Geophysical Research Letters

RESEARCH LETTER
10.1029/2021GL092505

Key Points:

- A strong sub-thermocline intrusion into the Makassar Strait in summer 2016 is drawn from enhanced North Equatorial Subsurface Current (NESC)
- The sub-thermocline water in the Makassar Strait is a mixture of intermediate-depth waters from the North and the South Pacific Ocean
- The enhancement of the NESC after the extreme 2015/2016 El Niño, is forced by westward and downward propagating baroclinic Rossby waves

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

D. Yuan and Y. Yang,
dyuan@fio.org.cn;
yangya112@mails.ucas.ac.cn

Citation:

Li, M., Yuan, D., Gordon, A. L., Gruenburg, L. K., Li, X., Li, R., et al. (2021). A strong sub-thermocline intrusion of the North Equatorial Subsurface Current into the Makassar Strait in 2016–2017. *Geophysical Research Letters*, *48*, e2021GL092505. https://doi.org/10.1029/2021GL092505

Received 14 JAN 2021
Accepted 24 MAR 2021

A Strong Sub-Thermocline Intrusion of the North Equatorial Subsurface Current Into the Makassar Strait in 2016–2017

Mingting Li[1], Dongliang Yuan[2,3,4], Arnold L. Gordon[5], Laura K. Gruenburg[5], Xiang Li[3], Rui Li[3], Xueli Yin[2,3,4], Ya Yang[2,3], Corry Corvianatie[2,3,4], Jun Wei[1], and Song Yang[1]

[1]School of Atmospheric Sciences and Guangdong Province Key Laboratory for Climate Change and Natural Disaster Studies, Sun Yat-sen University, Zhuhai, China; Southern Marine Science and Engineering Guangdong Laboratory, Zhuha, China, [2]Key Laboratory of Marine Science and Numerical Modeling, First Institute of Oceanography, Ministry of Natural Resources; Function Laboratory for Regional Oceanography and Numerical Modeling, Pilot National Laboratory for Marine Science and Technology (Qingdao), Shandong Key Laboratory of Marine Science and Numerical Modeling, Qingdao, China, [3]Key Laboratory of Ocean Circulation and Waves, Institute of Oceanology, and Center for Ocean Mega-Science, Chinese Academy of Sciences, Function Laboratory for Ocean and Climate, Pilot National Laboratory for Marine Science and Technology (Qingdao), Qingdao, China, [4]University of Chinese Academy of Sciences, Beijing, China, [5]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, USA

Abstract The poorly resolved pathway of the sub-thermocline waters (>300 m) within the Makassar Strait, the primary inflow path of the Indonesian Throughflow, is investigated using in situ mooring measurements and Argo profiles at the entrance to the Indonesian Seas. We focus on the strong sub-thermocline intrusion in the summer of 2016, when significant changes of sub-thermocline transport thrice as large as the interannual standard deviation occurred. Analysis suggests that the intrusion was drawn from the North Equatorial Subsurface Current (NESC) flowing westward below the North Equatorial Countercurrent, which was composed of a mixture of intermediate-depth waters from both the North and South Pacific. The anomalously strong NESC to the Makassar sub-thermocline in the summer 2016 is suggested to be in response to the 2015/2016 extreme El Niño event, forced by the trade wind anomalies over the western-central Pacific Ocean through westward and downward propagating baroclinic Rossby waves.

Plain Language Summary The transfer of waters from the tropical Pacific to the Indian Ocean via the Indonesian Throughflow (ITF), the majority of which flows through the Makassar Strait, plays an important role in global ocean circulation and climate variations. Here, we identify the sources of the sub-thermocline Makassar Strait waters by comparing their water mass properties in the Makassar Strait with those in the gateway region using ship-based and Argo Conductivity-Temperature-Depth data. Traditional understanding of the ITF source water in the Makassar Strait is that it is drawn from the western boundary currents of the tropical Pacific Ocean. Our finding identifies a new zonal pathway for the equatorial waters entering the ITF in the sub-thermocline layer (>300 m) in the summer of 2016, following the strong 2015/16 El Nino event. These results are anticipated to be the beginning of more comprehensive investigations of the Pacific-Indian Ocean sub-thermocline connection.

1. Introduction

The Indonesian Throughflow (ITF) transfers large amount of Pacific waters into the eastern Indian Ocean through the complex passages of the Maritime Continent (Figure 1a), impacting on the water properties and heat content in both oceans (Gordon, 1986; Sprintall et al., 2019). The heat transport of the ITF is sensitive to the vertical profile of the velocities (Gruenburg & Gordon, 2018; Potemra et al., 2003; Song & Gordon, 2004), which is forced by both local and remote forcing. High frequency (intraseasonal to seasonal) variations of the ITF vertical structure are associated with local forcing, propagating downward quickly into the sub-thermocline (Gordon et al., 2003, 2019; Pujiana et al., 2009, 2013). Low-frequencies (seasonal to interannual) variabilities of the ITF deep flows are forced primarily by remote forcing, through the pressure gradient between the western Pacific and eastern Indian Oceans and via the downward propagating

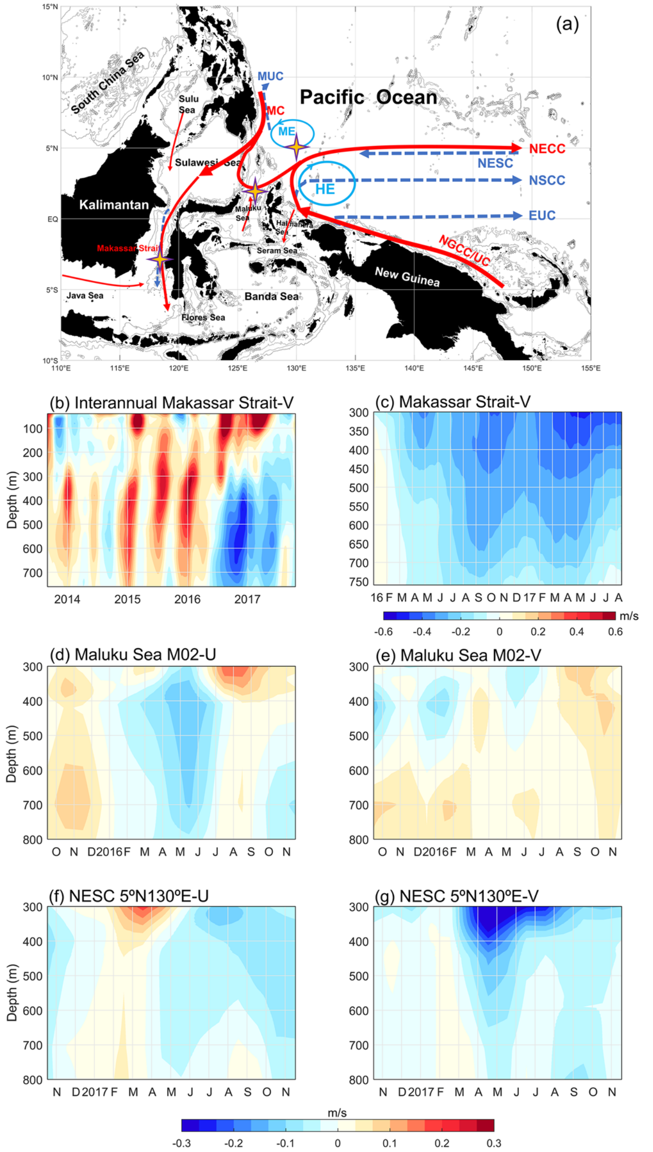


Figure 1. (a) Regional map and ocean circulation schematic of the western Pacific Ocean and Indonesian Seas. The yellow stars in the Makassar Strait, north of the Maluku Sea, and 5°N, 130°E mark the sites of the moorings. (b)–(g) show the moored ADCP measurements. (b) Interannual variations of Makassar Strait throughflow during 2013–2017, with the climatological seasonal cycle from 2004 to 2017 removed (whole time series was shown in Gordon et al., 2019). (c) Along channel velocities (m s^{-1}) measured in the Makassar Strait. Zonal (d) and meridional (e) velocities in the middle Maluku Channel (M02) from September 2015 to November 2016. Zonal (f) and meridional (g) velocities at 5°N, 130°E from October 2016 to November 2017. Negative values indicate southward (westward) velocities. ADCP, Acoustic Doppler Current Profiler.

