Moored Observations of the Currents and Transports of the Maluku Sea

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ABSTRACT: The mean circulation and volume budgets in the upper 1200 m of the Maluku Sea are studied using multiyear current meter measurements of four moorings in the Maluku Channel and of one synchronous mooring in the Lifamatola Passage. The measurements show that the mean current in the depth range of 60–450 m is northward toward the Pacific Ocean with a mean transport of 2.07–2.60 Sv (1 Sv ≡ 10^6 m^3 s^-1). In the depth range of 450–1200 m, a mean western boundary current (WBC) flows southward through the western Maluku Sea and connects with the southward flow in the Lifamatola Passage. The mean currents in the central-eastern Maluku Channel are found to flow northward at this depth range, suggesting an anticlockwise western intensified gyre circulation in the middle layer of the Maluku Sea. Budget analyses suggest that the mean transport of the intermediate WBC is 1.83–2.25 Sv, which is balanced by three transports: 1) 0.62–0.93 Sv southward transport into the Seram–Banda Seas through the Lifamatola Passage, 2) 0.97–1.01 Sv returning to the western Pacific Ocean through the central-eastern Maluku Channel, and 3) a residual transport surplus, suggested to upwell to the upper layer joining the northward transport into the Pacific Ocean. The dynamics of the intermediate gyre circulation are explained by the potential vorticity (PV) integral constraint of a semienclosed basin.

SIGNIFICANCE STATEMENT: The Indonesian Throughflow plays an important role in the global ocean circulation and climate variations. Existing studies of the Indonesian Throughflow have focused on the upper thermocline currents. Here we identify, using mooring observations, an intermediate western boundary current with the core at 800–1000-m depth in the Maluku Sea, transporting intermediate waters from the Pacific into the Seram–Banda Seas through the Lifamatola Passage. Potential vorticity balance suggests an anticlockwise gyre circulation in the intermediate Maluku Sea, which is evidenced by the mooring and model data. Transport estimates suggest northward countercurrent in the upper Maluku Sea toward the Pacific, supplied by the Lifamatola Passage transport and upwelling from the intermediate layer in the Maluku Sea. Our results suggest the importance of the intermediate Indonesian Throughflow in global ocean circulation and overturn. More extensive investigations of the Indo-Pacific intermediate ocean circulation should be conducted to improve our understanding of global ocean overturn and heat and CO2 storages.

KEYWORDS: Boundary currents; Potential vorticity; Transport; Upwelling/downwelling; Thermocline circulation

1. Introduction

The Indonesian Throughflow (ITF), which connects the western tropical Pacific Ocean with the eastern Indian Ocean circulation through the Indonesian archipelago, is an important component of the global ocean thermohaline circulation (Gordon 1986) and has great impact on the climate variations over the tropical Indo-Pacific Oceans and over the globe (Godfrey 1996; Schneider 1998; Wajsowicz and Schneider 2001; Gordon 2005; Sprintall et al. 2009; Yuan et al. 2011, 2013). The primary path of the ITF is the
Makassar Strait (Gordon 2005), the transport through which is estimated to be about 12–13 Sv (1 Sv ≡ 10^6 m^3 s^{-1}) lately (Gordon et al. 2019). Waters entering the Makassar Strait are mainly the upper thermocline waters from the North Pacific (Gordon and Fine 1996). Deeper than the threshold depth (680 m) of the Makassar Strait, the ITF must flow through the eastern Indonesian Seas, that is, the Maluku Sea into the Seram Sea and the Banda Sea (Van Riel 1956; Van Aken et al. 1988; Gordon and Fine 1996; Ilahude and Gordon 1996; Gordon et al. 2003; Tan et al. 2020).

The Maluku Sea is located at the northeastern Indonesian Seas, separated from the Philippine Sea by a line connecting Sangihe Island, Talaud Island, and Morotai Island (Fig. 1). It connects with the Seram Sea in the south through the Lifamatola Passage, and with the Halmahera Sea in the southeast through the shallower Obi Strait between Halmahera Island and Obi Island (Fig. 1). The water depths in the northern Maluku Sea are deeper than 2000 m, opening to the western Pacific Ocean. The sill depth of the Lifamatola Passage is about 1900–2000 m, whereas the sill depth of the Obi Strait is only about 910 m or so.

Historically, direct current measurements in the Maluku Sea were scarce and of short duration. Kashino et al. (2001) conducted a shipboard acoustic Doppler current profiler (sADCP) survey in the northern Maluku Sea, which did not cover depths deeper than ~500 m. A mooring in the western Maluku Channel (1°41’N, 125°40’E) during June 1993–July 1994 suggested a predominantly southward current at 740, 1250, and 1750 m and a steady northward current at 2240 m (Luick and Cresswell 2001). Currents in the eastern Maluku Channel have never been measured continuously until the 2010s, when a few moorings were deployed in the Maluku Channel as part of the western Pacific Ocean circulation and Indonesian Throughflow (WPOC-ITF) mooring array (Yuan et al. 2017). Based on these mooring measurements, the mean transport in the depth range of 60–315 m of the Maluku Channel is estimated to be 1.04–1.31 Sv northward (Yuan et al. 2018).

The northward transport in the upper layer of the Maluku Channel has been suggested to be a part of the reverse water transport from the Indian Ocean to the Pacific Ocean. Mooring measurements suggest a current flowing from the Indian Ocean into the Savu Sea through the Sumba and Savu Straits between 280 and 700 m (Wang et al. 2020) and into the Indonesian Seas through the northern Ombai Strait, with a surface current...
core at about 80 m and a deeper current core in the depth range of 220–800 m (Sprintall et al. 2009). These currents have been suggested to flow northward into the Maluku Sea through the Lifamatola Passage and farther into the Pacific Ocean through the upper 500- and 1000-2000-m layers of the Maluku Channel according to the latest model simulation (Liang and Xue 2020).

So far, the vertical profile of the transport and the pattern of the intermediate-depth circulation in the Maluku Sea are not clear.

