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Vertical structure of Indonesian throughflow in a large-scale model☆

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Abstract

The vertical structure of the exchange of water between the Pacific and Indian Oceans via the Indonesian throughflow and its temporal variability are examined. Since there are no simultaneous, direct observations of transport variations with depth at the inflow straits (Makassar, Maluku, and Halmahera) and outflow straits (Lombok, Ombai, and Timor), numerical model results are used. Analysis of depth-integrated transport through the model straits indicates differences in the vertical structure of the flow between the inflow and outflow straits. Generally speaking, local winds affect flow in a layer above the thermocline, while remote forcing, e.g., ENSO or coastal Kelvin waves, affect flow in a subsurface layer. On the outflow side, transport occurs primarily in two vertical modes. The dominant mode is characterized by a surface intensification that decays to zero around 400 m. The second mode is characterized by flow in the upper 100 m that is of opposite direction to flow from 100 to 400 m. The vertical decomposition of transport through the model's inflow straits varies between the straits. At Makassar, the western-most inflow passage, the dominant mode is similar to the outflow straits, with a surface intensification of southward transport that decays to zero at 800 m. At Halmahera, the eastern-most inflow strait, the dominant mode is two-layer, with surface to 200 m transport in the opposite direction of transport from 200 to 700 m, similar to the second mode at the outflow straits. At Maluku, the center inflow passage, the dominant vertical mode is three-layer. At this strait, there is a layer from about 100 to 800 m within which flow is in the opposite direction to flow in a surface layer above 100 m and in a deeper layer below 800 m. Phase lags on the annual cycle suggest that during April–October, peaking in May, there is a convergence of mass in the upper 100 m of the Indonesian seas. This convergence is balanced by a mass divergence from 100 to 710 m that occurs slightly earlier but is of shorter duration, from February to mid-June. While interannual variations of transport in the straits varies, the difference in inflow and outflow on interannual timescales is correlated to ENSO. There is a divergence (convergence) of mass in the upper 100 m (100–710 m) in the Indonesian seas during the El Niños of 1982/1983, 1986/1987, 1994/1995 and 1997/1998.

1. Introduction

There are three main entry passages from the Pacific into the central Indonesian seas: Makassar, Maluku and Halmahera. Similarly, there are three

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main outflow passages through which water exits the Indonesian seas into the Indian Ocean: Lombok, Ombai and Timor. Previous studies have identified these straits as contributing the bulk of the Pacific to Indian Ocean exchange (Godfrey, 1996). The objective of this paper is to determine the vertical structure of the volume transport through these straits.

An early examination into the dynamics of the ITF was made by Wyrtki (1987). The hypothesis in that work was that the easterly trade wind system set up a pressure head between the Pacific and Indian Oceans, and this pressure head is what drives the ITF. More recent efforts have shown that a geostrophic balance exists in the straits (Potemra et al., 2002), and Pacific winds control the pressure, or sea level, on the Pacific side (i.e. off the west coast of Australia), while local and Indian Ocean winds control the sea level on the Indonesian side of the archipelago (Potemra, 1999). Potemra et al. (2002) showed using a numerical model that the geostrophic approximation, at least on the outflow side, started to break down at depth. Here, the vertical structure of the ITF transport is investigated in more detail in both the inflow and outflow straits.

There have been few direct observations of flow in these straits. Particularly lacking are observations of flow throughout the water column over extended periods, with a few notable exceptions. On the inflow side, there have been mooring programs in the Halmahera Sea, Maluku Sea and in the Makassar Strait. On the outflow side only the Ombai Strait and Timor Passage have been sampled at depth for a significant (year or more) time period.

Gordon and Susanto (1999) describe the results of an almost 16-month mooring effort in the Makassar Strait. Two moorings within the strait measured velocities at approximately 200, 250, 350, 750 and 1500 m depth. The upper current meter recorded the strongest mean velocities of 30–50 cm s^{-1}. At 1000 m the mean velocity was less than 10 cm s^{-1}. An estimate of depth-integrated transport had a strong semiannual component with peak southward transport of near 14 Sv in March and July of 1997. Minimum transport occurred in May and October of the same year. Despite the relatively short time series, a relationship to the El Niño of 1997 was found, such that the transport was less and the temperature of the flow through the strait was lower during 1997 (Ffield et al., 2000).

Velocities in the Maluku and Halmahera Seas also have been measured with moorings, though at different time periods than Makassar. Similar to the Makassar mooring, the Maluku and Halmahera moorings only measured subsurface flow; current meters were located at 400, 700 and 900 m in the Halmahera Sea (Cresswell and Luick, 2001) and at 740, 1250, 1750 and 2240 m in the Maluku Sea (Luick and Cresswell, 2001). Both moorings were in place from June 1993 to July 1994. At Halmahera, the flow in 1994 was maximum to the south during January and February and near zero (or slightly to the north) in May and June (Cresswell and Luick, 2001). In Maluku transport is harder to estimate given the relatively wide (approximately 200 km) strait and potential cross-strait flow not captured by the single mooring, and the current meters showed a reversal of flow with depth. The upper two current meters measured mainly southward velocities with brief periods of northward flow in October and November 1993 and April and May of 1994. The deepest current meter showed northward flow throughout the year (Luick and Cresswell, 2001).

Molcard et al. (2001) have reported on year-long mooring measurements in the Ombai Strait on the outflow side of the ITF. This mooring was equipped with an upward-looking ADCP and thus could measure near-surface currents. The measured mean current in the strait for 1996 was surface intensified, about 60 cm s^{-1}, and it decayed to zero at 1200 m. By 400 m, the mean velocity was less than 20 cm s^{-1}. Total transport for the year was estimated to be 4–6 Sv toward the Indian Ocean. An empirical orthogonal function (EOF) analysis made on the velocity measurements showed that 87% of the variance was contained in a mode with surface intensified flow that decayed exponentially to less than 10 cm s^{-1} at about 200 m. The time modulation of this pattern was such that the flow was strongest toward the Indian Ocean in June–August. In November and December the flow was toward the internal Indonesian seas. The second EOF mode (10% of the variance) had velocity in a subsurface layer, from roughly 100 to 800 m, that was in the opposite direction to the flow in the near surface and deeper layers. This mode had a less distinct annual cycle, with peak flow toward the Indian Ocean in late December and January and flow toward the Indonesian seas in April and May.

Finally, velocity in Timor Passage was measured with a pair of moorings (Molcard et al., 1996). EOF analysis of flow through Timor from these moorings shows a three-layer structure, similar to the results at Ombai: surface-intensified flow captured by EOF-1 and mid-depth flow opposite to surface and deep flow in EOF-2. The annual cycle of the total transport through Timor Passage is slightly different from Ombai, with an estimated 9 Sv toward the Indian Ocean in April through June 1992 and a smaller maximum of 7 Sv in October.

1.1. Motivation

These observations, despite their limitations, suggest interesting vertical variability to the Indonesian throughflow. Measured inflow at Makassar, Maluku and Halmahera, albeit based on subsurface measurements, was strongly toward the Indonesian seas in January–March and low or reversed in May and October. Outflow transport in Ombai was high in June–August, while at Timor, transport was high in April–June. In addition, flow through the Makassar, Halmahera and Ombai Straits mostly decayed to zero with depth, whereas flow through Maluku and Timor exhibited reversal of flow at depth.

Due to the limited time period of the observations it is impossible to conclude to what extent the measurements are biased by interannual variations. Further, the inflow measurements, particular at Maluku and Halmahera, recorded relatively deep flows.

Several questions therefore arise. Is the apparent phase lag between the inflow and outflow due to interannual variability or vertical variability or a combination of both? Are the forcing mechanisms the same for the surface and subsurface flows? What is the contribution of the surface layer flow to the total transport? This paper will attempt to answer these questions with the use of a high-resolution numerical model.

This study is further motivated by an attempt to extrapolate the few single or depth-limited observations in the region to depth integrated transport variations. In addition to the programs described above, a recent in situ program on the outflow straits has recently been completed. The shallow pressure gauge array (SPGA) program (Chong et al., 2000), was responsible for the deployment of an array of bottom-mounted pressure gauges in various straits in the ITF outflow region, and various methods have been used to convert these surface variations to depth-integrated transport, e.g., Hautala et al. (2001) and Potemra et al. (2002). These data will be used to validate the model integration.

The first objective of the present study, therefore, is to determine the vertical structure of the ITF throughflow at both the inflow and outflow straits. Since the observations are not yet sufficient, a numerical model is used. A second objective is to understand the relationship between vertical variations on the inflow and outflow sides of the ITF, and the relationship between these vertical variations and the net, integrated transport from the Pacific to the Indian Ocean.

1.2. Model description

The Parallel Ocean Climate Model (POCM) (Semtner and Chervin, 1992) is a global-scale ocean model and has been used to estimate depth-integrated ITF transport on monthly mean time scales (Potemra et al., 1997). The model horizontal resolution is approximately 2/5° in both directions. The model uses a level approach (z-coordinate model) with 20 levels and active thermodynamics. The most shallow level represents the top 25 m, and the top 260 m are represented by seven levels. The model was forced by ECMWF wind stress, heat, and fresh water fluxes. Three-day model velocities from 1979 through 1998 were available for this study.