baroclinic Rossby waves from the Pacific Ocean into the Indonesian seas (Clarke & Liu, 1994; England & Huang, 2005; Liu et al., 2015; Murtugudde et al., 1998; Potemra et al., 1997; Potemra & Schneider, 2007; Wijffels & Meyers, 2004; Wyrtki, 1987; Yuan et al., 2011, 2013).

In the Indonesian seas, both the North and South Pacific waters are identified (Hautala et al., 1996; Waworuntu et al., 2000), which are carried to the entrance of the Indonesian seas by the low-latitude western boundary currents and mixed by the strong nonlinear processes in the gateway region of the ITF (Nof, 1996; Wang and Yuan, 2012, 2014; Yuan & Wang, 2011). The southward Mindanao Current (MC) and the northward New Guinea Coastal Current and Undercurrent (NGCC/NGCUC) meet and retroflect into the North Equatorial Counter Current (NECC), generating the cyclonic Mindanao Eddy and the anticyclonic Halmahera Eddy (Arruda & Nof, 2003; Kashino et al., 2013; Wang and Yuan, 2012). In the subsurface, the NGCUC crosses the equator and retroflects back into the Equatorial Undercurrent (EUC) and the Northern Subsurface Counter Current (NSCC), a.k.a. the Tsuchiya Jets (Tsuchiya et al., 1989). The upper thermocline waters of the ITF come mainly from the MC, originating from the split of the North Equatorial Current (NEC) off the east coasts of the Philippines (Hu et al., 2015; Lukas et al., 1991; Nitani, 1972; Toole et al., 1990). Off the east Australian coasts, the South Equatorial Current (SEC) splits and feeds into the northward flowing NGCC/NGCUC (Hu et al., 2015; Kessler et al., 2019; Lindstrom et al., 1987), which pass by the Halmahera Sea and connect with the ITF in the eastern Indonesian Seas (Cresswell & Luick, 2001; Yuan et al., 2018). The primary transport of the ITF from the North Pacific MC into the Makassar Strait (Du & Qu, 2010; Gordon et al., 2010; Gordon & Fine, 1996; Susanto & Gordon, 2005) underlines the importance of the North Pacific overturning circulation in the formation of the Great Ocean Conveyer Belt (Broecker, 1991; Gordon, 1986). The sub-thermocline throughflow in the Indonesian seas, where the South Pacific influence is present, is of importance to global heat and freshwater budget (Fine et al., 1994; Hautala et al., 1996; Molcard et al., 1994; Waworuntu et al., 2000). To date, the pathway of the South Pacific waters into the Indonesian seas is not clear.

13 years of mooring observations in the Makassar Strait have shown that the average transport of the Makassar Strait throughflow is about 12.5 Sv southward, 75% of which is above the thermocline (upper 300 m, Gordon et al., 2019; Li et al., 2018). Below the thermocline in the Makassar Strait, the transport is small (about 3 Sv) based on mooring observations from 2004 to 2015. Therefore, the sub-thermocline connection between the Pacific and Indian Oceans has not been emphasized before. A strong anomalous intrusion was recorded by the Makassar Strait mooring in the sub-thermocline following the extreme El Niño of 2015/2016 (Gordon et al., 2019), with an increase in sub-thermocline (300–760 m) transport more than twice the long-term average (2004–2017) of 3.4 Sv.

The eastward NECC is located between 2° and 10°N, and above 200 m (Gouriou & Toole, 1993; Hsin & Qiu, 2012; Sverdrup et al., 1942; Wang et al., 2016; Wyrtki, 1961; Yuan et al., 2014). Previous studies have suggested that the NGCC/NGCUC and the SEC carrying South Pacific Tropical Waters westward are prevented from entering the Sulawesi Sea by the retroflection of the MC that joins the NECC (Lukas et al., 1991; Kashino et al., 1996). An indirect pathway above the thermocline has been suggested that some of the retroflected SEC waters join the North Equatorial Current, which are transferred into the Makassar Strait via the MC (Godfrey et al., 1993; Gordon, 1995; Gordon & Fine, 1996; Yang et al., 2018). Mooring observations suggest that, at least in the upper 300 m or so, the currents in the Maluku Channel flow northeastward into the NECC (Yuan et al., 2018). A westward flow beneath the NECC has recently been discovered in the depths from 200 to 900 m between 3° and 7°N (Figure S1), which is named the North Equatorial Subsurface Current (NESC, Yuan et al., 2014), with a mean geostrophic transport of 4.2 Sv at 140°E. Its existence has been confirmed by the latest mooring measurements (X. Li et al., 2020; Wang et al., 2016; Yang et al., 2020). However, the connections between the NESC and the Makassar Strait sub-thermocline currents have not been investigated.

2. Data and Methods

The mooring in the Makassar Strait (118°27.3′E, 2°51.9″S) has recorded 13 years (from January 2004 to August 2011, and from August 2013 to August 2017) of velocities at several depths. A mooring deployed at the entrance of the Sulawesi Sea (5°N, 130°E) from October 2016 to November 2017 in the western equatorial Pacific Ocean has recorded velocities of upper 500 m or so using a upward-looking 75 kHz Acoustic Doppler Current Profiler (ADCP) manufactured by the U.S. RDI company. Another mooring M02 deployed in the middle Maluku Channel (1°59.7′N, 126°29.1′E) from September 2015 through November 2016 has a similar ADCP installed. The sampling interval of the ADCPs is one hour. A Butterworth low-pass filter with a cut-off period of 120 days is applied on the quality-controlled hourly data, which was filtered at a 3-day cut-off period.

The shipboard Conductivity-Temperature-Depth (CTD) data were obtained during cruises in the Makassar Strait, the specific time windows of the measurements are: January 18–19, 2004, July 8–9, 2005, August 2, 2011, June 8–9, 2013, August 14–16, 2015, December 11–13, 2016, and August 20–21, 2017. The Argo profiles during September 4–30, 2016 in the Makassar Strait are used to represent the sub-thermocline waters of the ITF in summer. In addition, Argo profiles in the western Pacific Ocean from 2004 to 2018 are used to map the salinity distributions on isopycnal surfaces using the successive corrections of the objective mapping analysis (Barnes algorithm).

Gridded Argo data from 2004 to 2018 are used to calculate geostrophic currents referenced to the 1,975 m depth of no motion. Geostrophic currents calculated from Argo profiles have been used to investigate transports and variations of NESC in previous studies (X. Li et al., 2020; Yang et al., 2020; Yuan et al., 2014), showing similar structure of mean currents as the SADCP measurements and mooring observations. Additionally, four reanalysis products and model outputs GODAS, SODA3, ECCO2, and OFES (details in Supporting Information) were used to investigate the NESC and the Makassar Strait sub-thermocline connection. The continuous wavelet transform is used in the wavelet analysis, and Morse wavelets is adopted as the mother wavelet (Farge, 1992; Torrence & Compo, 1998).