In the Lifamatola Passage, early current meter measurements revealed southeastward mean currents below 1500 m (Lek 1938; Broecker et al. 1986; Van Aken et al. 1988). During the International Nusantara Stratification and Transport (INSTANT) program 2003–06 (Sprintall et al. 2004), a mooring at the downhill side of the Lifamatola Passage sill suggested a bottom overflow with a mean southward transport of 2.5 Sv below 1250 m and weak northward currents above the depth with a mean transport of 0.9–1.3 Sv (Van Aken et al. 2009). The overflow is found to be near critical of the hydraulic control, the transport of which is enhanced by 0.6–1.2 Sv due to entrainment from above the overflow (Tan et al. 2020). The connection of the Lifamatola Passage currents with the flows through the Maluku Sea has not been studied before.

The WPOC-ITF mooring array was constructed jointly by the Institute of Oceanology, Chinese Academy of Sciences (IOCAS) and the Research Center for Oceanography, Indonesian Institute of Sciences (RCO/LIPI) during 2014–18 (Yuan et al. 2017, 2018; X. Li et al. 2020, 2021; Wang et al. 2020). Subsurface moorings equipped with current meters and conductivity–temperature–depth (CTD) instruments have been deployed in the Maluku Channel, the Halmahera Sea, the Lifamatola Passage, the Makassar Strait, the Savu Strait, and the Timor Passage to measure the currents in key straits of the Indonesian Seas directly and synchronously. Wang et al. (2020) and X. Li et al. (2020, 2021) have analyzed the current structure and the volume transport through the Savu Strait, the Jailolo Strait, and the Talaul–Halmahera Channel (TH Channel), respectively, based on these mooring measurements.

The mooring and the CTD measurements suggest that the Antarctic Intermediate Water (AAIW) subducted in the Sub-Antarctic Front zone of the Southern Ocean and arriving at the western equatorial Pacific Ocean has flowed into the Seram–Banda Seas in the form of a WBC through the TH Channel, the western Maluku Channel, and the Lifamatola Passage (Yuan et al. 2022). This connection is potentially important to our understandings of the ventilated circulation in the Indo-Pacific Ocean and is of new knowledge of the Great Ocean Conveyor Belt important for ocean heat and CO2 storages.

As continuation of the Yuan et al. (2018, 2022) study, this paper focuses on the circulation and volume budgets in the mid- and upper layers of the Maluku Sea, using the multiyear current meter measurements of four moorings in the Maluku Channel and of one synchronous mooring in the Lifamatola Passage. The data and methods of analysis are described in section 2. The main profiles of currents and transport estimates based on the mooring observations are described in section 3. The volume budgets and uncertainty of the transport estimates are analyzed in sections 4 and 5, respectively, with discussion and conclusions contained in sections 6 and 7, separately.

2. Data and method

a. The mooring data

A pilot mooring (M00) was deployed in the central Maluku Channel from December 2012 through November 2014, which only made current measurements in the upper ~350 m or so, with no current meters attached below ~350 m. Three moorings (called M01, M02, M03, Fig. 1) were deployed in the Maluku Channel from November 2014 through November 2016, which were replaced with two moorings in M01 and M00 from after November 2016 until October 2018, to measure the upper and middle depth currents. The M01 mooring has provided continuous current measurements for as long as 4 years from November 2014 to October 2018. Since November 2014, each mooring was equipped with an upward-looking 75-kHz ADCP fixed at the nominal depth of 500 m and a few recorded current meters (RCMs; Aanderaa or Nortek current meters) fixed at the depths of 250, 750, 1000, and 1800 m. The water depth at M02 is close to 1800 m, so the 1800 m RCM was moved to 1400 m instead. Two RCMs at the depths of 1400 and 2000 m on M00 were used instead of at 1800 m to cover the water depth to as deep as ~2400 m. Details of the mooring configuration are listed in Table 1.

A mooring was deployed at the saddle point of the Lifamatola Passage (called LF mooring hereinafter) since November 2015. An upward-looking 75-kHz ADCP was fixed at the nominal depth of 500 m and a few RCMs were mounted at the nominal depths of 250, 750, 1000, and 1800 m. During the last year deployment (October 2017–September 2018), a current meter was mounted at the nominal depth of 1300 m and a downward-looking 75-kHz ADCP was mounted at the nominal depth of 1500 m to replace the 1800 m RCM.

The 750-m RCM on M01 slipped to about 970 m from November 2014 through November 2015. The 1000-m RCM on M02 worked normally only in the first 7.5 months from November 2014 through November 2015. The 1800-m RCM on M03 from November 2015 through November 2016 was not recovered. The 1800-m RCM on the LF mooring did not return data from November 2016 through October 2017 and the 1000-m RCM failed since the 13th day after the deployment on 8 October 2017. Other than those, the five moorings have returned descent current meter data of upper and middle ocean circulation amenable to analysis.

The bin size, number of bins, and sampling interval of each ADCP were set to be 8 m, 60 bins, and 1 h, respectively. The procedure proposed by Cowley et al. (2008) was used for the quality control of the ADCP data, during which error velocity, percentage of good data, correlation magnitude, vertical velocity, horizontal velocity, and echo intensity were used as indices to determine whether data were accepted or rejected. Data in the top 50 m or so were abandoned due to contamination by the reflection from the sea surface of the acoustic signals. The RCMs were also configured to sample at hourly intervals, the data of which were quality checked to remove obvious unrealistic values.

The current meter data from the same mooring were interpolated to the same integer hour and then onto a 1-m vertical grid. The main float of the LF mooring was blown down by as
TABLE 1. Information about the moorings deployed in the Maluku Channel and Lifamatola Passage. Only current meters on each mooring are shown (75KADCP refers to the 75-kHz ADCP).

