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# Temperature and salinity variability in the exit passages of the Indonesian Throughflow

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## Abstract

The Indonesian Throughflow was monitored from December 1995 until May 1999 in the five major exit passages of the Lesser Sunda Islands, as it flows from the Indonesian interior seas into the southeast Indian Ocean. The monitoring array included pairs of shallow pressure gauges at each side of the straits, equipped with temperature and salinity sensors. As in the inferred geostrophic velocity from the cross-strait pressure gauge data, the temperature and salinity data show strong variability over all time scales related to the local regional and remote forcing mechanisms of heat, freshwater and wind. The annual cycle dominates the temperature time series, with warmest temperatures occurring during the austral summer northwest monsoon, except in Lombok Strait where the semi-annual signal is dominant, and related to the Indian Ocean westerly wind-forced Kelvin waves during the monsoon transitions that supply Indian Ocean warmer surface water to the strait. In the salinity data, the annual signal again dominates the time series in all straits, with a distinct freshening occurring in March–May. This is partly related to the rainfall and resultant voluminous river runoff impacting the region, one month after the wetter northwest monsoon ends in March. The fresh, warm water from the monsoon-transition Indian Ocean Kelvin wave also contributes to the freshening observed in May. There is little cross-strait gradient in near-surface temperature and salinity through the outflow straits, except in Lombok Strait, where Lombok is warmer (except during the northwest monsoon) and fresher than the Bali site (especially during March through May). A fortnightly signal in temperature is found in Ombai and Sumba Straits, and is probably related to the proximity of these straits to the interior Banda Sea where the fortnightly tidal signal is strong. The fortnightly signal is also evident at the Bali site, although not at the Lombok site. Numerous ADCP surveys taken during the survey period suggest a western intensification of the flow through Lombok Strait, such that the Bali site also may be more influenced by the internal Indonesian seas. Finally, there is regional variability in temperature and salinity on interannual time scales. From mid-1997 through early 1998, the region is cooler and saltier than normal. These property changes are related to both the strong 1997–1998 El Niño event in the Pacific, and the strong 1997 Dipole Mode in the Indian Ocean, which together can result in lower regional precipitation; lower transport of the fresh, warm Throughflow water; and changes in the upwelling regime along the Lesser Sunda Island chain. From mid-1998 on, warmer conditions returned to the region probably related to the La Niña event.

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## 1. Introduction

The heat and freshwater carried by the Indonesian Throughflow (ITF), as it follows its circuitous route through the basins and multiple narrow constrictions within the Indonesian seas, impacts the basin budgets of both the Pacific and Indian Oceans (Bryden and Imawaki, 2001; Wijffels, 2001). In turn, the interbasin exchange of properties also substantially affects atmosphere–ocean coupling, not just in the connected tropical Indian and Pacific Oceans, but on a global scale. Coupled modeling work by Schneider (1998) found that with a Throughflow moving heat from the Pacific to the Indian Ocean, the warmest sea-surface temperatures (SST) and associated atmospheric convection region are more westward relative to a no-Throughflow condition. The change in convection would drive changes in the global atmospheric circulation and affect mid-latitude winds. In addition, variability in the ITF mass and heat transport on interannual time scales has been strongly linked to the evolution of interannual climate anomalies, such as occur through the ENSO and monsoon systems (Webster et al., 1998). These effects have potentially large economic and societal impacts on the nations that border the Indian Ocean. For example, Nichols (1984) linked ruinous drought conditions in Australia to cool SST anomalies in the Indonesian seas and central Indian Ocean. Similarly, SST anomalies that contribute to the dipole mode of variability in the tropical Indian Ocean, first appear in the vicinity of Lombok Strait in Indonesia. This potentially internal mode of variability, characterized by basinwide gradients in tropical SST anomalies, was accompanied by wind and precipitation anomalies that resulted in catastrophic floods in eastern Africa and severe drought in Indonesia. Thus, while it is apparently well established that the ITF, in terms of mass and property fluxes, greatly impacts the Indian Ocean basin and beyond, efforts to characterize it have been primarily based on large-scale inverse-type observations or numerical models (Wijffels et al., 1992; MacDonald, 1998; Ganachaud et al., 2000). There are few time series of directly measured temperature and salinity data available in the Indonesian region so that making robust estimates of the long-term average ITF heat and freshwater transport is nearly impossible.

Observations suggest that the ITF is composed of North Pacific thermocline waters flowing through Makassar Strait, while lower thermocline and deeper water masses of South Pacific origin enter via an eastern route, north of the Banda Sea (Fig. 1; Gordon and Fine, 1996). While some of the Makassar Throughflow directly exits the Indonesian seas via the shallow Lombok Strait, most turns eastward within the Flores Sea to enter the Banda Sea. It is primarily within the Banda Sea that the relatively cool and salty upper Pacific inflow waters are modified by mixing, upwelling and air–sea fluxes before export to the Indian Ocean (Ffield and Gordon, 1992; Hautala et al., 1996). From the Banda Sea, the two main exit passages for the ITF into the eastern Indian Ocean are Ombai Strait and Timor Passage. Ombai Strait directly connects the modified waters of the Banda Sea to the Savu Sea, before they exit into the Indian Ocean via the Sumba and Savu/Dao Straits (Fig. 1). The Timor Passage is a long, narrow trench that lies between Timor Island and the wide shallow Northwest Australian coastal shelf.

The five major exit passages along the Lesser Sunda Island chain, through which the ITF Water (ITW; Wijffels et al., 2002) leaks into the southeast Indian Ocean, were monitored from December 1995 until May 1999. The monitoring array included pairs of shallow pressure gauges at each side of Lombok, Timor, Ombai, Sumba and Savu Straits (Fig. 1). Geostrophic upper layer velocity and transport, inferred from the cross-strait pressure gradient, show strong variability over all time scales related to the local and remote forcing mechanisms (Chong et al., 2000; Hautala et al., 2001). Each pressure gauge was also equipped with a temperature and salinity sensor, and it is these data that are the focus of this paper.

## 2. The data

In December 1995, as part of a joint US–Indonesian program, a shallow pressure gauge array (SPGA) was deployed to monitor the flow of

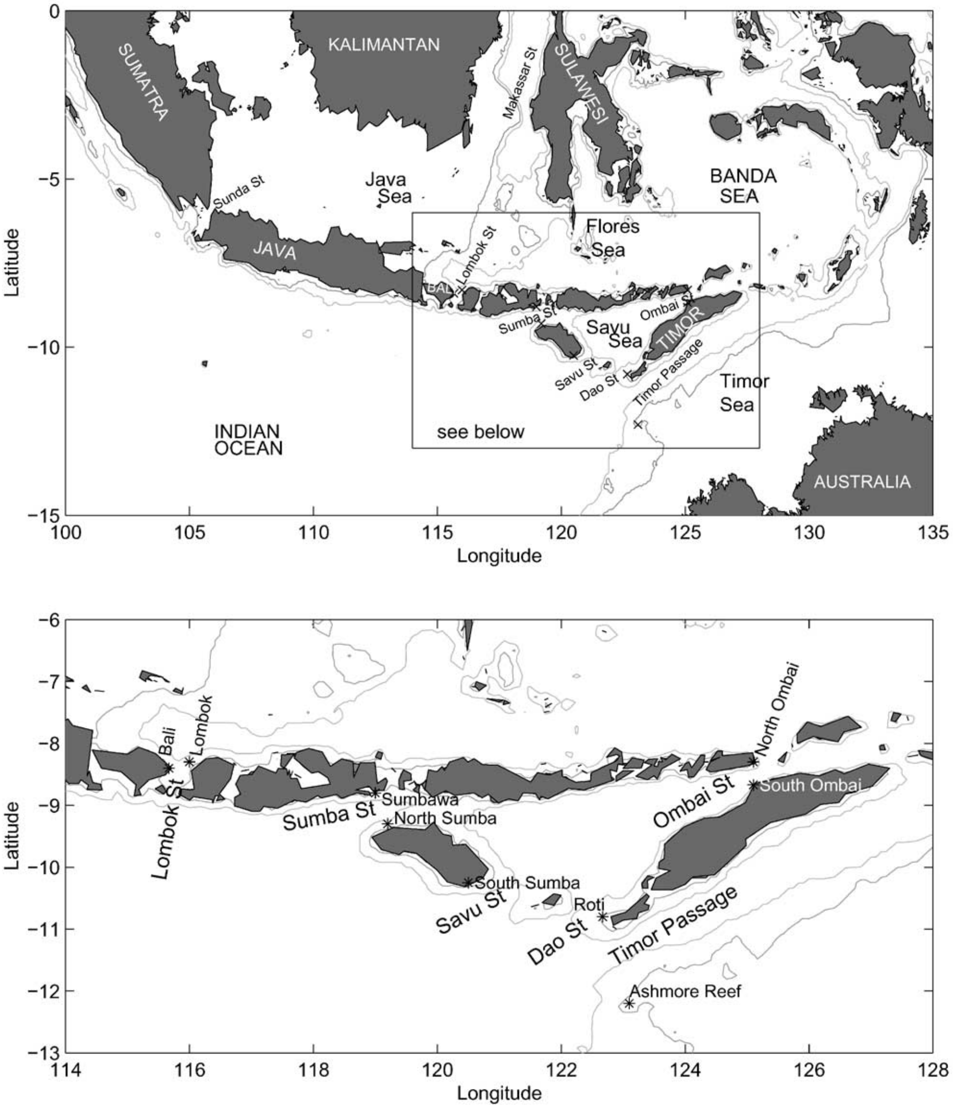

Fig. 1. The location of the temperature and salinity sensors (and shallow pressure gauges) in the Lesser Sunda Islands of Indonesia. Major seas, islands and passages referred to in the text are labelled. The 200 and 1000 m isobaths are indicated.

water from the Pacific Ocean as it exits the interior Indonesian seas into the Indian Ocean. The 9 subsurface pressure gauges, equipped with temperature and Seabird SBE-04 conductivity (salinity) sensors were deployed in the five major outflow straits along the Indonesian archipelago formed by the Lesser Sunda Islands and the edge of the Australian continental shelf: Lombok Strait, Sumba Strait, Savu Strait, Ombai Strait and Timor Passage (Fig. 1). Pressure gauge pairs that span a passage give the pressure (essentially sealevel) gradient, and thus shallow geostrophic velocity. Given measurements or assumptions about the correlation between shallow velocity and total transport, the cross-passage pressure gradient can provide a proxy measurement of transport through a strait. The processing and analysis of the pressure gauge data, in terms of variability in velocity and transport, is detailed in Chong et al. (2000), Hautala et al. (2001), and Potemra et al. (2002a). This paper will discuss the pressure and velocity variability from those analyses, as it relates to the companion temperature and salinity data.