3. Results

Within the context of 13-year mooring data, the interannual variability of the Makassar Strait currents reveals a strong sub-thermocline (300–760 m) intrusion into the Makassar Strait in 2016–2017 (Figure 1b). In particular, the recorded southward velocities at 300–800 m in the Makassar Strait increased to 0.5 m s^{-1} during the summer of 2016 from northward velocities at the beginning of the year (Figure 1c). The sub-thermocline layer transport of the Makassar Strait increased from southward 3.0–7.5 Sv during 2016–2017, matching the transport above the thermocline, with a change thrice as large as the interannual standard deviation between 2004 and 2017. This sudden change in the Makassar Strait velocity profile was coincident with the decay of the 2015/2016 extreme El Niño into a weak cooling state over the equatorial Pacific.

A mooring (M02) in the middle of the Maluku Channel at 2°N has observed northeastward currents in the summer of 2016 between 300 and 800 m depths (Figures 1d and 1e), which prevent the South Pacific waters in the NGCC/NGCUC from entering the Sulawesi Sea directly. From February 2016 to June 2016, the currents of the northern Maluku Sea (M02) indeed flowed from the Pacific Ocean into the Maluku Sea in the sub-thermocline. However, the currents occurred too early and were too weak to be responsible for the Makassar sub-thermocline intrusion in the summer 2016. The currents in the Makassar Strait sub-thermocline indicate a time lag of about 1–2 months from the far western Pacific to the Labani Channel. In the summer of 2016, the subsurface waters could only enter the Makassar sub-thermocline through the northeastern Sulawesi Sea, via either the MC sub-thermocline currents or the NESC intrusion. The mooring measurements at 5°N, 130°E (Figures 1f and 1g) have shown that the NESC was westward during October–November 2016 and the summer of 2017, suggesting a connection to the Makassar sub-thermocline currents.

The salinity of the Makassar Strait sub-thermocline waters are found too high to be drawn from the North Pacific (Region A in Figure 2). However, it is lower than the salinity of the South Pacific waters in the NGCC/NGCUC (Region C). The T-S diagram of the Argo floats drifting through the Makassar Strait in the summer 2016 shows T-S relations similar to those of the NESC waters in the western Pacific Ocean (Regions B and D in Figure 2b). Observed salinity in the sub-thermocline Makassar Strait ranges from 34.4 to 34.6 psu, with a minimum near 300 m, where temperature is 10°C (about 26.5σθ isopycnal surface). This salinity minimum is larger than the salinity minimum (<34.4 psu) of the North Pacific Intermediate Water (NPIW), suggesting mixing with the South Pacific Tropical Water (SPTW, $S > 34.6$) before entering the Makassar Strait. The NESC is located close to the hemispheric salinity front immediately north of the equator between the NSCC and the NESC. The core of the NESC is in between 26.5σ_θ ($\sigma_\theta = 26.5$ kg m^{-3}) and 26.8σ_θ isopycnals, with salinity between 34.5 and 34.6 psu (X. Li et al., 2020; Figure S2), which is consistent with the salinity in the sub-thermocline Makassar Strait. The water analysis here suggests that an intrusion of the NESC into the Makassar Strait took place in the summer 2016.

In the winter of 2016, higher salinity (>34.6 psu) is found north of 4°N and west of 130°E between 300 and 600 m in the far western Pacific, which is in contrast to the southward retreat of high salinity waters at the ITF entrance in summer (Figures S2 and S3). The seasonal variations of the salinity distributions can be explained by the seasonal movement of the Halmahera eddy, which facilitates more saline South Pacific waters to intrude directly into the northern Maluku Sea in winter (Luick & Cresswell, 2001). Higher salinity (Figure 2c) is found in the Makassar sub-thermocline in the winter 2016/2017 than in the summer of 2016. The mooring data at 5°N, 130°E show interruption of the westward NESC from December 2016 to February 2017, while the M02 mooring in the middle Maluku channel shows westward velocities in November 2016. All the above pieces of evidence suggest a direct pathway for South Pacific waters to enter the Makassar Strait through the Maluku Sea from the NGCUC in the winter of 2016/2017 due to the seasonal-to-interannual variability of the western Pacific circulation.

The year to year salinity changes in the Makassar Strait are not always consistent with the Region B (Figures 2d and 2e). The sub-thermocline salinity in the Makassar Strait in 2015 is not influenced by the NESC since the sub-thermocline currents were northward (Figure 1c), forced by the Indian Ocean Kelvin waves (Gordon et al., 2019). The sub-thermocline waters in the Makassar Strait and in Region B were fresher in the summers of 2013 and 2014 than in the summer of 2016. The large upper thermocline transport and small sub-thermocline transport in the summers of 2013 and 2014 (Figure 2f) suggest more North Pacific waters with low salinity have entered into the Makassar Strait. Conversely, more South Pacific waters with higher salinity joined the Makassar Strait throughflow with the significantly large sub-thermocline transport in the summer of 2016. The latter is believed to be induced by an anomalously stronger NESC intrusion after the 2015–2016 El Niño.

The geostrophic currents referenced by the 1,975 m depth of no motion, as well as the ocean currents from reanalysis data and model simulations, have suggested the NESC as a pathway for the equatorial Pacific waters to intrude into the Makassar Strait during the summer 2016. Consistent with previous findings (X. Li et al., 2020; Wang et al., 2016; Yuan et al., 2014), the geostrophic currents calculated from gridded Argo temperature and salinity profile data show clearly a westward NESC in the depths of 300–800 m at 4°–6°N in the sub-thermocline equatorial Pacific Ocean circulation (Figure 3a). An anomalous strengthening of the NESC in the sub-thermocline layer appeared during the summer of 2016 in the geostrophic currents, as well as in the data sets of the OFES, ECCO2, SODA3, and GODAS (Figures 3 and S4), showing the NESC intrusion into the Sulawesi Sea between 4°N and 6°N in the summer 2016.

The westward NESC was much stronger during the summer 2016, about three times above the climatological summer value (Figures S5a and S6), and is stronger in the west than in the east, due to the integrated

