AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2014GL060593

Key Points:

- First quantification of Indonesian throughflow (ITF) nutrient fluxes
- Shallow ITF nutricline drives large nutrient flux to Indian Ocean thermocline
- ITF outflow large enough to support a significant amount of new production

Supporting Information:

- Readme
- Table S1
- Figure S1
- Figure S2
- Figure S3

Correspondence to:
J. M. Ayers,
jennifer.ayers@utas.edu.au

Citation:
Ayers, J. M., P. G. Strutton, V. J. Coles, R. R. Hood, and R. J. Matear (2014), Indonesian throughflow nutrient fluxes and their potential impact on Indian Ocean productivity, *Geophys. Res. Lett.*, *41*, 5060–5067, doi:10.1002/2014GL060593.

Received 19 MAY 2014
Accepted 28 JUN 2014
Accepted article online 1 JUL 2014
Published online 17 JUL 2014

Indonesian throughflow nutrient fluxes and their potential impact on Indian Ocean productivity

Jennifer M. Ayers[1,2,3], Peter G. Strutton[1,2], Victoria J. Coles[4], Raleigh R. Hood[4], and Richard J. Matear[5]

[1]Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia, [2]Australian Research Council Centre of Excellence for Climate System Science, University of Tasmania, Hobart, Tasmania, Australia, [3]Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California, USA, [4]Horn Point Laboratory, University of Maryland Center for Environmental Science, Cambridge, Maryland, USA, [5]CSIRO, Hobart, Tasmania, Australia

Abstract The Indonesian throughflow (ITF) is a chokepoint in the upper ocean thermohaline circulation, carrying Pacific waters through the strongly mixed Indonesian Seas and into the Indian Ocean. Yet the influence of the ITF on biogeochemical fluxes into the Indian Ocean is largely unknown. This study determines the first depth- and time-resolved nitrate, phosphate, and silicate fluxes at the three main exit passages of the ITF: Lombok Strait, Ombai Strait, and Timor Passage. Nutrient flux as well as its variability with depth and time differs greatly between the passages. We estimate the effective flux of nutrients into the Indian Ocean by accounting for existing nutrients in the basin and find it largest in the upper 300–400 m. This suggests that the majority of ITF nutrient supply to the Indian Ocean is to thermocline waters, where it is likely to support new production and significantly impact Indian Ocean biogeochemical cycling.

1. Introduction

The Indonesian throughflow (ITF) is the passage of seawater westward from the Pacific Ocean, through the Indonesian Seas, and into the Indian Ocean at low latitudes. This inflow is a unique feature of the Indian Ocean basin and impacts both ocean currents and basin-scale biogeochemistry [*Talley and Sprintall*, 2005; *van Sebille et al.*, 2014]. Flow through the ITF feeds the South Equatorial Current (SEC), contributes to the anomalous southward flowing Leeuwin Current, feeds the Agulhas Current on the western side of the basin, and impacts the Indian Ocean Eastern Gyral Current [*Menezes et al.*, 2013], among others.

The ITF has been the subject of numerous field and modeling studies over the last 30 years focused on characterizing the volume transport and its variability [see *Godfrey*, 1996; *Sprintall et al.*, 2009; *Gordon et al.*, 2010, and references cited therein]. Quantification of mass, heat, and salt transports through the ITF is crucial for developing a complete understanding of the global thermohaline circulation as well as the near-surface circulation in both the Pacific and Indian Oceans. Present estimates suggest that the transport through the ITF varies between ~10 and 14 Sverdrups with most of the flow exiting through Lombok Strait, Ombai Strait, and Timor Passage [*Sprintall et al.*, 2009]. Variations in the ITF transport manifest seasonally and interannually in response to local forcing from the Monsoon winds and remote forcing from planetary waves [*Schott and McCreary*, 2001; *Schott et al.*, 2009].

In marked contrast to the numerous studies on volume transport, there has been little to no research on nutrient fluxes through the ITF, though nutrient distributions in the Indian Ocean and Indonesian Seas have been mapped and studied by several previous authors [e.g., *Broecker et al.*, 1986; *Van Bennekom and Muchtar*, 1988; *Levitus et al.*, 1993]. *Talley and Sprintall* [2005] mapped silicate on the 31.96 σ_1 density surface, revealing a striking silicate maximum in the South Equatorial Current that highlights the broad reach of ITF nutrients into the Indian Ocean. The same study offers the only quantification of nutrient flux through the ITF, in the form of time- and depth-averaged convergences of oxygen and silicate (as well as heat and salt) in the Indonesian Seas.

Quantifying ITF nutrient fluxes is crucial for understanding the nutrient budgets of the Indian Ocean. Some important questions to be addressed include: Are the fluxes of nitrate, phosphate, and silicate from the Indonesian Seas large enough to have a significant impact on production in the Indian Ocean? How are these fluxes distributed between the exit passages of Lombok Strait, Ombai Strait, and Timor Passage? How much do they vary seasonally, interannually, and with depth? Could the influx of nutrients through the ITF impact nutrient ratios in the Indian Ocean and therefore influence nutrient limitation patterns?