At each strait, transport at each model level was computed from a cross-strait integral of model velocity normal to the strait multiplied by the level thickness. The model transects of the outflow straits, Ombai Strait and Timor Passage, were chosen to match the locations of the SPGA gauges: along 8.6°S across the Ombai Strait and along 123.8°E across the Timor Passage. The model transects along 1°N across the Maluku Strait and along a section from Halmahera (1°N, 129°E) to New Guinea (1°S, 131°N) across the Halmahera Strait, closely coincide with the location of the two moorings located there during 1993–1994 (Cresswell and Luick, 2001; Luick and Cresswell, 2001). The model transect for Makassar Strait is located on the equator, at the northern end of this strait and well north of the 3°S location of the Arlindo moorings deployed in 1996–1998 (Gordon et al., 1999). The northern location of the model transect was chosen to avoid proximity to the shallow sill and strait constriction at 3°S, which could significantly impact the vertical structure of the inflow. The rationale for the equatorial transect is that it is more representative of the inflow, nonetheless, the results for a transect located at 4°S do not substantially change the results discussed below. Fig. 1 shows the model geometry at the five straits analyzed here, along with satellite-derived bathymetry (Smith and Sandwell, 1997) at the same locations, and a similar comparison for the entire region.

The model is limited in that it does not resolve flow through the Lombok Strait, which is about 35 km wide, but it does resolve the other two outflow and three inflow straits. Model salinity in the Indonesian seas is also suspect, and it consistently simulates higher salinities than observed in the region. This is possibly due to insufficient mixing in the region, or perhaps too much South Pacific water entering the region via the Torres Strait (Gordon and McClean, 1999). The model thermocline is in agreement with Levitus and Boyer (1994), and it produces a reasonable throughflow (e.g., Potemra et al., 1997) and very good coastal sea level in the region (Potemra et al., 2002).

Model volume transport through each of the various straits was examined using seasonal harmonics and then decomposed to vertical empirical modes using EOF decomposition. These results are presented in the following sections. As previously stated, there are not enough observations to do this investigation directly, but in the following sections, model results are compared to the limited measurements in specific straits as a check on the model validity. The temporal variability of the vertical EOF modes and possible forcing mechanisms are discussed in Sections 3 and 4.

2. Mean vertical variations

Volume transport was computed from the spatial integral of POCM velocity at Makassar, Maluku and Halmahera. The 1979–1998 mean through-strait velocity and volume transports are given in Fig. 2.

The western (Makassar) and eastern (Halmahera) inflow straits have similar long-term mean velocity profiles in the model (Figs. 2a and c). It is interesting to note that the maximum velocities are sub-surface, 50 m for Makassar and 50–100 m for Halmahera. The near-surface values are a little more than 12 cm s^{-1} and decay to zero around 400 m. The center inflow strait (Maluku; see Fig. 2b) has mean northward flow in the upper layer and mean southward flow of 4 cm s^{-1} from 200 to 500 m. For the POCM upper levels, in the mean, flow enters the Banda Sea from the Makassar Strait, and part exits to the Indian Ocean via Ombai Strait, but a portion returns to the north through Maluku Strait. The surface mean counterclockwise flow around the island of Sulawesi, that lies between the Makassar and Maluku Straits (Fig. 1), was first inferred from wind forcing by Wyrtki (1961, Chapter 3).

The long-term mean total transport in these straits is −3.6 Sv for Makassar, −1.8 Sv for Maluku, and −2.2 Sv for Halmahera (negative indicative of southward flow). In the case of Makassar and Halmahera, most of the southward transport occurs in the upper ocean (upper 400 and 200 m, respectively). For Maluku, however, the bulk of the southward transport occurs from 200 to 700 m. These numbers are much less than the estimates from the observations (−9.3, −1.5 and −7.0 Sv from the Makassar (Gordon and Susanto, 1999), Maluku (Luick and Cresswell,

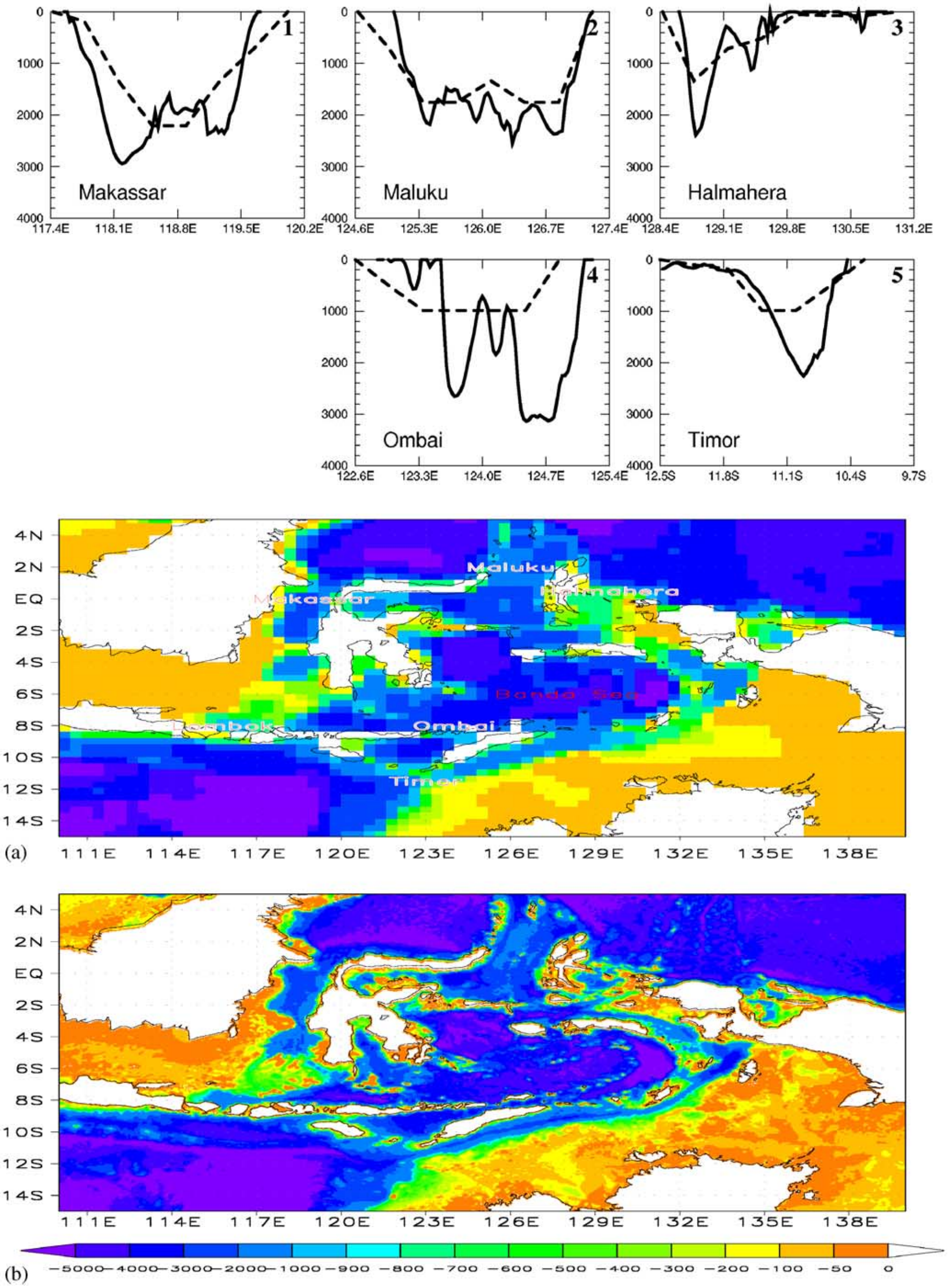

Fig. 1. The upper panels show the cross-strait bathymetry for the straits analyzed in this study. The solid line is from remote observations (Smith and Sandwell, 1997), and the dashed line is from the model. The lower panels show the bathymetry for the entire region, again for the model (a) and observations (b). The locations for the specific straits are given by the numbers in panel (a). A scale in meters is given below each plot.