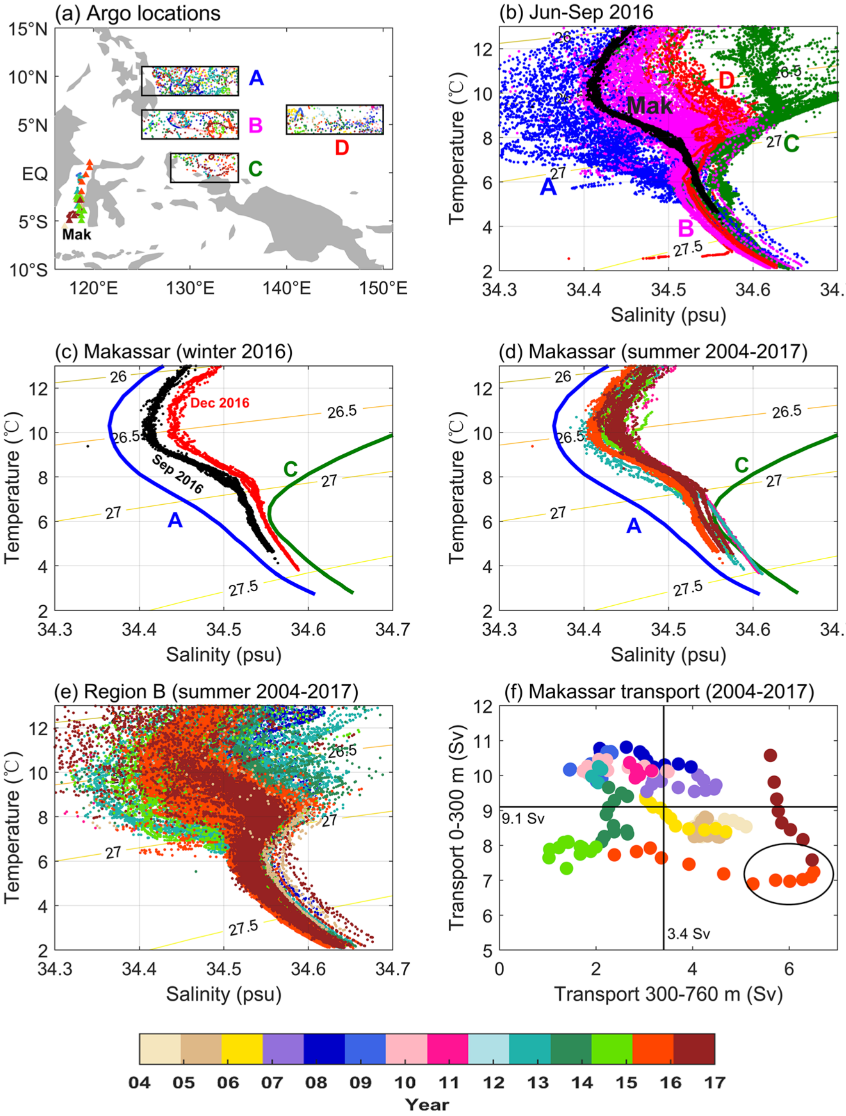


Figure 2. Water mass analysis in sub-thermocline layer. (a) Argo profiles and CTD stations. Regions A to D are used to compare the T/S relation with Makassar Strait CTD data: A (125°–135°E, 8°–11°N), B (125°–135°E, 4°–7°N), C (128°–135°E, 1°S–2°N), and D (125°–135°E, 3.5°–6.5°N). (b) T/S diagrams of regions A through D in boreal summer of 2016. (c) Comparison of T/S profiles in the Makassar Strait during summer and winter of 2016. (d) T/S diagrams of all available Makassar Strait CTD and Argo data in summers of 2011, 2013, 2015, 2016, and 2017. The solid blue and green lines show the mean profiles in regions A and C, representing that of the North and South Pacific waters, respectively. (e) T/S diagrams of Argo data in region B from 2004 to 2017. (f) Observed Makassar Strait transport in thermocline (0–300 m) and sub-thermocline (300–760 m) layers. Two black lines give the mean values of thermocline transport of 9.1 Sv and sub-thermocline transport of 3.4 Sv. The black circle indicated the anomalous time period of 2016–2017. Note that the colors of T/S dots represent waters in different years in (a), (d), (e), and (f). CTD, Conductivity-Temperature-Depth.

wind curl forcing from the western-central Pacific (Yang et al., 2020). Exchanges between equatorial and off-equatorial currents allow the South Pacific waters to enter the NESC mainstream from the NGCC/NGCUC directly. The eastward flowing NSCC and EUC coming from the NGCC/NGCUC retroflection carry high salinity South Pacific waters eastward north of the equator (Fine et al., 1994; Kashino et al., 1996), which join the NESC through the gyre circulation in the eastern equatorial Pacific.

The correlation coefficient of the Makassar sub-thermocline transport and the NESC transport at 140°E is above 0.7 at a 3-month lag, significantly exceeding the 95% confidence level (Figure 4a inset). The

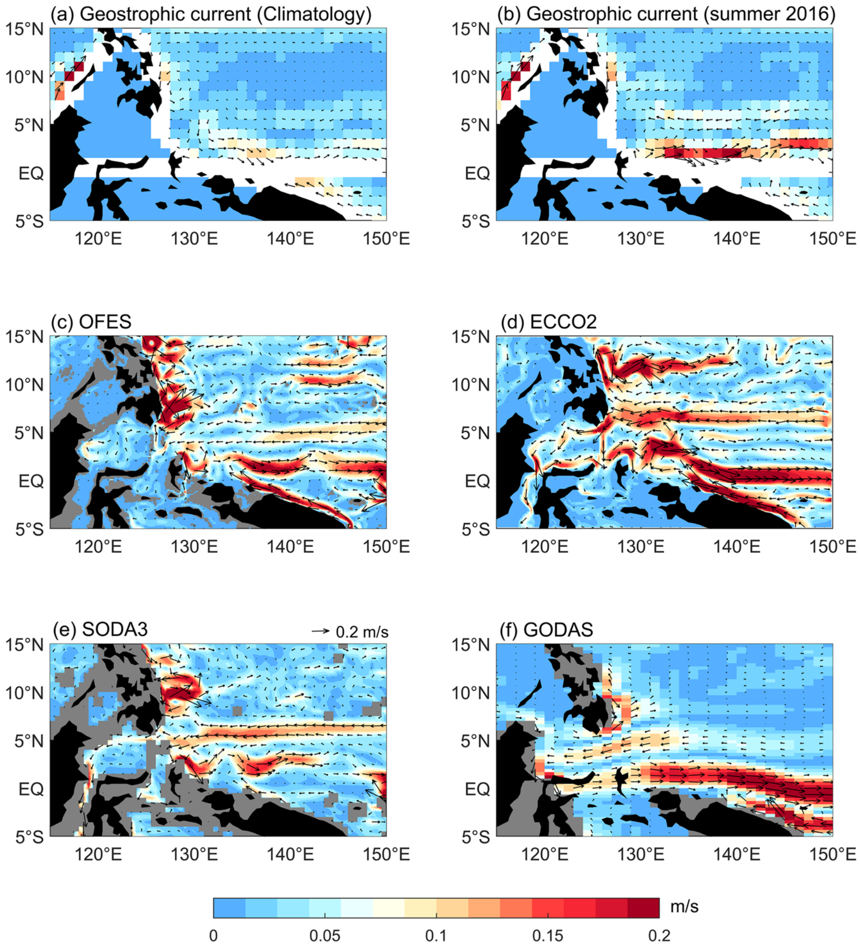


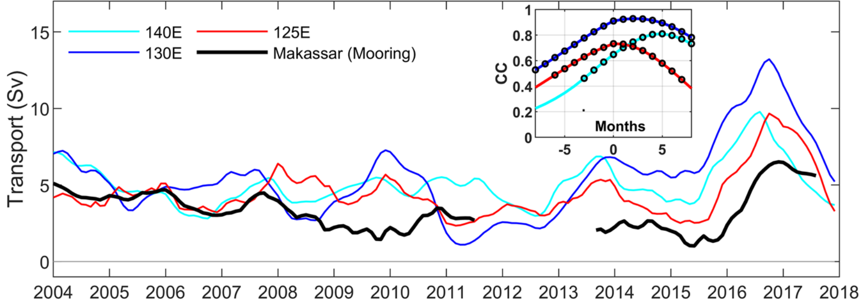
Figure 3. Geostrophic currents averaged between 300 and 800 m depths in the summers of 2004–2018 (a) with those in the summer of 2016 (b). Simulated 300–800 m depth-averaged currents based on OFES (c), ECCO2 (d), SODA3 (e), and GODAS (f) data sets in the summer of 2016. Unit of velocity is m s^{-1}. ECCO2, Estimating the Circulation and Climate of the Ocean, phase-II; GODAS, Global Ocean Data Assimilation System; OFES, Ocean General Circulation Model for the Earth Simulator; SODA3, Simple Ocean Data Assimilation v3.