<table>
<thead>
<tr>
<th>Mooring name</th>
<th>Lon</th>
<th>Lat</th>
<th>Deployment date</th>
<th>Recovery date</th>
<th>Instrument type</th>
<th>Deployment depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M01</td>
<td>125°41.5'E</td>
<td>2°N</td>
<td>23 Nov 2014</td>
<td>6 Nov 2015</td>
<td>Aanderaa RCM</td>
<td>250, 750, 750, 1000, 1400, 2000</td>
</tr>
<tr>
<td></td>
<td>8 Nov 2015</td>
<td></td>
<td>25 Nov 2016</td>
<td></td>
<td>Nortec RCM</td>
<td>1000, 1800, 1000, 1800</td>
</tr>
<tr>
<td></td>
<td>5 Dec 2016</td>
<td></td>
<td>3 Oct 2017</td>
<td></td>
<td>7SKADCP (upward)</td>
<td>500, 500, 500, 500</td>
</tr>
<tr>
<td>M02</td>
<td>126°29.1'E</td>
<td>2°N</td>
<td>24 Nov 2014</td>
<td>6 Nov 2015</td>
<td>Aanderaa RCM</td>
<td>250, 750, 250, 750</td>
</tr>
<tr>
<td></td>
<td>8 Nov 2015</td>
<td></td>
<td>24 Nov 2016</td>
<td></td>
<td>Nortec RCM</td>
<td>1000, 1400, 1000, 1400</td>
</tr>
<tr>
<td></td>
<td>5 Nov 2015</td>
<td></td>
<td>23 Nov 2016</td>
<td></td>
<td>7SKADCP (upward)</td>
<td>500, 500, 500, 500</td>
</tr>
<tr>
<td>M03</td>
<td>127°17.2'E</td>
<td>2°N</td>
<td>25 Nov 2014</td>
<td>5 Nov 2015</td>
<td>Aanderaa RCM</td>
<td>250, 750, 250, 750</td>
</tr>
<tr>
<td></td>
<td>5 Nov 2015</td>
<td></td>
<td>23 Nov 2016</td>
<td></td>
<td>Nortec RCM</td>
<td>1000, 1800, 1000, 1800</td>
</tr>
<tr>
<td></td>
<td>23 Nov 2016</td>
<td></td>
<td>20 Oct 2017</td>
<td></td>
<td>7SKADCP (upward)</td>
<td>500, 500, 500, 500</td>
</tr>
<tr>
<td></td>
<td>20 Oct 2017</td>
<td></td>
<td>22 Sep 2018</td>
<td></td>
<td>Nortec RCM</td>
<td>1000, 1800, 1000, 1800</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7SKADCP (upward)</td>
<td></td>
<td>500, 500, 500, 500</td>
<td></td>
</tr>
<tr>
<td>LF</td>
<td>126°47.6'E</td>
<td>1°45.7'S</td>
<td>1 Nov 2015</td>
<td>9 Nov 2016</td>
<td>Aanderaa RCM</td>
<td>250, 750, 250, 750, 1000, 1800</td>
</tr>
<tr>
<td></td>
<td>9 Nov 2016</td>
<td></td>
<td>8 Oct 2017</td>
<td></td>
<td>Nortec RCM</td>
<td>1000, 1800, 1000, 1800</td>
</tr>
<tr>
<td></td>
<td>8 Oct 2017</td>
<td></td>
<td>16 Sep 2018</td>
<td></td>
<td>7SKADCP (upward)</td>
<td>500, 500, 500, 500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7SKADCP (downward)</td>
<td>500, 500, 500, 500</td>
</tr>
</tbody>
</table>

JOURNAL OF PHYSICAL OCEANOGRAPHY VOLUME 53
much as 400 m, and sometimes up to 900 m, periodically, by strong tidal currents, resulting in periodic data void in the upper layer. Data at depths with more than 20% data loss were not used in this study. The missing data at depths where the data void was less than 20% were filled with monthly mean residual currents plus the M2, S2, K2, N2, K1, O1, P1, Q1, and Mf tidal harmonics (Van Aken et al. 2009). The monthly mean residual currents were derived from the hourly series, which were calculated with these tidal harmonics removed. The amplitudes of tidal blowout are relatively weak in the Maluku Channel, with the instrument depths oscillating at less than 30 m generally. The Thompson filter (Thompson 1983) was applied to remove tidal signals from the hourly velocity series, which were then averaged into daily mean series for further analysis. After the above data processing, the shallowest effective depths of the mooring observations are essentially from ~50 to ~60 m.

b. Ocean circulation model data

The Ocean General Circulation Model for the Earth Simulator (OFES; Masumoto et al. 2004; Sasaki et al. 2004) is based on the Modular Ocean Model (MOM 3.0). It has a horizontal resolution of 0.1° longitude × 0.1° latitude and vertical uneven 54 levels. The K-profile parameterization boundary layer mixing scheme is employed for the vertical mixing in the surface mixed layer. We used the monthly mean OFES outputs from January 2000 through December 2019, which were forced by daily National Center for Environment Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis winds, surface heat fluxes (Kalnay et al. 1996), and relaxation to the climatological salinity of the World Ocean Atlas 1998 (Boyer et al. 1998a,b,c).

In the existing publications, the OFES model simulation has been widely used and validated with observational data and is shown to simulate the western tropical Pacific Ocean circulation well (e.g., Zhang et al. 2014, 2020; Chen et al. 2016; Ren et al. 2018). The long-term mean currents in and around the Maluku Sea averaged in the 60–450- and 450–1200-m layers from the OFES simulation of 2000–19 are shown in Fig. 2, with the mooring locations in the present and historical observations marked with black hollow triangles and black hollow stars, respectively.

The OFES simulation is consistent with mooring observations at 8°N, 127°3′E (Zhang et al. 2014), showing the southward Mindanao Current (MC) in the upper layer along the east Mindanao coast. The MC takes a retroreflection path around Talaud Island (Fig. 2a), which is consistent with the trajectories of satellite-tracked drifters (Yuan et al. 2018). The model simulated currents are consistent with mooring observation, showing strong eastward outflow through the TH Channel (X. Li et al. 2021; Yuan et al. 2022). The upper thermocline waters of the TH Channel outflow consist of the MC retroreflection, the northward outflow from the Maluku Channel, and the eastward outflow from the Sulawesi Sea, which has been suggested by the surface drifters (Li et al. 2018; Yuan et al. 2018), the sectional hydrographic data in this area.
(X. Li et al. 2021), and the mooring observations in the Maluku Channel (Yuan et al. 2018, 2022). The simulated current east of New Guinea showing northwestward New Guinea Coastal Current carrying South Pacific thermocline water across the equator has been observed by Zhang et al. (2020) using moorings. Part of this current joins the ITF through the Halmahera Sea, consistent with the mooring observations in the Jailolo Strait (Li et al. 2020), and flows farther into the southern Maluku Sea and the Seram Sea as suggested by the hydrographic data (Gordon and Fine 1996; Ilahude and Gordon 1996). The northwestward mean currents near the Morotai and Talaud Islands are consistent with the two historical mooring observations at about 350 m of Kashino et al. (1999).

