Deep-Sea Research I 56 (2009) 1942–1954

Contents lists available at ScienceDirect

Deep-Sea Research I

journal homepage: www.elsevier.com/locate/dsri

Characteristics and variability of the Indonesian throughflow water at the outflow straits

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ARTICLE INFO

Article history:
Received 8 September 2008
Received in revised form
10 June 2009
Accepted 17 June 2009
Available online 24 June 2009

Keywords:
Indonesian throughflow water
Seasonal cycles
Freshening thermocline
Java Sea

ABSTRACT

Property structure and variability of the Indonesian Throughflow Water in the major outflow straits (Lombok, Ombai and Timor) are revised from newly available data sets and output from a numerical model. Emphasis is put on the upper layers of the Indonesian Throughflow that impacts the heat and freshwater fluxes of the South Equatorial Current in the Indian Ocean. During the April–June monsoon transition the salinity maximum signature of the North Pacific thermocline water is strongly attenuated. This freshening of the thermocline layer is more intense in Ombai and is related to the supply of fresh near-surface Java Sea water that is drawn eastward by surface monsoon currents and subject to strong diapycnal mixing. The freshwater exits to the Indian Ocean first through Lombok Strait and later through Ombai and Timor, with an advective phase lag of between one and five months. Because of these phase lags, the fresher surface and thermocline water is found in the southeast Indian Ocean from the beginning of the monsoon transition period in April through until the end of the southeast monsoon in September, a much longer time period than previously estimated.

1. Introduction

The Indonesian Throughflow (ITF), from its Pacific Ocean entrances to its exits into the Indian Ocean, follows different pathways within the Indonesian archipelago, along which it undergoes modification through air-sea interaction and mixing of water masses (Gordon and Fine, 1996). As a result, as the ITF exits into the Indian Ocean through the major outflow straits of Lombok Strait, Ombai Strait and the Timor Passage (Fig. 1) which all exhibit different hydrographic characteristics.

During the International *Nusantara* Stratification and Transport (INSTANT) program 11 moorings were deployed in the major straits from December 2003 to December 2006 (Gordon et al., 2008; Van Aken et al., 2008; Sprintall et al., 2009), and three intensive hydrographic surveys were conducted during the deployment and recovery cruise. The analysis of this new CTD data, together with the historical CTD and Argo profiling data, complemented by the output of a numerical model, leads to a more accurate description of the hydrographic characteristics of the ITF water masses and their variability. In particular, this study reveals the importance of the input of the Java Sea water that freshens not only the surface layer of the ITF, but also the lower thermocline.

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doi:10.1016/j.dsr.2009.06.004

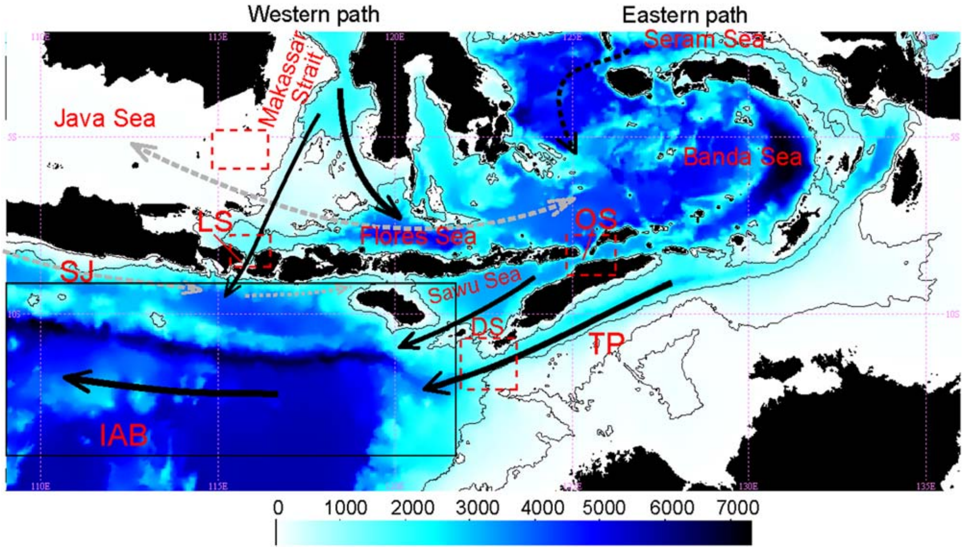

Fig. 1. Schematic circulation of the Indonesian Throughflow near the outflow straits. Part of the Makassar throughflow passes directly to Lombok Strait (LS) and the remnant continues eastward to Flores Sea, then Banda Sea, before outflowing into both Ombai Strait (OS) and Timor Passage (TP). South Pacific lower thermocline water enters into the western Banda Sea via the Seram Sea. Near-surface circulation north and south of Java is indicated by gray dashed arrow. During the northern winter (December–February), the eastward monsoonal coastal current north of Java transports near-surface fresh and warmer water. Red dashed lines indicate sample boxes used to average CTD data in Fig. 6, and the black box in the Indo-Australian Basin (IAB) is used for averaging Argo *T*–*S* profiling data. Bathymetry contours are for 100 and 1000 m depth.