10.1002/2014GL060593

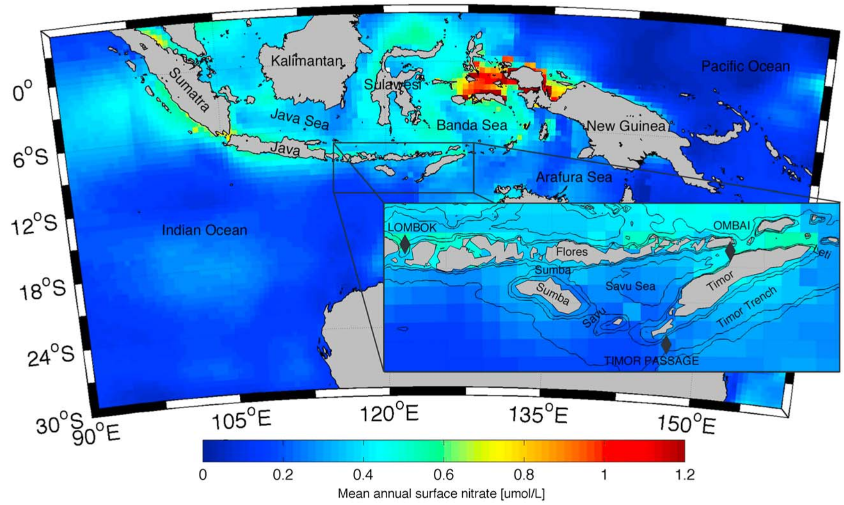

Figure 1. Map of the Indonesian archipelago with surface nitrate concentration. Enlarged insert shows the location of the three exit straits of the Indonesian throughflow (Lombok, Ombai, and Timor Passage) in which nutrient fluxes are calculated.

To address these questions, we calculate the nitrate, phosphate, and silicate flux from the Indonesian throughflow into the Indian Ocean in Lombok Strait, Ombai Strait, and Timor Passage (Figure 1). We use a 3 year, mooring-derived time series of volume transport along with independently measured nutrient concentrations. These calculations reveal that the ITF delivers significant nitrate, phosphate, and silicate to the Indian Ocean with large temporal- and depth-dependent variability.

2. Data and Methods

2.1. Traditional Nutrient Fluxes

We calculated depth-resolved nutrient fluxes (nitrate, phosphate, and silicate) into the Indian Ocean at the three exit passages of the ITF (Lombok Strait, Ombai Strait, and Timor Passage) daily over the 3 year (2004–2006) period of the INSTANT program [*Sprintall et al.*, 2004] as follows:

$$F = \int_0^B [\, v(z) \times C_{ITF}(z) \,] dz \quad (1)$$

where v is the cross-strait integrated volumetric flux, C_{ITF} is the average nutrient concentration in each ITF passage, z is the depth with 10 m spacing, B is the bottom or sill depth, and F is the cross-strait integrated nutrient flux.

Volumetric fluxes were determined by *Sprintall et al*. [2009] from the INSTANT mooring array velocity data. We determined daily, depth-resolved nutrient concentrations using the INSTANT mooring temperature data in conjunction with best-fit polynomials to temperature-nutrient relationships generated from the CARS (CSIRO Atlas of Regional Seas) 2009 data set [*Ridgway et al*., 2002; *Condie and Dunn*, 2006] (Figure S1 and Table S1 in the supporting information).

The average temperature profile in each strait was determined as the mean of the individual mooring temperature profiles, as there are multiple moorings per strait. The upper ~100 m for which there are no mooring temperature data were filled in with the CARS annual cycle. As the shallowest mooring temperature data were cooler on average than the CARS data at the same depth (a mean difference of −0.8°C in Timor passage and −3.1°C in both Lombok and Ombai Straits), we offset the CARS temperature data by the time-varying difference for each strait. This offset is unlikely to significantly impact the flux calculations, as due to biological uptake, nutrients are low in upper waters (for instance, in Lombok Strait the average concentration of nitrate is 7.3 μmol/m^3 in the upper 100 m, and 21.5 μmol/m^3 from 100 m to the 300 m sill depth).

The nutrient flux uncertainty is dominated by the volume flux uncertainty. Volume flux uncertainty results primarily from its cross-strait integration: the need to interpolate instrument velocities between the moorings and also extrapolate the velocities to the side walls. *Sprintall et al*. [2009] considered a number of possible