In the middle layer, the OFES simulated pathway of the AAIW, carried by the northwestward New Guinea Coastal Undercurrent (NGCUC; Zhang et al. 2020) and entering the eastern Indonesian Seas through the middle and northern part of the TH Channel, the western Maluku Sea, and the Lifamatola Passage, has been evidenced by historical mooring observations and the hydrographic data in this area (Luick and Cresswell 2001; Yuan et al. 2022) (Fig. 2b). These above validations suggest that the OFES simulation has effectively captured the main circulation pattern in and near the Maluku Sea in the upper 1200 m.

The eddy-resolving Hybrid Coordinate Ocean Model (HYCOM) combines the isopycnal layer (density tracking), z level (constant fixed depths), and σ level (terrain following) and has a simulation with a horizontal resolution of 0.08° in a 41-layer hybrid vertical grid (Chassignet et al. 2009). The model is forced by the Navy Global Environmental Model (NAVGEM) atmospheric forcing. The available observational data, such as the ocean temperature, salinity, and satellite altimeter data, etc. are assimilated into the model using the Navy Coupled Ocean Data Assimilation (NCODA) system (Cummings 2005; Cummings and Smedstad 2013). The velocity data exported from the model experiments 56.3 and 57.2 were averaged into monthly means, and the data from November 2015 to November 2016 were used in this study.

c. Other data

The 2-arc-min ETOPO2v2 data of the U.S. National Geophysical Data Center were used to derive the water depths for transport estimation in the Maluku Channel and the Lifamatola Passage.

d. Transport estimation

The Maluku Channel is divided by a midchannel ridge between M01 and M02 into the western and eastern channels. The shallowest water depth of about 1314 m is at (2°N, 126°13′2.28″E), which is used as the boundary between these two subchannels. The section used to estimate the transport through the western and eastern Maluku Channel is the same as that used in Yuan et al. (2018) (Fig. 1). In the Lifamatola Passage, the current directions vary greatly with depth and are only relatively stable in the deep layers (>1300 m) restricted by topography. If the transport should be estimated based on the along-strait velocity, great uncertainty will exist in the upper and middle depths. Therefore, the transports through the Lifamatola Passage are estimated through a section of the shortest distance between the coasts. The section turns out to have a direction of 79.5° clockwise from due north.

In the Maluku Channel section, the velocity east of M03 is kept the same as at M03 (free-slip condition) or interpolated linearly to the coast using a nonslip sidewall condition along the 2°N section. West of M01, the velocity is either kept the same as at M01 or interpolated linearly to the coast of Sulawesi using a nonslip sidewall condition along a section of 41.2° clockwise from due north. Between M01 and M02, the velocity is interpolated linearly.

Between M02 and M03, a special interpolation scheme is applied, based on the mooring and simulated upper- and midlayer currents in the Maluku Channel. It has been found that the mean and time series of current profiles between 350 and 1200 m are similar at M00 and M02, in spite of the different observational periods (Figs. 3b–d), which is supported by the OFES simulation. Therefore, the velocity below 350 m is kept constant between M02 and M00 as that at M02 and is interpolated linearly between M00 and M03. In the upper 350 m, the velocity between M00 and M03 is kept the same as at M03 and is interpolated linearly between M00 and M03. The interpolation scheme has been tested in the OFES simulation and is proven to be better than the simple linear interpolation between M02 and M03. During the periods when only M00 is deployed in the eastern channel, the velocity between M00 and M01 is interpolated linearly from the two mooring data.

In the Lifamatola Passage, the velocity east of the LF mooring is interpolated to the coast using the nonslip and free-slip conditions, separately, for comparisons. West of the mooring, the velocity is kept constant because of the significant westward intensification in this channel, as simulated by the OFES model. Volume transport normal to the cross-channel section is estimated based on the mooring data and model simulations.

The missing velocity data in the upper 50 or 60 m caused by the blow down of the main floats and the acoustic signal contamination from the sea surface reflection are filled using three extrapolation methods: 1) vertical linear interpolation assuming zero velocity at the surface, 2) extrapolation to the surface using the shallowest two observations at the 10 m grid, and 3) assuming constant in the surface layer. The transport estimates using these three methods are compared to determine the range and uncertainty of the transport estimates in the surface layer.

The standard error (SE) of the mean value is computed as \( SE = \sigma / \sqrt{r} \), where \( \sigma \) is the standard deviation of the time series, and \( r \) is the number of degrees of freedom. Considering the autocorrelation of the time series, the number of degrees of freedom is calculated as (Bretherton et al. 1999)

\[
v = \frac{1 - r(\Delta t)^2}{1 + r(\Delta t)^2} \times N_T,
\]

where \( r(\Delta t) \) is the autocorrelation coefficient at one time step, \( \Delta t \) the sampling interval, and \( N_T \) the number of observations.
3. Observed mean currents and transports

Mean current profiles measured by the moorings deployed in the Maluku Channel and the Lifamatola Passage are described in this section, with the transport through these two channels estimated using different sidewall boundary conditions.

a. Maluku Channel currents and transports

The multiyear average profiles of the currents measured by the four moorings in the Maluku Channel suggest a northward mean current through the upper layer of the channel joining the beginning of the North Equatorial Countercurrent (NECC; Figs. 3a–d), the dynamics of which have been suggested to be associated with the MC retroreflection (Yuan et al. 2018). The northward mean currents are found to reach as deep as 452 m at M01 (Fig. 3a). In the eastern Maluku Channel, northward mean currents extend into deeper layers, such as to 674 m at M03 (Fig. 3d). At M02, the mean current is northward at most depths above 1185 m, above the 95% significance level, except in the depth range of 118–254 m (Fig. 3b). No mean current data were available below 1345 m at M00, the mean current is essentially northward in the upper 1170 m, except for weak southward mean flows at 138–183- and 348–433-m depths (Fig. 3c). The upper-layer southward mean currents in the depth ranges shown by M02 and M00 are also present at M01 and M03 in special years (Figs. 3a,d). These may indicate direct intrusions of the high-salinity North and South Pacific Tropical Water and low-salinity North Pacific Intermediate Water and their mixture, which has been discussed in a separate paper (Li et al. 2018; M. Li et al. 2021; X. Li et al. 2021).