The pressure gauges and their accompanying CTD sensors are located just offshore of the bounding islands in each strait at a depth of 5–10 m. Along the Lesser Sunda Islands the 8 gauges are located off the islands of Bali and Lombok (Lombok Strait), Sumbawa and North Sumba (Sumba Strait), South Sumba and Roti (Savu/Dao Strait), and North Ombai and South Ombai (Ombai Strait) (Fig. 1). These gauges were deployed from an Indonesian research vessel in December 1995, with recovery and redeployments in March 1997 and April 1998. The gauges were mostly recovered in May 1999, except South Sumba where poor visibility due to suspended sediment prevented location of the instruments, and South Ombai where the political situation on East Timor prevented recovery. Consequently, there is no temperature and salinity (or pressure) data for the period April 1998–May 1999 for these locations. At all other periods and locations, temperature data were 100% successfully recorded. Full 3.5-yr salinity records are also available for North Ombai, Sumbawa and North Sumba. Partial salinity records (mostly $>2$ yr) are available for Bali, Lombok, South Ombai and Roti. No salinity data are available from the South Sumba sensor. Salinity sensors at these locations were impacted during the missing periods by biological or sediment fouling. Bottle samples taken at the gauge locations during each deployment and recovery dive were analyzed by the Ocean Data Facility at SIO and used to calibrate the salinity data collected by the sensors. The ninth pressure gauge, at Ashmore Reef in Australian waters, was deployed with the help of Australian agencies ANCA and Environment Australia, on a different schedule. The gauge at Ashmore Reef is a companion to the gauge at Roti Island, Indonesia: together they measure flow through Timor Passage (Fig. 1). The instruments at Ashmore Reef were initially deployed in February 1995, recovered and redeployed in April 1996, October 1997, and October 1998, with subsequent recovery in January 2000. While there is a full-length 5-yr record of temperature, the salinity sensor failed from September 1995 till April 1996, and again during the final deployment period from October 1998 onwards.

Underway measurements include ADCP and CTD surveys taken throughout the region during the four deployment and recovery cruises. During the initial deployment cruise in December 1995, a towed package consisting of a 150 kHz RD Instruments BroadBand ADCP and an Ocean Sensors CTD was used. The subsequent surveys in April 1997, May 1998, and May 1999 used a shipboard ADCP, and the CTD was setup through an onboard intake system. Bucket samples were routinely collected underway for calibration of the CTD salinity sensor. Corrections to salinity ranged from $<0.05$ to 0.2. In addition, during the first three cruises, repeat transects of 1–2 days duration were made across each of the outflow straits to determine the time-average velocity and help resolve the tidal cycle within each strait. The technique used for processing and tidal correction of the repeat ADCP transects across the straits is covered in Hautala et al. (2001). No tidal correction was applied to the single transect survey pattern for the May 1999 data, and tidal analysis of the complete underway data set is to be explored more fully in a subsequent paper. For this paper, the underway data provide four snapshots of regional conditions that help to put the individual time series from each gauge location into perspective.

## 3. Temporal variability of temperature and salinity

### *3.1. Dominant frequencies in the daily temperature time series*

In Ombai Strait, Timor Passage, Savu Strait, and Sumba Strait the dominant signal in the daily averaged temperature time series is the annual cycle (Fig. 2). Highest temperatures are found during the Northwest monsoon, and coincide with the austral summer months from January through March. Geostrophic velocity, determined from the

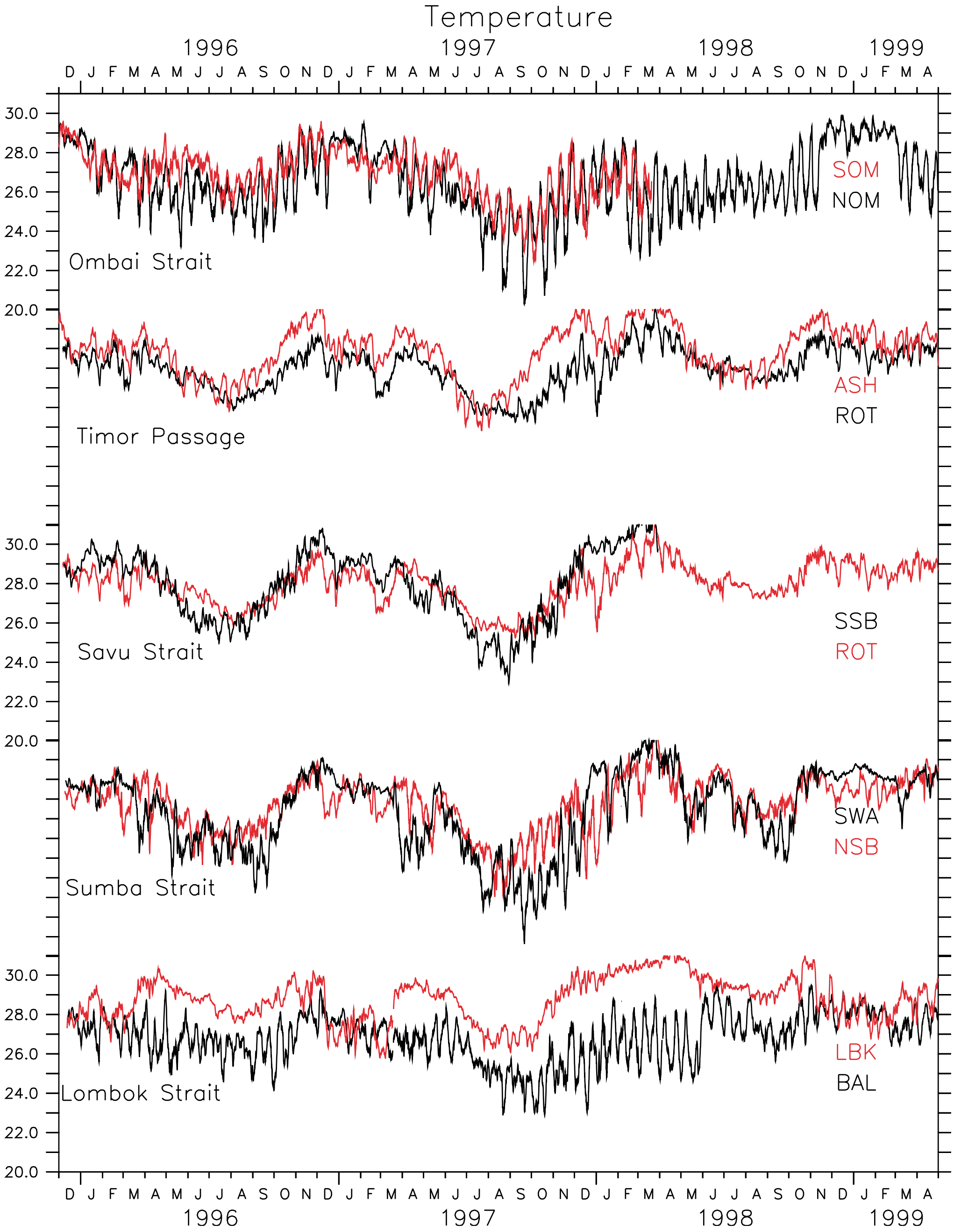

Fig. 2. Time series of daily averaged temperature at: (a) North Ombai and South Ombai (Ombai Strait); (b) Roti and Ashmore Reef (Timor Passage); (c) South Sumba and Roti (Savu/Dao Strait); (d) Sumbawa and North Sumba (Sumba Strait); and (e) Bali and Lombok (Lombok Strait). The location of the gauges are given in Fig. 1. The gauges on the western and northern side of each passage are given in black, and the eastern and southern sites are in red.

pressure gauge array, is directed toward the Indian Ocean and is weakest during this period (Chong et al., 2000; Hautala et al., 2001). The phase of the maximum temperature for the annual harmonic does not appear to have much progression around the archipelago, although the spectra (not shown) find the strongest annual peaks at Sumba and Savu Straits. Interestingly, the temperature data at Ashmore Reef show a strong annual cycle, but the semi-annual cycle also contains half as much energy as the annual signal. Here, the warmest temperatures have a double maxima, warming early around September each year, then, after a brief period of moderate cooling over December, warming again in January through March in concert with the other passages (Fig. 2). Cooler temperatures along these four eastern passages in the Lesser Sundas are found during the Southeast monsoon coinciding with austral winter, when along-shore winds drive offshore Ekman transport that also result in the upwelling of cooler waters at depth. Average temperatures on either side of each of these four passages are within less than a degree of each other, being lowest in Ombai Strait, and increase moving westward along the island chain (Table 1). In addition, the temperature time series from within each of these straits are highly correlated to each other, as well as with their corresponding pressure field. Variability in the temperature time series is highest in Sumba Strait (Table 1), which also has the highest amplitude (1.7°C) in the annual harmonic (not shown).

