# Observed Transport Variations in the Maluku Channel of the Indonesian Seas Associated with Western Boundary Current Changes

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ABSTRACT

The Maluku Channel is a major opening of the eastern Indonesian Seas to the western Pacific Ocean, the upper-ocean currents of which have rarely been observed historically. During December 2012–November 2016, long time series of the upper Maluku Channel transport are measured successfully for the first time using subsurface oceanic moorings. The measurements show significant intraseasonal-to-interannual variability of over 14 Sv ($1\,\mathrm{Sv} \equiv 10^6\,\mathrm{m^3\,s^{-1}}$) in the upper 300 m or so, with a mean transport of 1.04–1.31 Sv northward and a significant southward interannual change of over 3.5 Sv in the spring of 2014. Coincident with the interannual transport change is the Mindanao Current, choked at the entrance of the Indonesian Seas, which is significantly different from its climatological retroflection in fall–winter. A high-resolution numerical simulation suggests that the variations of the Maluku Channel currents are associated with the shifting of the Mindanao Current retroflection. It is suggested that the shifting of the Mindanao Current outside the Sulawesi Sea in the spring of 2014 elevates the sea level at the entrance of the Indonesian Seas, which drives the anomalous transport through the Maluku Channel. The results suggest the importance of the western boundary current nonlinearity in driving the transport variability of the Indonesian Throughflow.

## 1. Introduction

The water mass transport permeating the porous western boundary of the Pacific Ocean into the Indian Ocean is called the Indonesian Throughflow (ITF), which is known to play an important role in the evolution of short- and long-term climate variations through modulating the heat content of the Pacific warm pool. Because of the lack of observations of the oceanic transports at the entrance of the Indonesian Seas, the

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precise role of the ITF in determining the warm pool heat content is still not clear. Since December 2012, the Institute of Oceanology of the Chinese Academy of Sciences (IOCAS), collaborating with the Research Center for Oceanography of the Indonesian Institute of Sciences (RCO/LIPI), has been deploying deep ocean moorings at the entrance of the Indonesian Seas. In this paper, the ITF variability based on these observations will be reported.

The upper-ocean currents of the ITF flow mainly along two paths inside the Indonesian Seas: the western path (i.e., the Makassar Strait) and the eastern path, from the Maluku Channel and the Halmahera Sea through the Lifamatola Passage into the Banda Sea. The Maluku Channel is one of the primary openings of the eastern path to the western Pacific Ocean. Historical observations of the ITF have focused on the transports through the western path (Gordon et al. 1999, 2008; Susanto and Gordon 2005) and the exit straits (Murray and Arief 1988; Arief and Murray 1996; Cresswell et al. 1993; Molcard et al. 1994, 1996, 2001; Sprintall et al. 2009; Gordon et al. 2010). Direct observations of the ocean currents in the Maluku Channel are rare, except for a few cruise surveys (Sprintall et al. 2004; Gordon 2005; Gordon et al. 2010; Kashino et al. 2011) and a mooring with failed measurements above the 740-m depth (Luick and Cresswell 2001).

Traditional understanding of the ITF interannual variability dynamics is based on linear equatorial wave theory, which suggests that the equatorial Rossby waves are reflected into equatorial Kelvin waves at the western boundary of the Sulawesi Sea and are connected with the equatorial Pacific Ocean circulation through the zonal flows west of the northern tip of the Halmahera Island across the Maluku Channel (Clarke 1991). High efficiency of the reflection of the equatorial Rossby waves into the equatorial Kelvin waves at the Indonesian Maritime Continent has been suggested (du Penhoat and Cane 1991; Clarke 1991). Recent studies suggest that the western boundary reflections are nonlinear (Yuan et al. 2004; Yuan 2005; Spall and Pedlosky 2005; Yuan and Han 2006). A western boundary current (WBC) flowing by a gap has nonlinear bifurcation and hysteresis (Sheremet 2001; Kuehl and Sheremet 2009) and is subject to regime shifts if perturbed by mesoscale eddies or winds (Yuan and Li 2008; Wang et al. 2010; Yuan and Wang 2011). The nonlinear collisions of two WBCs at a gappy boundary are also shown to have multiple equilibria (penetration, choke, and eddy shedding) and are subject to significant regime shifts if perturbed by Rossby waves and eddies (Wang and Yuan 2012, 2014). These studies provide us with the theoretical basis to understand the observed transport variations through the Maluku Channel.

## 2. Data and method

The first mooring, M00, was deployed at the deepest point in the central Maluku Channel (Fig. 1) in December 2012–November 2014. A 75-KHz upward-looking acoustic Doppler current profiler (ADCP) was mounted at a nominal depth of 350 m. This mooring was replaced with three moorings (M01–M03) along 2°N (Fig. 1) with upward-looking ADCPs at a nominal depth of 500 m in November 2014, which were further rotated in November 2015. All three 2015 moorings were recovered successfully in November 2016.

The bin size and the time interval of the ADCP sampling are 8 m and 1 h, respectively. A few bins of missing value are filled with linear interpolation in the vertical. The velocities of the ADCPs are interpolated onto a 1-m vertical grid. The 2014–16 moorings also have several current meters attached. The ADCP measurements are nearly identical to those of Aanderaa current meters at the nominal depth of 250 m, suggesting the veracity of the velocity measurements. The ADCP time series are filtered with the Thompson filter (Thompson 1983) to remove tides and then averaged into daily means. A fourth-order Butterworth low-pass filter with a 120-day cutoff period is applied to suppress the high-frequency oscillations. The currents at M00 during 2014–16 are interpolated from those at M02 and M03.