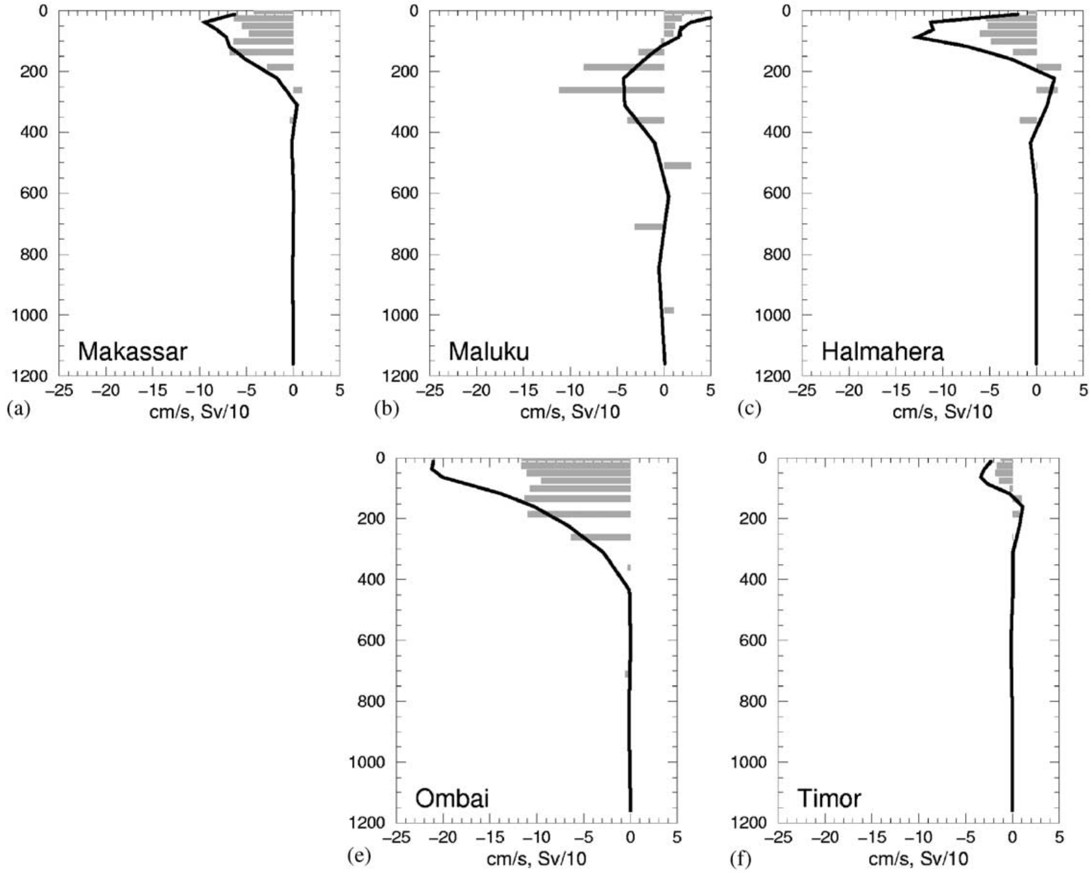

Fig. 2. Long-term mean through-strait velocity (in cm s^{-1}; lines) and transport (in Sv/10; shading) from each level of the POCM. Negative values indicate southward and/or westward flow.

2001), and Halmahera moorings (Cresswell and Luick, 2001), respectively). The model underestimates the current speeds, but the temporal variations and variations in the vertical structure are consistent with the limited observations. It also should be noted that the sum of the three estimates based on the observations, −17.8 Sv, is somewhat higher than current estimates (e.g., −8.4±3.4 Sv in Hautala et al., 2001), and this may be due to interannual variations (the observations occurred during different years) or due to problems resolving the vertical variations (the observations did not measure continuously from the surface to the bottom).

Flow exits the Indonesian seas in the POCM mainly through two straits: Ombai and Timor (see Fig. 1). The model does permit flow through the Sunda Strait, between Sumatra and Java, and through Torres Strait, between Australia and New Guinea, but these straits are very shallow and together these result in less than 1.5 Sv. The long-term mean POCM velocity profile at Ombai Strait (Fig. 2d) indicates surface intensified flow of about 22 cm s^{-1} down to 75 m, and an exponential decay to zero flow at about 420 m. The model velocity structure through Timor is similar but much weaker (Fig. 2e). It also exhibits slight return flow to the north at depth around 200 m.

The total POCM transport through Ombai and Timor is 8.9 Sv of which 8.4 Sv exits via the Ombai Strait. Molcard et al. (2001) estimate 4–6 Sv for Ombai in 1996 and 3.4 to 5.3 Sv for Timor in

1992/1993. Most of the long-term mean transport through Ombai (92%) occurs in the upper seven levels of the model (260 m): 7.7 Sv of the 8.4 Sv over the entire depth range (Fig. 2d). Similarly for Timor, most of the transport is carried in the upper layers (98% of it above 260 m; Fig. 2e).

The seasonal fluctuations through the inflow/outflow passages can be large. Fig. 3 shows the transport in the upper 260 m (the model's top seven levels). On the inflow side, upper-ocean transport through Halmahera varies by as much as 8 Sv; sometimes reaching 8 Sv toward the Indonesian Seas and other times reaching 8 Sv toward the Pacific. Makassar, with a slightly larger long-term mean, has a smaller range, from about 4 Sv to the north to 8 Sv to the south.

Similarly, the outflow transports exhibit large fluctuations. For Timor, where the POCM long-term mean is less than 1 Sv, the annual range of upper-ocean transport can go from 4 Sv into the Indian Ocean to 4 Sv into the Indonesian Seas (see Fig. 3). Model transport in the Ombai Strait has even larger extremes, although flow is primarily always directed toward the Indian Ocean.

Three-day upper-ocean model transport through Makassar is well correlated to that through Halmahera, Ombai and Timor (correla-

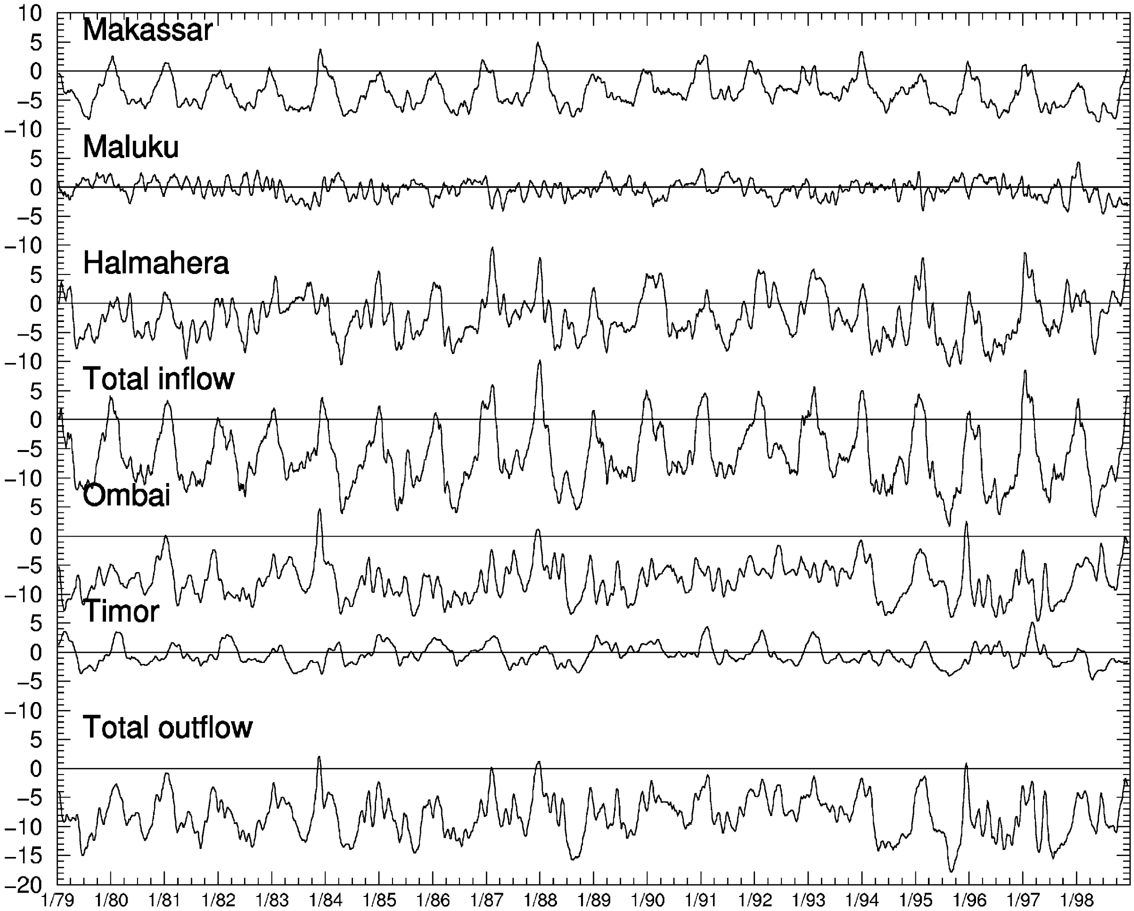

Fig. 3. Transport was computed from the upper 260 m (top 7 levels) of the POCM through three inflow and two outflow straits. The results were fit with a 30-day running mean filter to remove higher frequency variability. Negative values indicate flow from the Pacific to the Indian Ocean.

tions of 0.45, 0.57, 0.60, respectively), while transport through Maluku, that results from convergence of flow in the Banda and Sulawesi Seas, correlates to Halmahera (−0.47) only.

At lower frequencies the transport variations between the straits become largely uncorrelated (see Fig. 4). POCM upper 260 m transport variations filtered with an annual running mean at Ombai and Halmahera appear the most correlated (0.74), with variations at Ombai lagging those at Halmahera by four months. In both straits, upper ocean transport decreases during El Niño years 1983, 1987, and 1992, and increases during the La Niña years 1988 and 1996. In 1996 the two signals start to diverge, with Halmahera transport becoming anomalously weak by 6 Sv from early 1996 to mid-1997, and Ombai transport remaining anomalously strong throughout 1996 and mid-1997. Only toward the end of 1997 does transport through Ombai start to decrease. There is a similar convergence during 1980/1981, when transport through Halmahera is anomalously strong and transport through Ombai is weak. Upper-ocean transport through the other three straits is not well correlated to ENSO, despite some having significant energy at the 2.5 year period. For example, transport in Makassar increases during the 1982/1983 El Niño but decreases during the 1986/1987 event.