Temperature variability in Lombok Strait is strikingly different than the other four exit passages located further eastward. Here there is little annual cycle, and it is the semi-annual signal that dominates the temperature time series at both Bali and Lombok (Fig. 2). Some weaker semi-annual energy also is found from temperature spectra of the Sumbawa, North Ombai, and South Sumba measurements (not shown). The maximum in this semi-annual harmonic is felt in May in the western archipelago and subsequently in June at Ombai Strait. The semi-annual frequency is most likely related to the arrival of the Kelvin wave along the coastal wave guide, forced through strong westerly wind bursts in the equatorial Indian Ocean during the April–May monsoon transition period. This period also coincides with eastward flow in the semi-annually reversing South Java Current, found along the south coast of the Lesser Sunda Island chain (Quadfasel and Cresswell, 1992). Another Kelvin wave may be forced during the November monsoon transition, although its effect on the temperature variability may not be as evident given that it coincides with the maximum temperature of the annual harmonic (Fig. 2). Note that the semi-annual signal is highest along the northern edge of Sumba Strait (at Sumbawa), Ombai Strait (North Ombai), and Suva Strait (South Sumba). This is consistent with Hautala et al. (2001), who found northern boundary currents with strong eastward velocity cores in their ADCP sections of these passages, associated with the eastward incursion of the South Java Current. Apart from North Ombai, the temperature field measured along the northern sides of the passages, as well as at the Bali location, are highly correlated with velocity through the straits. The correlations are of the sense that

Table 1

Average Temperature ($T_{\mathrm{Mean}}$) and Salinity ($S_{\mathrm{Mean}}$) and their standard deviations (TSdev, SSdev), from the multi-year measurements along the Lesser Sunda Island chain, Indonesia

| Strait: | LOMBOK | | SUMBA | | SAVU/DAO | TIMOR | | OMBAI | |
|---|---|---|---|---|---|---|---|---|---|
| Gauge: | BAL | LBK | SWA | NSB | SSB | ROT | ASH | NOM | SOM |
| $T_{\mathrm{Mean}}$ | 26.82 | 28.77 | 27.46 | 27.77 | 27.93 | 27.99 | 28.66 | 26.54 | 26.88 |
| $T_{\mathrm{Sdev}}$ | 1.32 | 1.15 | 4.11 | 2.06 | 1.84 | 1.10 | 1.35 | 1.93 | 1.43 |
| $S_{\mathrm{Mean}}$ | 33.58 | 33.25 | 33.85 | 33.93 | — | 33.94 | 33.98 | 33.72 | 33.64 |
| $S_{\mathrm{Sdev}}$ | 0.48 | 0.77 | 0.09 | 0.11 | — | 0.24 | 0.39 | 0.38 | 0.36 |

See Fig. 1 for gauge locations.

eastward (northern) flow through the passages are associated with higher temperatures. This is consistent with the Indian Ocean source of warmer waters (compared to that of ITW) found off the coast of Sumatra and advected eastward in the South Java Current.

Unlike the other passages in the Lesser Sundas, in Lombok Strait there is little correlation ($r = 0.13$) between the temperature time series at Bali and Lombok (Fig. 2). The average temperature at Lombok is 28.77°C, much warmer than the average temperature of 26.82°C at Bali (Table 1). In fact the temperature time series shows that Lombok is consistently warmer than Bali, with the striking exception during the December–March period of each year, when Lombok cools to the same temperature found at the Bali gauge (apart from the El Niño years of 1997–1998). Recall that for the other four passages in the Lesser Sundas, these months coincide with the annual maximum temperatures.

Temperature variations at the Lombok site are not significantly correlated with either local pressure at Lombok, or geostrophic velocity through Lombok Strait, whereas Bali temperature is significantly correlated with both local Bali pressure ($r = 0.64$) and flow through the strait ($r = 0.5$). Bali pressure is also highly correlated ($r = 0.87$) to flow through Lombok Strait, and to pressure at Lombok ($r = 0.7$). As discussed in Potemra et al. (2002a), the correlations are of the sense that higher sealevel at Lombok is indicative of higher southward flow of warmer water through Lombok Strait. Whereas higher sealevel at Bali is associated with higher sealevel across the strait, and hence decreased southward flow. These variations are consistent with that of Murray and Arief (1988) and will be explored more fully in Section 4.

Finally, the temperature time series at Bali shows a prominent fortnightly signal, as do the North Ombai and South Ombai time series, and to a lesser extent the Sumbawa and North Sumba data in Sumba Strait (Fig. 2). This strong fortnightly tidal signal is also found in the internal Indonesian seas, caused through the interaction of the M2 and S2 tides (Ffield and Gordon, 1996). All three passages where the fortnightly energy is found are directly linked to the internal Indonesian seas. It may be that the fortnightly signal itself is a local tidal effect, since the pressure variations are correlated to temperature variations ($r = 0.6-0.7$) at these sites. However, salinity is not correlated to pressure at any site, except at Lombok where salinity and pressure are correlated ($r = -0.52$) whereas temperature is not ($r = 0.32$). In Lombok Strait, the ADCP surveys of Hautala et al. (2001) suggested a western intensification of the southward flow through the strait, and thus a more direct connection between conditions at the Bali site to the internal seas compared to the Lombok site. This notion is supported by the dominance of the fortnightly signal at Bali, and the lack of the signal in the Lombok temperature time series (Fig. 2). Consistent with Ffield and Gordon (1996), the fortnightly signal in the temperature time series is much diminished during the austral summer months of the Northwest monsoon from December through March, again with the exception of these months during the 1997–1998 El Niño (Fig. 2).

### 3.2. *Dominant frequencies in the daily salinity time series*

Salinity measured at either side of a strait is significantly correlated (Fig. 3). The average salinity is higher in the eastern passages compared to that of Lombok Strait, which also has the highest variability (Table 1). In the annual cycle, maximum salinity occurs in each passage during October, at the end of the drier Southeast monsoon. The higher wind speeds during the Southeast monsoon enhance evaporation during this season (Wyrtki, 1961), also contributing to increases in the upper-layer salinity. Further, the steadier southeasterly wind flow also likely causes upwelling of the higher-salinity waters found at depth, at least along the southern archipelago.

The phase of the semi-annual signal (not shown) appears to propagate eastward around the archipelago, occurring first in February in Lombok Strait, then mid-March in Sumba Strait, and early April in Ombai Strait (Fig. 3). The semi-annual signal is characterized by a distinct freshening in all the passages at these times (Fig. 3). While both

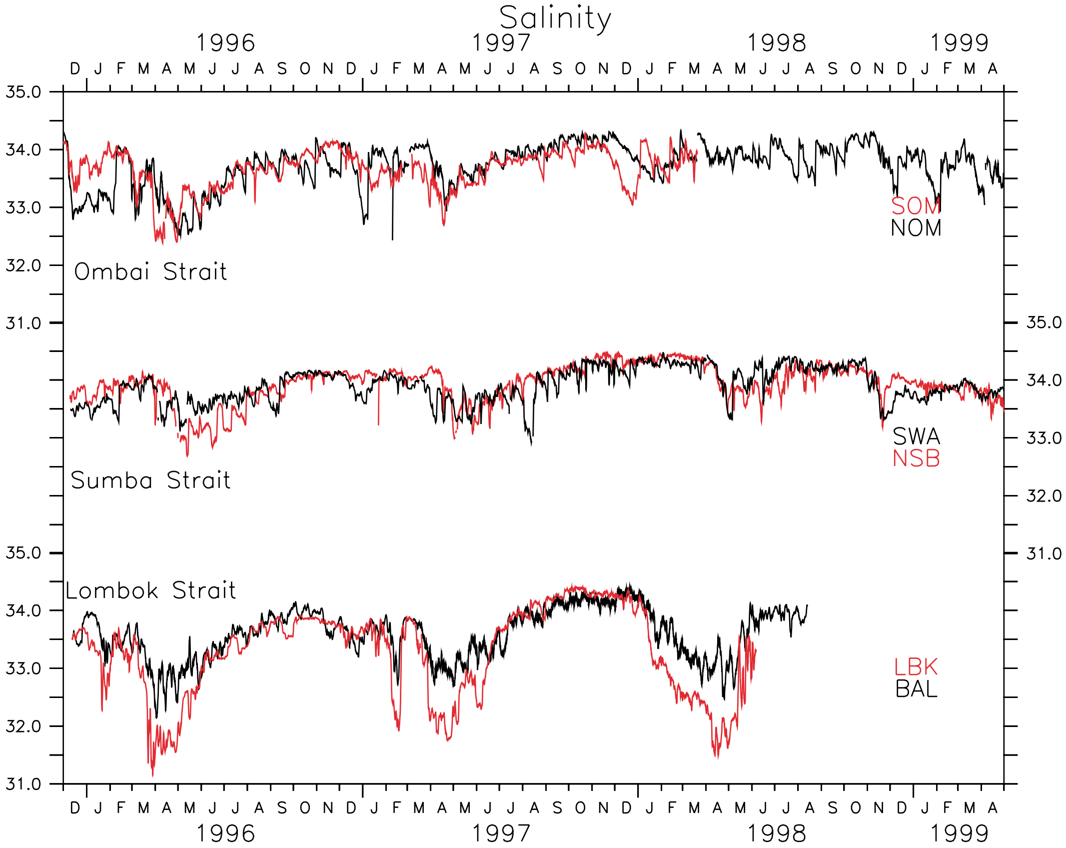

Fig. 3. As in Fig. 2, but for daily averaged salinity. Note, there are no salinity data available for South Sumba.