Daily NCEP reanalysis surface wind data (http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html) are used to represent the wind forcing in the Maluku Channel. Surface drifter trajectories are obtained from the Global Lagrangian Drifter Data of AOML/NOAA from 1979 to 2011 (http://www.aoml.noaa.gov/envids/gld/dirkrig/parttrk_spatial_temporal.php). The 2-Minute Gridded Global Relief Data (ETOPO2v2) of the U.S. National Geophysical Data Center are used to calculate the width of the Maluku Channel section (https://ngdc.noaa.gov/mgg/global/etopo2.html). The drifters released in the western Pacific Ocean during the summer of 2014 were manufactured by the Qingdao Xiaolong Instruments Co. Ltd, the design of which follows the WOCE standards (http://itf.qdio.ac.cn/dataaccess.htm).

The 0.1°-resolution simulation of the Max Planck Institute of Meteorology Ocean Model (MPIOM) is used to describe the nonlinear variations of the Mindanao Current retroflection. The STORM simulation (Von Storch et al. 2012, 2016) of the model employs a tripolar grid with a horizontal resolution of about 0.1° at the equator (https://verc.enes.org/storm). Eighty vertical layers from the sea surface to 6038.5 m are used in the vertical. The model was spun up for 25 years using the German Ocean Model Intercomparison Project (OMIP) forcing derived from the 15-yr ERA data and then

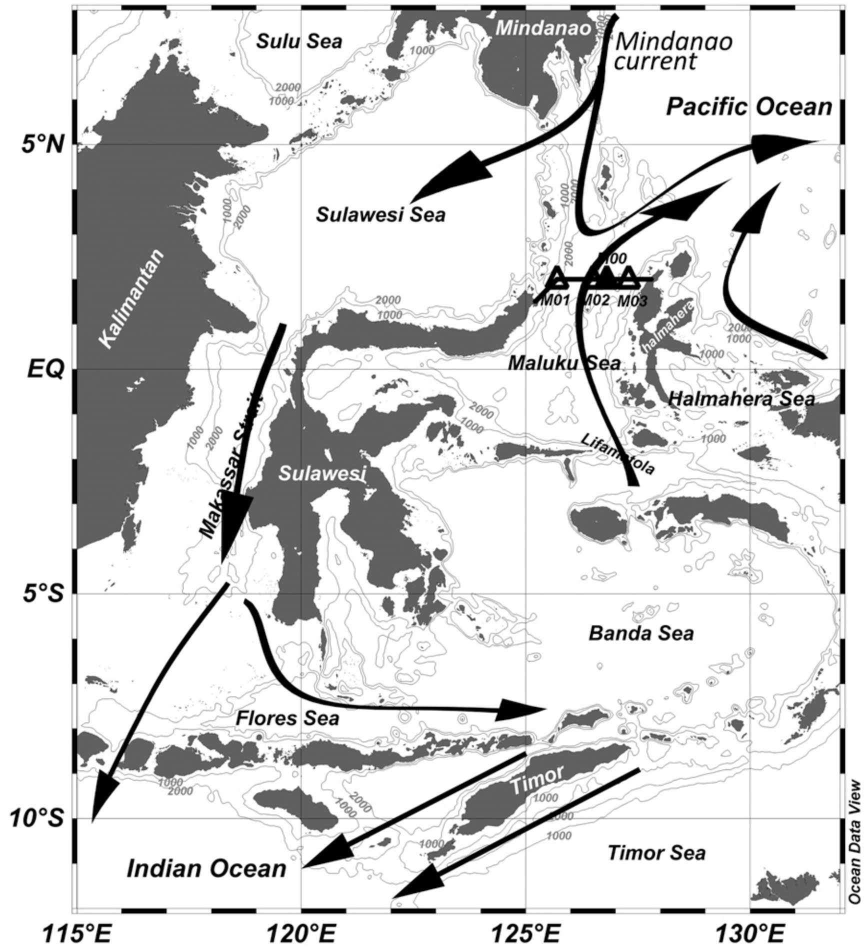


FIG. 1. Schematic of the upper-ocean circulation of the Indonesian Seas. Solid and empty triangles mark the positions of the 2012–14 and 2014–16 mooring positions, respectively. Solid line across the Maluku Channel indicates the section of the normal transport calculation.

forced by the 6-hourly NCEP–NCAR reanalysis data from 1948 to present.

## 3. Observed currents in the Maluku Channel

The current data at the center of the Maluku Channel (M00) show a prominent seasonal cycle in the upper ocean above approximately the 150-m depth (Fig. 2b). The seasonal cycle of the zonal currents is found to be inconsistent with the circulation forced by the local winds and is suggested to be associated with the movement of the Mindanao Current retroflection in this area (Fig. 3). The proximity of the Mindanao Current to the Maluku Channel during fall–winter, shown by historical satellite-tracked surface drifter trajectories in the area, suggests strongly that the seasonal eastward and northward currents in the Maluku Channel in fall–winter are dragged by the WBC. In spring–summer, the main stream of the Mindanao Current shifts to the north so that the currents in the Maluku Channel are less influenced by the WBC. The meridional currents in the upper ocean are frequently opposite to the local winds, especially in winter–spring (Figs. 2a,c), suggesting that they are not forced by the local winds. It is hypothesized, therefore, that the Maluku Channel currents are forced by the movement of the Mindanao Current retroflection.