We shall focus on the transport in the 2-yr period from late 2014 through late 2016, when three moorings in the cross-channel section of the Maluku Channel have returned uninterrupted measurements. The northward mean transport through the Maluku Channel based on the three moorings is estimated to be 2.07 Sv, above the 95% confidence level with 0.66 Sv SE, for nonslip condition, and 2.60 Sv (0.72 Sv SE) for free-slip condition, respectively, in the depth range of 60–450 m, the zero crossing of the mean currents at M01. We shall call the depth range from 60 to 450 m as the upper layer hereinafter.

Because of the deeper extending depths of the northward mean currents in the eastern Maluku Channel, the northward mean transport through the Maluku Channel actually extends to 685 and 634 m, based on the nonslip and free-slip sidewall conditions, respectively, with the northward transport of 2.27 Sv (0.90 Sv SE) and 2.86 Sv (0.89 Sv SE), respectively. The latter estimates are only increases of less than 10% from that in the upper layer.

Below 450 m at M01, the 4-yr mean current is southward with a core speed of ~6.4 cm s$^{-1}$ at about 800–1000 m (Fig. 3a), larger than those at M02, M03, and M00, all of which are below 5 cm s$^{-1}$ (Figs. 3b–d). The low-passed time series at M01, with the cutoff period at 120 days, show a persistent southward current below about 650 m, almost uninterrupted in the entire

![Mean current profiles during each deployment period](image-url)
observational period (Fig. 4a). The mooring measurements suggest strongly that this intermediate current at M01 is a WBC in the Maluku Channel (Yuan et al. 2022). In the eastern Maluku Channel, mean currents are generally northward above 1200 m as described above, except between 675 and 1177 m at M03, where the mean currents are weakly southward (Figs. 3b–d).

The southward currents near the eastern boundary may be associated with the intrusions of the South Pacific currents (e.g., NGCUC). Except for this intrusion, an anticlockwise gyre circulation is suggested in the depth range of 450–1200 m in the Maluku Sea (called the midlayer hereinafter).

The midlayer circulation in the Maluku Sea is studied using the 4-yr time series of the mooring measurements (from late 2014 through late 2018). The mean transport of the intermediate WBC in the western Maluku Channel is estimated to be 1.83 Sv (0.75 Sv SE) and 2.25 Sv (0.93 Sv SE) southward, based on the nonslip and free-slip western sidewall conditions, respectively. On the eastern side of M01, velocities are derived from linear interpolation between the M01 and other moorings. Some transport overestimates are expected from the linear interpolation between the M01 and other moorings. The WBC transport is statistically significant and much larger than the transport of the

El Niño event (Fig. 4a). The mean transport of the intermediate WBC from early November 2015 through late November 2016 (M01 dep2 period, Table 1) is estimated to be 2.46 Sv (1.38 Sv SE) and 3.01 Sv (1.77 Sv SE) southward, based on the nonslip and free-slip western sidewall conditions, respectively, larger than the 4-yr mean transport by about 34.4% and 33.8% due to interannual variations. If the velocity west and east of M01 was kept as constant (free-slip) or reduced to zero (nonslip) at the middle ocean ridge and the western coast, the mean transport of the intermediate WBC from early November 2015 through late November 2016 is 4.52 Sv (2.52 Sv SE) or 2.26 Sv (1.26 Sv SE), respectively, about 45.0% or 44.9% larger than the 4-yr means. Below 1200 m, the mean current in the western Maluku Channel is also southward (Fig. 3a). The mean southward transport of the western boundary current is estimated to be 2.28 Sv in the depth range of 450–1800 m, using the nonslip sidewall conditions at the west coast of the middle ocean ridge and at the western boundary of the Maluku Channel, based on the 4-yr M01 observation (Yuan et al. 2022).

In the eastern channel, the 2-yr mean northward transport in the middle layer is estimated to be 1.01 Sv (0.90 Sv SE) and 0.97 Sv (0.95 Sv SE) for the nonslip and the free-slip eastern sidewall conditions, respectively. The WBC transport is statistically significant and much larger than the transport of the
b. Lifamatola Passage currents and transports

Northward mean currents are observed in the upper 434 m in the Lifamatola Passage (Fig. 3e), with a core speed of near 14 cm s\(^{-1}\) at around the 100-m depth normal to a cross-strait section, suggesting that the mean transport in the upper 450 m of the Maluku Sea comes from the Banda and Seram Seas. The mean transport from late 2015 through late 2018 in the upper layer of the Lifamatola Passage is estimated to be 1.23 Sv (0.73 Sv SE) and 1.83 Sv (1.08 Sv SE) northward for the nonslip and free-slip conditions, respectively. The mean transport is much smaller than the northward transport through the upper-layer Maluku Channel although based on different observation periods, the difference of which is suggested to be supplied by upwelling in the Maluku Sea or/and transports through the Obi Strait from the Halmahera Sea.

Below 450 m, the mean current in the Lifamatola Passage is southward (Fig. 3e), with the 3-yr mean transport in the middle layer as large as 0.62 Sv (0.56 Sv SE) and 0.93 Sv (0.83 Sv SE) for the nonslip and free-slip eastern sidewall conditions, respectively, and free-slip condition west of LF mooring. The southward transport in the middle layer is consistent with the transport surplus between the WBC and the interior return flows in the Maluku Sea (Table 2), suggesting that the Maluku Sea intermediate WBC has reached the Seram and Banda Seas through the Lifamatola Passage. However, the midlayer transport through the Lifamatola Passage is found less than the transport difference between the WBC and the interior return flows in the Maluku Channel. This may suggest upwelling inside the Maluku Sea to balance the transport difference between the two straits.

The LF mooring data coverage is shallower than 1200 m from 9 November 2016 through 8 October 2017. Three kinds of extrapolation schemes mentioned above used at M03 were employed here at the LF mooring to fill in the data gap to the 1200-m depth, which generates mean transport differences less than 0.03 Sv, significantly smaller than the standard errors of the intermediate-layer mean transport through the Lifamatola Passage.

Based on the LF mooring observation from November 2015 through November 2016 and from October 2017 through September 2018 (dep2 and dep4, Fig. 3), the mean current below 1200 m of the Lifamatola Passage is southward as that in 450–1200 m, with estimated transport of 1.36 Sv in the depth range of 450–1800 m, using free-slip western sidewall and nonslip eastern sidewall conditions (Yuan et al. 2022).