The Indonesian Throughflow Water (ITW) is composed of two water mass components, one of North Pacific origin and the other of South Pacific origin (Wyrtki, 1961; Gordon and Fine, 1996; Ilahude and Gordon, 1996). The North Pacific water is drawn by the Mindanao Current and follows the western path from its entrance in the north-eastern Sulawesi Sea to the Makassar Strait then to the Flores Sea (Fig. 1). From here, about 20% of the throughflow exits directly to the Indian Ocean via Lombok Strait (Murray and Arief, 1988) and the bulk continues eastward to the Banda Sea, before outflowing to the Indian Ocean through Ombai Strait and Timor Passage. The North Pacific water is characterized by a salinity maximum in the thermocline layer (North Pacific Subtropical Water, NPSW), and a salinity minimum in the lower thermocline layer (North Pacific Intermediate Water, NPIW). The South Pacific water is a minor component in the throughflow water (Gordon and Fine, 1996). This water consists of South Pacific Subtropical Lower Thermocline Water (SPSLTW) that appears at lower thermocline depths along the eastern path via the Halmahera Sea and the Maluku Sea to the Seram Sea, and then to the Banda Sea (Wyrtki, 1961; Ilahude and Gordon, 1996).

Surface salinity exhibits strong annual variation in the Indonesian seas associated with a huge supply of freshwater from the Java Sea during the rainy northwest monsoon from December to March (Wyrtki, 1961). Conductivity–temperature–depth (CTD) surveys were taken during the *Arus Lintas Indonesia* (ARLINDO) experiment during both the peak rainy and dry monsoon periods in 1993 and 1994 (Gordon and Fine, 1996; Ilahude and Gordon, 1996). These data confirmed Wyrtki's (1961) results within the internal Indonesian seas, but did not extensively sample in the outflow straits. Less salty water occupied the surface to upper thermocline in southern Makassar Strait during the peak northwest monsoon period during ARLINDO. Near the outflow straits, near-surface salinity remained relatively high during both monsoon phases (Gordon and Fine, 1996). Murray et al. (1991) found a near-surface fresh layer in Lombok strait in June 1988, spreading from northern Lombok strait into the Indian Ocean. Sprintall et al. (2003) showed a distinct freshening of near-surface salinity during the April–June monsoon transition season (hereafter referred to as transition-1) in Lombok Strait. Similarly during the Java-Australia Dynamics Experiment (JADE) survey in April–May 1993, a fresh near-surface layer was observed in Ombai Strait (Molcard et al., 2001). We will show that this low salinity surface water is carried by a monsoon current that flows eastward from the Java Sea to the Banda Sea. Along this pathway, the ITW profile is subject to strong tidal mixing that modifies the thermocline layer of the ITF as it exits into the Indian Ocean. These property characteristics and their variability give clues to the heat and freshwater budgets of the internal Indonesian Seas and also affect the Indian Ocean downstream.

2. Observational and model data sets

CTD measurements in the outflow straits (Lombok Strait, Ombai Strait and Timor Passage) were collected during the deployment and servicing of INSTANT mooring arrays in August 2003, December 2003/January 2004, and June 2005 (Fig. 2). In Lombok Strait, the RV *Baruna Jaya VIII* (BJ8) obtained 24 casts in January 2004 and June 2005. Fifteen additional CTD-oxygen casts were obtained from the RV *Umitaka-Maru* in December 2003 from central

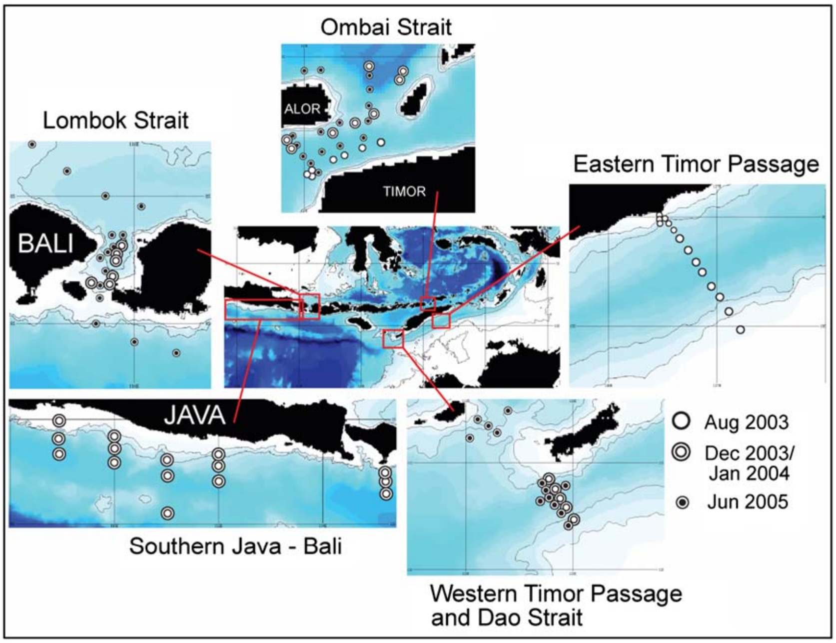

Fig. 2. Map of the CTD stations in the outflow straits during deployment (2003) and redeployment (2005) of INSTANT mooring arrays. Additional CTD stations south of Java-Bali were obtained during the Deepsea Trawling Experiment in December 2003.

South Java coast to south of Lombok Strait. In Ombai Strait, CTD measurements were collected from the RV *Southern Surveyor* in August 2003 and the BJ8 in January 2004 and June 2005 to give a total of 32 casts. In Timor Passage, two CTD sections were completed by the BJ8 during all three INSTANT cruises in the western passage, near the Timor sill, and one section was done by the *Southern Surveyor* in the eastern passage in August 2003, giving a total of 31 CTD casts (Fig. 2). Five CTD stations were also made in Dao Strait, just north of Timor sill in June 2005. In addition, we used 12 CTD archive data collected from the BJ8 during the southeast monsoon (July–September) in Sulawesi Sea, Makassar Strait, Halmahera Sea, southern Maluku Sea, northwestern Banda Sea, and during the transition-1 in the central Flores Sea.