In Fig. 2, the southward wind and eastward currents in winter are correlated, which might be due to the strengthening of the Mindanao Current off Mindanao and the weakening of the coastal currents off New Guinea. The currents above the 40-m depth of the ADCP are discarded due to the contamination by the sea surface reflection of the acoustic signals. The meridional currents in the surface mixed layer above the 50-m depth change directions with the winds due to the small Coriolis parameter.

It is worth mentioning that the seasonal paths of the Mindanao Current in Fig. 3 are indicated by sparse

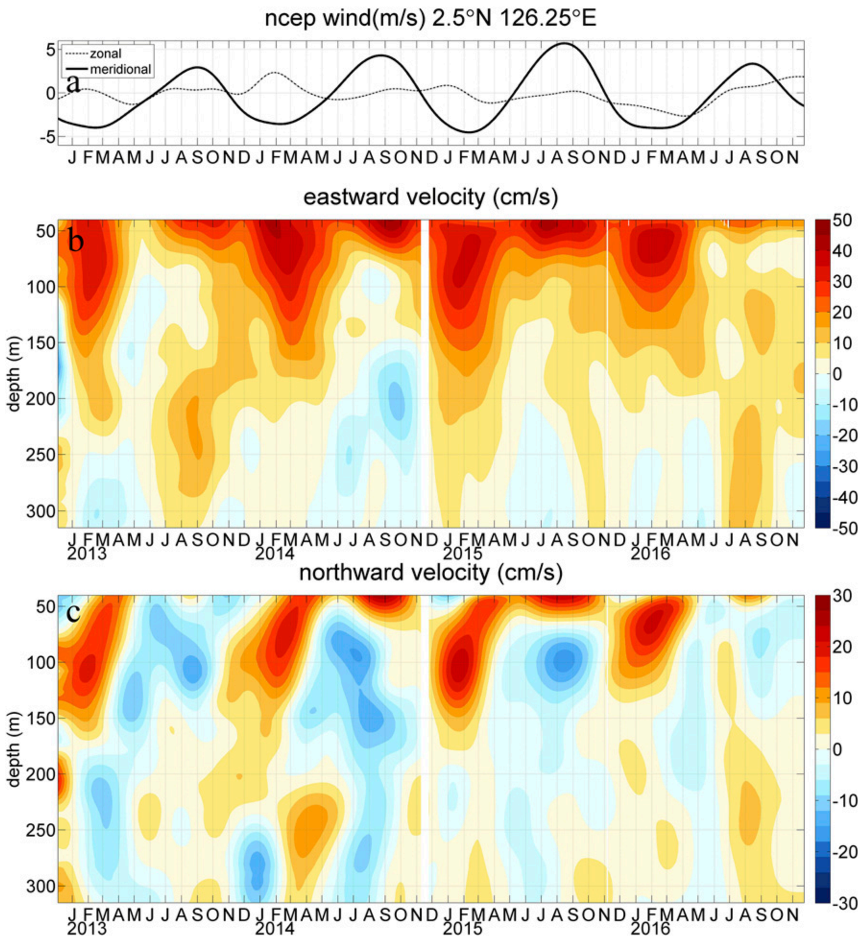


FIG. 2. NCEP (a) winds ($m\,s^{-1}$) and the (b) zonal and (c) meridional components of the moored ADCP velocity ($cm\,s^{-1}$) time series at M00 in the Maluku Channel during December 2012–November 2016.

trajectories of historical surface drifters released in the WBCs. Caution should be exercised in accepting these paths, as the climatology of the Mindanao Current. Modern satellite altimeters cannot measure the mean sea level from the geoid accurately, so the main stream of the Mindanao Current cannot be diagnosed from the altimeter data.

Below about 150 m, the currents are not correlated well with the surface currents. In particular, the subsurface zonal currents in the Maluku Channel reversed in May and June 2014 to flow to the west during the summer–fall of that year (Fig. 2b). The subsurface meridional currents in the Maluku Channel also reversed coincidentally (Fig. 2c), resulting in significant southward transports in the eastern Indonesian Seas in the summer–fall of 2014 in the upper ocean. The mooring time series suggest that the reversal of the meridional subsurface currents in the Maluku Channel is a seasonal phenomenon, but the southward anomalies in the summer of 2014 are particularly strong.

The interannual anomalies of the Maluku Channel currents based on the 4-yr climatology between the 50- and 300-m depths have shown clearly the significant westward current anomalies in the summer–fall of 2014 resulting from the current reversal (Fig. 4). Coincident with the zonal current reversal, the meridional current anomalies suggest significant southward ITF transport anomalies in the eastern Indonesian Seas. The comparison of the wind and current anomalies suggests that the Maluku Channel current reversal was not forced by the local winds. During the summer of 2016, strong northward current anomalies were observed in the subsurface Maluku Channel. This event is found to be connected with a northward transport event through the Lifamatola Passage. The investigation of this connection will be postponed until long-enough time series are obtained from the Lifamatola mooring, which started in late 2015.