4. Volume budgets in the Maluku Sea

In this section, transport estimates based on the synchronous moorings at M01, M02, M03, and LF moorings from November 2015 through November 2016 are used to analyze the volume budgets in the upper and middle layers of the Maluku Sea.

In the upper layer, the northward transport through the Lifamatola Passage shows similar seasonal variability as that through the Maluku Channel with northward transport anomaly during boreal fall–winter, which has been suggested to be related to the seasonal movement of the MC retroreflection (Yuan et al. 2018), except that the magnitude of the transport through the Lifamatola Passage is smaller than that through the Maluku Channel during the entire period (Fig. 5a). In the middle layer, the transports through the western and eastern Maluku Channels vary in opposite phases to each other during the period (Fig. 5b). The transport through the western Maluku Channel is southward throughout the year except for occasionally intraseasonal weakening or reversing, due to possibly wind or eddy forcing. The transport through the eastern Maluku Channel is in the opposite direction, indicating the anticyclonic gyre circulation in the Maluku Sea almost in the entire period.

### Table 2. The statistics of the estimated mean transports (Sv) through the upper and middle layers of the Maluku Channel and the Lifamatola Passage, with their standard errors (in parentheses) shown. Standard errors are calculated at 95% significance level. The WM and EM represent the western and eastern Maluku Channel, respectively. Positive sign means northward.

<table>
<thead>
<tr>
<th>Passage</th>
<th>Integration range</th>
<th>Nonslip</th>
<th>Free slip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maluku (November 2014–November 2016)</td>
<td>60–450 m</td>
<td>+2.07 (0.66)</td>
<td>+2.60 (0.72)</td>
</tr>
<tr>
<td>WM (November 2014–September 2018)</td>
<td>450–1200 m</td>
<td>−1.83 (0.75)</td>
<td>−2.25 (0.93)</td>
</tr>
<tr>
<td>EM (November 2014–November 2016)</td>
<td>450–1200 m</td>
<td>+1.01 (0.90)</td>
<td>+0.97 (0.95)</td>
</tr>
<tr>
<td>Lifamatola (November 2015–September 2018)</td>
<td>60–450 m</td>
<td>+1.23 (0.73)</td>
<td>+1.83 (1.08)</td>
</tr>
<tr>
<td></td>
<td>450–1200 m</td>
<td>−0.62 (0.56)</td>
<td>−0.93 (0.83)</td>
</tr>
</tbody>
</table>
The volume budgets in the upper 1200 m of the Maluku Sea are shown to be significantly unbalanced (Fig. 5c). Cross-channel integration of the velocity normal to the cross-channel sections in the Lifamatola Passage minus the integrated velocity across the Maluku Channel leads to the vertical profiles of transport surplus in the Maluku Sea (Fig. 5c). It shows that the inflow transport in the upper 754 m is less than the outflow transport by 1.23 Sv using the nonslip sidewall condition. The deficit becomes 1.11 Sv in the upper 724 m using the free-slip sidewall condition. The mass deficit in the upper 754/724-m layer is suggested to be balanced by upwelling in the Maluku Sea.

Below 754/724 m and above 1200 m, the inflow transport is significantly larger than the outflow transport, with a mean net transport surplus of 0.61 Sv for the nonslip condition, and of 0.82 Sv for the free-slip condition. This net inflow transport in the middle layer is suggested to be upwelled into the upper layer to compensate for the net mass deficit above.

In summary, the Pacific water is transported into the middle layer of the Maluku Sea, part of which upwells into the upper layer and flows back to the Pacific Ocean, and part of which flows into the Seram and Banda Seas.

5. Transport estimates based on model simulations

In this section, currents simulated by the OFES model during November 2015–November 2016 are used to evaluate the uncertainty of the transport estimates of the Maluku Sea.

a. Verification of simulated velocity

The simulated currents show similar vertical mean profiles of longshore velocity as observed at M01, with significant northward current in the upper layer and southward current in the middle layer, except that the simulated zero-velocity depth is a little deeper (by about 60 m) than the observed one (Figs. 6a,c). The same opposite flows in the upper and middle layers exist in the Lifamatola Passage, except that the simulated zero-velocity depth is deeper by about 150 m than the observed (Figs. 6d,f). In the eastern Maluku Channel, the simulated upper-layer mean currents are more variable than the observed due to the weak mean flows, and the simulation in the middle layer reproduces the return flow of the Maluku Sea circulation reasonably (Fig. 6a).

Using the nonslip sidewall condition, the interpolation using the simulated velocity at the mooring sites has reproduced the simulated mean currents through the Maluku Channel.
reasonably well (Figs. 6a,b), except that the WBC is slightly weaker than the simulated due to the coarse resolution of the mooring array, possibly leading to the underestimated transports using the nonslip sidewall condition. In the eastern channel, the linear interpolation between M02 and M03 would have missed a current core at about 1000–1200 m (Fig. 6a). The special interpolation scheme is designed to replicate the simulated currents by keeping the velocity constant between M02 and M00 but interpolating linearly between M00 and M03 below 350 m and keeping the velocity constant between M00 and M03 in the upper 350 m (see section 2d). Experimentation suggests that this scheme can make up a lot of the shortcomings of the simple linear interpolation based on the mooring array with coarse resolution (Fig. 6b).

The simulated currents in the Lifamatola Passage demonstrate significant westward intensification (Fig. 6d). Transport estimates based on a single mooring in this passage will...
Table 3. The transports (Sv) through the western and eastern Maluku Channel and the Lifamatola Passage, calculated based on the OFES model simulated currents and the estimates based on the simulated velocities at the mooring sites, respectively, are shown. The RMSE between the simulated and estimated monthly transports are also shown to be compared with the standard deviation (std) of the simulated transports.