10.1002/2014GL060593

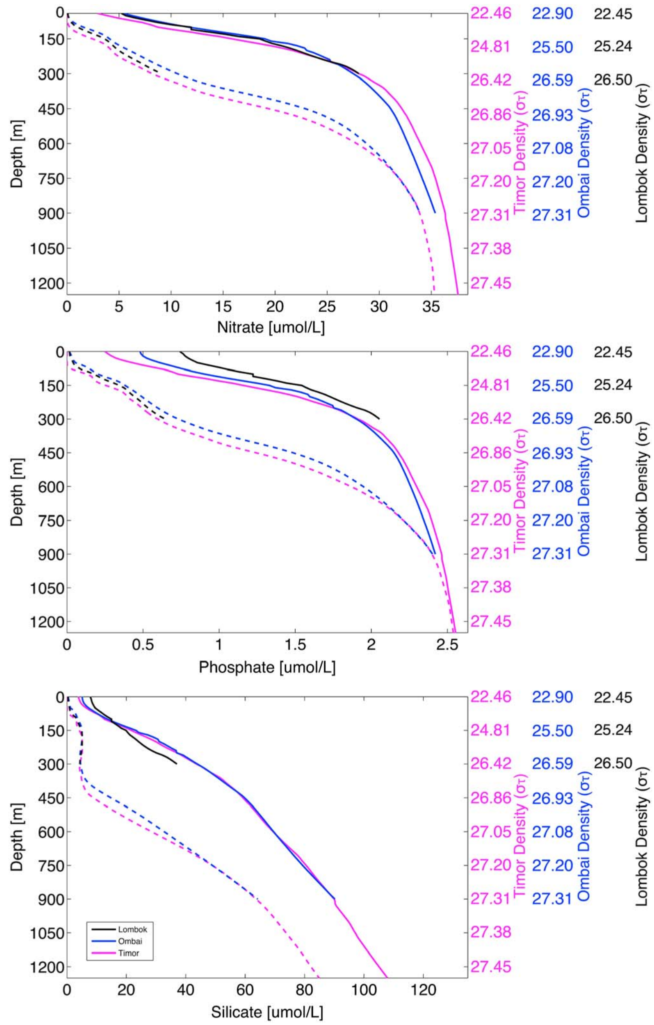

Figure 2. Mean nutrient concentrations for Lombok Strait, Ombai Strait, and Timor Passage (black, blue, and magenta solid lines, respectively) and corresponding nutrient profiles in the background region of the Indian Ocean (black, blue, and magenta dotted lines, respectively). Nutrient profiles for each strait are readable on both the left (depth) and right (density) *y* axes. Background Indian Ocean nutrient profiles are shown for each passage's density profile and readable only with density (right *y* axis).

methods to accomplish this and presented their best estimate along with the range of transport values given by the various methods. Here we calculate nutrient fluxes using each of these different transports, and similarly report the best estimate along with uncertainty as the range of nutrient fluxes resulting from the transport schemes.

We present nutrient fluxes calculated in this traditional manner for consistency with previous estimates of volume, heat, and salt. However, these nutrient fluxes are not relevant to our goal of quantifying the net impact of the ITF on Indian Ocean biogeochemistry and primary production without the context of the ambient Indian Ocean nutrient concentration. To illustrate the problem, consider a simplified scenario in which the nutrient profiles of the Indian Ocean and Indonesian Seas are the same. Regardless of the magnitude of the ITF volume transport, it would produce no net change in Indian Ocean nutrients: waters entering the Indian Ocean would simply displace existing waters with the same nutrient characteristics. As our interest is in quantifying the importance of the ITF on the Indian Ocean nutrient budget, we present what we refer to as "effective" nutrient fluxes, described next.

2.2. Effective Nutrient Fluxes

Effective nutrient fluxes are calculated as follows:

$$F = \int_0^B [v(z) \times (C_{\mathrm{ITF}}(z) - C_{\mathrm{IO}}(\rho_{\mathrm{ITF}}(z)))]\,\mathrm{d}z \qquad (2)$$

where variables are as in equation (1), and $C_{\mathrm{ITF}}(z) - C_{\mathrm{IO}}(\rho_{\mathrm{ITF}}(z))$ is the nutrient anomaly, or difference, between the nutrient concentration in the given Indonesian strait at depth z, and the background nutrient concentration in the Indian Ocean calculated within the same density waters as those of depth z in the Indonesian strait ($\rho_{\mathrm{ITF}}(z)$).

As our purpose is to investigate how ITF nutrients influence the Indian basin generally, we make the simplest conceptual choice for the background nutrient concentrations and define them as the average over a large region of the Indian Ocean oligotrophic subtropical gyre (65–80°E and 18–23°S). This region is chosen to be outside of the immediate pathway of ITF waters, which flow zonally westward across the basin primarily between ~8 and 18°S [*Talley and Sprintall*, 2005; *van Sebille et al.*, 2014], and also to cross a World Ocean Circulation Experiment (WOCE) line at 20°S, for improved coverage of nutrient observations. Implicit in this methodology is the assumption that ITF waters will mix with or replace waters of the same density in this "background" region of the Indian Ocean, on some timescale. As the transport from the ITF to the central Indian basin is not instantaneous, we use mean annual data from CARS 2009 for determining the background nutrient values.