Bali and Lombok salinity time series show freshening early in the year, Lombok is noticeably fresher than Bali by more than 1 psu. The distinct freshening in Lombok Strait can last for months, with salinities as fresh as 32 psu and below commonly found at the Lombok site. The Lombok gauge is located close to a river mouth that probably influences salinity variability at the site. In Section 4, we will show that most of the semi-annual freshening is probably accounted for by the higher precipitation during the Northwest monsoon that is followed by maximum river discharge. The semi-annual arrival of the coastal Kelvin wave from the equatorial Indian Ocean can also contribute a source of freshwater in the surface layer.

In Lombok Strait, salinity variations at the Lombok site are correlated with both the temperature ($r = -0.57$) and pressure ($r = -0.52$) variations at the Lombok site, although there is no significant correlation between temperature and pressure at this site per se ($r = 0.32$). The significant correlations are of the sense that low (high) salinity is associated with high (low) temperature or pressure at the Lombok site. The Lombok gauge is the only location in all the Lesser Sunda Island measurements where temperature and salinity variations are significantly correlated with each other. Interestingly, there is also a correlation, of the same sense, between the salinity at the Bali site and pressure at the Lombok site ($r = -0.5$), although there is little correlation between local salinity and pressure at the Bali site. Further, recall that while salinity variations across Lombok Strait are highly correlated ($r = 0.8$), there is no significant correlation between temperature variations across this strait ($r = 0.13$). This confusing pattern of correlations is interpreted in Section 4 in terms of the western intensification of the flow through Lombok Strait, and the flow's vertical separation into two layers that is particularly evident during the semi-annual northward passage of the Kelvin wave through the strait.

### *3.3. Interannual variations in temperature and salinity in the Indonesian exit passages*

Removing the annual and semi-annual harmonics from the temperature (Fig. 2) and salinity (Fig. 3) time series, and averaging over monthly time periods, leaves a regional perspective of the interannual variations in temperature and salinity. While the 3.5-yr time series are relatively short for a comprehensive analysis, a fairly coherent response in the interannual temperature (Fig. 4) and salinity (Fig. 5) variations is found around the Lesser Sunda Island exit passages, although there are slight differences in the phases and amplitudes between the individual passages. In early 1996, the temperature in Lombok Strait and Ombai Strait

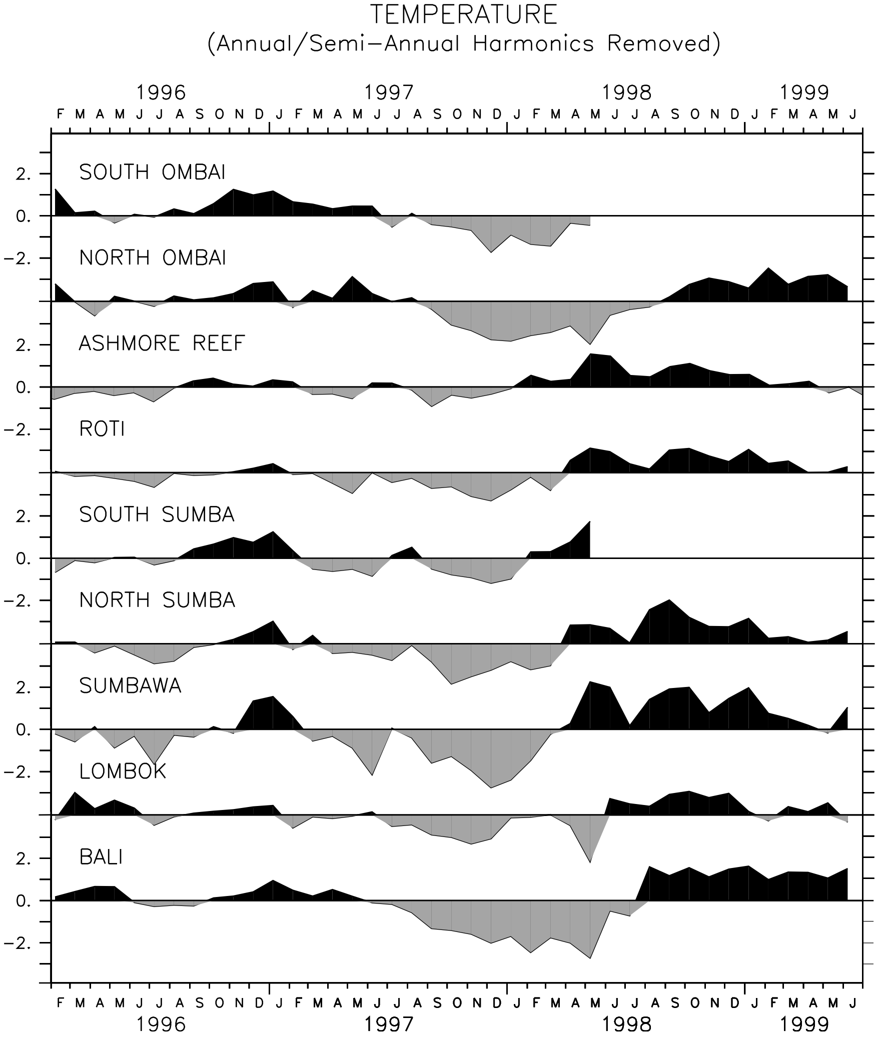

Fig. 4. Monthly average temperature anomalies, calculated by removing the annual and semi-annual harmonics from the time series in Fig. 2, for each site in the SPGA. Positive (negative) anomalies indicate warming (cooling) at each location, and are marked in black (grey).

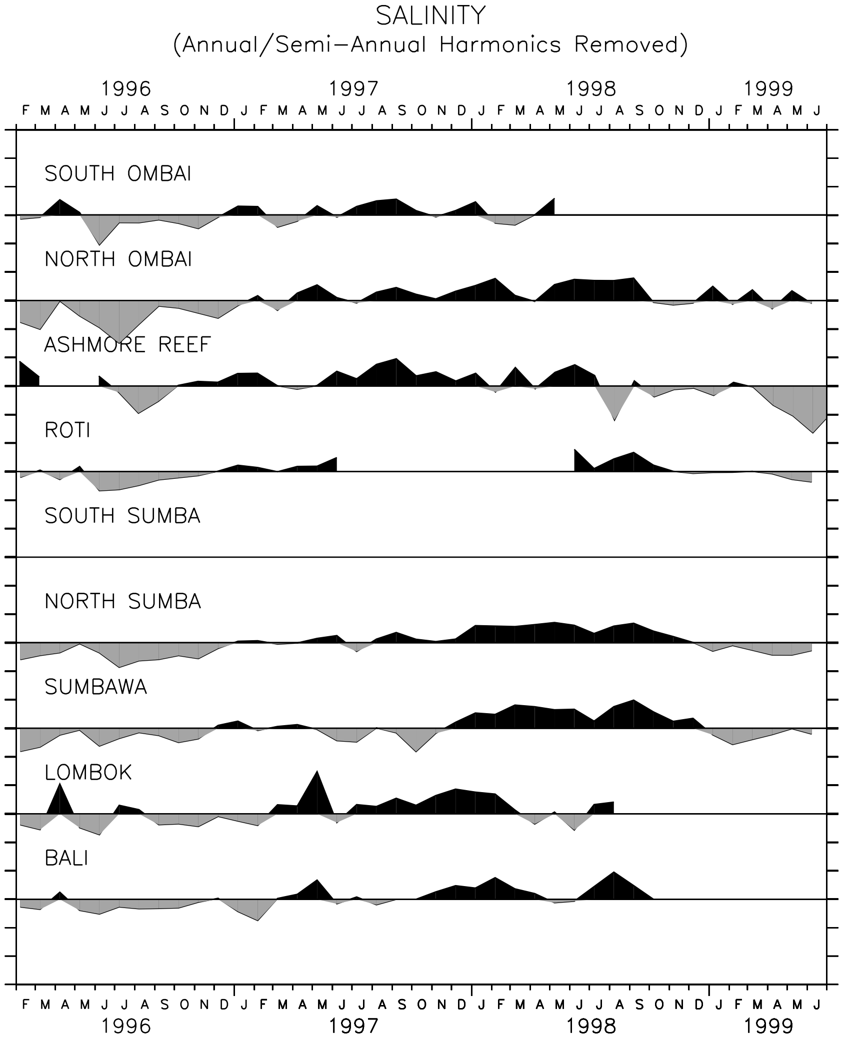

Fig. 5. Monthly average salinity anomalies, calculated by removing the annual and semi-annual harmonics from the time series in Fig. 3, for each site in the SPGA. Positive (negative) anomalies indicate saltier (fresher) water at each location, and are marked in black (grey).

was warmer than average, whereas in the other eastern passages it was slightly cooler than average or near normal (Fig. 4). The period of annual maximum temperature in September 1996 through January 1997 was slightly warmer than normal in all passages, but by mid-1997 the whole region had dramatically cooled, with small phase differences in onset between the passages. The region remained cool throughout the remainder of 1997, then warmed substantially around February–March 1998 in Sumba, Savu/Dao and Timor Passages, and a bit later around May–June in Lombok and Ombai Straits. The warming trend mostly continued till the end of the records in May 1999.

The corresponding interannual signal in salinity (Fig. 5), particularly the phasing around the Lesser Sundas, are not as clear cut as in the temperature record. Nor, given the low correlation between temperature and salinity at all locations except the Lombok site, are the phases in interannual salinity and temperature anomalies necessarily consonant.

Nonetheless, in general, the salinity records show an anomalous freshening of the region occurred through mostly all of 1996, followed by a saltier than normal period during all of 1997 and on until mid-to-late 1998. A freshening occurred in early 1999 till the end of the remaining records. The low frequency variability in the temperature and salinity records are related to the patterns associated with Pacific ENSO and basin-wide Indian Ocean dynamics, as described in Section 4.