CTD profiles taken from the BJ8 were not complemented by bottle measurements for calibration purposes. Thus, the performance of the BJ8 CTD sensor was assessed by comparing the mean and standard deviation of salinity and potential temperature from all the different cruises at depths of 1300–1320 m in western Timor Passage and depths of 3100–3200 m in Ombai Strait. These layers contain a diluted ITW of Banda Sea origin with relatively homogeneous salinity (Fieux et al., 1994, 1996; Molcard et al., 1996, 2001). In Timor Passage the mean salinity obtained from the BJ8 CTD is within 0.01 of the calibrated values of the other cruise salinity data (Table 1). In Ombai Strait, the deep salinity of BJ8 CTD measurements is within 0.0002 of the well-calibrated *Southern Surveyor* values (CSIRO Division of Marine Research, 2003) (Table 1). Mean temperatures also are within 0.01 °C of the other cruise temperatures (Table 1). These differences are much smaller than the large signals we describe below.

Monthly mean salinity is derived from Argo profile *T*–*S* data downstream of the outflow straits in the Indo-Australian Basin (IAB) to illustrate the seasonality of the upper 200 m of the water column. In particular, we analyzed time series of monthly salinity anomaly in the eastern IAB box 9–14°S; 109–122°E (Fig. 1). Salinity anomaly is calculated as the departure from the mean gridded (1° latitude by 1° longitude) Argo data, spanning from 2004 to 2007, which covers the INSTANT measurement period.

Model output from a 1/4° horizontal resolution Ocean General Circulation Model (OGCM) simulation with seasonal climatology forcing was used for dynamical interpretation of the observed large-scale salinity changes. The model formulation and tuning are described by Koch-Larrouy et al. (2007) (hereafter referred to as KL07). KL07's model differs from conventional formulations in that tidal vertical mixing is explicitly taken into account using an energy constrained parameterization. This means that the vertical diffusivity resulting from internal tide breaking (k_{tides}) is expressed by a function of the energy transfer from barotrophic tides to baroclinic tides which is a function of space and stratification (KL07):

$$ktides = \frac{q\Gamma E(x,y)F(z)}{\rho N^2} \tag{1}$$

where $\Gamma = 0.2$ is the mixing efficiency, N the Brünt–Vaisala frequency, ρ the density, q the tidal dissipation efficiency, $E(x,y)$ the energy transfer per unit of area from barotropic tides to baroclinic tides and $F(z)$ its vertical structure. Model bathymetry is carefully checked by adjusting the depth and the width of each passage in the model domain to allow the major flow pathways of the ITF. The resulting simulation has annual mean transports, paths and water masses characteristics in good agreement with observations

Table 1
Mean and standard deviation of salinity and potential temperature in Timor Passage and Ombai Strait, obtained from RV *Marion Dufresne* (MD) of JADE89 & JADE92, RV *Baruna Jaya 1* (BJ1) of JADE95, RV *Baruna Jaya 8* (BJ8) of INSTANT 2003–2005, and RV *Southern Surveyor* (SS) of INSTANT 2003.

	Timor passage						Ombai strait	
	MD-89	MD-92	BJ1-95	BJ8-03	SS-03	BJ8-05	SS-03	BJ8-05
Depth (m):	1300–1320						3100–3200	
Number of data	20	50	16	18	22	40	51	85
Mean salinity	34.6221	34.6105	34.6081	34.6209	34.6288	34.6166	34.6153	34.6151
Stdev.	0.0012	0.0018	0.0006	0.0015	0.0014	0.0004	0.0001	0.0001
Mean θ (°C)	3.872	3.981	4.049	3.974	3.506	3.94	3.150	3.154
Stdev.	0.02	0.037	0.007	0.029	0.023	0.036	0.001	0.001

(KL07). In particular, the homogeneous salinity profile in Timor Passage is well reproduced along with other observed water mass changes.

3. Results from CTD observations

3.1. Characteristics of the ITW along the throughflow paths

Pacific water enters the interior Indonesian seas from different entrances and follows different paths before exiting to the Indian Ocean via the outflow straits. Along the western path the temperature–salinity relationship (flow is from dark-red to green locations in Fig. 3) clearly shows the reduction of the salinity extremes of the NPSW, centered near $\sigma_\theta = 24.5$, and the NPIW, centered near $\sigma_\theta = 26.5$. The observed salinity maximum of NPSW is reduced from 34.90 near the entrance to 34.53 at the exit channels—a salinity change of >0.4. The NPIW minimum is 34.35 at the entrance and is modified to 34.47 on exit. Previous observation and model studies indicate that strong tidal mixing in the interior seas erodes the salinity extremes of the Pacific water (e.g., Ffield and Gordon, 1992; Hautala et al., 1996; Hatayama, 2004; KL07).

South Pacific water penetrates the interior seas through an eastern pathway (dark-blue to violet in Fig. 3), and is particularly evident at intermediate levels between $\sigma_\theta = 26$ and 27. However, high-salinity lower thermocline water of SPSLTW may be very strongly mixed by tides along this path with peak salinities changing from 34.60 to 34.25. In eastern Timor passage salinity is nearly homogeneous in the thermocline and intermediate waters derived from the Banda Sea.