10.1002/2014GL060593

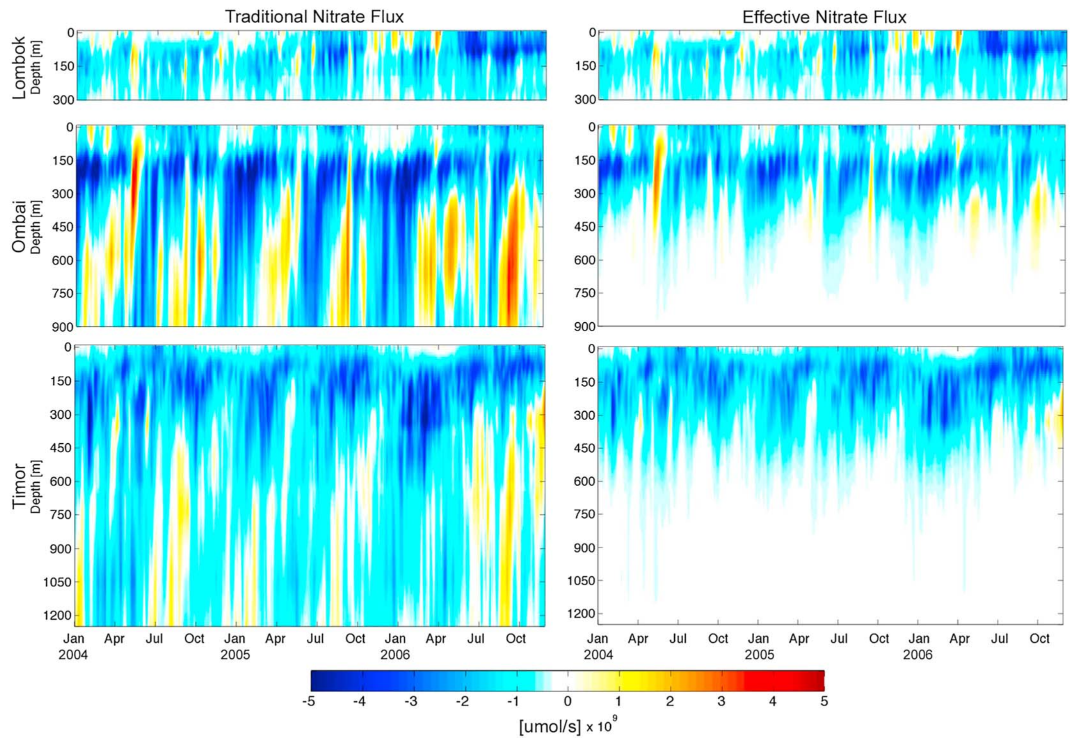

Figure 3. (left) Traditional and (right) effective nitrate fluxes for Lombok Strait, Ombai Strait, and Timor Passage. Fluxes are shown down to the sill depth for each passage and with a daily temporal resolution over the 3 years of the INSTANT time series.

Figure 2 shows the mean nutrient profiles for each strait as well as for the background region of the Indian Ocean. The difference between the ITF and the background nutrient profiles, due largely to the shallower nutricline in the Indonesian Seas, drives the effective flux.

3. Indonesian Throughflow Nutrient Fluxes

Hovmöller plots of the traditional and effective nitrate fluxes for Lombok Strait, Ombai Strait, and Timor Passage are shown in Figure 3. The traditional nitrate flux has a number of notable characteristics. Ombai and Timor passages show strong reverse fluxes at depth, indicating nutrient transport from the Indian Ocean back into the Indonesian Seas. This feature is absent in shallow Lombok Strait. These deep reverse fluxes are driven by the transport, thought to be forced by Kelvin waves originating in the equatorial Indian Ocean [*Sprintall et al.*, 2009]. The main timescale of flux variability is seasonal, due to the dominance of reversing monsoon winds in the region.

The primary difference between the traditional and effective nutrient fluxes is that the deep reverse fluxes are nearly absent in the effective flux. The effective fluxes are largest at mid-depths, from just below the surface to ~300–400 m. In the highly mixed Indonesian Seas the nutricline is elevated relative to that in the subtropical gyre, creating a large nutrient difference in these lighter density waters (see Figure 2) and thus a large effective flux. In contrast, the effective fluxes are small to negligible at depth, as deep, dense waters in both locations have similarly high nutrient concentrations. The exception to this is silicate, which is enriched in the Indonesian Seas relative to the Indian Ocean throughout the water column, resulting in significant effective fluxes even at depth.

Though only nitrate graphs are shown, the traditional and effective fluxes for all nutrients (nitrate, phosphate, and silicate) were calculated in the three exit passages of the ITF and are listed in Table 1. Nutrient fluxes are listed integrated down to the functional sill depths used by *Talley and Sprintall* [2005] for each strait, as the moorings are not all located on or near the sills. The Lombok sill is at 300 m. The functional sill depth for Ombai is 900 m, which is the minimum sill depth at Sumba Strait, one of two straits downstream of Ombai through which the ITF exits the Savu Sea into the Indian Ocean (see Figure 1). For Timor Passage, the sill which controls flow exiting the Indonesian Seas is that of Leti Strait at 1250 m, located on the eastern end of the Timor Trench.

Table 1. Indonesian Throughflow Nutrient Fluxes[a]