The Maluku Channel transport between 60 and 315 m is calculated based on the velocity normal to a coast-to-

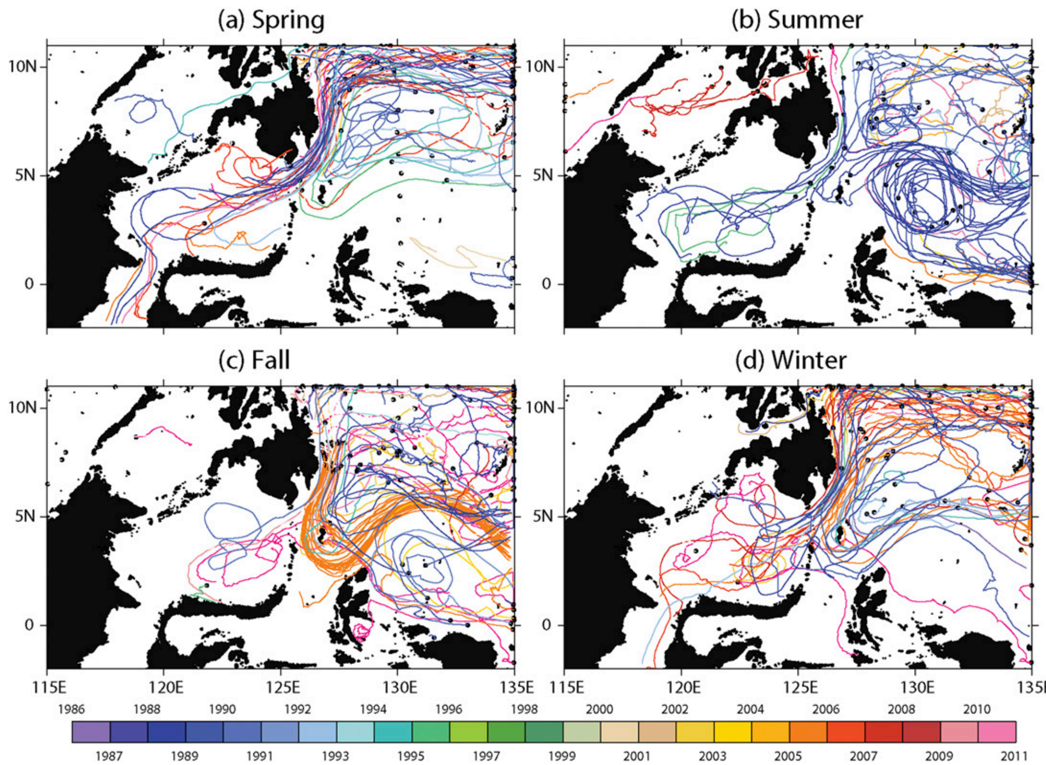


FIG. 3. Historical satellite-tracked surface drifter trajectories grouped into (a) spring, (b) summer, (c) fall, and (d) winter seasons.

coast section near 2°N (the solid line in Fig. 1) using the ADCP data of the three moorings during 2014–16. The M01 mooring was deployed too deep to return measurements in the upper 60 m of the ocean. The time series of the eastern two moorings (M02 and M03) during December 2014–November 2016 are first interpolated linearly onto M00 (the 2012–14 mooring site). Then, the meridional velocity at M00 is used in a linear regression model to approximate the 2014–16 transports estimated from the three moorings. The correlation coefficients between the regression model and the three mooring transports are 0.80 and 0.84 for the free-slip and nonslip conditions, respectively, above the 99.9% significance level, suggesting the success of the regression model. The root-mean-square differences between the regressed and calculated transports using the free-slip and nonslip boundary conditions are 1.53 and 1.23 Sv ($1\,\mathrm{Sv} \equiv 10^6\,\mathrm{m^3\,s^{-1}}$), respectively, significantly smaller than the standard deviations of the transports of 2.39 and 2.20 Sv, respectively.

The linear regression is then extended into the period of December 2012–November 2014 using the only M00 data available in the central Maluku Channel (Fig. 5a). Based on the regression model, the mean transports through the Maluku Channel between 60 and 315 m during the 4 years are estimated to be 1.31 and 1.04 Sv northward, assuming free-slip and nonslip conditions, respectively. These mean transport estimates are significantly above the standard errors of 0.56 and 0.52 Sv, respectively, at the 95% significance level, suggesting the statistical significance of the estimates. The schematic in Fig. 1 describes the mean upper-ocean circulation in the Indonesian Seas based on the mooring data and historical INSTANT data.

The regression model based on the M00 mooring measurements between 60 and 315 m suggests that the Maluku Channel transport reaches the maximum of more than 7 Sv northward in early 2014, which decreases to more than 7 Sv southward in the summer of 2014, a total of more than 14 Sv of intraseasonal-to-interannual changes. The low-passed interannual anomalies of the meridional transport between 60 and 315 m through the Maluku Channel change from 1.5 Sv northward in the spring of 2014 to 2.0 Sv southward in the summer of 2014 (Fig. 5b). The southward transport anomalies are the largest in amplitude over the 4-yr period, suggesting significant driving force of the event. In the summer of 2016, northward transport anomalies of about 2.5 Sv are indicated by the regression model. These are significant interannual variations of the ITF transport, given that the full-depth transport in the Makassar Strait is about 12 Sv on average (Gordon et al. 2010).