Property structure of ITW north of 5°S (Fig. 3) sampled during the southeast monsoon (July–August) is in good agreement with that found previously (Gordon and Fine, 1996; Ilahude and Gordon, 1996). However, during the transition-1 cruise, the ITW characteristics near Lombok Strait, in central Flores Sea, and near Ombai Strait exhibit much fresher near-surface and thermocline water, compared to those observed during the rainy northwest monsoon (Fig. 3). The near-surface fresh layer is confined to southern Makassar Strait during the rainy season (Ilahude and Gordon, 1996).

3.2. Contrasts between the outflow straits

The *T–S* relation of the observed ITW at the various outflow straits (Lombok, Ombai, Dao, and Timor) with

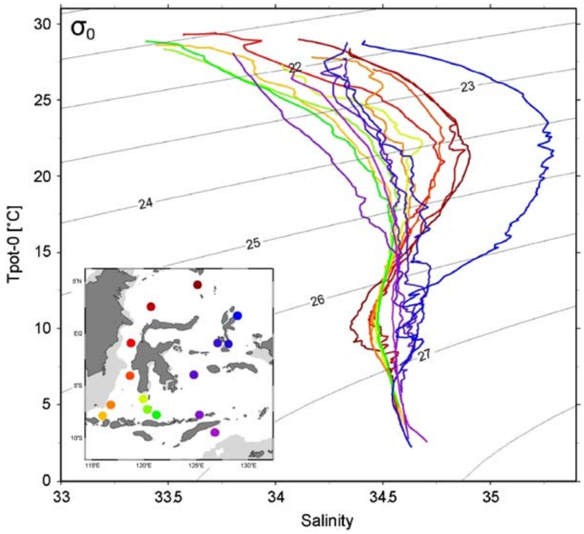

Fig. 3. *T–S* relationship along the primary throughflow paths: the western path (dark red to green) and eastern path (dark blue to violet) from the INSTANT CTD surveys (inset). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

respect to longitude is shown in Fig. 4a. For comparison results from KL07's model are also presented (Fig. 4b). The warm near-surface layer from 20 to 22 σ_θ consists of Java Sea water, water from south of Java and near-surface more saline (~34.40) and warmer (29.0 °C) surface waters found at Timor Passage. Fresher surface water is also observed at Ombai between 20 and 22 σ_θ. Some surface salinity changes are likely due to monsoonal freshwater forcing. All straits show variations during the different monsoon periods, although Ombai Strait shows the strongest variability between cruises.

Along the 22–25 σ_θ surfaces (Fig. 4a), large salinity contrasts between the straits appear: a relatively fresh thermocline at Ombai and Dao Straits; homogeneous (across temperatures) saline water at Timor; an evident salinity maximum of NPSW near $\sigma_\theta = 24.5$ at Lombok; and high saline North Indian Subtropical Water south of Java and Bali. At intermediate depths (Fig. 4a), NPIW with a salinity minimum at $\sigma_\theta = 26.5$ around Lombok Strait contrasts with the relatively homogeneous and saline water of Timor Passage. At Ombai, relatively saline SPSLTW is found at $\sigma_\theta = 26.5$ and North Indian

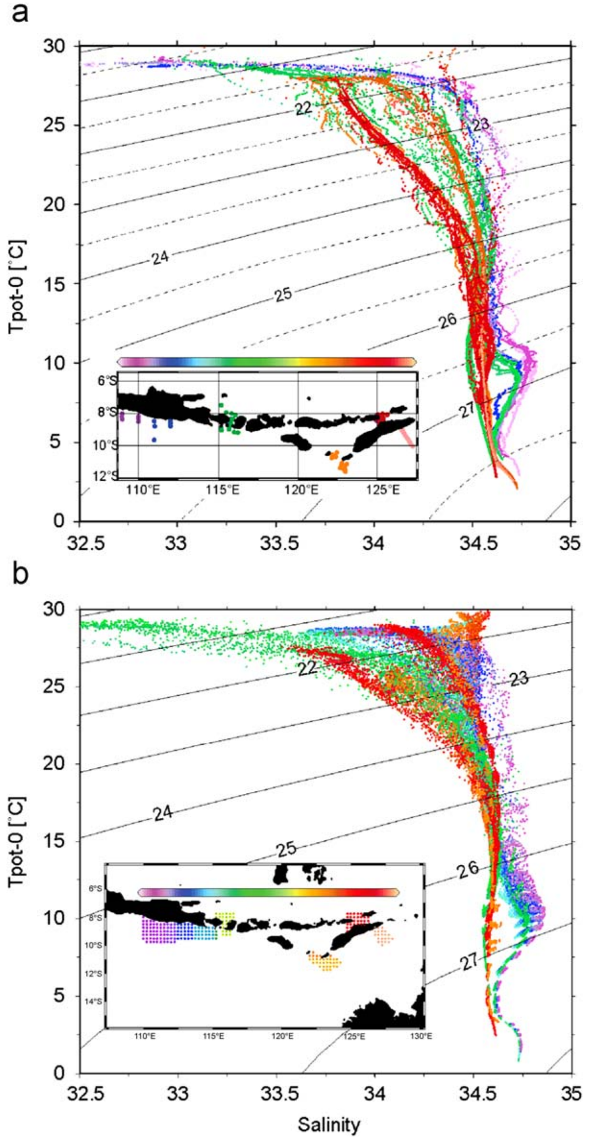

Fig. 4. *T–S* relationship in the outflow straits and southern Java-Bali waters from (a) INSTANT surveys 2003–2005, and (b) the KL07 model result. The color key indicates the longitude of the CTD stations shown in the insets. Violet and blue colors (109–112.5°E) represent southern Java-Bali; green (115–117.5°E) is Lombok Strait; orange (120–122.5°E) is Dao Strait and western Timor Passage; red-light red (125–127.5°E) is Ombai Strait and eastern Timor Passage. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Intermediate Water (NIIW) at $\sigma_\theta = 26.8$ lies off southern Java-Bali with the core layer at the western section being much saltier than that in the eastern section. Below $\sigma_\theta = 27.5$, saline and cold upper Indian Ocean Deep Water (IDW) is dominant south of Java and in Timor Passage.