	Nitrate (10^{10} μmol/s)		Phosphate (10^{9} μmol/s)		Silicate (10^{11} μmol/s)	
	Traditional	Effective	Traditional	Effective	Traditional	Effective
	Flux; Uncertainty	Flux; Uncertainty	Flux; Uncertainty	Flux; Uncertainty	Flux; Uncertainty	Flux; Uncertainty
Lombok Strait to 300 m						
2004	−2.45; −1.84 to −2.57	−2.07; −1.56 to −2.18	−2.47; −1.89 to −2.72	−2.08; −1.61 to −2.33	−0.31; −0.24 to −0.34	−0.26; −0.20 to −0.29
2005	−2.97; −2.24 to −3.00	−2.52; −1.91 to −2.54	−2.92; −2.22 to −2.96	−2.44; −1.86 to −2.49	−0.37; −0.28 to −0.38	−0.31; −0.23 to −0.31
2006	−4.74; −3.57 to −4.76	−4.02; −3.04 to −4.04	−4.54; −3.44 to −4.57	−3.74; −2.84 to −3.77	−0.59; −0.44 to −0.59	−0.47; −0.35 to −0.47
Annual mean	−3.36; −2.53 to −3.42	−2.85; −2.15 to −2.90	−3.29; −2.50 to −3.40	−2.74 −2.09 to −2.85	−0.42; −0.32 to −0.43	−0.34; −0.26 to −0.36
Ombai Strait to 900 m						
2004	−9.41; −4.98 to −9.42	−5.18; −2.76 to −5.18	−6.69; −3.53 to −6.69	−3.58; −1.90 to −3.58	−1.56; −0.82 to −1.56	−1.12; −0.59 to −1.12
2005	−12.13; −6.64 to −12.13	−5.88; −3.24 to −5.88	−8.58; −4.68 to −8.58	−4.11; −2.25 to −4.11	−2.09; −1.14 to −2.09	−1.42; −0.78 to −1.42
2006	−6.65; −3.45 to −6.65	−4.64; −2.51 to −4.64	−4.88; −2.52 to −4.88	−3.26; −1.74 to −3.26	−0.96; −0.49 to −0.96	−0.73; −0.37 to −0.73
Annual mean	−9.46; −5.06 to −9.47	−5.25; −2.85 to −5.25	−6.76; −3.60 to −6.76	−3.66; −1.97 to −3.66	−1.55; −0.83 to −1.55	−1.10; −0.58 to −1.10
Timor Passage to 1250 m						
2004	−13.68; −12.79 to −18.56	−7.13; −6.67 to −9.69	−9.86; −9.13 to −13.43	−5.08; −4.68 to −6.94	−2.51; −2.32 to −3.42	−1.56; −1.46 to −2.09
2005	−13.77; −12.88 to −18.65	−7.21; −6.79 to −9.83	−9.97; −9.20 to −13.56	−5.19; −4.77 to −7.10	−2.53; −2.34 to −3.44	−1.58; −1.48 to −2.12
2006	−12.42; −11.33 to −16.83	−7.17; −6.48 to −9.68	−9.17; −8.20 to −12.45	−5.27; −4.60 to −7.11	−2.22; −2.00 to −3.02	−1.46; −1.31 to −1.95
Annual mean	−13.31; −12.36 to −18.04	−7.17; −6.66 to −9.73	−9.68; −8.85 to −13.16	−5.18; −4.68 to −7.05	−2.42; −2.22 to −3.30	−1.54; −1.42 to −2.06
Total, all straits	−26.13; −19.95 to −30.93	−15.27; −11.66 to −17.88	−19.73; −14.95 to −23.32	−11.58; −8.74 to −13.56	−4.34; −3.37 to −5.28	−2.98; −2.26 to −3.52

[a]Negative indicates a westward flux into the Indian Ocean. Integration depths are the functional sill depths for each strait.

Overall the effective fluxes are notably smaller than the traditional fluxes, with the difference varying from strait to strait. In shallow Lombok Strait, the mean effective nitrate, phosphate, and silicate fluxes are only 15–20% smaller than the traditional flux. However, in deeper Ombai Strait and Timor Passage, the effective nitrate and phosphate fluxes are 30–52% smaller, and the effective silicate flux 30–38% smaller, than the traditional nutrient fluxes. The difference between the effective and traditional flux is less for silicate than for nitrate and phosphate due to the enrichment of silicate at all depths in the Indonesian Seas relative to the Indian Ocean (see Figure 2).

In addition to being smaller, the effective nutrient fluxes are less variable than the traditionally calculated nutrient fluxes. This can readily be seen in Figure 4, which shows the same fluxes as Figure 3, but now depth-integrated to highlight different features. The decreased variability is due to the effective fluxes accounting for the lack of significant deep water nutrient differences between the ITF and the Indian Ocean, which removes the deep reverse nutrient exchange seen in the traditional fluxes. In Ombai Strait, traditional nitrate and phosphate fluxes vary interannually by 27–29% of the annual mean, while the effective fluxes vary by only 12% of the annual mean. For Timor Passage nitrate and phosphate, the interannual variability drops from 4–5% of the annual mean for traditional fluxes to 1–3% for effective fluxes. Again, silicate is slightly different due to its elevated deep values in the ITF and exhibits higher interannual variability in effective flux than the other nutrients, though this variability still remains below that of the traditional flux. Lombok Strait does not exhibit these marked differences between effective and traditional nutrient flux variability, primarily because in the absence of the deep, seasonally reversing transports, the traditional flux in this shallow strait is less variable to begin with.