## 4. Discussion

As in the inferred geostrophic velocity data (Hautala et al., 2001), the temperature and salinity data from the SPGA in the Indonesian exit passages for the Throughflow show strong variability over all time scales related to the local and remote forcing mechanisms of wind, heating and precipitation. The forcing on different time scales and from different regions, results in water masses of different temperature and salinity characteristics being advected into or formed locally within the Indonesian archipelago. In addition, the situation is further complicated in the region as these different forcing mechanisms overlap and interact, and thus partitioning direct effects in the property signals is a complex exercise.

### *4.1. Why is T–S variability in Lombok Strait different to the other ITF exit passages?*

Lombok Strait displays distinctly different property characteristics between the two sites across the passage, as well as compared to the other four main exit passages located farther east along the Lesser Sunda Island chain. Perhaps not surprisingly, this is directly related to Lombok's geography. First, nearly all of the southward Lombok Throughflow is considered to come directly from Makassar Strait via the Java Sea. The remainder of the Makassar Throughflow that does not exit via Lombok flows east, and spends time mixing in the internal Flores and Banda Seas before exiting through the other eastern passages along the Lesser Sunda Islands (Gordon and Fine, 1996). Second, Lombok Strait has the shallowest sill depth ($\sim 250$ m) and therefore the Throughflow here consists of primarily surface waters that are more readily and rapidly altered through direct surface air–sea heating and freshwater fluxes. Third, Lombok Strait opens directly onto the Southeast Indian Ocean, and is the first major strait along the southern archipelago to be impacted by remotely forced coastal Kelvin waves that bring water within the eastward South Java Current of distinct Indian Ocean origins (Sprintall et al., 1999; Susanto et al., 2001; Wijffels et al., 2002). While Lombok Strait, at 37 km wide, is narrower than the Rossby radius of deformation, the Kelvin waves may temporarily reverse the shallow along-strait pressure gradient (Potemra et al., 2002a), and thus their impact may be felt within the strait and even further "upstream" at Makassar Strait (Sprintall et al., 2000).

An example of the interaction of all these forces on properties within Lombok Strait can be observed during the distinct freshening of over 2 psu that occurs from March to May of each year over the measurement period (Fig. 3). South of the equator, the rainy season is during the Northwest monsoon, lasting from November through March. The maximum river discharge from the mountainous islands of Java, Kalimantan and Sumatra that surround the Java Sea, occurs about one month later in April (Wyrtki, 1961). Indeed, the upper layer salinity for the region from the Levitus and Boyer, (1998) climatology, finds the freshest salinity values for the region occur during April in the Java Sea, located just to the north of Lombok Strait (Fig. 6). Some of the freshening in the salinity signals at Lombok Strait are in all likelihood related to the local high precipitation and voluminous river runoff into the Java Sea during this period. A simple salinity balance finds that the local precipitation during April in Lombok Strait (from the Janowiak and Xie (1999) rainfall data set) accounts for a time rate of change in salinity of only $\sim 1.1$ psu/month, not enough to fully compensate for the signal observed in Lombok Strait during this period. Generally southward flow is found through Lombok Strait in March and April (Hautala et al., 2001) that also could account for the freshening. In May, however, the surface flow through Lombok Strait, as

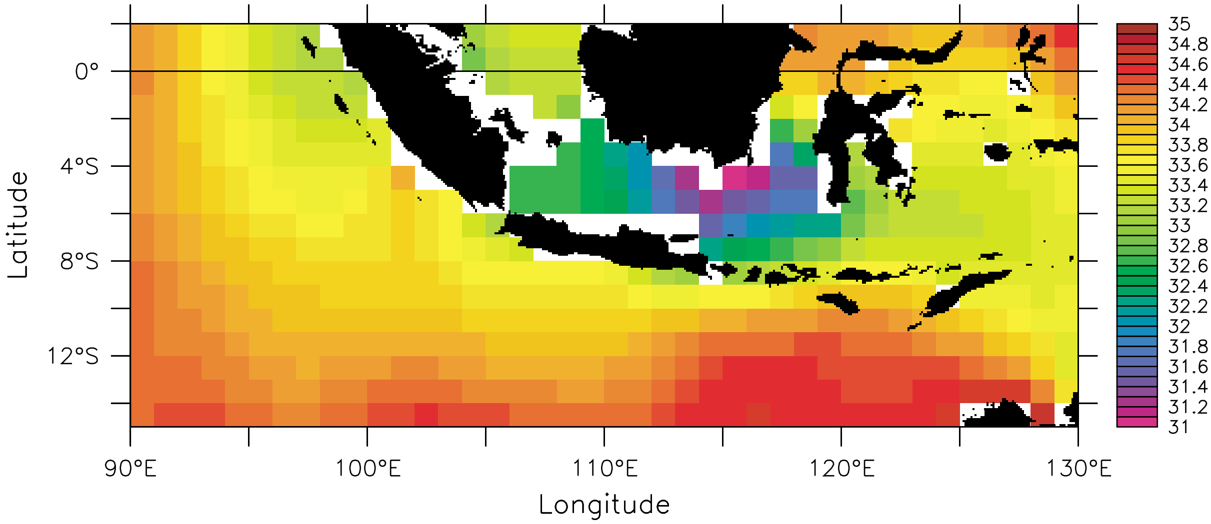

Fig. 6. Average 10-m salinity in April for the Indonesian region, from Levitus and Boyer (1998).

inferred from the pressure gauges, is consistently northward (Hautala et al., 2001). The flow reversal is due to the arrival of the coastal Kelvin wave forced by westerly wind bursts during the May monsoon transition period in the equatorial Indian Ocean. This downwelling Kelvin wave consists of the relatively fresh and warm surface water found along the west coast of Sumatra (Fig. 6). As in the Java Sea, the freshwater pool located on the equator off the west Sumatra coast is related to a regional maximum in precipitation (Janowiak and Xie, 1999), as well as contribution from river runoff. Fig. 6 also shows some of the leakage of very freshwater through Sunda Strait (between southern Sumatra and western Java) during April, that may contribute to the freshening observed along the coast of Java and into Lombok Strait. In May 1997, the Kelvin wave was observed at a mooring located south of Java, when the flow in the South Java Current reversed eastward in the face of strong local southeasterly winds, surface salinity freshened by over 1 psu, and the water column dramatically warmed by over 4°C in the upper 160 m (Sprintall et al., 1999). These fresh, warm conditions during May 1997 are also evident in the temperature and salinity time series at Lombok Strait (Figs. 2 and 3).

The complex relationship as inferred from the correlations between the properties in Lombok Strait suggests a spurious nature to the flow through Lombok when compared to that of the more eastern exit passages. To recap, while the temperature variations across the strait were uncorrelated with each other, the salinity variations were highly correlated. Further, salinity variations at either side of the strait were significantly correlated with their respective pressure variations, while only Bali temperature variations were significantly correlated with Bali pressure and flow through the Lombok Strait. Bali pressure variations also were correlated with Lombok pressure variations and flow through the strait. Higher sealevel on the Lombok side is indicative of higher southward flow and is accompanied by warmer, fresher water in Lombok Strait (Potemra et al., 2002a). Higher sealevel on the Bali side is indicative of lower southward flow, or even northward flow, through Lombok Strait. Modeling work by Potemra et al. (2002a) suggests that pressure variations on the eastern side of Lombok Strait (at Lombok) are more related to low-frequency, large-scale wind forcing from the Pacific Ocean, while variations on the western side of the strait (at Bali) respond more to higher-frequency Indian Ocean forcing. This is evident given that northward flow through the strait (i.e. higher sealevel at Bali) occurs primarily during the semi-annual Kelvin wave events, driven by winds in the Indian Ocean. What is more, Potemra et al. (2003) further suggests that the modes of variability have a vertical separation: lower frequency Pacific-related variability is found at depth in the outflow passages, whereas the upper-surface flow through these straits has more of an annual or semi-annual signal related to local regional and Indian Ocean winds. This is consistent with Hautala et al. (2001) who note that the repeat ADCP surveys in the outflow passages show a two-layer flow structure, with flow in the lower layer consistently directed toward the Indian Ocean, whereas upper-layer flow can episodically reverse. The property correlations suggest support for the variations in the upper layer: at Lombok warm, freshwater is associated with high pressure, and therefore higher southward flow of ITW, as occurs during March and April (Figs. 2 and 3); whereas at Bali higher sealevel and northward flow is associated with the warm temperatures found off the Sumatra coast, and at most times is not significantly correlated to salinity (although the negative correlation implies the relatively freshwater found off Sumatra). Hautala et al. (2001) further suggest that the strongest core of outflow through Lombok Strait shows a consistent intensification toward the Bali side, a lateral separation also noted by Murray and Arief (1988). This is true whether the southward high-velocity core occurs in the upper or lower layer, and explains why the correlation between Bali pressure and temperature variations with flow through the strait are significant, whereas the variations at the Lombok site are not significantly correlated with the outflow. In addition, as noted earlier, the western intensification also accounts for the presence of the fortnightly tidal energy in the temperature signal at Bali that is not found at Lombok.