The contrasts between the water masses in the outflow straits are related to the length of the pathway from the Pacific inflow and the different residence times within the internal Indonesian seas. Lombok Strait, with the most direct connection with Makassar Strait, features much stronger salinity extremes of NPSW and NPIW. In contrast, Timor Passage, with the longest connection to Makassar Strait, features relatively homogeneous and saline water at thermocline and intermediate depth (Fig. 4). The Timor throughflow is drawn from the Banda Sea basin, where local fresh surface water and Pacific water mix over long residence times, and thus Timor carries the most modified waters of all the outflow straits. Below $\sigma_\theta = 27.6$ (depth >1400 m to the bottom) more saline ($S > 34.60$) and colder ($T < 4$ °C) upper IDW is observed, which fills the Timor Trough as shown by the similar *T–S* values between the eastern and western Passage (Fig. 4).

Most ITW features described above confirm previous observations (Gordon et al., 1994; Ilahude and Gordon, 1996; Fieux et al., 1994, 1996). However, our new data (Fig. 4) clearly show the formation of a very fresh layer not only in the near-surface, but extending to lower thermocline depths where it acts to attenuate the salty NPSW thermocline water. This is most obvious in Ombai Strait (Fig. 4), where salinity at the near-surface falls from 34.3 to 33.8, and at thermocline depths from 34.65 to 34.25.

3.3. Temporal variability

On monsoonal time scales, the largest change in property structure of ITW in the outflow straits take place during the transition-1. The changes are likely due to phase lags between the inflow (e.g. Makassar Strait, Java Sea) and the outflow straits (Fig. 5). During June 2005, at the transition-1, very freshwater ($S < 33.75$) is evident in Lombok Strait extending down into the upper thermocline, near $\sigma_\theta = 23.5$ (Fig. 5a). A remnant salinity maximum of NPSW is evident at $\sigma_\theta = 24.5$, and the salinity minimum of NPIW at $\sigma_\theta = 26.5$ are detectable during both the June 2005 and December 2003 cruises. During December 2003, the NPIW south of Lombok Strait is emphasized by the sharp elbow caused by the salinity maximum of the NIIW at $\sigma_\theta = 26.8$.

The strong freshening of the near-surface to lower thermocline layers in June 2005 is also observed in Ombai Strait (Fig. 5b). By comparison, the cruise data during both the dry southeast monsoon (August 2003) and the northwest monsoon (December 2003–January 2004) show a much saltier surface and thermocline, which is consistent with Gordon et al. (1994) and Ilahude and Gordon (1996). Near-surface freshening in the outflow straits was previously reported by Sprintall et al. (2003), but Fig. 5 clearly shows the freshening layer is not only confined to the near-surface layer, but extends down to the upper thermocline in Lombok Strait, and to the lower thermocline in Ombai and Dao Straits.

It is likely that this freshening occurs annually in the ITW with the near-surface and thermocline in the outflow straits lagging the monsoon-forced freshening in the Java Sea and southern Makassar Strait by several months. Precipitation data over the Java Sea show the contrast between the dry southeast monsoon and the rainy northwest monsoon, whereas the June 2005 survey occurred during the transition-1 from the rainy to the