10.1002/2014GL060593

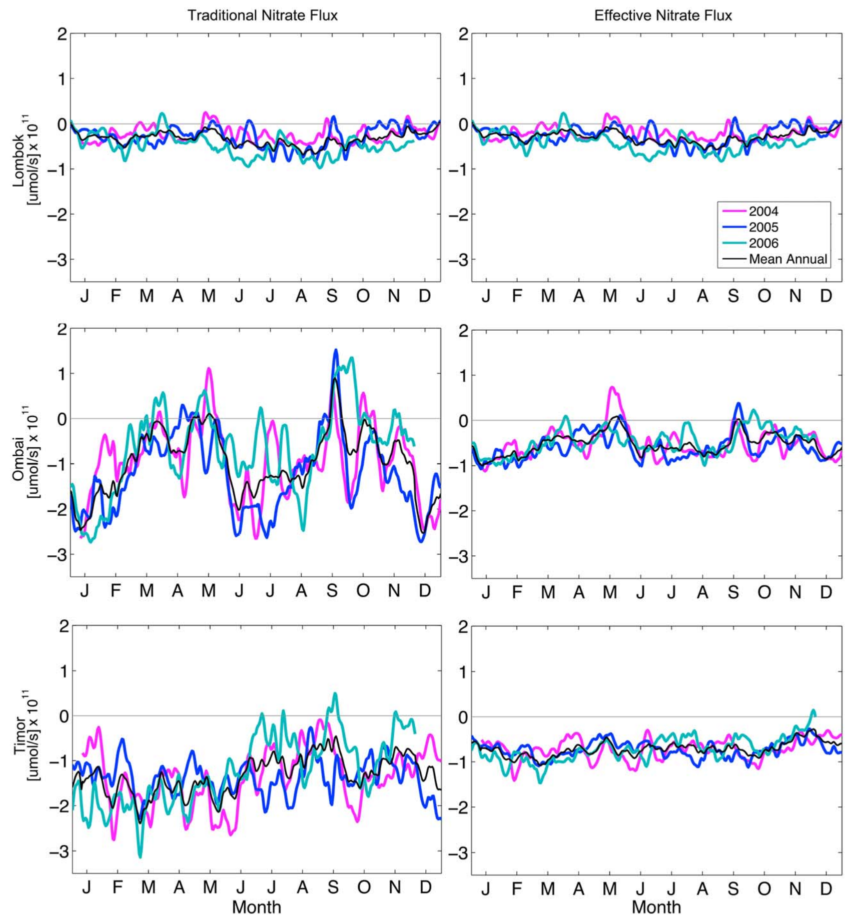

Figure 4. (left) Traditional and (right) effective nitrate fluxes as in Figure 2, now integrated to the sill depths but resolved in time. The effective nitrate flux is notably less variable on seasonal and interannual timescales.

Finally, comparing our traditional silicate flux numbers to *Talley and Sprintall* [2005] reveals ours to be ~30% lower. The discrepancy is likely explained by the fact that the largest volume flux occurs in surface waters where nutrients are depleted, which is unaccounted for in the depth-averaged estimates of Talley and Sprintall.

4. Variability With Indian and Pacific Climate Modes

The considerable interannual variability seen in the nutrient fluxes appears linked in part to forcing associated with the major climate modes of the Indian and Pacific Oceans. Table 2 shows correlations between the volume and nutrient fluxes through the exit passages of the ITF, and the Indian Ocean Dipole (IOD) and Multivariate ENSO (El Niño–Southern Oscillation) Index (MEI), significant at $p < 0.05$. Correlations were determined using detrended and deseasonalized monthly data. Previous studies have shown that the volume transport through different passages of the ITF reacts differently to wind forcing associated with the climate modes [*England and Huang*, 2005; *Sprintall et al.*, 2009; *van Sebille et al.*, 2014], and the same is seen in the nutrient fluxes.

In times of positive IOD and positive MEI (El Niño events), volume and nutrient fluxes through Lombok Strait increase (a negative correlation, as southward fluxes are negative), while the opposite occurs in Timor passage. The response of the water column to these conditions can be seen in Figure 3, beginning in April 2006 and lasting through the end of the time series. The stratified response of the water column drives the differing responses of the passages: in Ombai and Timor, nutrient fluxes to the Indian Ocean decrease as the deep reverse flows strengthen; in shallow Lombok, surface nutrient fluxes toward the Indian Ocean increase and dominate the signal.

Attributing interannual variability to climate modes is done noting two caveats: the INSTANT field program provides a relatively short 3 year time series with which to correlate climate modes; and, while 2006 was a strong

Table 2. Correlations With the Indian Ocean Dipole (IOD) and the Multivariate ENSO Index (MEI Index)[a]

	Lombok		Ombai		Timor		Total	
	R	P	R	P	R	P	R	P
Transport								
IOD	−0.37	0.03	0.50	0.00	0.51	0.00	0.53	0.00
MEI	−0.39	0.02	–	–	0.62	0.00	0.41	0.01
Traditional nutrient fluxes								
IOD	−0.40	0.01	0.55	0.00	0.50	0.00	0.63	0.00
MEI	−0.39	0.02	0.33	0.05	0.56	0.00	0.52	0.00
Effective nutrient fluxes								
IOD	−0.40	0.02	0.36	0.03	0.51	0.00	0.34	0.04
MEI	−0.39	0.02	–	–	0.56	0.00	–	–

[a]Negative transport (and also negative nutrient flux) values indicate westward flow into the Indian Ocean. Correlations are monthly with 0 lag, as this was the most significant lag time. Correlations not significant at $p < 0.05$ are shown with a dash symbol.

positive IOD event, no significant ENSO events occurred during the deployment. A second series of mooring deployments in the ITF is currently underway, supported by Australia's Integrated Marine Observing System (IMOS) and may give a clearer picture as to the ITF transport and nutrient response to these events.