### *4.2. Regional variability observed by underway ADCP and CTD measurements*

In December 1995, the underway ADCP and CTD data show that near-surface flow in the western archipelago was predominantly toward the Indonesian Seas (Fig. 7a). The flow is suggestive of coastal Kelvin wave propagation, forced in response to equatorial Indian Ocean westerly wind bursts during the November monsoon transition (Wyrtki, 1973). Typically the November Kelvin wave is considered to be weaker than the May transition Kelvin wave (Han et al., 1999). Nonetheless, in December 1995 the repeat ADCP surveys across the straits found northward flow in the upper 100 m of Lombok Strait, and eastward flow in the South Java Current extending through Sumba Strait, and into the Savu Sea (Hautala et al., 2001). Eastward flow also was observed in the upper 160 m of the moored ADCP data collected during December 1995 in Ombai Strait (Molcard et al., 2001). The surface temperature–salinity structure from the concurrent underway CTD measurements (Fig. 7a) shows that the eastward flow consisted of the relatively fresh, warm water consistent with that found in the near equatorial Indian Ocean west of Sumatra. A direct outflow of the freshwater found in the internal Java, Flores and Banda seas is not found during this period (Fig. 7a). This implies that the South Java Current, at least during its semi-annual maximum, may provide a very efficient mechanism for transporting the relatively low-salinity Indian Ocean surface water through the Lesser Sunda passages and into the internal Indonesian seas. Surface flow toward the Indian Ocean during December 1995 was confined to Dao Strait and Timor Passage (Fig. 7a). During March 1997 (Fig. 7b), and again in March 1998 (Fig. 7c), the ADCP/CTD near-surface measurements return to a more classical picture of the Throughflow, in which there is flow mostly toward the Indian Ocean throughout the archipelago. The fresher Java Sea temperature–salinity characteristics (compared to the Indian Ocean surface thermohaline structure) are present in the strong southward flow emerging from Lombok Strait. This is consistent with the very freshwater observed at the Lombok and Bali pressure gauge sites during these months (Fig. 3). Finally, the underway ADCP/CTD survey in May 1999, again shows the likely presence of the semi-annual Kelvin wave, at least in the vicinity of Lombok Strait, as evidenced by the northward flow through the strait, and eastward flow along the south coast of Sumbawa (Fig. 7d). However, what is obviously most striking about the regional conditions during May 1999, is the extreme freshness of the near-surface layer throughout the eastern Lesser Sunda region. Given the

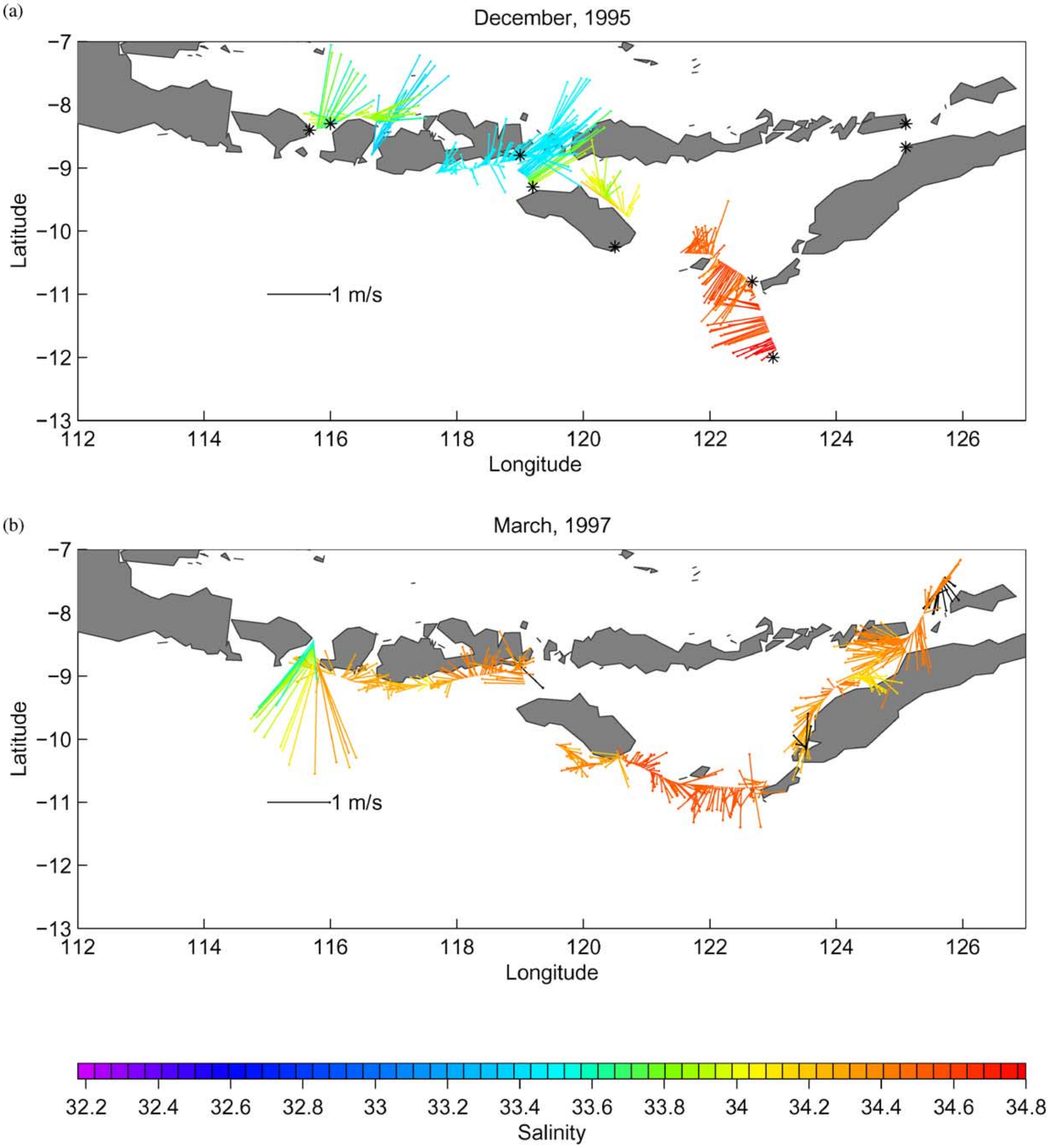

Fig. 7. Underway ADCP velocity vectors, averaged over the top 20–70 m depth, color coded by surface salinity from underway CTD measurements for surveys conducted in the Indonesian region in: (a) December 1995; (b) March 1997; (c) March 1998; and (d) May 1999.

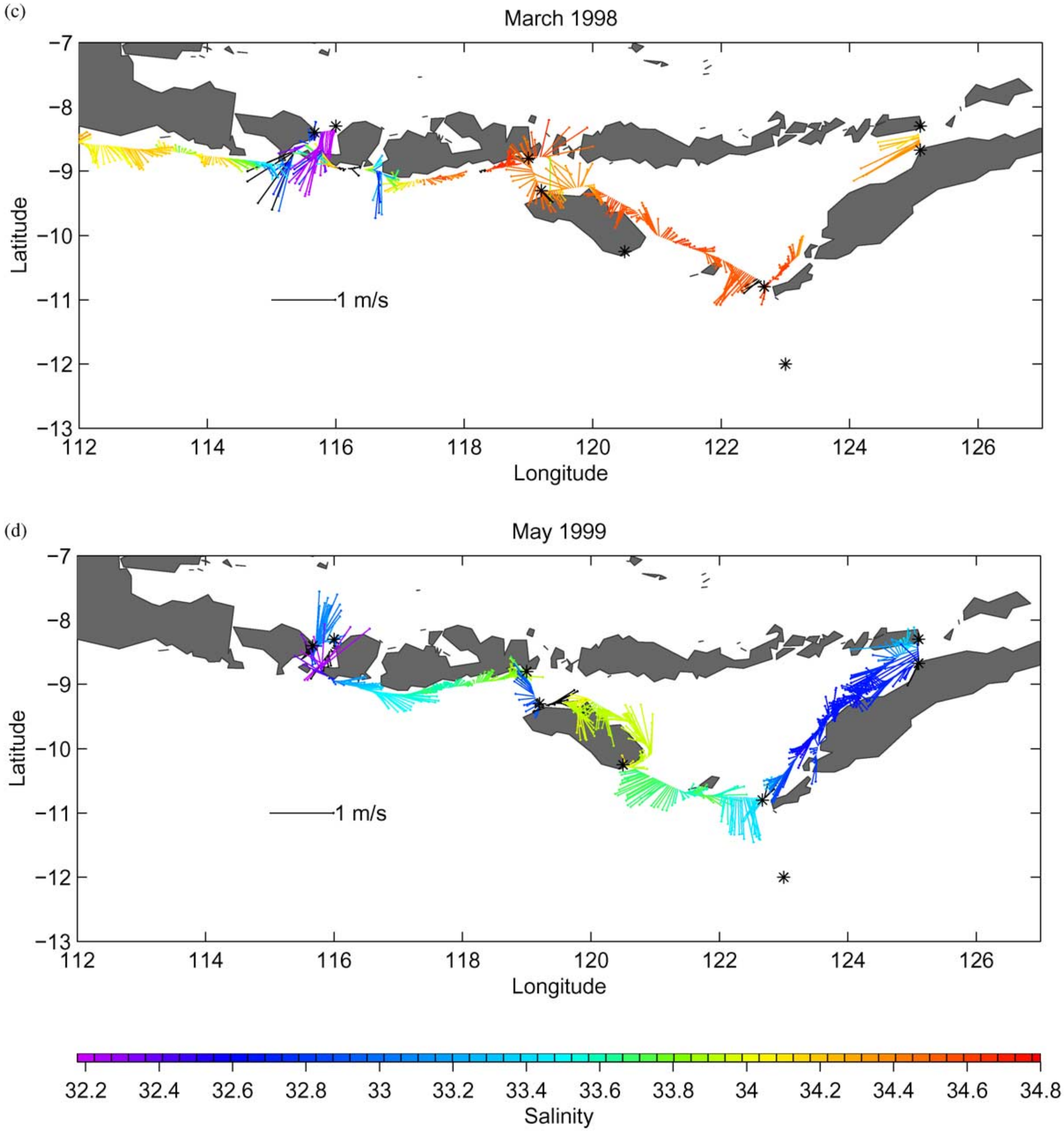

Fig. 7 (*continued*).

westward direction of flow, it is most likely that the very freshwater found flowing through Ombai Strait, across the Savu Sea and out through Savu/Dao Straits and Sumba Strait during this period, is related to the heavy local precipitation and runoff. Recall, however, that tides have not been removed from the ADCP velocity data, hence some of this signal may be tidally related. We note however, that the freshening is consistent with that found at the salinity sensors in these straits during the month of May in other years of the time series (Fig. 3).