anomalous increases in the NESC and the Makassar Strait sub-thermocline throughflow in 2016 are the largest within the 2004–2017 period, because the 2015/2016 El Niño is an extraordinarily strong event (Santoso et al., 2017), inducing large changes in the sub-thermocline currents. Recent studies have demonstrated that low-frequency variations of the NESC are forced by the central-eastern Pacific winds through the westward and downward propagating baroclinic Rossby waves (X. Li et al., 2020; Yang et al., 2020), which could explain the anomalous enhancement of the NESC after the 2015/2016 extreme El Niño event. In contrast to weak El Ninos, e.g., the 2009/2010 event, unusually stronger zonal wind anomalies during the 2015/2016 El Niño appeared between 175° and 170°W with periods of 3–8 months (Figure 4c). The ray line calculations suggest that the interannual variability of western and central equatorial Pacific winds can force variations of the sub-thermocline western Pacific Ocean currents through westward and downward propagation of the baroclinic Rossby waves at time lags of about 6 months.

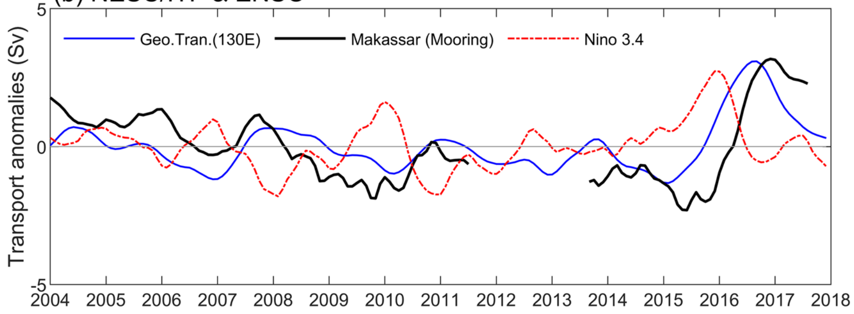
4. Summary

In this study, mooring-recorded velocities in the Makassar Strait and at the entrance of the Indonesian seas, geostrophic currents based on Argo data, and several reanalysis products are used to investigate a strong sub-thermocline intrusion into the Makassar Strait during the summer of 2016 after the extreme 2015/2016 El Niño. Water mass analyses suggest that the source of the sub-thermocline intrusion is a

(a) NESC & ITF (sub-thermocline)



(b) NESC/ITF & ENSO



(c) Wavelet power spectrum of zonal wind (175W-170W)

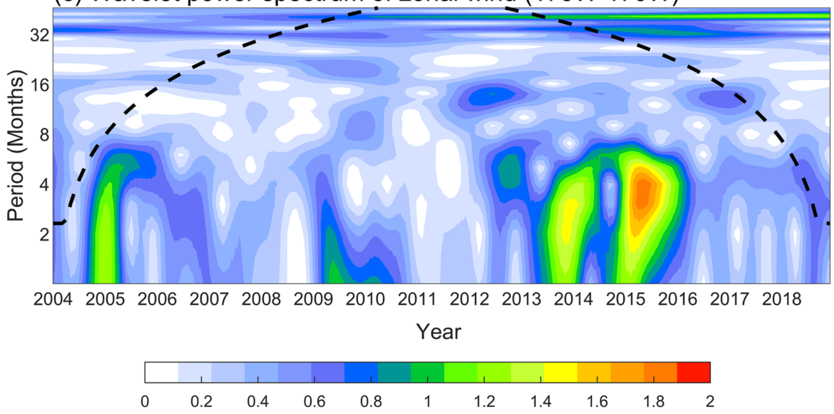


Figure 4. (a) Monthly timeseries of 300–800 m observed Makassar Strait transport (Sv) and the westward NESC (4°–6°N) transport based on reanalysis data. Inset figure shows lead and lag correlations between the NESC and Makassar Strait transports. Black circles are above the 95% significance level. (b) Comparisons of the Makassar Strait transport anomalies and geostrophic NESC transport in 130°E with the Niño 3.4 index. Positive value means more southward (westward) transport. All timeseries in (a) and (b) experience 12-month low-pass filter. (c) Wavelet power spectrum of averaged zonal wind anomalies between 175° and 170°W. The black dash line indicates the 95% significance level. NESC, North Equatorial Subsurface Current.

mixture of intermediate-depth waters from both the North and South Pacific. Mooring observations suggest that the NESC is the source of the intrusion. The South Pacific waters are suggested to enter the NESC through the retroflection of the NGCC/NGCUC in the western Pacific and via the gyre circulation connecting the eastward NSCC and EUC with the NESC in the eastern Pacific (Figure 5). The anomalously stronger NESC-Makassar sub-thermocline currents in the summer of 2016 are suggested to be forced by the trade wind anomalies over the western-central Pacific Ocean, in response to the 2015/16 extreme El Niño, through westward and downward propagating baroclinic Rossby waves.