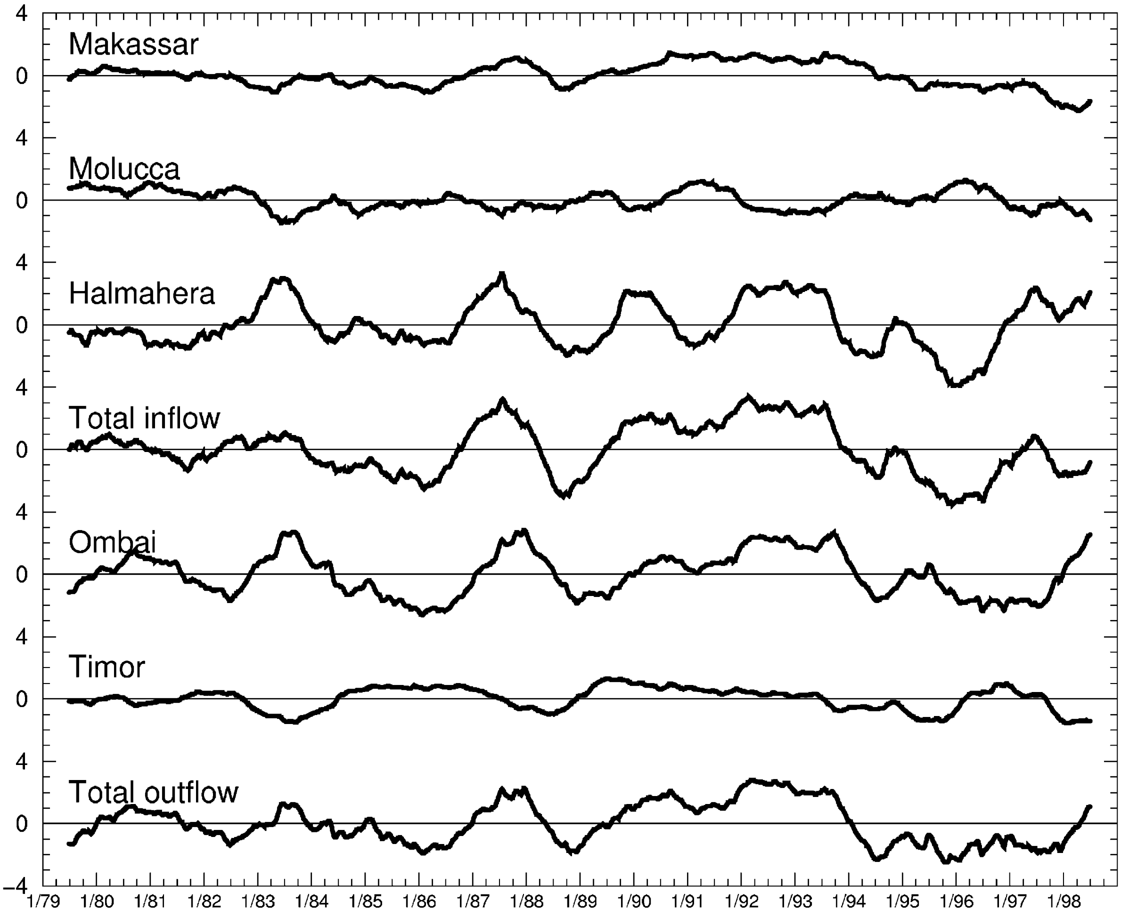

Fig. 4. Low frequency variability of POCM transport in the upper 260 m estimated as a one-year running mean filter to the 3-day model output. The long-term mean was removed, and negative values indicate an increase in flow from the Pacific to the Indian Ocean.

3. Vertical structure of transport

3.1. Seasonal cycle

Fig. 3 shows the dominance of the seasonal cycle in the near-surface transport in all the straits. In fact, the seasonal cycle accounts for a different fraction of the total variance in each strait. Fig. 5 shows the percentage of variance contained in the annual and semiannual harmonics of transport for each model level. Annual variations account for almost 75% of the variance in the upper model levels at Makassar, 50% at Halmahera and Timor, and 30% at Maluku and Ombai. There is also a peak in annual variations at depth (400 m) at Halmahera, Maluku and Timor. Energy in the semiannual harmonic is mostly small at each of the straits, except at depth in the Ombai, Timor and Maluku Straits where it reaches 20%.

The seasonal cycle of transport in each of the straits, defined here as the sum of the annual and semiannual harmonics of through-strait transport, is characterized by two layer flow in most of the straits, and this is consistent with the observations.

3.2. Outflow passages

To further investigate the variations of the flow through the straits as a function of depth, empirical orthogonal function (EOF) analysis was done on the POCM transport in each strait. The procedure was done on both the total model transport in each strait and the transport

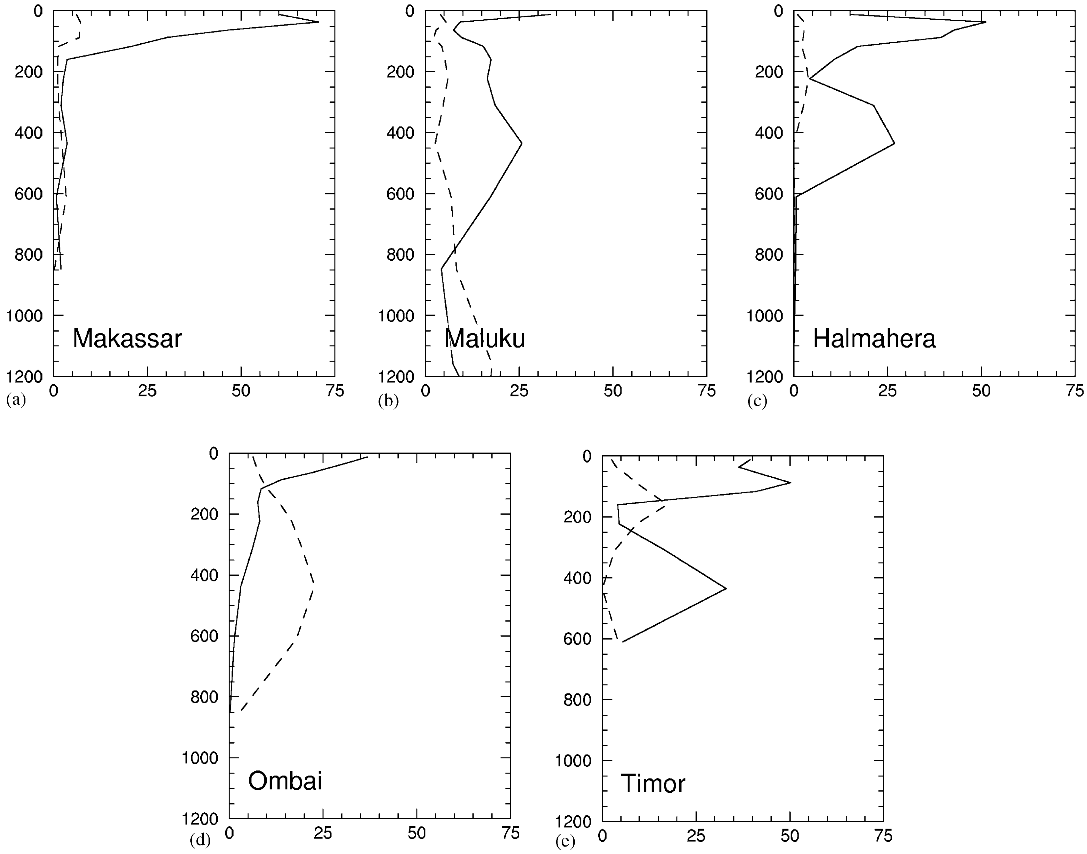

Fig. 5. The percent variance contained in the annual (solid line) and semiannual harmonics (dashed line) of model transport at each level is given for each strait.