5. Broader Implications: Nutrient Cycling and Primary Production

The Indonesian throughflow influences Indian Ocean biogeochemistry by supplying an effective or net flux of nutrients primarily to thermocline waters (see Figure 3). A comparison of N:P ratios in the ITF and Indian Ocean (Figure S2) shows the ITF to be relatively richer in nitrate. Mean N:P ratios from the surface to the sill depths in Lombok, Ombai, and Timor Passage are 10.5, 13.9, and 14.0, respectively, while the N:P ratios corresponding to the same density profiles in the Indian Ocean are 8.4, 12.8, and 13.2. This indicates that the ITF acts to enrich the nitrate to phosphate ratio of the Indian Ocean thermocline, though it remains below Redfield (16N:1P).

How the ITF compares to other potentially large sources of nutrients to the Indian Ocean such as Antarctic Intermediate Waters [*Talley and Sprintall*, 2005], Subantarctic Mode Waters [*Sarmiento et al.*, 2004; *Ayers and Strutton*, 2013] and the Tasman Leakage [*van Sebille et al.*, 2014] is not yet quantitatively known. However, one way to think about the impact of ITF nutrients on the Indian Ocean is in terms of how much new production it could potentially support. We calculated an effective nitrate supply from the ITF to the Indian Ocean of 1.53×10^{11} μmol N s^{-1}, equivalent to 8.76×10^{13} mmol C day^{-1} via a Redfield ratio of 106C:16N. For an idea of scale, this is the new productivity in an area 1.46×10^{7} km^{2} (5–6 times as large as the Mediterranean Sea), determined using primary productivity estimates from the Vertically Generalized Production Model [*Behrenfeld and Falkowski*, 1997] and an approximate *f*-ratio of 0.15 (Figure S3). We do not suggest that the entire ITF nutrient flux is available to Indian Ocean primary producers but make this comparison to demonstrate that ITF nutrient supply to the Indian Ocean is large enough to be of consequence.

Finally, we have addressed the question of the rate at which nutrients exit the Indonesian Seas but have not asked the equally interesting question as to their origin. Are the nutrients primarily flow-through from the western Pacific, or might a substantial portion originate from depth in the Indonesian Seas, brought to the surface by upwelling and strong mixing? Land masses may also be a source of nutrients, though a cursory look suggests riverine contribution likely to be small. *Alongi et al*. [2013] estimated nitrogen runoff into the Timor and Arafura Seas to be 2.9×10^{6} t N yr^{-1}. This is equivalent to only about 5% of our estimates for downstream nitrogen flux through Timor Passage (from Table 1, 13.31×10^{10} μmol N s^{-1}, equivalent to 5.9×10^{7} t N yr^{-1}). The origin of nutrients exiting the ITF is left as a topic for future studies.

6. Conclusion

Though Indonesian throughflow nutrients are thought to exert significant influence on Indian Ocean biogeochemistry, these nutrient fluxes had not been previously quantified. Here we present the first depth- and time-resolved fluxes of nitrate, phosphate, and silicate, calculated in the three passages where the ITF exits the Indonesian Seas and enters the Indian Ocean. To more meaningfully describe the change in Indian Ocean nutrients due to the influence of the ITF, we calculated effective nutrient fluxes, using the isopycnal nutrient anomaly between each exit passage and an area of the greater Indian Ocean. Effective nutrient fluxes are roughly half as large as the traditional nutrient fluxes and less variable in time, suggesting that considering only traditional nutrient fluxes would significantly overestimate the magnitude and variability of the ITF nutrient influence on the Indian Ocean. Intense mixing in the marginal seas shoals the nutricline in the ITF relative to the Indian Ocean, resulting in effective fluxes that are largest in the upper ~300–400 m. Thus, the Indonesian throughflow works to enrich the thermocline nutrient pool and is estimated large enough to support a substantial amount of downstream new production. As ITF nutrient fluxes are likely to significantly impact biogeochemical cycling in the Indian Ocean, they should be accounted for in biogeochemical models. We suggest future studies should examine the magnitude and spatial distribution of their effects.

Acknowledgments

All data used are publicly available. Data from the INSTANT field program are available at http://www.marine.csiro.au/~cow074/index.htm. The CSIRO CARS 2009 data can be found here: http://www.marine.csiro.au/~dunn/cars2009/. Behrenfeld and Falkowski productivity data are here: http://www.science.oregonstate.edu/ocean.productivity/. Our calculated traditional and effective fluxes, shown in Figure 3, are available from the Australian Oceans Data Network (AODN; http://mest.imas.utas.edu.au/geonetwork/srv/en/metadata.show?uuid=2a569d7c-7b10-4c52-9bea-c95ce6df86db). The authors thank Janet Sprintall of Scripps Institution of Oceanography for comments that improved our manuscript and Rebecca Cowley of CSIRO for assistance with the INSTANT data. The work of J. Ayers and P. Strutton was supported by the Australian Research Council Centre of Excellence for Climate System Science. Funding for R. Matear was provided by CSIRO, through the Wealth from Oceans National Research Flagship and through the Royal Australian Navy. R. Hood was supported by a Frohlich Fellowship from CSIRO.