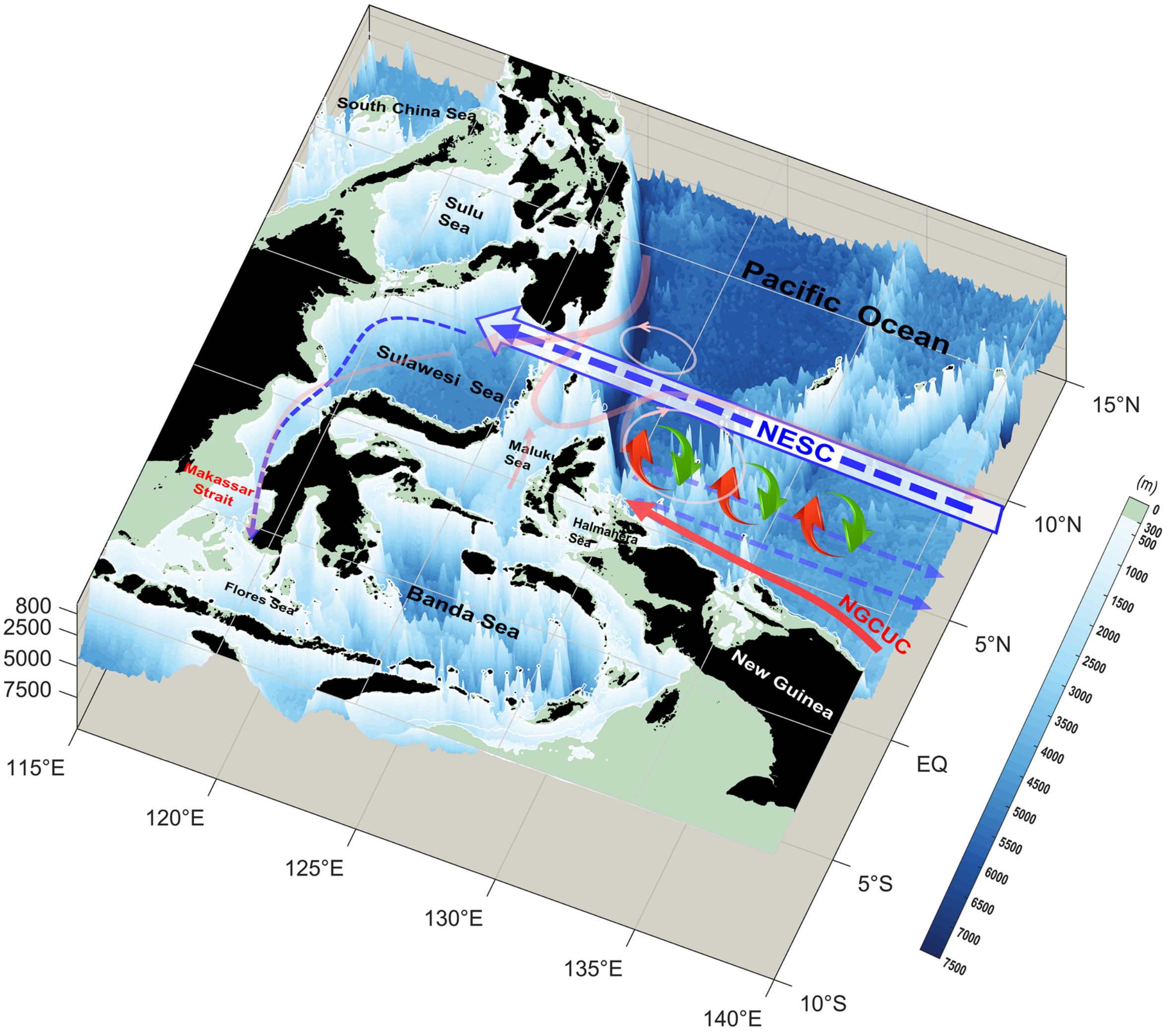


Figure 5. Schematic of tropical pathway of the NESC intrusion into the sub-thermocline Makassar Strait. Light red arrows show surface currents, and blue dashed arrows show sub-thermocline currents. High salinity South Pacific waters enter the NESC through mixing across the hemispheric salinity front in sub-thermocline layer (red curved arrows), while fresh NPIW upwelled in the NESC area and mixing across the salinity front (green curved arrows). NESC, North Equatorial Subsurface Current; NPIW, North Pacific Intermediate Water.

The T-S profiles in the Makassar Strait and in the NESC region show interannual variations, which may be related to ENSO and the associated displacement of the North and South Pacific Convergence Zones (Brown et al., 2020; Linsley et al., 2017). Under global warming, the frequency of extreme El Niños and the variability of eastern Pacific El Niños may increase (Cai et al., 2015, 2018). How these changes influence the transfer of the ITF waters in the sub-thermocline layers has enormous implications for the Pacific and Indian Ocean interactions. Previous studies (Hautala et al., 1996; Molcard et al., 1994) have suggested that more than half of the Timor Strait transport occurs in sub-thermocline layer, where South Pacific waters contributed predominantly. The asymmetric responses of tropical North and South Pacific to climate changes suggests that the upper thermocline and sub-thermocline of the ITF are driven by different mechanisms (M. Li et al., 2020). In addition, a recent study based on a subsurface mooring in the Savu Strait has indicated a sub-thermocline flow from the Indian Ocean to the Indonesian Seas (Wang et al., 2020). How this Indian Ocean current exchanges with the Indonesian Seas and the North and South Pacific circulation in the sub-thermocline layer is still unclear. More observations and model simulations are required to understand the processes and mechanisms of these exchanges.

Data Availability Statement

The Makassar Strait mooring data are available online http://ocp.ldeo.columbia.edu/res/div/ocp/projects/MITF/cm_data/. The M02 and 130°E mooring data can be accessed via http://itf.qdio.ac.cn/xzlxz/index.html. The Argo profiles are downloaded from the Global Data Centers (https://argo.ucsd.edu/data/data-from-gdacs/). The gridded Argo data set is available online (http://sio-argo.ucsd.edu/RG_Climatology.html). Four reanalysis and model outputs are obtained from http://www.cpc.ncep.noaa.gov/products/GODAS; http://dsrs.atmos.umd.edu/DATA/soda3.12.2/REGRIDED/ocean/; http://apdrc.soest.hawaii.edu/data/; http://apdrc.soest.hawaii.edu/datadoc/ofes/ofes.php. The Niño 3.4 data are downloaded from https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/.

Acknowledgments
The authors are grateful to the two anonymous reviewers for their insightful comments and suggestions. This work was supported by the National Key Research and Development Program of China (2020YFA0608800), National Natural Science Foundation of China (41906004, 91958101, 41720104008, 91858204 and 41906012), CAS (XDB42000000), QMSNL (2018SDKJ0104-02), MNR Program on Global Change and Air-Sea interactions (GASI-04-WLHY-03), the Shandong Provincial project (U1606402), and the Guangdong Province Key Area Research and Development Program (2020B1111020003). The funding for A.L.G. was from the NOAA (UCAR Z15-17551). L. Gordon was supported by NASA (80NSSC17K0438). D. Yuan is supported by the "Kunpeng Outstanding Scholar Program" of the Ministry of Natural Resources of China. Lamont-Doherty Earth Observatory contribution number 8485.

References

Anantasena, Y., Atmadipoera, A., Kuroda, Y., & Lukijanto (2013). Observed features of the Halmahera and Mindanao Eddies. *Journal of Geophysical Research: Oceans*, *118*(12), 6543–6560. https://doi.org/10.1002/2013jc009207

Arruda, W. Z., & Nof, D. (2003). The Mindanao and Halmahera Eddies-Twin Eddies Induced by Nonlinearities. *Journal of Physical Oceanography*, *33*, 2815–2830. https://doi.org/10.1175/1520-0485(2003)033<2815:tmahee>2.0.co;2

Broecker, W. (1991). The Great Ocean Conveyor. *Oceanography*, *4*, 79–89.

Brown, J. R., Lengaigne, M., Lintner, B. R., Widlansky, M. J., Wiel, K. V. D., Dutheil, C., et al. (2020). South Pacific Convergence Zone dynamics, variability and impacts in a changing climate. *Nature Reviews Earth & Environment*, *1*, 530–543. https://doi.org/10.1038/s43017-020-0078-2

Cai, W., Wang, G., Dewitte, B., Wu, L., Santoso, A., Takahashi, K., et al. (2018). Increased variability of eastern Pacific El Niño under greenhouse warming. *Nature*, *564*, 201–206. https://doi.org/10.1038/s41586-018-0776-9

Cai, W., Wang, G., Santoso, A., McPhaden, M. J., Wu, L., Jin, F.-F., et al. (2015). Increased frequency of extreme La Niña events under greenhouse warming. *Nature Climate Change*, *5*, 132–137. https://doi.org/10.1038/nclimate2492

Clarke, A. J., & Liu, X. (1994). Interannual Sea Level in the Northern and Eastern Indian Ocean. *Journal of Physical Oceanography*, *24*, 1224–1235. https://doi.org/10.1175/1520-0485(1994)024<1224:islitn>2.0.co;2

Cresswell, G. R., & Luick, J. L. (2001). Current measurements in the Halmahera Sea. *Geophysical Research Letters*, *106*, 13945–13951. https://doi.org/10.1029/2000jc000688

Du, Y., & Qu, T. (2010). Three inflow pathways of the Indonesian throughflow as seen from the simple ocean data assimilation. *Dynamics of Atmospheres and Oceans*, *50*(2), 233–256. https://doi.org/10.1016/j.dynatmoce.2010.04.001