<table>
<thead>
<tr>
<th></th>
<th>Simulation</th>
<th>Nonslip</th>
<th>Free slip</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std</td>
<td>Mean</td>
</tr>
<tr>
<td>Maluku</td>
<td>60–450 m</td>
<td>+0.79</td>
<td>1.41</td>
</tr>
<tr>
<td>WM</td>
<td>450–1200 m</td>
<td>-2.72</td>
<td>2.57</td>
</tr>
<tr>
<td>EM</td>
<td>450–1200 m</td>
<td>+1.30</td>
<td>1.82</td>
</tr>
<tr>
<td>Lifamatola</td>
<td>60–450 m</td>
<td>+0.89</td>
<td>1.22</td>
</tr>
<tr>
<td></td>
<td>450–1200 m</td>
<td>-1.53</td>
<td>1.37</td>
</tr>
</tbody>
</table>

Inevitably generate large errors. Fortunately, our LF mooring is located in the western passage, which nearly captures the middle layer WBC core, but misses the upper current core miserably. Keeping the velocity constant west of the mooring LF can make up for the interpolation errors, to some extent, in the estimation of the transports (Figs. 6d,e).

b. Uncertainty of transport estimates

Transports through the Maluku Channel and the Lifamatola Passage are calculated based on the simulated currents of the OFES model from November 2015 through November 2016, which are compared with the estimates based on the simulated velocity at the four mooring sites. The errors of the estimates are calculated as the root-mean-square errors (RMSE) between the estimated and the simulated monthly transports. The estimated mean transports and the RMSE are compared with the simulated mean transports and their standard deviations, respectively, in Table 3. The RMSE of the estimated transports are all much smaller than the standard deviations of the simulated transports, showing that the estimated transport series are close to the simulated.

In the middle layer, the error of the estimated mean transport is 8.1% and 17.6% for the nonslip condition and free-slip condition, respectively, in the western Maluku Channel. The error is 16.9% and 13.1% for the nonslip condition and free-slip condition, respectively, in the eastern Maluku Channel. In the upper layer, the error of the estimated mean transport in the Maluku Channel is 29.1% and 25.3% for the nonslip condition and free-slip condition, respectively. In the Lifamatola Passage, the error based on the free-slip sidewall condition is 11.2% in the upper layer and 15.0% in the middle layer. These estimates of the uncertainty of the interpolation scheme give us confidence of the volume budget analyses of the Maluku Sea based on the concurrent mooring data from November 2015 through November 2016 in the previous subsection.

6. Discussions

a. Obi Strait transport

The time series of the currents and transports through the Obi Strait have never been measured historically. The OFES and HYCOM model simulations were used to help evaluate the effect of the Obi Strait transports on the volume budget estimates in the Maluku Sea. The HYCOM model performs by and large as well as the OFES model in reproducing the observed current pattern in the Maluku Sea (Figs. S1a,b in the online supplemental material; Fig. 6c,d). The HYCOM model has a much deeper and wider Obi Strait than the OFES model (Figs. S1c,d). Its simulated transport is used as an upper limit of the Obi Strait transport.

The OFES simulation indicates mean westward transports of 0.07 Sv in the upper layer and 0.04 Sv in the middle layer through the Obi Strait in November 2015–November 2016. The HYCOM model simulation indicates mean transports through the Obi Strait of 0.24 Sv westward in the upper layer and 0.05 Sv eastward in the middle layer. The mean transports through the Obi Strait in these two models are much smaller than those through the Maluku Channel and the Lifamatola Passage (Fig. S2; Table S1) and can be neglected in our budget analysis.

b. Transports in the upper 60 m

The moored ADCP instruments do not make valid current measurements in the upper 50 m or so, due to the sound noise reflected from the sea surface that contaminates the Doppler shift signals. We use three methods to estimate the transports in the upper 60-m layer, which are expounded below.

Using constant velocity in the upper 50 or 60 m based the valid ADCP data, the northward mean transport from late 2014 through late 2016 in the upper 60 m of the Maluku Channel is estimated to be 0.67 Sv (0.33 Sv SE) using nonslip sidewall condition and 0.60 Sv (0.35 Sv SE) using free-slip condition, respectively, based on the three moorings. The northward transport is estimated to be 0.93 and 0.86 Sv, for the two sidewall conditions, respectively, if the currents are extrapolated linearly above from the 10-m grid nearest to the surface of the ocean. The transports are reduced to 0.37 and 0.35 Sv, assuming zero velocity at the surface and linear interpolation between 60 m and the sea surface. The difference of the maximum and minimum estimates from the intermediate estimates above is no larger than 0.30 Sv, for nonslip sidewall condition, and 0.26 Sv, for free-slip condition, respectively, both of which are below the standard errors of the intermediate mean transport at 0.33 and 0.35 Sv, suggesting the validity of the intermediate estimates (constant velocity).

Assuming zero velocity at the surface, the mean transport from late 2015 through late 2018 in the upper 60 m of the
Lifamatola Passage is estimated to be 0.12 Sv (0.09 Sv SE) and 0.18 Sv (0.14 Sv SE) northward using the non-slip and free-slip sidewall conditions, respectively. Assuming constant velocity in the upper 60 m, the northward transport is estimated to be 0.20 and 0.30 Sv, respectively. The extrapolation to the surface results in 0.04 and 0.05 Sv, respectively. The difference of the maximum and minimum estimates from the intermediate estimates is only 0.08 Sv, for non-slip sidewall condition, and 0.12 Sv, for free-slip sidewall condition, respectively, which are below the standard errors of the intermediate mean transport at 0.09 and 0.14 Sv.

The coverage of M01, M02, M03, and LF moorings overlaps during only about one year from November 2015 to November 2016. During this period, the mean transport through the upper 60 m of the Maluku Channel is estimated to be 0.44 Sv (0.56 Sv SE) and 0.36 Sv (0.58 Sv SE) using the non-slip and free-slip sidewall conditions, respectively, assuming constant velocity in the surface layer. The mean transport through the upper 60 m of the Lifamatola Passage is estimated to be 0.15 Sv (0.22 Sv SE) and 0.22 Sv (0.33 Sv SE), respectively, assuming zero velocity at the surface. The mean transport through the upper 60 m transport of 1.83 Sv, a significant part of which returns back to the western Pacific Ocean, suggest the existence of a countercurrent in the eastern Indonesian Seas. The mean transport through the upper-layer Maluku Channel is estimated to be 2.07–2.60 Sv from November 2014 through November 2016, and the mean transport through the upper-layer Lifamatola Passage is estimated to be 1.23–1.83 Sv from November 2015 through September 2018. So far, it is not clear whether this mean northward transport in the upper Maluku Sea comes directly from the Makassar Strait or from the Ombai Strait. Observations have suggested rich countercurrents and undercurrents from the Indian Ocean into the Indonesian Seas through the Savu Strait (Wang et al. 2020) and the Ombai Strait (Sprintall et al. 2009). The northward transport through the upper Lifamatola Passage and Maluku Channel is likely a mixture of the waters from the Makassar Strait and from the Ombai Strait. The modeling study of Liang and Xue (2020) has indeed suggested the reverse water from the Indian Ocean toward the Pacific Ocean through the eastern Indonesian Seas. The connection of the ITF countercurrent with the northward transport through the upper-layer Lifamatola Passage is beyond the scope of this study; the observational analysis of which will be reported in a following paper.