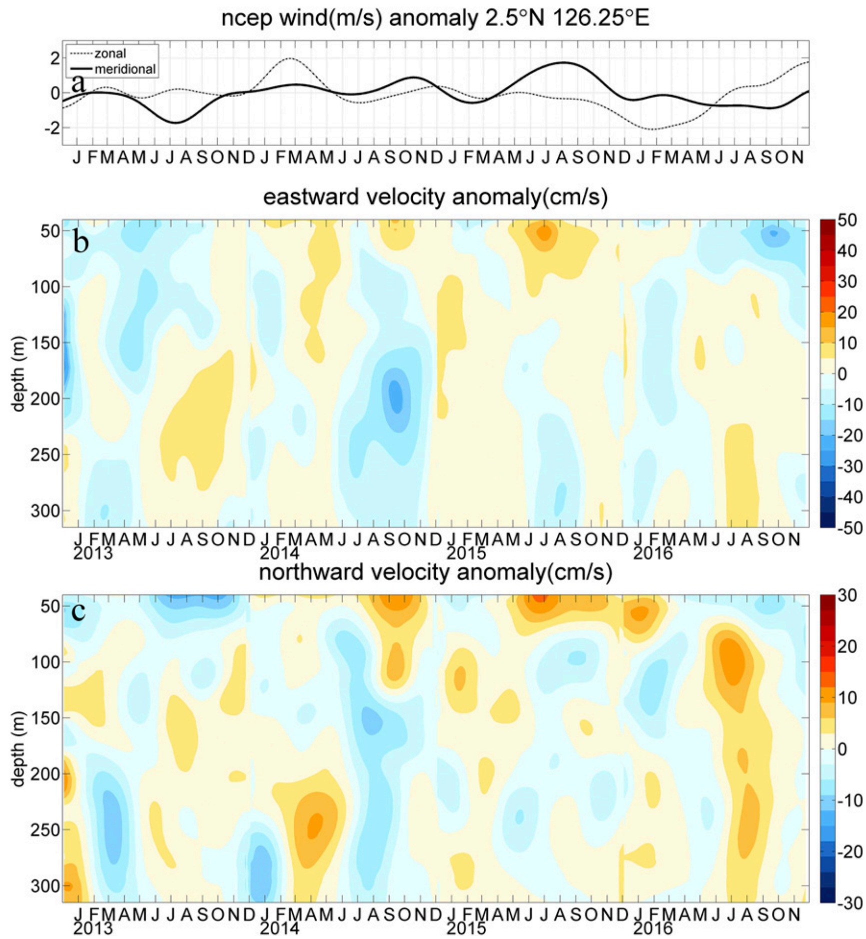


FIG. 4. NCEP (a) winds anomalies (m s$^{-1}$) and (b) zonal and (c) meridional current anomalies (cm s$^{-1}$) at station M00 in the Maluku Channel relative to the climatology of 2013–16.

## 4. Changes of the WBCs

The strong current reversals in the Maluku Channel are not consistent with local wind forcing and are hypothesized to be associated with the changes of the WBCs. The satellite altimeter sea level anomalies off Java in the eastern Indian Ocean were weakly positive in the summer 2014, suggesting unlikely connections with the strong current anomalies in the Maluku Channel (figure omitted).

There are very few data at the entrance of the ITF to describe the path of the WBCs, unfortunately. We rely primarily on the trajectories of the satellite-tracked surface drifters to identify the path of the Mindanao Current. The Mindanao Current retroflection has evidently receded to north of 5°N in the summer–fall of 2014, as suggested by the drifter trajectories released in the western Pacific Ocean in August 2014 (Fig. 6a). Compared with the fall climatological path in the area, which suggests southward extension of the Mindanao Current retroflection to the northern Maluku Sea in fall–winter, the trajectories in the summer of 2014 suggest that the Mindanao Current retroflection moved away from the northern Maluku Sea during the spring–summer of 2014.

In March 2014, the satellite altimeter data have shown that the sea level anomalies at the entrance of the ITF are very small (Fig. 6c), suggesting that the Mindanao Current is close to its winter climatological retroflection early in that year. Evidently, the Mindanao Current path has experienced a regime shift from penetration to choke in the spring–summer of 2014 (Figs. 3, 6a). The coincidence of the transport reversal in the Maluku Channel with the significant change of the Mindanao Current path suggests that the two are related. It is suggested that the significant Mindanao Current change elevated the sea level in the northern Maluku Sea and induced westward and southward current anomalies in the Maluku Channel (Fig. 6b).

The 0.1°-resolution simulation of the MPIOM has indeed simulated one such change. The STORM experiment has simulated a regime shift of the Mindanao Current in