England, M. H., & Huang, F. (2005). On the Interannual Variability of the Indonesian Throughflow and Its Linkage with ENSO. *Journal of Climate*, *18*(9), 1435–1444. https://doi.org/10.1175/jcli3322.1

Farge, M. (1992). Wavelet transforms and their applications to turbulence. *Annual Review of Fluid Mechanics*, *24*, 395–458. https://doi.org/10.1146/annurev.fl.24.010192.002143

Fine, R. A., Lukas, R., Bingham, F. M., Warner, M. J., & Gammon, R. H. (1994). The western equatorial Pacific: A water mass crossroads. *Journal of Geophysical Research*, *99*, 25063–25080. https://doi.org/10.1029/94jc02277

Godfrey, J. S., Wilkin, J., & Hirst, A. C. (1993). Why Does the Indonesian Throughflow Appear to Originate from the North Pacific? *Journal of Physical Oceanography*, *23*(6), 1087–1098. https://doi.org/10.1175/1520-0485(1993)023<1087:wdtita>2.0.co;2

Gordon, A. L. (1986). Interocean exchange of thermocline water. *Journal of Geophysical Research*, *91*(C4), 5037–5046. https://doi.org/10.1029/jc091ic04p05037

Gordon, A. L. (1995). When is Appearance Reality? A Comment on Why Does the Indonesian Throughflow Appear to Originate from the North Pacific. *Journal of Physical Oceanography*, *25*, 1560–1567. https://doi.org/10.1175/1520-0485(1995)025<1560:wiarac>2.0.co;2

Gordon, A. L., & Fine, R. A. (1996). Pathways of Water Between the Pacific and Indian Oceans in the Indonesian Seas. *Nature*, *379*, 146–149. https://doi.org/10.1038/379146a0

Gordon, A. L., Napitu, A., Huber, B. A., Gruenburg, L. K., Pujiana, K., Agustiadi, T., et al. (2019). Makassar strait throughflow seasonal and interannual variability: An overview. *Journal of Geophysical Research: Oceans*, *124*, 3724. https://doi.org/10.1029/2018JC014502

Gordon, A. L., Sprintall, J., Van Aken, H. M., Susanto, D., Wijffels, S., Molcard, R., et al. (2010). The Indonesian throughflow during 2004-2006 as observed by the INSTANT program. *Dynamics of Atmospheres and Oceans*, *50*(2), 115–128. https://doi.org/10.1016/j.dynatmoce.2009.12.002

Gordon, A. L., Susanto, R. D., & Vranes, K. (2003). Cool Indonesian throughflow as a consequence of restricted surface layer flow. *Nature*, *425*, 824–828. https://doi.org/10.1038/nature02038

Gouriou, Y., & Toole, J. (1993). Mean circulation of the upper layers of the western equatorial Pacific Ocean. *Journal of Geophysical Research*, *98*, 22495–22520. https://doi.org/10.1029/93jc02513

Gruenburg, L. K., & Gordon, A. L. (2018). Variability in Makassar Strait heat flux and its effect on the eastern tropical Indian Ocean. *Oceanography*, *31*(2), 80–87. https://doi.org/10.5670/oceanog.2018.220

Hautala, S. L., Reid, J. L., & Bray, N. (1996). The distribution and mixing of Pacific water masses in the Indonesian Seas. *Journal of Geophysical Research*, *101*(12), 375–389. https://doi.org/10.1029/96jc00037

Hsin, Y.-C., & Qiu, B. (2012). Seasonal fluctuations of the surface North Equatorial Countercurrent (NECC) across the Pacific basin. *Journal of Geophysical Research*, *117*, a. https://doi.org/10.1029/2011jc007794

Hu, D., Wu, L., Cai, W., Sen Gupta, A., Ganachaud, A., Qiu, B., et al. (2015). Pacific western boundary currents and their roles in climate. *Nature*, *522*(7556), 299–308. https://doi.org/10.1038/nature14504

Kashino, Y., Aoyama, M., Kawano, T., Hendiarti, N., Syaefudin, Anantasena, Y., et al. (1996). The water masses between Mindanao and New Guinea. *Journal of Geophysical Research*, *101*, 12391–12400. https://doi.org/10.1029/95jc03797

Kessler, W. S., Hristova, H. G., & Davis, R. E. (2019). Equatorward western boundary transport from the South Pacific: Glider observations, dynamics and consequences. *Progress in Oceanography*, *175*, 208–225. https://doi.org/10.1016/j.pocean.2019.04.005

Li, M., Gordon, A. L., Gruenburg, L. K., Wei, J., & Yang, S. (2020). Interannual to decadal response of the Indonesian Throughflow vertical profile to Indo-Pacific forcing. *Geophysical Research Letters*, *47*, e2020GL087679. https://doi.org/10.1029/2020gl087679

Li, M., Gordon, A. L., Wei, J., Gruenburg, L. K., & Jiang, G. (2018). Multi-decadal timeseries of the Indonesian throughflow. *Dynamics of Atmospheres and Oceans*, *81*, 84–95. https://doi.org/10.1016/j.dynatmoce.2018.02.001

Li, X., Yang, Y., Li, R., Zhang, L., & Yuan, D. (2020). Structure and dynamics of the Pacific North Equatorial Subsurface Current. *Scientific Reports*, *10*(1), 1–9. https://doi.org/10.1038/s41598-020-68605-y

Lindstrom, E., Lukas, R., Fine, R., Firing, E., Godfrey, S., Meyers, G., & Tsuchiya, M. (1987). The Western Equatorial Pacific Ocean Circulation Study. *Nature*, *330*, 533–537. https://doi.org/10.1038/330533a0

Linsley, B. K., Wu, H. C., Rixen, T., Charles, C. D., Gordon, A. L., & Moore, M. D. (2017). SPCZ zonal events and downstream influence on surface ocean conditions in the Indonesian Throughflow region. *Geophysical Research Letters*, *44*(1), 293–303. https://doi.org/10.1002/2016GL070985

Liu, Q. Y., Feng, M., Wang, D., & Wijffels, S. (2015). Interannual variability of the Indonesian Throughflow transport: A revisit based on 30 year expendable bathythermograph data. *Journal of Geophysical Research: Oceans*, *120*(12), 8270–8282. https://doi.org/10.1002/2015jc011351

Luick, J. L., & Cresswell, G. R. (2001). Current measurements in the Maluku Sea. *Journal of Geophysical Research*, *106*(C7), 13953–13958. https://doi.org/10.1029/2000JC000694

Lukas, R., Firing, E., Hacker, P., Richardson, P. L., Collins, C. A., Fine, R., & Gammon, R. (1991). Observations of the Mindanao Current during the western equatorial Pacific Ocean circulation study. *Journal of Geophysical Research*, *96*, 7089–7104. https://doi.org/10.1029/91jc00062

Molcard, R., Fieux, M., Swallow, J. C., Ilahude, A. G., & Banjarnahor, J. (1994). Low frequency variability of the currents in Indonesian channels (Savu-Roti and Roti-Ashmore Reef). *Deep Sea Research Part I: Oceanographic Research Papers*, *41*, 1643–1661. https://doi.org/10.1016/0967-0637(94)90066-3

Murtugudde, R., Busalacchi, A. J., & Beauchamp, J. (1998). Seasonal-to-interannual effects of the Indonesian throughflow on the tropical Indo-Pacific Basin. *Journal of Geophysical Research*, *103*, 21425–21441. https://doi.org/10.1029/98jc02063

Nitani, H. (1972). *Beginning of the kuroshio. Kuroshio: Its physical aspects*. In H. Stommel, & K. Yoshida (Eds.), (pp. 129–163). University of Tokyo Press.