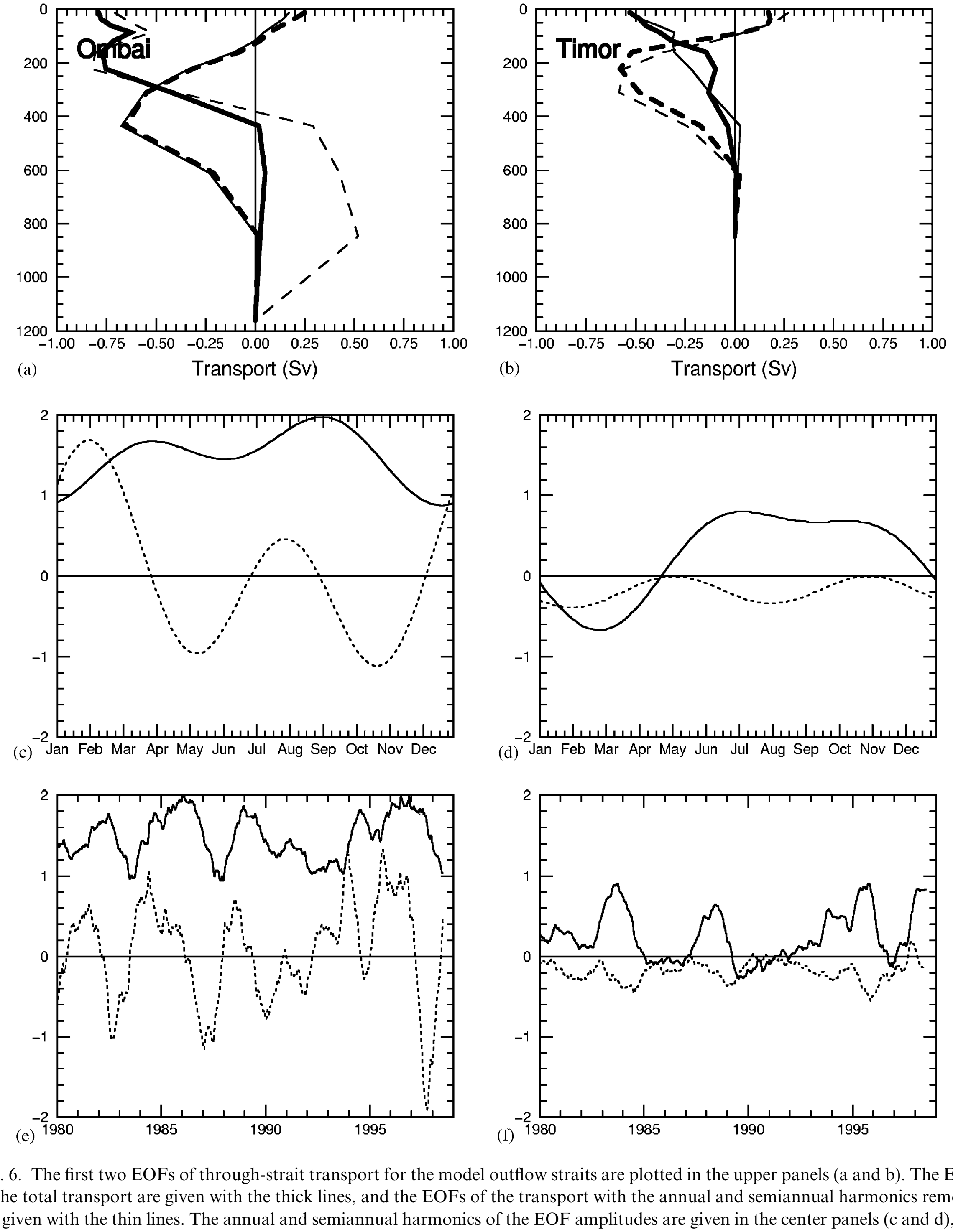

Fig. 6. The first two EOFs of through-strait transport for the model outflow straits are plotted in the upper panels (a and b). The EOFs of the total transport are given with the thick lines, and the EOFs of the transport with the annual and semiannual harmonics removed are given with the thin lines. The annual and semiannual harmonics of the EOF amplitudes are given in the center panels (c and d), and long-term variations are given in the lower panels (e and f). In each panel the first EOF is plotted with a solid line and the second EOF with a dashed line.

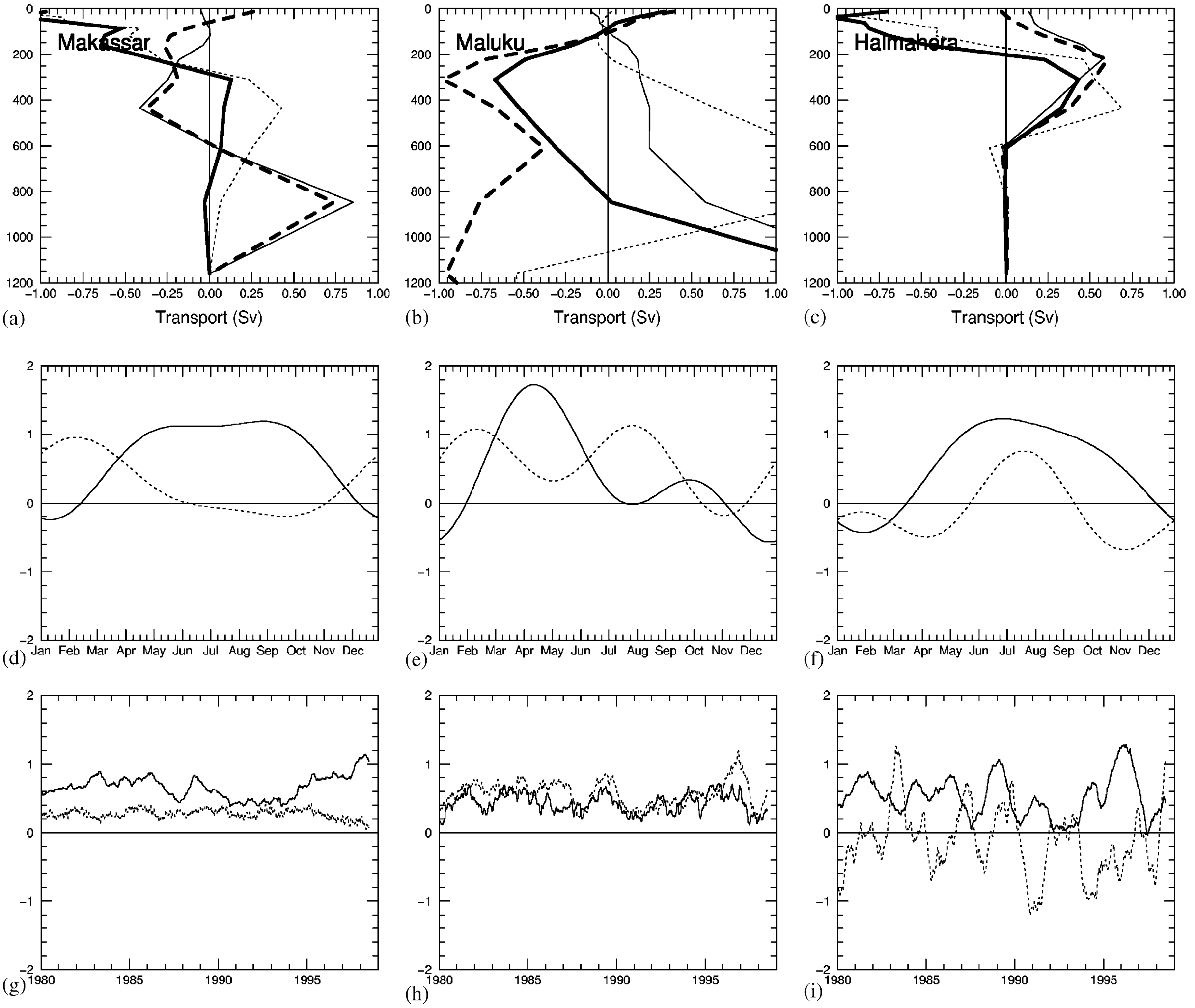

Fig. 7. The first two EOFs of through-strait transport for the model inflow straits are plotted in the upper panels (a–c). The EOFs of the total transport are given with the thick lines, and the EOFs of the transport with the annual and semiannual harmonics removed are given with the thin lines. The annual and semiannual harmonics of the EOF amplitudes are given in the center panels (d–f), and long-term variations are given in the lower panels (g–i). In each panel the first EOF is plotted with a solid line and the second EOF with a dashed line.

with the annual and semiannual harmonics removed (Figs. 6 and 7).

Transport through the outflow passages occurs primarily in two empirical modes (Figs. 6a and b). The first EOF is surface intensified flow that decays to zero at about 400 m. For Ombai, this accounts for 79% of the variance and at Timor 67%. The second EOF is more baroclinic, with flow in the upper 100 m in opposite direction to flow from 100 to 800 m, and this mode accounts for 18% and 20% of the variance at Ombai and Timor, respectively. These modes are very similar to the EOFs of the observations of Molcard et al. (1996, 2001).

Interestingly, there are marked differences in the temporal variations of these EOF modes despite the similarities in the vertical structure. At both straits, the first EOF is modulated with more of an annual period, while the second mode is more semiannual (Figs. 6c and d). At Ombai the first EOF mode flow is always toward the Indian Ocean and is strongest in August and September just after the peak southeasterly winds, and it is weakest during November through January when winds are northwesterly. At Timor, first EOF mode flow is toward the Indonesian seas in January–April, slightly after the time of minimum flow through Ombai.

Conversely, in the second EOF at Ombai, flow is toward the Indian Ocean in the upper layer in April–June, and again in September–November, with the reverse in the lower layer. These times correspond to when downwelling Kelvin waves are formed in the Indian Ocean during the monsoon transitions (Wyrtki, 1973). These downwelling waves reduce the transport in the strait by lowering the thermocline and raising sea level on the western side of the (model) strait. The EOF captures this reduction in a combination of the first two modes; the first mode contains more local, wind-driven effects, while the second mode captures more of the thermocline displacement. The total effect can be seen in Fig. 3.

At Timor the second EOF is marked by upper layer flow toward the Indian Ocean and lower layer flow toward the Indonesian seas throughout the annual cycle, and the net flow in EOF-2 is toward the Indonesian seas. The coastal Kelvin waves affect the northern side of the strait as they propagate eastward along the south shore of the archipelago. The gap between Timor and the northwest Australian shelf is too broad for wave energy to cross, so the effect of the Kelvin waves are only on the northwestern side of the Timor Passage. This, along with the dissipation of energy along the gappy coastline, significantly weakens the effect of these waves on flow through the Timor Passage, and in the model the waves are not sufficient to reverse the surface flow.