In the middle layer, a strong WBC flows into the Maluku Sea through the western Maluku Channel, with a 4-yr mean transport of 1.83–2.25 Sv, a significant part of which flows southward into the Seram Sea and Banda Sea through the Lifamatola Passage with a 3-yr mean transport of 0.62–0.93 Sv, and a part of which returns back to the western Pacific Ocean through the central and eastern Maluku Channel with a 2-yr mean transport of 0.97–1.01 Sv. An anticlockwise circulation is suggested in the middle layer of the Maluku Sea forced by the negative PV transport through the Maluku Channel and the Lifamatola Passage, which must be dissipated by an anticlockwise dissipation term, a Rayleigh friction is applied to replace the term as \(-\lambda_f C_1 (\mathbf{v} \cdot \mathbf{l}) ds\), where \(\lambda\) is the Rayleigh friction coefficient. The forcing from surface wind stress is absent in the middle layer. Therefore, Eq. (2) can be rewritten as

\[
\frac{Q_{\text{Ma}}}{H_\text{Ma}} f_{\text{Ma}} + \frac{Q_{\text{Lifa}}}{H_\text{Lifa}} f_{\text{Lifa}} = -\lambda f C_1 (\mathbf{v} \cdot \mathbf{l}) ds.
\]

The mean southward volume transports through the Maluku Channel and the Lifamatola Passage lead to \(Q_{\text{Ma}} < 0\) and \(Q_{\text{Lifa}} > 0\). The locations of the Maluku Channel and the Lifamatola Passage suggest \(f_{\text{Ma}} > 0\) and \(f_{\text{Lifa}} < 0\). The PV transport through the middle layer of the Maluku Sea is therefore negative, which is balanced by the term \(-\lambda f C_1 (\mathbf{v} \cdot \mathbf{l}) ds\). Therefore, the midlayer circulation must be an anticlockwise gyre.

7. Conclusions

In this study, the volume budgets in the middle and upper layers of the Maluku Sea are studied based on ADCP and RCM data of four moorings in the Maluku Channel and of one mooring in the Lifamatola Passage. The mean transports in the upper 450 m of the Maluku Channel and Lifamatola Passage are found to flow toward the Pacific Ocean, suggesting the existence of a countercurrent in the eastern Indonesian Seas. The mean transport through the upper-layer Maluku Channel is estimated to be 2.07–2.60 Sv from November 2014 through November 2016, and the mean transport through the upper-layer Lifamatola Passage is estimated to be 1.23–1.83 Sv from November 2015 through September 2018.

In the middle layer, the overturning circulation of the Maluku Sea plays the dominant role in PV balance. Therefore, the left term in Eq. (2) can be simplified to \((Q_{\text{Ma}}/H_\text{Ma}) f_{\text{Ma}} + (Q_{\text{Lifa}}/H_\text{Lifa}) f_{\text{Lifa}}\), where \(Q_{\text{Ma}}\) and \(Q_{\text{Lifa}}\) are the volume transports out of the Maluku Sea in the middle layer through the Maluku Channel and the Lifamatola Passage, respectively; \(f_{\text{Ma}}\) and \(f_{\text{Lifa}}\) are the Coriolis parameters in the Maluku Channel and the Lifamatola Passage, respectively; \(H_\text{Ma}\) is the thickness of the middle layer. For the PV integral constraint. The PV equation is written as (Yang and Price 2000; Yang 2005; Lan et al. 2013, 2015; Liang et al. 2019):

\[
\int_C (\mathbf{v} \cdot (\mathbf{n} f + \frac{\mathbf{f}}{H})) ds = \int_A D_p \mathbf{v} dy + \int_C (\mathbf{F} \cdot \mathbf{l}) ds,
\]

where \(C\) is the closed integral line along the lateral boundary of the basin and \(A\) is the area enclosed by boundary \(C\); \(\mathbf{n}\) and \(\mathbf{l}\) are the unit vectors normal outward and tangential to \(C\), respectively; \(\mathbf{v}\) is the horizontal velocity vector, \(H\) the layer thickness, \(f\) and \(\xi\) the planetary and relative vorticity, respectively; \(D_p\) and \(\mathbf{F}\) stand for the PV dissipation and surface stress, respectively.

In practice, the relative vorticity \(\xi\) is usually too small to be important compared with the planetary vorticity. In the middle layer of the Maluku Sea, the volume transports through the Maluku Channel and the Lifamatola Passage are influenced by the planetary and relative vorticity, respectively; the forcing from surface wind stress is absent in the middle layer. Therefore, Eq. (2) can be rewritten as

\[
\int_C (\mathbf{v} \cdot (\mathbf{n} f + \frac{\mathbf{f}}{H})) ds = \int_A D_p \mathbf{v} dy + \int_C (\mathbf{F} \cdot \mathbf{l}) ds.
\]
circulation inside the Maluku Sea. From late 2015 through late 2016, the mean transport of the intermediate WBC increased to 2.46–3.01 Sv due to interannual variations associated with the 2015/16 strong El Niño event.

Volume budget analysis based on synchronous mooring measurements in the Maluku Channel and the Lifamatola Passage suggests upwelling from the middle to the upper layers in the Maluku Sea. The imbalance is found to be enhanced by the transport estimates in the surface layer of the ADCP data void. The qualitative budgets are robust despite the large uncertainty in transport estimates based on the mooring data. A schematic circulation is given in Fig. 7.

Our study provides more detailed analysis of the mooring measurements, discussing both the intermediate and the upper-layer circulation, its volume budgets, and the controlling dynamics above 1200 m, suggesting upwelling currents in the Maluku Sea, which is a valued extension of the Yuan et al. (2018, 2022) publications. As the Maluku Sea is an important entrance of the AAIW in flow toward the Indian Ocean (Yuan et al. 2022), the processes of water exchange revealed in this paper help us understand the AAIW movement in the Maluku Sea better, providing new insight for the global ocean overturn and the heat and CO₂ storages associated with it.

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