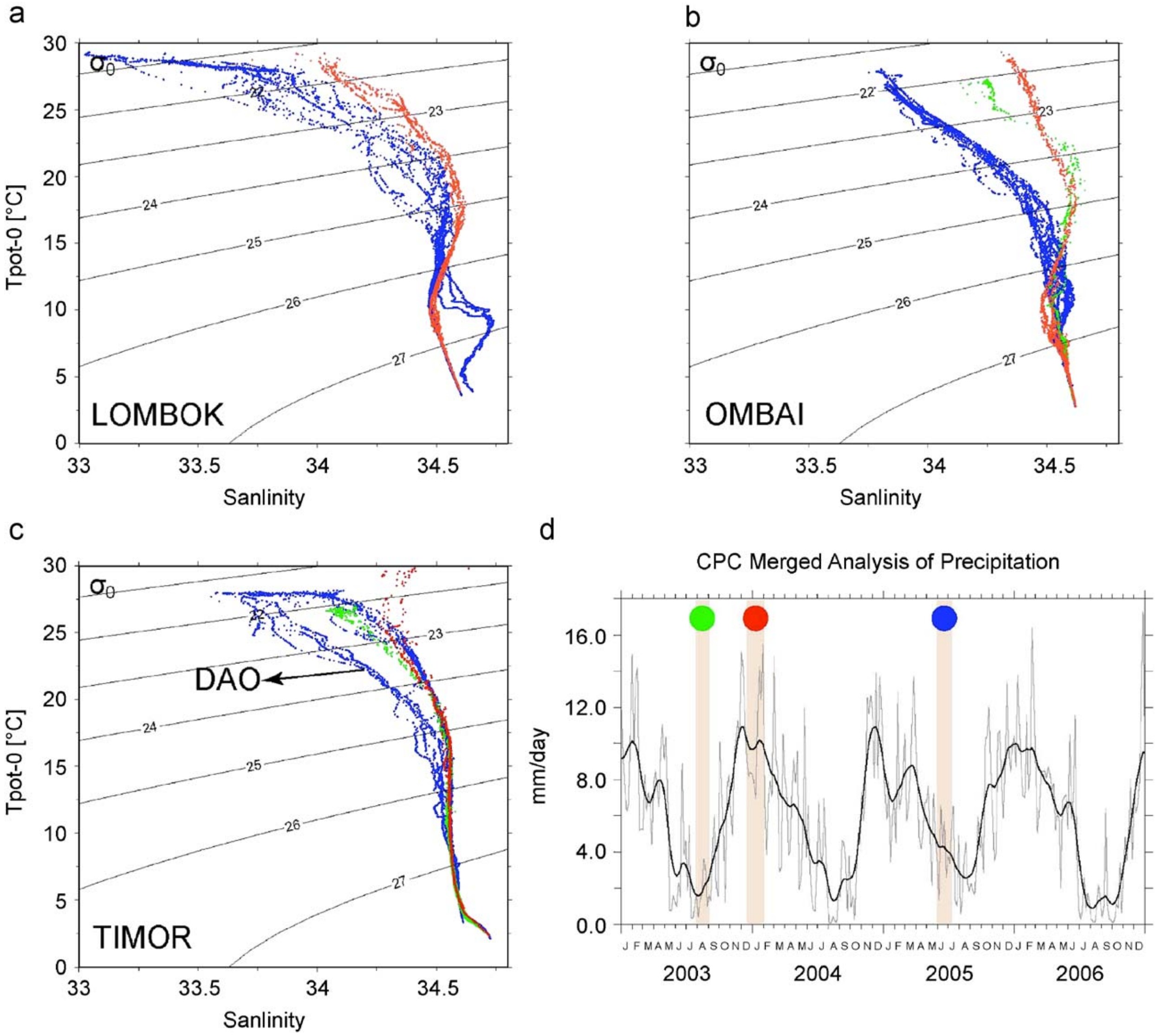

Fig. 5. *T–S* relationship for CTD data collected during August 2003 (green), December 2003–January 2004 (red) and June 2005 (blue) cruises in (a) Lombok Strait, (b) Ombai Strait, and (c) Timor Passage, including Dao Strait; and (d) Time series of pentad precipitation data from the CPC Merged Analysis of Precipitation (CMAP) over the Java Sea. Thick line is the 20-day low-pass filter. Shading bars denote the time of the INSTANT surveys. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

dry season (Fig. 5d). Since the freshening reaches thermocline depths, this suggests that strong vertical mixing must take place between the near-surface freshwater from the Java Sea and the inflowing NPSW/NPIW via Makassar Strait as suggested by Gordon et al. (2003). The model will be used to investigate this idea in Section 4.

Another striking feature is the presence of high-salinity water at intermediate depths in Ombai Strait (26.5 σ_θ) in June 2005 (Fig. 5b). During the peak monsoon periods of August 2003 and January 2004 this depth range was dominated by the salinity minimum of NPIW (Fig. 5b). This high-salinity core may originate from lower thermocline water of South Pacific origin, which enters via the Halmahera to Seram Seas, and then flows to the Banda Sea to reach Ombai Strait (as shown in Section 3.1). In June 2005, SPSLTW occupies most of southern Ombai Strait while less salty intermediate water is confined to northern Ombai Strait along southern Alor Island. This less salty intermediate water suggests an intrusion of upper NIIW via weak eastward flow in the South Java Undercurrent as observed by the INSTANT mooring located at North Ombai (Sprintall et al., 2009).

In Timor Passage, salinity changes are largely confined to the near-surface layer. Higher salinity occurs in August 2003 and January 2004 than during the transition-1 period of June 2005 (Fig. 5c). During June 2005 a fresh layer is observed above $\sigma_\theta = 22$. However, in Dao Strait, just north of the western Timor Passage, the surface and thermocline are distinctly fresher in June 2005 (Fig. 5c), similar to that observed in Ombai Strait during June 2005

(Fig. 5b). This confirms that part of the Ombai ITW is exiting into the Indian Ocean via Dao Strait between Sumba and Roti, while the rest may outflow through Sumba Strait between Sumbawa and Sawu Islands (Fieux et al., 1996). The relatively saline ($S>34.30$) and warm near-surface waters in the Timor Passage are probably derived from the northern coast of Australia, as reported by Cresswell et al. (1993) and Fieux et al. (1996). Below the surface layer, only small salinity changes are evident at thermocline and intermediate levels between the eastern and western Timor sections.

4. Variability of ITW: model output and Argo data

4.1. Near-surface freshwater

Our snapshot cruise data are not sufficient to describe the complete spatial and temporal variability of the surface to lower thermocline fresh layer observed in the outflow straits. Here, we use the OGCM results from KL07 to assess the seasonal changes of ITW and understand the origin of the freshwater flux, as well as the monsoonal phase lags between the inflow and outflow straits.