These vertical empirical modes are maintained when the seasonal cycle (annual plus semiannual harmonics) is removed (Figs. 6a and b). In the case of Ombai, however, the seasonal cycle is dominant in the upper layer, and the order of the EOFs switches when the seasonal cycle is removed: EOF-1 (EOF-2) of the total signal is the same as EOF-2 (EOF-1) of the signal without the seasonal cycle. The percent variance explained in each EOF of the transport anomalies is lower when the seasonal cycle is removed: 43% and 37% for Ombai and 59% and 27% for Timor.

Recent ADCP observations that measure the upper 250 m across Ombai Strait (Hautala et al., 2001) show two-layer flow. In March of 1997, shipboard ADCP-measured flow at depth was more intense than the surface flow which was weakly toward the Pacific (Hautala et al., 2001), similar to the POCM's second vertical mode. While in March of 1998, the observed flow was strongest near the surface and decayed with depth, similar to the first vertical mode in the POCM. Again, the large El Niño in 1997/1998 could explain the difference in the two years (recall the second mode of the POCM results had much more of a ENSO modulation).

The Ombai Strait mooring described in Section 1 (Molcard et al., 2001) shows a similar vertical structure. Molcard et al. (2001) found that in 1996 the mean current was about 60 cm s^{-1} over the upper 160 m, and decayed to less than 20 cm s^{-1} at 415 m. EOF decomposition of their observations yields a first mode similar to that in Fig. 6a, although the observed flow decays at a slower rate; flow at 160 m is about 20% of the surface flow, and flow from 160 m steadily decayed to zero at about 1000 m (Molcard et al., 2001). The second mode (10% of the variance in the observations) also shows surface flow to 100 m in opposition to flow at depth from 100 to 1000 m (Molcard et al., 2001).

The Timor Passage mooring records show a similar vertical structure of transport. The first mode, however, is similar to the model flow through Ombai, with a surface intensified flow that decays to zero at about 500 m for the 1989/1990 mooring (Molcard et al., 1994) and 400 m for the 1992/1993 mooring (Molcard et al., 1996). The second mode in each case had surface flow in the opposite direction to flow in a deeper layer. In both records the surface layer was to about 100 m. The lower layer extended to 500 m in the 1992/1993 mooring and to 900 m in the 1989/1990 mooring.

There are differences in the low-frequency variations of the two vertical EOF modes. Figs. 6e and f show the temporal variations fit with an annual running mean. The low-frequency variations of the EOF amplitudes of anomalous transport (seasonal cycle removed) are the same as those shown in Figs. 6e and f, but as stated previously, the first two EOFs are switched.

At Ombai, the low-frequency variations of the first EOF mode lag the second EOF by 7 months, which could be due to local process influencing the lower level flow differently from the upper level flow. This will be discussed further in Section 4. Together, the first two EOFs sum to represent a decrease in Pacific to Indian Ocean transport during El Niño events, and an increase in Pacific to Indian Ocean transport during La Niña events, consistent with the observations of Meyers (1996) and Gordon et al. (1999) and the theory of Clarke and Liu (1994). In this theory, westerly (easterly) wind anomalies during warm (cold) ENSO events lower (raise) sea level on the western side of the Pacific and reduce (increase) the inter-ocean pressure gradient.

Low-frequency variations of the two modes at Timor are out of phase. The second mode varies similar to Ombai in the sense that during warm events flow from the Pacific to the Indian Ocean is reduced. The amplitude of the first EOF is larger, however, and it dominates the signal; flow from the Pacific to the Indian Ocean increases during El Niño events and decreases during La Niña events, contrary to flow at Ombai. However, the magnitude of the transport through Timor is much smaller than through Ombai.

3.3. *Inflow passages*

Transport through the model inflow straits is not as straightforward. Makassar has a first EOF mode similar to Ombai and Timor, characterized by surface intensified flow that decays to zero at about 300 m (see Fig. 7a), slightly more shallow than for the first EOF mode of the exit straits. Again, similar to the outflow straits, this EOF shows maximum southward transport from May–September and accounts for 58% of the variance in the model Makassar Strait.

The second EOF mode, 16% of the variance, is not two-layer flow as in Ombai and Timor, but has a three-layer structure. Mid-depth flow (from 50 to 600 m; seven model levels) is opposite to flow in the surface and deeper levels. Gordon and Susanto (1999) have shown that surface flow, forced directly by local winds, is weakly northward. In December–February, when the first mode is weak, the second mode is maximum, with mid-depth transport southward and upper and lower level flow northward. The lowest mode could be due to the shallow sill to the south that blocks the subsurface flow.

The seasonal cycle is strongest in the surface layer in Makassar Strait. When this is removed, the EOFs are reversed, and the first EOF (second EOF) of the anomalous transport is like the second EOF (first EOF) of the total transport. The first two EOFs of the anomalous transport account for 37% and 23% of the variance.

The first two vertical modes of transport through Halmahera are unlike those at Makassar, but the removal of the seasonal cycle has a similar effect in reversing the order of the EOFs. The two vertical EOFs of total transport through Halmahera are in phase and have a subsurface maximum. Each has a different annual cycle: the first mode (44% of the variance) is more annual, while the second mode (26%) has some semiannual variability. Together, the two modes add so that maximum transport occurs in April–November, peaking in July and August, when flow is to the south in the upper 200 m and to the north from 200 to 600 m. The first EOF becomes the second EOF when the seasonal cycle is removed, and accounts for 39% of the variance in the anomalous transport signal. The second EOF of the transport anomalies accounts for 28% of the variance.

Transport in Maluku is different from Makassar and Halmahera in several respects. The first EOF at Maluku is similar to the second EOF at Makassar. The second EOF at Maluku is different from all the other straits, and shows extended flow from 100 to 1600 m. There is not much difference in the variance explained by the first two EOF modes (32% and 30% of the variance in the first two modes, respectively), and when the seasonal cycle is removed, the vertical EOF structure changes. This strait, unlike the other four, has significant energy in the annual harmonic at depth (see Fig. 5). In addition, the deep flow at Maluku is much stronger in both EOF modes; the sum of the two EOFs is 2 Sv (northward) at 1200 m in March and April.

The long-term variations of these vertical modes of transport are quite different between the three inflow straits (see Figs. 7g–i). The associated time-series for the transport anomalies are very similar and are therefore not shown. At Makassar, flow in the second EOF does not have any interannual variability. The first EOF at Makassar shows slight variations during the El Niños of 1986/1987 and 1997/1998. Most of the interannual variations in the model inflow are at Halmahera. Here, the first two EOF modes act out of phase (Fig. 7i), unlike the annual cycle when they are in-phase (Fig. 7f). For example, the annual cycle of both modes has maximum northward transport at 200–400 m during June–September. But, in 1990/1991 and 1994 the first mode transport is larger than normal and the second EOF transport is less than normal. Interannual variations of the first EOF are almost biennial. Variations in the second mode are more consistent with ENSO-type variations, with increases in northward transport at depth during 1983, 1986/1987, and 1998. There is not an exact agreement with ENSO, as the second EOF mode shows increases in southward flow (again at depth) in 1980, 1985, 1988, 1990/1991, 1994 and 1997.

The deep flow observed at Halmahera is stronger than in the model, about 2.5 Sv for flow between 350 and 700 m compared to 0.5 Sv in the model. The temporal variations are similar, with an increase in deep transport measured by the gauge at 900 m during December–February 1993/1994. In the model, the increase occurs in January and February only (results not shown).

The observations at Maluku show a series of strong subsurface flows, and Luick and Cresswell (2001) estimate a mean transport of 7 Sv between 740 and 1500 m. It is difficult to determine whether this mooring is representative of the entire strait, or if there is some sort of lateral recirculation occurring, in which case the transport from Luick and Cresswell (2001) is an overestimate. The model has very weak and variable flows at these depths, but does show a lateral, cross-strait circulation at 1500 m.

4. Long-term variations

The estimate of ITF transport based on XBTs (Meyers et al., 1995; Meyers, 1996) is the only observational-based estimate that covers more than a few years. These observations show a positive correlation between the SOI and ITF outflow measured in the upper 400 m along a section from Java to Australia particularly at the northern (Java) end of the section. The interannual range in transport is about 5 Sv. During warm events of 1985/1986 and 1992/1993, upper-ocean outflow transport was less, while during the cold event of 1988/1989 the outflow transport was greater. It is also interesting to note an increase in the outflow in 1983 during which time there was no significant positive phase of the SOI. Similarly, Gordon et al. (1999) measured a reduction of ITF inflow in the Makassar Strait during the El Niño of 1997/1998. Ffield et al. (2000) found a relationship of temperature to transport, such that transport is smaller and the thermocline shallower during El Niño.

To examine the interannual variations more closely, Fig. 8 shows the POCM transport through the five straits computed over two depth ranges, roughly corresponding to the modes determined from the EOF analysis: 0–100 m and 100–710 m. The Southern Oscillation Index (SOI) also is given as a reference for ENSO variations. In the model, Makassar Strait shows stronger southward transport in the upper layer during the 1997–1998 El Niño (Fig. 8), and thus opposite to that found in the Arlindo mooring data. There is little signal in the second deeper mode of the model Makassar Strait. Part of the discrepancy may be due to the location of the model transect further north on the equator, whereas the moorings were located at 3°S. Although transport computed through a model transect at 4°S in Makassar Strait did not substantially change the model results in this regard. During the deployment, the Makassar instruments were largely below 200 m, and thus may not have adequately captured the surface flow during this period.