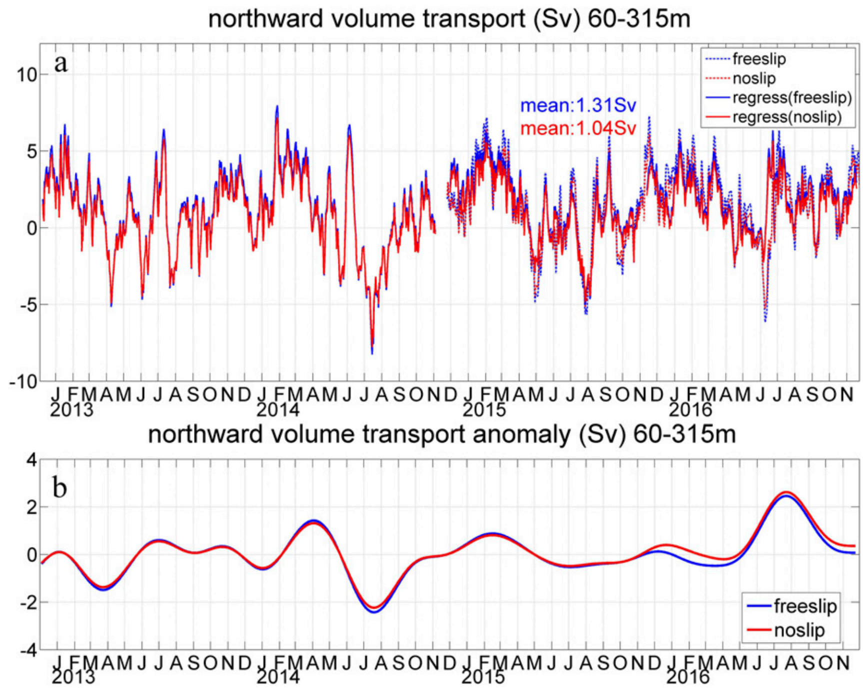


FIG. 5. (a) Time series of the Maluku Channel transport ($10^6\,m^3\,s^{-1}$). Dashed blue and red curves are the integrated transports through the Maluku Channel between the 60- and 315-m depths using the ADCP data of the three moorings (M01–M03) during 2014–16, assuming free-slip and nonslip conditions at the coasts, respectively. Solid blue and red curves are the regressions of the above transports using the meridional velocity at station M00 during the same period. The regression model is then used to estimate the transports during 2012–14. (b) The low-pass-filtered transport anomalies of the regression model.

the spring of 2003, similar to the one indicated by the trajectories of satellite-tracked drifters (Fig. 7). Because of the internal variability and the inaccuracies of the Reynolds number in the model, the simulated variations of the Mindanao Current generally do not occur at the same time as in the observations. The spring 2003 event suggests that the regime shift of the Mindanao Current has resulted in the reversal of the Maluku Channel currents from northeastward to southwestward, which is in agreement with the observations. It is worth mentioning that the satellite sea level anomalies in the vicinity of the Maluku Channel are heavily aliased by the strong internal wave and tidal signals there, so the dynamics of the Maluku Channel flow should not be analyzed quantitatively using the satellite sea level anomalies.

To quantify the dynamical relation between the Mindanao Current retroflection and the Maluku Channel transport variability, the coherency-squared and phase functions between area-averaged sea level near the Talaud Islands and the Maluku Channel transport in the MPIOM simulation are calculated using the monthly output of the model from 2000 to 2014 (Fig. 8a). The sea level variability near the Talaud Islands within a rectangular area (3.2°–5°N, 126.2°–127.6°E) is used to represent the variability of the Mindanao Current retroflection, which is significantly correlated with the Maluku Channel transport, with the correlation coefficient of $-0.34$ above the 95% significance level. The coherency-squared function of the two suggests that they are significantly correlated at the time scales of a few months and near the annual cycle (Fig. 8b). The phase function indicates that they are out of phase in the frequency bands of significant coherencies (Fig. 8c). The above analyses suggest that the Maluku Channel transport is related to the sea level variability at the entrance of the Indonesian Seas. The observed transport time series are too short, with the altimeter sea level near the Talaud Islands heavily contaminated by tidal signals, to estimate coherencies above statistical significances.

It is worth mentioning that the ITF transport in linear models is controlled by two pressure heads: one offshore of the east Mindanao coast, and the other on the equatorial western Pacific Ocean (Yuan et al. 2011). The former corresponds to the coastal Kelvin waveguide. The latter is connected with the zonal currents west of the north tip of the Halmahera Island through the linear