### 4.3. T–S variability in response to local forcing

Local forcing from wind and heating can also play a role in causing the variability observed in the upper-ocean measurements of temperature and salinity in the Indonesian exit passages. For example, in December 1995, the regional winds south of Java were eastward (see Fig. 3 of Potemra et al., 2002a, 2003) and hence may have enhanced flow of the eastward South Java Current observed along the Lesser Sunda island chain during this period (Fig. 7a). Similarly, some of the temperature variability may be attributed to regional air–sea heat fluxes. For instance the NCEP monthly climatology shows that the net surface heat flux for the region is maximum in October and March, and minimum in June–July. This partially agrees with what we find in the annual cycle of the temperature measurements at least in the eastern passages (Fig. 2): warmest from October through March and coolest from June through September. In particular, the temperature time series at Ashmore Reef (Fig. 2) shows peak temperatures in October/November with a secondary maximum around March. This suggests that at Ashmore Reef, vertical mixing of the air–sea heat flux may determine the annual cycle temperature variability. However, as we have outlined, the regional monsoon winds also play a large role in defining the annual cycle of the Indonesian region. The relationship between wind forcing and the horizontal advective effects (Potemra et al., 2002a) appears to be consistent with the annual cycle observed in temperature.

The relationship of salinity variability to the regional precipitation and runoff has been discussed. However, given the proximity of the Lombok site gauge to a river mouth, local forces probably also play a prominent role in influencing the salinity and temperature variability at this site. It is likely that the enhanced freshening observed at Lombok during March through May of each year is due to the influx of river discharge directly onto the site. In addition, the prevailing winds during this Northwest monsoon period imply that local precipitation also would be higher on the western side of Lombok Island where the gauge is located.

### 4.4. T–S variability related to ENSO

There is substantial evidence that the ITF is also modulated on interannual time scales. The changes are of the sense that transport is smaller (larger), and the thermocline is shallower (deeper) during El Niño (La Niña) time periods (Meyers, 1996; Bray et al., 1996; Fieux et al., 1996; Gordon and Fine, 1996; Potemra et al., 1997). Wyrtki (1987) suggested that the reversal in the Pacific Ocean trade winds that occurs during an El Niño reduces the pressure gradient between the Pacific and the Indian Ocean, thought to be the driving force for the Throughflow on low-frequency time scales. Indeed, the Arlindo mooring observations within Makassar Strait find an average transport of 5.1 Sv during the El Niño months of December 1997–February 1998, while during the La Niña months of December 1996–February 1997 the average is 12.5 Sv, a 2.5-fold difference (Gordon et al., 1999). Further, using nearly 15 years of XBT data in the region, Ffield et al. (2000) show that the Makassar upper thermocline temperature is also highly correlated with ENSO, a feature that may prove useful for developing proxy measurements of ITF transport.

In the Lesser Sunda Island exit passages, the relationship of transport to ENSO is much less certain, and a different response is evident between the passages (Hautala et al., 2001). In the transport estimated from the shallow pressure gauges, there is some suggestion of weaker flow through Ombai Strait, with increased flow through Timor Passage during the El Niño event in 1997–1998. This is consistent with a 20-yr run of the POCM model, in which there is stronger flow through Timor Passage and weaker flow through Ombai Strait during ENSO events (Potemra et al., 2002a), although the magnitude of the transport changes through the two model straits do not fully compensate each other. In Lombok Strait, and to a lesser extent in Sumba Strait, it appears that through-strait transport was much stronger than normal for most of 1997 till mid-1998, and then weaker than normal (or even more northward) from mid-1998 until the end of the record in May 1999 (Hautala et al., 2001). The uncertainty of the ENSO signal in the outflow straits may be related to the fact that the SPGA pressure gauges infer the flow for the surface layer, whereas models suggest that the low-frequency signal appears strongest in the deeper layers (Potemra et al., 2003).

Clearly, however, in the temperature and salinity measurements of the upper layer, the 1997–1998 El Niño period corresponds to a strong cooling in every exit passage, with a general sense of increased salinity (Figs. 4 and 5). While it is apparent that there are phase differences for the onset of the cooling trend, for the most part it appears that at least for the period July 1997 through February 1998, every exit passage was cooler than normal. A simple explanation would be that there is simply less of the warm, fresh ITF entering the Indonesian seas during an El Niño, as the flow is being diverted from the western Pacific warm pool toward the eastern Pacific Ocean. Such an explanation due to advective effects would be suitable for the ENSO temperature–transport relationship observed in Makassar Strait (Ffield et al., 2000), as this strait is more directly connected to the western Pacific warm pool, and the ENSO impact would be more direct. For the outflow passages, however, a simple relationship to transport may not be as clear cut, due to the impact of storage that probably occurs on seasonal time scales in the Banda Sea (Hautala et al., 2001; Gordon and Susanto, 2001). Gordon and Susanto (2001) found cooler surface temperatures in the Banda Sea during El Niño periods, and further suggest that during the 1997 ENSO event surface-layer divergence (loss) from the Banda Sea was as high as 4 Sv. However, given the varying ratios of transport carried through each of the outflow straits during ENSO events, as observed in the pressure gauge data (Hautala et al., 2001; Potemra et al., 2002a), the gating of this Banda Sea divergence through the respective exit passages along the Lesser Sunda chain appears an extremely complex issue that may not be answerable with the limited number of observations to date. Of interest, however, we note that the strongest outflow during the 1997 El Niño occurred through Lombok Strait, consistent with the hypothesis of Wyrtki (1961), who suggested that Banda Sea divergence may at times be exported westward into the Flores and Java Seas.

In addition to advective effects, the regional cooling and saltiness evident in the upper ocean measurements along the Lesser Sunda Island chain during the 1997–1998 El Niño may be attributed to associated variability in the air–sea and wind momentum fluxes. Certainly during El Niño events, the center of atmospheric convection that normally resides over Indonesia shifts eastward toward the central Pacific (Ropelewski and Halpert, 1987). In 1997–1998, the lack of rainfall over the Indonesian region resulted in a catastrophic drought with subsequent devastating wide-spread fires, that left a legacy of profound economic and political consequences. This anomalously low precipitation also reduced the normally voluminous freshwater outflow from the rivers in the region, and both effects would act to raise the upper layer salinity in 1997, as observed in the salinity time series around the archipelago (Fig. 5). A further effect of the reduced precipitation in Indonesia during 1997 was a significant increase in the absorbed short-wave and outgoing long-wave radiation fluxes (Gutman et al., 2000). The change in these fluxes during 1997 was actually compounded by the injection of smoke aerosols into the atmosphere from the wide-spread fires during the 1997 drought (see Gutman et al. (2000) for an interesting discussion on the chain of atmospheric events). The net effect of the increase in outgoing radiative fluxes may have partially resulted in the cooler upper-ocean temperatures observed during 1997 in the Lesser Sunda exit passages (Fig. 4), that also were observed in AVHRR satellite SST measurements over the entire Indonesian archipelago (Gutman et al., 2000). Finally, a change in the wind regime to enhanced easterlies over Indonesia during the 1997 El Niño probably increased upwelling activity, raising the depth of the thermocline and bringing cooler and saltier water to the surface along the southern coast of the Lesser Sunda Islands (Sprintall et al., 1999; Susanto et al., 2001).

### 4.5. *T–S variability related to the Indian Ocean Dipole Mode*

Unfortunately, the picture is further complicated as the strong 1997–1998 El Niño event coincided with the equally strong 1997 Indian Ocean dipole event (Saji et al., 1999; Webster et al., 1999; Yu and Rienecker, 1999; Murtugudde et al., 2000). This coincidence is considered unfortunate from three standpoints: first, it is a hotly contested debate in the climate community whether the two phenomena are related or not (see Saji et al., 1999; Murtugudde et al., 2000 for a review of the arguments); second, within the Indonesian seas the impacts on the regional atmospheric and oceanic conditions from both phenomena are very similar, if not indistinguishable; and third, both phenomena may be amplified or modulated by the "normal" shifts induced by the annual regional monsoon. The 1997 Indian Ocean Dipole event is characterized by anomalously cool SSTs occurring in the eastern tropical Indian Ocean off the coast of Sumatra and Java, while the western tropical Indian Ocean is warmer than usual (hence the "dipole"). Strong easterly wind anomalies also were present along the equator in the tropical Indian Ocean (Saji et al., 1999). The ENSO-dependent camp suggest that these anomalous easterlies were induced by an ENSO-related reversal in the Walker Cell that subsequently caused the cooler eastern Indian conditions (Yu and Rienecker, 1999), whereas the ENSO-independent camp suggests that the warm SSTs in the western tropical Indian Ocean shifted and increased convection over eastern Africa, thus producing the easterly wind anomalies in the central Indian Ocean (Webster et al., 1999). Whatever the sequence of events, both groups note that the enhanced equatorial Indian Ocean SST gradient from June to December 1997 in turn maintained and prolonged the easterly wind anomalies during this period. Furthermore, the equatorial easterlies probably forced upwelling Kelvin waves leading to a shallower thermocline with lower sea-surface height in the east (Murtugudde et al., 2000), bringing cold, relatively salty water to the surface along the coasts of Sumatra and Java (Susanto et al., 2001), and a sustained period of anomalously eastward flow of cooler, saltier water in South Java Current lasting from July 1997 through January 1998 (Sprintall et al., 1999). Thus, the impact of the Indian Ocean Dipole Mode on atmospheric conditions and oceanic properties, at least in the vicinity of the ITF exit passages, are strongly reminiscent of those equally attributable to El Niño: cooler water (Fig. 4) due to an enhancement of upwelling caused by a shift in the surface winds; and saltier water (Fig. 5), also attributable to increased upwelling, as well as to a decrease in rainfall, caused by a shift in the locus of the atmospheric convection (eastward to the central Pacific Ocean in the case of ENSO, and westward to over Africa in the case of the dipole mode). Finally, we note that the upwelling response along the Sumatra and Java coasts of cooler SST due to alongshore wind forcing is actually typical of that observed during the southeast monsoon (June–October), although Susanto et al. (2001) suggest that the upwelling here extended both in time (till November) and space (to the equator) during 1997.

