region and so regulate the amplitude and variability of
126 both ENSO and the IOD¹⁵. We do not as yet fully understand which mixing processes are
127 responsible for the modification of the Pacific water masses. Climate model experiments
128 suggest the pattern and magnitude of precipitation and air-sea heat exchange in the entire
129 Indo-Pacific region is highly sensitive to the choice of model vertical diffusivity to
130 represent mixing within the Indonesian seas³⁰. Yet it is likely that the same processes that
131 form the ITF stratification also contribute to the relatively large vertical flux of nutrients
132 that support the high primary productivity of the Indonesian seas. Quantitative knowledge
133 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 circulation¹ 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 ($1 \text{ Sv} = 10^6 \text{ m}^3\text{s}^{-1}$) 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 Passage¹². Around 13 Sv was measured in the Makassar Strait inflow¹³ suggesting the remaining 2 Sv is contributed via the north-eastern passages that were not particularly well-resolved²².

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 levels¹¹⁻¹³ 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 ITF³³. 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. Inter-ocean heat transfer through the Indonesian Seas had been thought to be surface intensified and warm¹⁰, around 22°C-24°C.

However, the Makassar Strait transport profile was recently shown to have a subsurface maximum⁴ 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 layer³⁸. The increase of the South China Sea throughflow during El Niño also induces a cooler ITF¹³. 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 passage³⁹.

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 range¹³. 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 throughflow¹³. 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 period³⁶. 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 1970s⁴⁰ 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 shifts³⁹. A corresponding surface warming, subsurface cooling and net decrease in the volume

203 transport was observed where the ITF enters into the Indian Ocean⁴¹. A companion study
204 of 20th century simulations from a suite of IPCC AR4 models showed subsurface cooling
205 in the tropical Indian Ocean was consistent with shoaling of the thermocline and
206 increased vertical stratification⁴². Although the coarse grid spacing of these climate
207 models did not fully resolve the narrow Indonesian passages, a majority of the models
208 confirmed this trend was linked to the observed weakening of the Pacific tradewinds and
209 transmitted by the ITF⁴². The ITF profile changes resulted in the decreasing heat content
210 and falling sea level in an isolated zonal band of the Indian Ocean that are at odds with
211 trends in the rest of the basin over the late 20th century^{43,44}. Since the early 1990s, the
212 Indian Ocean cooling trend has reversed⁴⁴ in response to a gradual intensification of the
213 Pacific easterlies increasing the sea level in the western tropical Pacific^{44,45}. As a
214 consequence models and proxy-derived transports have indicated a significant increase in
215 the ITF^{36,44,46-48} from the early 1990s through the first decade of the 21st century.

216 It is worth remembering that these decadal changes are embedded within much
217 longer-term secular trends of the climate system. Most anthropogenic climate change
218 simulations predict a weakening of the Walker Circulation in response to a warming
219 world⁴⁹ and so project a decrease in the ITF transport⁵⁰. This would likely have similar
220 impacts on the Indian Ocean thermocline structure and sea level as observed when
221 analogous conditions prevailed during the late 20th century. What remains unclear is how
222 these changes in the Indian Ocean might impact the downstream Agulhas Current system
223 and perhaps even the Atlantic Meridional Overturning Circulation¹. The connectivity
224 between the ITF and the Agulhas system has remained fairly elusive, at least in terms of
225 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 period⁶.

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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Acknowledgements:

The material is partially based upon work supporting J.S. by the National Aeronautics and Space Administration (NASA) under award No. NNX13AO38G. ALG support is derived from NA08OAR4320754 from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce. The research was carried out in part by TL at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. SEW was partly funded by the Australian Climate Change Science Program.

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 ($^{\circ}\text{C}$; 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 parameterization¹⁴. High OLR values imply increased cloudiness and likely increased precipitation. Differences in **b**, SST ($^{\circ}\text{C}$) 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 Strait¹³. 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.

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a) OLR

b) SST anomaly

c) Rain anomaly