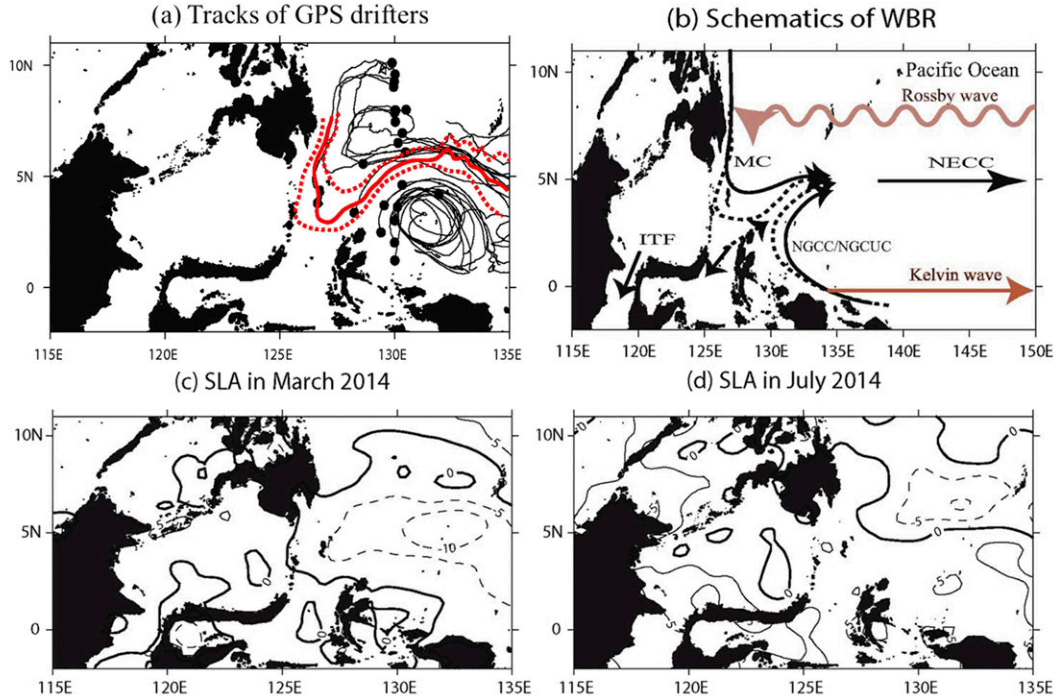


FIG. 6. (a) Satellite-tracked surface drifter trajectories in the western Pacific in August–November 2014. Dots mark the releasing positions of the drifters. Red solid and dashed curves mark the mean and standard deviation of the historical drifter trajectories in fall. (b) Schematic of the ITF variability induced by the WBC path change. Brown arrows indicate the propagation of the equatorial Rossby and Kelvin waves. Satellite altimeter sea level anomalies (cm) in (c) March and (d) July 2014. The contour interval is 5 cm. Solid and dashed contours indicate positive and negative sea level anomalies, respectively.

coastal and equatorial Kelvin waves. The pressure head we use in the vicinity of the Talaud Islands is far away from either waveguide and is only responsible for the ITF forcing through the MC retroflection.

The seasonal paths and the newly identified choking path of the Mindanao Current clearly suggest that the WBCs at the ITF entrance are controlled by nonlinear dynamics of the quasigeostrophic vorticity equation

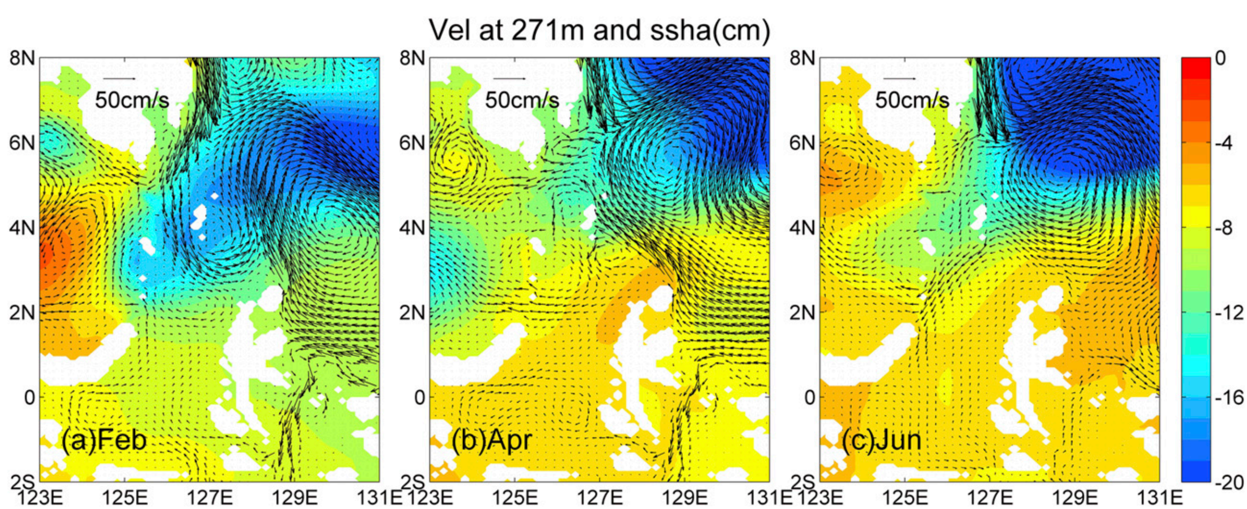


FIG. 7. (a) The MPI 0.1°-resolution ocean model simulated sea level anomalies (color) and the currents (vectors) at the 271-m depth in the spring of 2003, showing the regime shift of the WBCs similar to that of the trajectories of the satellite-tracked drifters in the spring–summer of 2014. The contour interval for sea level anomalies is 1 cm.