We examine 5-day averages of temperature and salinity at the 46 depth levels from the model, and form a climatology based on 5 years of model output forced by a mean seasonal climatology of surface fluxes (Molines et al., 2007; KL07). The *T–S* relationship from the model at the outflow straits and along the southern coasts of Java and Bali agree well with the INSTANT CTD data (Fig. 4b). Near-surface and thermocline fresh layers are represented well in the model at Lombok and Ombai. In particular, the large observed salinity changes from the surface through the thermocline in Ombai Strait (Fig. 4b) between January and June is replicated well by the model. At intermediate and deep levels, the model *T–S* relationships are also quite realistic.

The mean annual cycle from monthly averaged surface salinity in the model (Fig. 6), does a remarkable job of reproducing the available observed salinity data in the regional sampling boxes (Fig. 1). In most cases the modeled

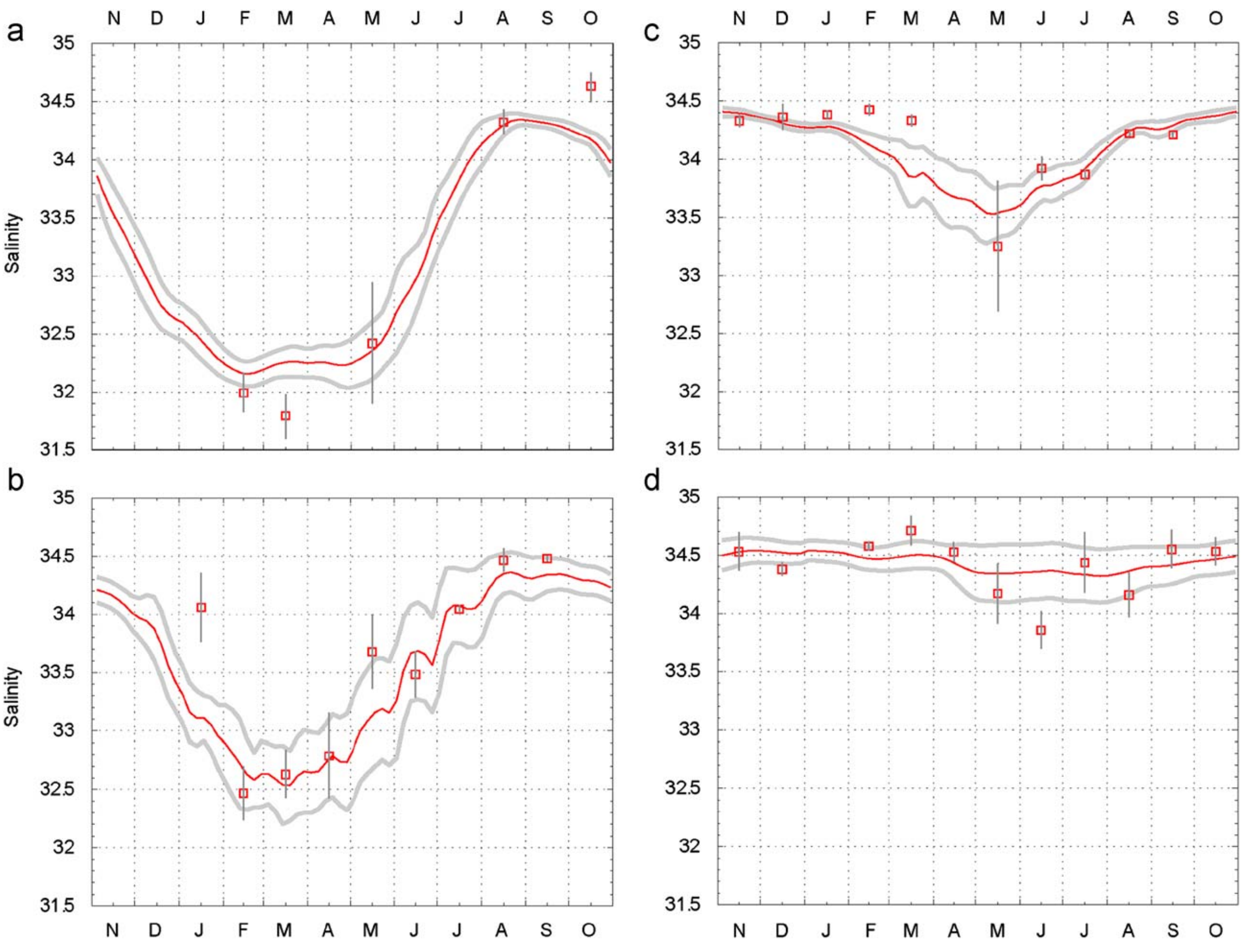

Fig. 6. The annual cycle of mean monthly near-surface (3–52 m depth averaged) salinity from the model (red line) and historical salinity data including the INSTANT CTD data (red squares) in the (a) eastern Java Sea, (b) Lombok Strait, (c) Ombai Strait, and (d) the western Timor Passage (see Fig. 1 for sample locations). Standard deviations for the mean model and observed salinity are indicated by the gray lines. The cycle starts in November, at the end of the dry season. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and observed mean monthly salinities (when available) agree within their respective error bars and show a similar amplitude and phase for the seasonal cycle (Fig. 6).

Strong annual variation of near-surface salinity is evident in eastern Java Sea and Lombok Strait with a minimum ($\sim$32.2 and $\sim$32.7, respectively) between February and April and a maximum ($>$34.3) in August–September (Fig. 6a and b). The salinity decrease of 1.7 from November to March is due to heavy precipitation during the northwest monsoon (see Fig. 5d). A salinity maximum ($\sim$34.3) during the southeast monsoon, may correspond to much stronger inflow of relatively high-salinity water from Makassar Strait and the eastern internal Indonesian seas. Gordon et al. (1999) found the surface Makassar throughflow is stronger during the southeast monsoon.