### *4.6. T–S variability related to La Niña*

The 1997–1998 El Niño event was immediately followed by a La Niña, beginning around April 1998 (Climate Diagnostics Bulletin, 1998). The La Niña period corresponds with larger ITF and deeper thermocline in Makassar Strait (Gordon et al., 1999), and reduced upwelling, deeper thermocline and warmer SST along the coasts of Sumatra and Java (Susanto et al., 2001). In the Lesser Sunda Island passages, warmer upper-ocean temperatures are evident in Timor Passage, Savu/Dao and Sumba Straits from April 1998 until near the end of the record in May 1999 (Fig. 4). In Lombok Strait and at North Ombai, the onset of warmer than normal temperatures occurs 1–3 months later. In Lombok Strait, this delay may be related to the arrival of the transitional Kelvin wave that resulted in northward flow of cooler water through the strait during May–June 1998 (Fig. 4; Hautala et al., 2001). Concurrent pressure data for inferring velocity through Ombai Strait are unavailable over this time period (Hautala et al., 2001), although there are (weak) eastward flow and a reduction in the anomalous warm temperatures in Sumba Strait (Fig. 4) at the eastern edge of the Savu Sea in June 1998, which could indicate the Kelvin wave passage through the Savu Sea to North Ombai. As during the El

Niño period, the relationship of transport to temperature during the La Niña period is equally as complicated, and with the non-recovery of pressure gauge data in Ombai and Timor Passage during this period, no clear-cut signal can be determined. Again, however, transport and flow through Lombok Strait displays an inverse relationship to that found during La Niña periods in Makassar Strait: southward flow through Lombok is much weaker than average. In fact, after the northward flow in May–June 1998 associated with the Kelvin wave, there is only a short return to weak southward flow, and from November 1998 onwards, Lombok Strait is characterized by periods of strong, prolonged northward flow (Hautala et al., 2001). Again we invoke Wyrtki's (1961) hypothesis of increased convergence into the Banda Sea, supported by Gordon and Susanto (2001) who found maximum convergence into the internal sea occurs during the northwest monsoon (November–March), that is enhanced under La Niña conditions. The salty conditions that existed in the outflow passages during the 1997 El Niño appear to continue until at least mid-1998, and until late-1998 in the passages that still had active salinity sensors at this time (Fig. 5). Precipitation from the Janowiak and Xie (1999) data set, shows a severe rainfall deficit existed throughout the entire Indonesian region in January 1998, rainfall was as scarce during this period as during the September–October 1997 El Niño period (Gutman et al., 2000). The anomalous drought conditions remained throughout most of the region in March and April 1998, apart from anomalously high rainfall that occurred in the Java Sea region. The freshening that appears at the Lombok and Bali sensors in March–May 1998 (Fig. 5) is likely related to this heavy local rainfall and subsequent runoff, as well as the arrival of the Kelvin wave in May–June 1998. The precipitation fields show a return to normal rainfall patterns over the southeast monsoon period from May through October 1998, with slightly wetter conditions in the eastern archipelago. We can therefore offer no reasonable explanation for the prolonged saltiness observed in the Lesser Sunda exit passages during this period, for instance in the upper-ocean records at Sumba Strait and at North Ombai (Fig. 5). During the northwest monsoon from January to April 1999, however, heavier than normal rainfall occurred, and the freshening in the Sumba Strait salinity sensors (Fig. 5) and evident in the (early) May 1999 underway ADCP/CTD survey (Fig. 7d) indicate the regional and cumulative impact of this precipitation.

## 5. Conclusions

The upper-ocean temperature and salinity data from a $3\frac{1}{2}$ year deployment in the five major passages along the Lesser Sunda Island chain in Indonesia document the property characteristics of the Throughflow as it exits into the Southeast Indian Ocean. As in the concurrent pressure gauge data that yield estimates of geostrophic surface flow and upper layer transport (Hautala et al., 2001), the property data show variability over many time scales, with different responses evident within each passage along the island chain due to different forcing mechanisms. In particular, it seems that Lombok Strait displays very distinct property characteristics compared to the more eastern passages of Sumba, Savu/Dao, Ombai, and Timor passages. Lombok Strait is more directly connected to Makassar Strait, the major inflow passage for ITF upper surface and thermocline water masses from the Pacific Ocean (Gordon et al., 1999), as well as being the first major strait impacted by remote forcing from the Indian Ocean. In addition, the temperature and salinity data on either side of Lombok Strait, at Bali island on the western side and Lombok island on the east, reveal different scales of variability from each other. The water at Lombok is much warmer and much fresher than that found at the Bali site, whereas in the other exit passages there is little cross-strait gradient evident in temperature and salinity.

We have attempted to explain the variability in the temperature and salinity time series in terms of the different local and remote forcing mechanisms that impact both property and mass fluxes in the Indonesian region. However, it should not necessarily be assumed that the forcing impacts the velocity variations and the temperature and salinity variations in the same way. For example, Potemra et al. (2002a) find a dominant intraseasonal signal in the inferred geostrophic velocity and transport time series from the shallow pressure gauges that was not evident or particularly strong in the spectra of temperature or salinity. The velocity obviously only contributes the advective effects to changes in the salinity and temperature balance, as shown above, other equally strong contributions are from the local or large-scale air–sea fluxes of heat and wind momentum, as well as precipitation and evaporation in the salinity balance.

During the 1996–1999 SPGA deployment period, there was a strong El Niño occurring in the Pacific Ocean, and an equally strong Dipole Mode in the Indian Ocean. Whether they are related or not, the complex dynamics from the interplay between these two events that geographically must interact within the Indonesian region, is evident in the property and velocity observations in the outflow straits. From mid-1997 till early 1998, when both the El Niño and Dipole Events occurred, the upper ocean was warmer and saltier than normal. We presented reasons why both of these interannual climatic events could cause the property fluxes in the outflow passages to respond in this way: a deficit in precipitation (due to both climate phenomena); less warm, fresh Throughflow (ENSO-related); and an influx of cooler, salty water from the Indian Ocean (Dipole-related). Again, the interaction between the forcing mechanisms from the two basins appears to be more complex in Lombok Strait. In particular, it is interesting that during the Northwest monsoon months of December–February when Lombok and Bali temperatures are generally similar, in 1997–1998 there is a large cross-strait temperature difference and there was no decrease in the fortnightly cycle in temperature at the Bali site. The fortnightly signal at Bali, due to tidal forcing at this frequency in Makassar Strait and the internal Indonesian seas, is further evidence for the western intensification of flow through Lombok Strait (Hautala et al., 2001), and also its direct connection to flow from Makassar Strait. Since there was no seasonal decrease in the fortnightly signal during the 1997–1998 Northwest monsoon, we speculate that during this period, flow at Bali was more related to upstream conditions and possibly Pacific Ocean forcing. Shallow southward flow through Lombok Strait was stronger than normal during this time adding support to the connection, although this is counter-intuitive to that expected during El Niño events. However, the response in the outflow straits to ENSO is uncertain due to the lack of lower layer velocity observations, and further, the inability of state-of-the-art models to adequately resolve the width of the shallow Lombok Strait (Potemra et al., 2002a, 2003).

Although the interannual signals from both the Indian Ocean and the Pacific Ocean are interesting, it is the annual cycle that tends to dominate the time series of both temperature and salinity, at least in the eastern passages along the Lesser Sunda Island chain. Here, each year during the warm, wet summer months of the Northwest monsoon from November through March, the upper ocean temperatures rise and salinity falls in concert around the archipelago. During the cooler, drier and windier Southeast monsoon, temperature falls and salinity increases. The semi-annual signal is dominant in Lombok Passage, and is related to both high local precipitation and runoff, as well as the arrival of freshwater in the transitional Kelvin wave around May, manifested as eastward flow in the South Java Current. The semi-annual signal also is seen in the salinity time series of Sumba Strait and Ombai Strait, evidence that the eastward flow of freshwater in the South Java Current is advected into the Savu Sea and beyond into the internal seas. The two regional monsoon phases, and the two periods between the transitioning of the wind direction, even with their inherent year-to-year variability in onset and strength (Webster et al., 1998), still explain most of the upper ocean property variability in the outflow passages.

Finally, we draw attention to the fact that the observations presented in this paper were all recorded at only 5–10 m depth, and were single-point measurements very close to land at either side of the major passages that make up the exit channels. It is somewhat remarkable then that we are able to observe and explain so much of the rich spatial and temporal variability evident in the temperature and salinity series as it relates to known remote and local forcing. Given the location and depth of the observations, however, they are of limited use in calculating definitive estimates of heat and freshwater fluxes through the passages. Obviously a coherent time series of simultaneous observations of temperature, salinity and velocity measurements that adequately resolve the cross-passage and the vertical structure of the flow and property characteristics through the exit passages, should be of high priority to accurately determine the ITF transport of heat and freshwater flux into the Indian Ocean.

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