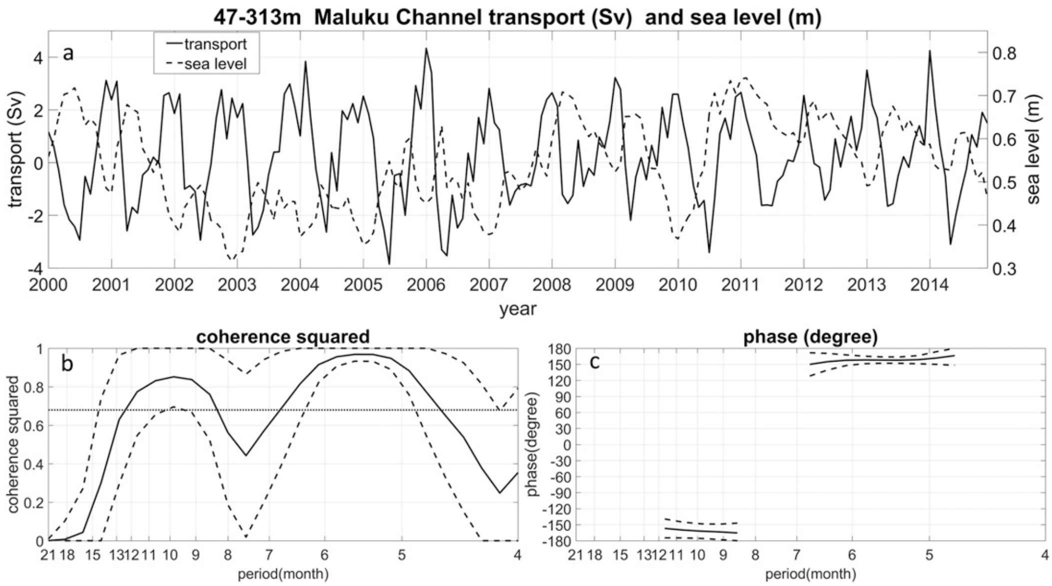


FIG. 8. (a) Time series of area-averaged sea level near the Talaud Islands (dashed line) and the Maluku Channel transport (solid line) in the MPIOM simulation during 2000–14. (b) Coherence-squared and (c) phase functions of the two series in (a) (solid lines). The 95% confidence intervals are plotted in dashed lines in (b) and (c). The dotted line in (b) indicates the 95% significant level of the coherency-squared function.

(Wang and Yuan 2012, 2014). If the WBCs should be controlled by the linear dynamics, the Mindanao Current would behave like a $\beta$ plume, reaching the western boundary of the Sulawesi Sea. In the summer of 2014, the Mindanao Current takes a path that is significantly different from the climatological fall path and stays in the choke path for a few months, far exceeding the period for the Rossby waves to propagate across the area. Therefore, the new path is suggested to be another quasi-equilibrium state, the dynamics of which must not be controlled by the linear dynamics. The deviation from the $\beta$ plume, the existence of the multiple equilibrium states, and the shifting from one equilibrium to another of the Mindanao Current suggest that the regional circulation is controlled by strong nonlinear dynamics.

The interactions of the Rossby waves with the WBCs are suggested to be through two mechanisms. One mechanism is the variations of the North Equatorial Current branching latitude off the east coast of the Philippines (Hu et al. 2015), which changes the Mindanao Current transport, hence the Reynolds number of the nonlinear system. The system, therefore, shifts to another equilibrium state corresponding to the new Reynolds number. It is also possible that the nonlinear system has multiple equilibrium states at a similar Reynolds number (hysteresis) and shifts from the penetrating equilibrium to the choking equilibrium at the perturbation of the Rossby waves (Wang and Yuan 2014). Because of the lack of observations at the ITF entrance, the detailed trigger processes cannot be analyzed in this study. The MPIOM is computationally too expensive to examine the bifurcation dynamics associated with the Reynolds number changes or the equilibrium shifts.

## 5. Summary

Moored current meters are deployed in the northern Maluku Sea during the period of December 2012–November 2016 to measure the transport through the Maluku Channel of the Indonesian Seas. The measurements have suggested more than 14 Sv of intraseasonal-to-interannual variations between 60- and 315-m depths, which include a significant southward interannual transport change of over 3.5 Sv in the spring of 2014. This is the first time that the upper Maluku Channel transport is measured directly, the significant variations of which suggest its importance to the total ITF variability.

Observations suggest that the significant change of the Maluku Channel transport in the spring of 2014 is associated with a WBC regime shift, which is evidenced by the drifter trajectories showing a choke path of the Mindanao Current in the summer–fall of 2014 and the small sea level anomalies of the satellite altimeter measurements in early 2014 at the entrance of the ITF. The small sea level anomalies suggest that the Mindanao Current is close to its climatological path in winter, which is a nonlinear penetrating retroflection into the Indonesian Seas, according to historical drifter trajectories. The change of the Mindanao Current from the penetrating to choking states results in elevated sea level at the entrance of the ITF, forcing enhanced ITF transport through the Maluku Channel. The forcing of the Maluku Channel transport is evidenced by its significant coherency and out-of-phase relation with the sea level at the entrance of the ITF at the time scales of a few months and near the annual cycle based on the 0.1°-resolution MPIOM simulation. The WBC path change is an adjustment from one equilibrium state to another, which generally takes from a few weeks to a month or so, as suggested by the MPIOM simulation.

The annual variations of the Maluku Channel currents are generally against local winds, suggesting they are not forced by the winds. The significant eastward and northward currents in the upper Maluku Channel are speculated as being forced by the penetrating Mindanao Current retroflection in winter. The nonlinear nature of the Mindanao Current retroflection and its movement indicated by the high-resolution MPIOM simulation suggest strong nonlinear dynamics of the driving force of the Maluku Channel currents. The observations and the dynamics in this study suggest that future simulation and prediction of the ITF transport variability should take the nonlinear dynamics and the regime shifts of the WBCs into consideration.

Because of the lack of observations of the main stream of the Mindanao Current during the period of the Maluku Channel mooring measurements, the interactions between the Maluku Channel currents and the Mindanao Current retroflection have to be evidenced by the MPIOM high-resolution simulation. More mooring data in the Talaud–Halmahera Strait have been collected after this study to evidence the shifting of the Mindanao Current, the analysis of which will be reported in a separate study.

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