Nof, D. (1996). Why are rings regularly shed in the western equatorial Atlantic but not in the western Pacific? *Progress in Oceanography*, *38*, 417–451. https://doi.org/10.1016/s0079-6611(97)00004-9

Potemra, J. T., Hautala, S. L., & Sprintall, J. (2003). Vertical structure of Indonesian throughflow in a large-scale model. *Deep Sea Research Part II: Topical Studies in Oceanography*, *50*, 2143–2161. https://doi.org/10.1016/s0967-0645(03)00050-x

Potemra, J. T., Lukas, R., & Mitchum, G. T. (1997). Large-scale estimation of transport from the Pacific to the Indian Ocean. *Journal of Geophysical Research*, *102*(C13), 27795–27812. https://doi.org/10.1029/97jc01719

Potemra, J. T., & Schneider, N. (2007). Interannual variations of the Indonesian throughflow. *Journal of Geophysical Research*, *112*, C05035. https://doi.org/10.1029/2006JC003808

Pujiana, K., Gordon, A. L., & Sprintall, J. (2013). Intraseasonal Kelvin wave in Makassar Strait. *Journal of Geophysical Research: Oceans*, *118*, 2023–2034. https://doi.org/10.1002/jgrc.20069

Pujiana, K., Gordon, A. L., Sprintall, J., & Susanto, R. D. (2009). Intraseasonal variability in the Makassar Strait Thermocline. *Journal of Marine Research*, *67*(6), 757–777. https://doi.org/10.1357/002224009792006115

Santoso, A., Mcphaden, M. J., & Cai, W. (2017). The defining characteristics of ENSO extremes and the strong 2015/2016 El Niño. *Reviews of Geophysics*, *55*. https://doi.org/10.1002/2017RG000560

Song, Q., & Gordon, A. L. (2004). Significance of the vertical profile of the Indonesian Throughflow transport to the Indian Ocean. *Geophysical Research Letters*, *31*, L16307. https://doi.org/10.1029/2004GL020360

Sprintall, J., Gordon, A. L., Wijffels, S. E., Feng, M., Hu, S., Koch-Larrouy, A., et al. (2019). Detecting change in the Indonesian Seas. *Frontiers in Marine Science*, *6*, 257. https://doi.org/10.3389/fmars.2019.00257

Susanto, R. D., & Gordon, A. L. (2005). Velocity and transport of the Makassar Strait throughflow. *Journal of Geophysical Research*, *110*, 1–10. https://doi.org/10.1029/2004jc002425

Sverdrup, H. U., Johnson, M. W., & Fleming, R. H. (1942). *The oceans: Their physics, chemistry, and general biology*, p. 1087. Englewood Cliffs: Prentice Hall, Inc.

Toole, J. M., Millard, R. C., Wang, Z., & Pu, S. (1990). Observations of the Pacific North equatorial current bifurcation at the Philippine coast. *Journal of Physical Oceanography*, *20*, 307–318. https://doi.org/10.1175/1520-0485(1990)020<0307:ootpne>2.0.co;2

Torrence, C., & Compo, G. P. (1998). A practical guide to wavelet analysis. *Bulletin of the American Meteorological Society*, *79*(1), 61–78. https://doi.org/10.1175/1520-0477(1998)079<0061:apgtwa>2.0.co;2

Tsuchiya, M., Lukas, R., Fine, R. A., Firing, E., & Lindstrom, E. (1989). Source waters of the Pacific equatorial undercurrent. *Progress in Oceanography*, *23*(2), 101–147. https://doi.org/10.1016/0079-6611(89)90012-8

Wang, F., Wang, J., Guan, C., Ma, Q., & Zhang, D. (2016). Mooring observations of equatorial currents in the upper 1000 m of the western Pacific Ocean during 2014. *Journal of Geophysical Research: Oceans*, *121*(6), 3730–3740. https://doi.org/10.1002/2015jc011510

Wang, J., Yuan, D., Li, X., Li, Y., Wang, Z., Hu, X., et al. (2020). Moored observations of the Savu Strait currents in the Indonesian seas. *Journal of Geophysical Research: Oceans*, *125*, e2020JC016082. https://doi.org/10.1029/2020jc016082

Wang, Z., & Yuan, D. (2012). Nonlinear dynamics of two western boundary currents colliding at a gap. *Journal of Physical Oceanography*, *42*, 2030–2040. https://doi.org/10.1175/jpo-d-12-05.1

Wang, Z., & Yuan, D. (2014). Multiple equilibria and hysteresis of two unequal-transport western boundary currents colliding at a gap. *Journal of Physical Oceanography*, *44*, 1873–1885. https://doi.org/10.1175/jpo-d-13-0234.1

Waworuntu, J. M., Fine, R. A., Olson, D. B., & Gordon, A. L. (2000). Recipe for Banda Sea water. *Journal of Marine Research*, *58*, 547–569. https://doi.org/10.1357/002224000321511016

Wijffels, S., & Meyers, G. (2004). An intersection of oceanic waveguides: Variability in the Indonesian Throughflow region. *Journal of Physical Oceanography*, *34*, 1232–1253. https://doi.org/10.1175/1520-0485(2004)034<1232:aioowv>2.0.co;2

Wyrtki, K. (1961). *Physical oceanography of the southeast Asian waters*. University of California. NAGA Report. No. 2, p. 195.

Wyrtki, K. (1987). Indonesian through flow and the associated pressure gradient. *Journal of Geophysical Research*, *92*(C12), 12941–12946. https://doi.org/10.1029/jc092ic12p12941

Yang, L., Zhou, L., Li, S., & Wei, Z. (2018). Spreading of the South Pacific Tropical Water and Antarctic Intermediate Water over the Maritime Continent. *Journal of Geophysical Research: Oceans*, *123*, 4423–4446. https://doi.org/10.1029/2018jc013831

Yang, Y., Li, X., Wang, J., & Yuan, D. (2020). Seasonal Variability and Dynamics of the Pacific North Equatorial Subsurface Current. *Journal of Physical Oceanography*, *50*, 2457–2474. https://doi.org/10.1175/jpo-d-19-0261.1

Yuan, D., Li, X., Wang, Z., Li, Y., Wang, J., Yang, Y., et al. (2018). Observed transport variations in the Maluku Channel of the Indonesian seas associated with western boundary current changes. *Journal of Physical Oceanography*, *48*(8), 1803–1813. https://doi.org/10.1175/jpo-d-17-0120.1

Yuan, D., & Wang, Z. (2011). Hysteresis and dynamics of a western boundary current flowing by a gap forced by impingement of mesoscale eddies. *Journal of Physical Oceanography*, *41*, 878–888. https://doi.org/10.1175/2010jpo4489.1

Yuan, D., Zhang, Z., Chu, P. C., & Dewar, W. K. (2014). Geostrophic circulation in the tropical North Pacific Ocean based on Argo profiles. *Journal of Physical Oceanography*, *44*(2), 558–575. https://doi.org/10.1175/jpo-d-12-0230.1

Yuan, D., Zhou, H., & Zhao, X. (2013). Interannual climate variability over the tropical Pacific Ocean induced by the Indian Ocean Dipole through the Indonesian Throughflow. *Journal of Climate*, *26*, 2845–2861. https://doi.org/10.1175/jcli-d-12-00117.1