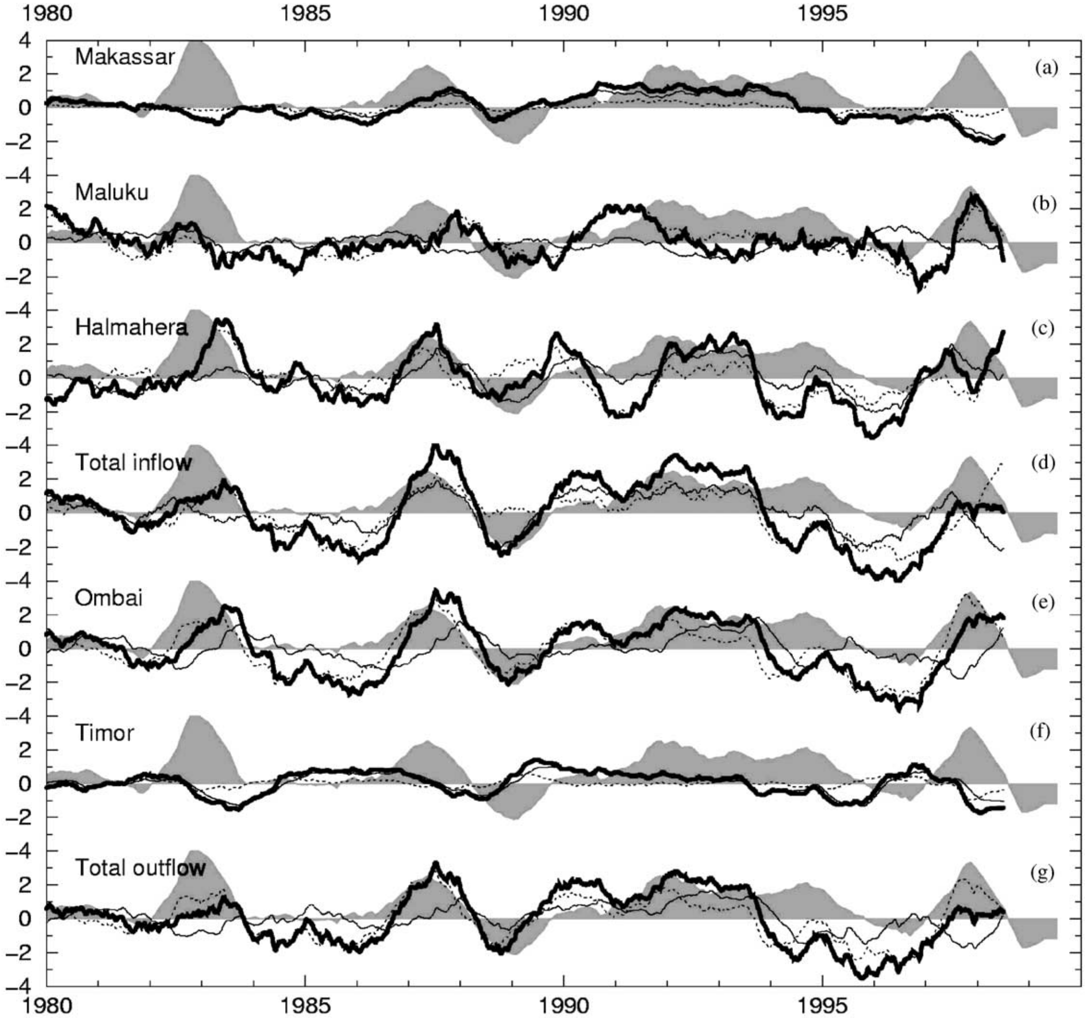

Fig. 8. The southern oscillation index (SOI) is shaded in each panel with a 12-month running-mean filter applied. For comparison, the SOI signal has been inverted. Upper ocean transport anomalies (0–100 m; long-term mean removed, one-year running mean filter) for each strait is given with the thin line. The transport anomalies for 100–710 m are given with the dotted line and the total transport anomalies are given with the thick line. A negative anomaly indicates an increase in ITF transport toward the Indian Ocean.

Flow through Ombai Strait shows the most qualitative correlation with ENSO. Mainly due to changes in mid-depth transport (100–710 m), Ombai Strait has weaker transport during the El Niño years of 1983, 1986/1987 and 1997. Transport in the surface layer does not seem to follow the SOI, or in some cases varies inversely to the SOI, the result being that transport anomalies in Ombai lag the SOI by about 7 months.

Transport anomalies in Timor are dominated by the upper level flow, and the relationship to ENSO is opposite that at Ombai. There is also a significant lag (again 7 months) between the total anomalies at Timor and the SOI. For example, in late 1982 the SOI goes negative (the 1982/1983 El Niño). Seven months later flow through Timor is almost 2 Sv higher than normal (toward the Indian Ocean).

Transport anomalies through Halmahera are similar to those at Ombai. Changes in mid-depth flow are similar to the SOI and transport anomalies through Ombai, with the exception of 1997. Flow through the other two inflow straits does not seem to consistently follow ENSO variations. At Makassar, for example, flow increases during the 1982/1982 and 1997/1998 events, but decreases in 1986/1987.

The long-term variations of the flow suggest that the interannual variations are projected more onto the subsurface flow. This would be consistent with interannual variations being forced in the Pacific. Fig. 9 shows a correlation of the NINO-3 index (SST anomalies in a region of the eastern equatorial Pacific) and the model velocity in two different depth regions (same depth ranges as in Fig. 8). The outflow from Ombai, correlated to ENSO variations, can be seen most clearly in the subsurface zonal velocity as a zonal jet along 11°S and as a meridional jet through the Ombai Strait. The correlation is positive; warm ENSO events are correlated to an increase in subsurface eastward flow along 11°S and northward flow through Ombai, i.e. a decrease in ITF flow. Negative correlations are seen in Timor. The correlation to upper layer flow is not as high, and is only seen in the inflow straits. The correlation was done at 3

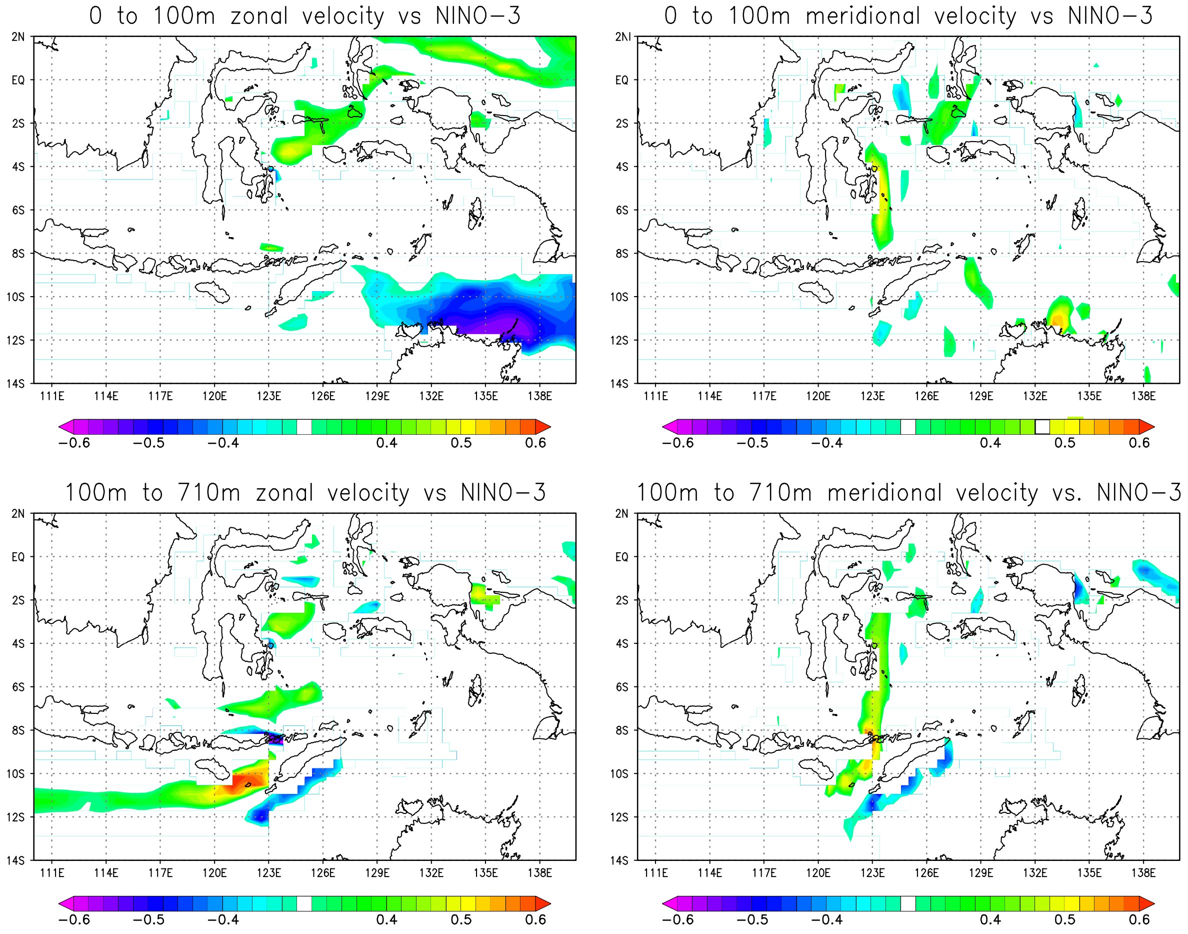

Fig. 9. Model zonal and meridional velocity anomalies correlated to the NINO-3 SST anomalies for the surface to 100 m levels (upper panels) and 100–710 m levels (lower panels). Velocity anomalies lag NINO-3 by three months. Correlations greater than 95% confidence have been shaded.

months lag (model velocity lagging NINO-3), but the pattern does not change significantly for zero lag.