The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

References

Alongi, D. M., M. de Silva, R. J. Wasson, and S. Wirasantosa (2013), Sediment discharge and export of fluvial carbon and nutrients into the Arafura and Timor Seas: A regional synthesis, *Mar. Geol.*, *343*, 146–158, doi:10.1016/j.margeo.2013.1007.1004.

Ayers, J. M., and P. G. Strutton (2013), Nutrient variability in Subantarctic Mode Waters forced by the Southern Annular Mode and ENSO, *Geophys. Res. Lett.*, *40*, 3419–3423, doi:10.1002/grl.50638.

Behrenfeld, M. J., and P. G. Falkowski (1997), Photosynthetic rates derived from satellite-based chlorophyll concentration, *Limnol. Oceanogr.*, *42*, 1–20, doi:10.4319/lo.1997.42.1.0001.

Broecker, W. S., W. C. Patzert, J. R. Toggweiler, and M. Stuiver (1986), Hydrography, chemistry, and radioisotopes in the Southeast Asian basins, *J. Geophys. Res.*, *91*(C12), 14,345–14,354, doi:10.1029/JC09liC12p14345.

Condie, S. A., and J. R. Dunn (2006), Seasonal characteristics of the surface mixed layer in the Australasian region: Implications for primary production regimes and biogeography, *Mar. Freshwater Res.*, *57*, 1–22.

England, M. H., and F. Huang (2005), On the interannual variability of the Indonesian Throughflow and its linkage with ENSO, *J. Clim.*, *18*, 1435–1444.

Godfrey, J. S. (1996), The effect of the Indonesian Throughflow on ocean circulation and heat exchange with the atmosphere: A review, *J. Geophys. Res.*, *101*, 12,217–12,237, doi:10.1029/95JC03860.

Gordon, A., J. Sprintall, H. M. Van Aken, D. Susanto, S. Wijffels, R. Molcard, A. Ffield, W. Pranowo, and S. Wirasantosa (2010), The Indonesian throughflow during 2004–2006 as observed by the INSTANT program, *Dyn. Atm. Ocean.*, *50*, 115–128, doi:10.1016/j.dynatmoce.2009.1012.1002.

Levitus, S., M. E. Conkright, J. L. Reid, R. G. Najjar, and A. Mantyla (1993), Distribution of nitrate, phosphate and silicate in the world oceans, *Prog. Ocean.*, *31*(3), 245–273, doi:10.1016/0079-6611(1093)90003-V.

Menezes, V. V., H. E. Phillips, A. Schiller, C. M. Domingues, and N. L. Bindoff (2013), Salinity dominance on the Indian Ocean Eastern Gyral current, *Geophys. Res. Lett.*, *40*, 5716–5721, doi:10.1002/2013GL05788.

Ridgway, K. R., J. R. Dunn, and J. L. Wilkin (2002), Ocean interpolation by four-dimensional least squares—Application to the waters around Australia, *J. Atmos. Oceanic Technol.*, *19*(9), 1357–1375.

Sarmiento, J. L., N. Gruber, M. A. Brzezinski, and J. P. Dunne (2004), High- latitude controls of thermocline nutrients and low latitude biological productivity, *Lett. Nat.*, *427*, 56–60.

Schott, F. A., and J. P. McCreary (2001), The monsoon circulation of the Indian Ocean, *Prog. Ocean.*, *51*, 1–123, doi:10.1016/S0079-6611(01)00083-0.

Schott, F. A., S.-P. Xie, and J. P. McCreary (2009), Indian Ocean circulation and climate variability, *Rev. Geophys.*, *47*, RG1002, doi:10.1029/2007RG000245.

Sprintall, J., S. Wijffels, A. L. Gordon, A. Ffield, R. Molcard, R. D. Susanto, I. Soesilo, J. Sopaheluwakan, Y. Surachman, and H. M. vanAken (2004), INSTANT: A new international array to measure the Indonesian Throughflow, *Eos Trans. AGU*, *85*(39), 369–376, doi:10.1029/2004EO390002.

Sprintall, J., S. E. Wijffels, R. Molcard, and I. Jaya (2009), Direct estimates of the Indonesian Throughflow entering the Indian Ocean: 2004–2006, *J. Geophys. Res.*, *114*, C07001, doi:10.1029/2008JC005257.

Talley, L. D., and J. Sprintall (2005), Deep expression of the Indonesian Throughflow: Indonesian Intermediate Water in the South Equatorial Current, *J. Geophys. Res.*, *110*, C10009, doi:10.1029/2004JC002826.

van Bennekom, A. J., and M. Muchtar (1988), Reactive phosphate in the eastern Indonesian seas, *Neth. J. Sea Res.*, *22*(4), 361–367, doi:10.1016/0077-7579(88)90006-3.

van Sebille, E., J. Sprintall, F. U. Schwarzkopf, A. S. Gupta, A. Santoso, M. H. England, A. Biastoch, and C. W. Böning (2014), Pacific-to-Indian Ocean connectivity: Tasman leakage, Indonesian Throughflow, and the role of ENSO, *J. Geophys. Res. Oceans*, *119*, 1365–1382, doi:10.1002/2013JC009525.