5. Summary

The long-term POCM results show that flow from the Pacific to the Indian Ocean via the Indonesian seas occurs in distinct vertical modes. Transport through the model's exit passages of Ombai and Timor is a combination of two vertical modes. The first mode is surface enhanced flow, and the second mode is two-layer flow, with flow in the near surface in the opposite direction to flow at depth. There are also significant differences in the temporal variability of these two modes in the two POCM outflow straits. At Ombai, the long-term mean vertical profile of velocity is like the first mode (surface intensified, decaying to zero at depth), while at Timor, the long-term mean vertical velocity profile is more like the second mode (subsurface return flow). At Ombai Strait flow in the first mode is always toward the Indian Ocean and varies more annually than semiannually. In the second mode, modulated by more of a semiannual variation, flow reverses in the upper and lower layers twice during the year, in May and November, due to the passage at this time of Kelvin waves. The variations of the second mode are larger than the first mode. At Timor Passage, the first mode is also primarily annual and the second mode semiannual, but here the first mode changes direction during the year, flowing from the Pacific to the Indian Ocean in June–December and toward the Pacific the rest of the year. The second mode is more constant, with flow throughout the year from the Pacific to the Indian Ocean in the upper layer and reverse flow in the second layer.

Inflow through Makassar and Halmahera is also a combination of two modes, but the structure is slightly different; Makassar has a first mode characterized by surface intensification and a second mode with three-layer structure, while at Halmahera the first mode is composed of flow in two layers, and the second has flow in one layer. The center inflow strait, Maluku, is unlike the other straits and is characterized by significant flow at depth.

The general flow in the POCM surface layer is into the Indonesian seas via Makassar and Halmahera. This surface flow is strongest in April–November. A portion of this water returns to the Pacific via Maluku, and the rest exits to the Indian Ocean via Ombai and Timor. In the POCM second layer, from about 100–400 m, flow enters the Indonesian seas through both Makassar and Maluku from the Pacific and through Timor from the Indian Ocean. Flow exits the Indonesian seas in this depth range to the Indian Ocean through Ombai and to the Pacific through Halmahera.

The POCM results, spanning 1979 through 1998, show a complicated relationship between ENSO and the ITF. Like the Meyers (1996) estimates, the upper-ocean ITF outflow transport in the model is lower than usual in 1986/1987 and 1992/1993, and it is larger than usual during the La Niña of 1988/1989. This appears to be due to a reduction in mid-depth flow (from 100 to 710 m; see Fig. 8).

There does not seem to be much interannual variability of flow through Makassar except small variations in the first mode. Flow through Maluku has more interannual variability, mainly driven by variations in subsurface flow. Interannual variations in the POCM flow through Halmahera are also driven by subsurface variability, and flow through Halmahera is very similar to the flow through Ombai.

The El Niño of 1997/1998 shows a curious change in the response of the ITF to ENSO forcing. In 1982/1983, subsurface flow is reduced in Halmahera and Ombai, causing the net ITF to be lower. In 1997/1998 however, surface flow through both Halmahera and Ombai is reduced, but subsurface flow increases. Subsurface flow through Maluku is reduced, and contrary to Gordon et al. (1999), upper-layer flow through Makassar Strait increases by 2 Sv in 1997/1998. This could be due to local wind effects, or may be a problem with the extrapolation technique, one that is time independent, used by Gordon et al. (1999) to estimate the surface flow.

Finally, the difference in phase of the inflow and outflow modes, particularly on longer time scales,

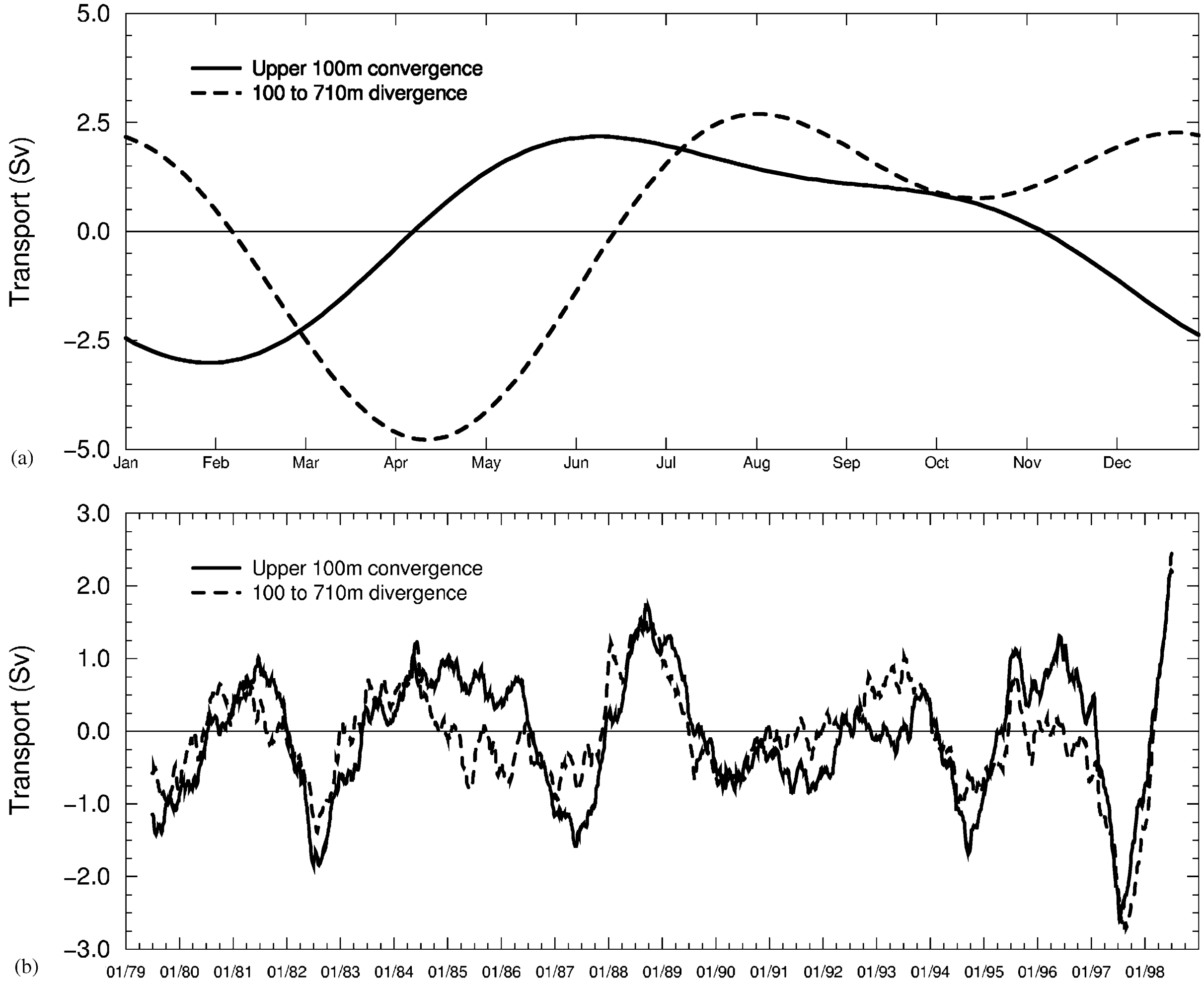

Fig. 10. Volume convergence in the Indonesian seas was computed as the difference between the inflow and outflow transport in two levels: the surface to 100 m (solid line) and from 100 to 700 m (dashed line). The lower-layer difference has been inverted, so positive values indicate a convergence of mass in the upper layer and a divergence of mass in the lower layer. The upper panel is the annual cycle, and the lower panel shows the low-frequency variations of the convergence.

could have important implications for water mass mixing in the region. Fig. 10 shows the difference in inflow and outflow, surface to 100 and 100–710 m transport. In the upper levels, transport into the Indonesian seas exceeds the transport out of the seas by about 1–2 Sv in May–October. This convergence of mass is balanced by divergence in the lower levels from February to June. Transport in the two layers is balanced without lag on interannual timescales. It is also interesting to note that while transport through individual straits varies interannually in different ways, the difference in total inflow and outflow is well correlated to ENSO. There is divergence in the model's upper levels during the El Niños of 1982/1983, 1986/1987, 1994/1995 and 1997/1998. This divergence reaches a maximum of almost 3 Sv in 1997/1998, but is closer to 2 Sv for the other events. Conversely, there is convergence in the La Niñas of 1984/1985, 1988/1989, and 1996. While there is convergence in the upper levels there is divergence in the lower levels.

The issue of mass convergence in the Indonesian seas has important implications, for example, for water-mass mixing, and requires more observations of water mass characteristics in the region and a more complex model that can accurately estimate mixing. This will be the focus of future work.

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