Annual salinity variations are much smaller ($\sim$0.9) in Ombai Strait and Timor Passage (Fig. 6c and d) compared to Lombok Strait and the Java Sea. This suggests that either strong vertical mixing in the Flores Sea causes an increase of surface salinity or that much of the freshest Java Sea water is diverted through Lombok Strait. The size of the annual surface salinity variation appears to erode with distance from the Java Sea (Fig. 6d).

Evolution of monthly mean near-surface salinity from November to May in the model clearly shows an eastward propagation of fresh surface waters from the eastern Java Sea to the Flores Sea and the Banda Sea, before reaching the outflow straits (Fig. 7). During the southeast monsoon, the Makassar throughflow supplies saltier surface water to the Java and Flores Seas, displacing the northwest monsoon fresh layer. Salty water from the western Seram Sea and eastern Banda Sea replaces the fresh surface water also during the southeast monsoon.

During the peak rainy season in January, freshwater is confined to only the eastern Java Sea, southern Makassar Strait, and central Flores Sea (Fig. 7). At the outflow straits, salty water is dominant at this time. Lombok Strait is the first outflow strait that experiences the subsequent freshwater pulse from the Java Sea. The maximum extent of freshwater incursion into the Banda Sea takes place in April. In May, the fresh layer moves eastward covering central/eastern Flores Sea, the western Banda Sea, and subsequently enters Ombai Strait, southern Savu Sea, Dao Strait, and along Timor Passage. During this period, more saline water from the Makassar throughflow begins to block the eastward freshwater flow from the Java Sea. During the peak southeast monsoon in September, the fresh layer drains from the outflow straits into the Indian Ocean, and salinity of $\sim$34.2 is visible near Ombai, southern Savu Sea, and western Timor Passage (Fig. 7). At this time, most of the upper Makassar throughflow passes directly to the Lombok Strait, and the remainder continues eastward into Flores Sea. The maximum extent of salty water in the Java and western Banda Seas takes place in September. The near-surface salinity maps in Fig. 7, suggest it takes about 1–5 months for the freshwater formed in the Java Sea during the northwest monsoon to reach the outflow straits: about one month to Lombok, 3 months to Ombai and 5 months to Timor. The evolution of the surface freshwater from the Java Sea and the southern Makassar ITW, documented in Fig. 7, is consistent with the results of Gordon et al. (2003). During the northwest monsoon, the Ekman drift pushes the near-surface freshwater from the Java Sea into the southern Makassar Strait. In contrast, the southeast monsoon facilitates southward flow from the Makassar Strait.

Strong diapycnal mixing in the interior seas, mainly over Dewakang sill in southern Makassar Strait, central Flores Sea, and in the exit straits (KL07), leads to a vertical penetration of the near-surface freshwater from the Java Sea into the deeper thermocline layers. The freshening of the upper thermocline layer is shown by model salinity on the potential density surface 23-σ_θ (Fig. 8) that lies in the upper throughflow component entering the IAB. At this thermocline depth, the freshwater from Lombok Strait appears between February and May, and from Ombai and Timor in May–September. Thus, the freshening of the IAB takes place around February–September (Fig. 8). In July–August, the freshening of the IAB corresponds to a saltier Flores Sea, and conversely, in March–April the freshening in the Flores Sea coincides with a saltier IAB. This suggests, a migration time of freshwater from Flores Sea to the IAB of about 5–6 months.

4.2. Near-surface and thermocline fresh layer in the IAB

To follow the temporal and spatial variation of the near-surface fresh layer of throughflow water into the IAB, we performed an EOF analysis on the monthly average (0–50 m) salinity anomaly from the mapped Argo profile *T–S* data over the INSTANT time period from 2004 to 2007. The two leading EOF modes explain 68% and 20% of the variance respectively, and account for 88% of the total monthly salinity variance. Fig. 9 shows the spatial pattern and associated temporal variation of these modes. The first mode (EOF1) is strong over the entire IAB, but lessens near the western IAB boundary (Fig. 9a). The associated temporal variation illustrates the seasonal fluctuation in salinity, with negative expansion coefficients from May to September and positive coefficients from October to April (Fig. 9a). The second mode (EOF2) displays a dipole pattern between the northern and southern IAB (Fig. 9b). The associated temporal variation also indicates seasonal fluctuations with the EOF2 time series leading EOF1 by 3 months. The third mode with 3% of variance, has a weak spatial pattern in the central and eastern/western IAB with associated higher temporal fluctuation on 3–7 months (not shown).

To examine the cause of the variability shown by EOF1, we average the salinity anomaly in the box (9–14°S; 109–122°E). The time series of the monthly salinity anomaly in this box reveals prominent seasonal fluctuations in the upper 200 m with freshening (negative anomaly) in May–September, and becoming saltier (positive anomaly) in October–April (Fig. 10). These periods represent the transition-1 to the southeast monsoon, and the monsoon transition (transition-2) to the northwest monsoon, respectively. The amplitude of variation (Fig. 10a) is much stronger in the upper 50 m (about 0.45) than that between 60 and 200 m (about 0.15).

The fresh layer observed in the IAB between the transition-1 and the southeast monsoon period (Fig. 10)

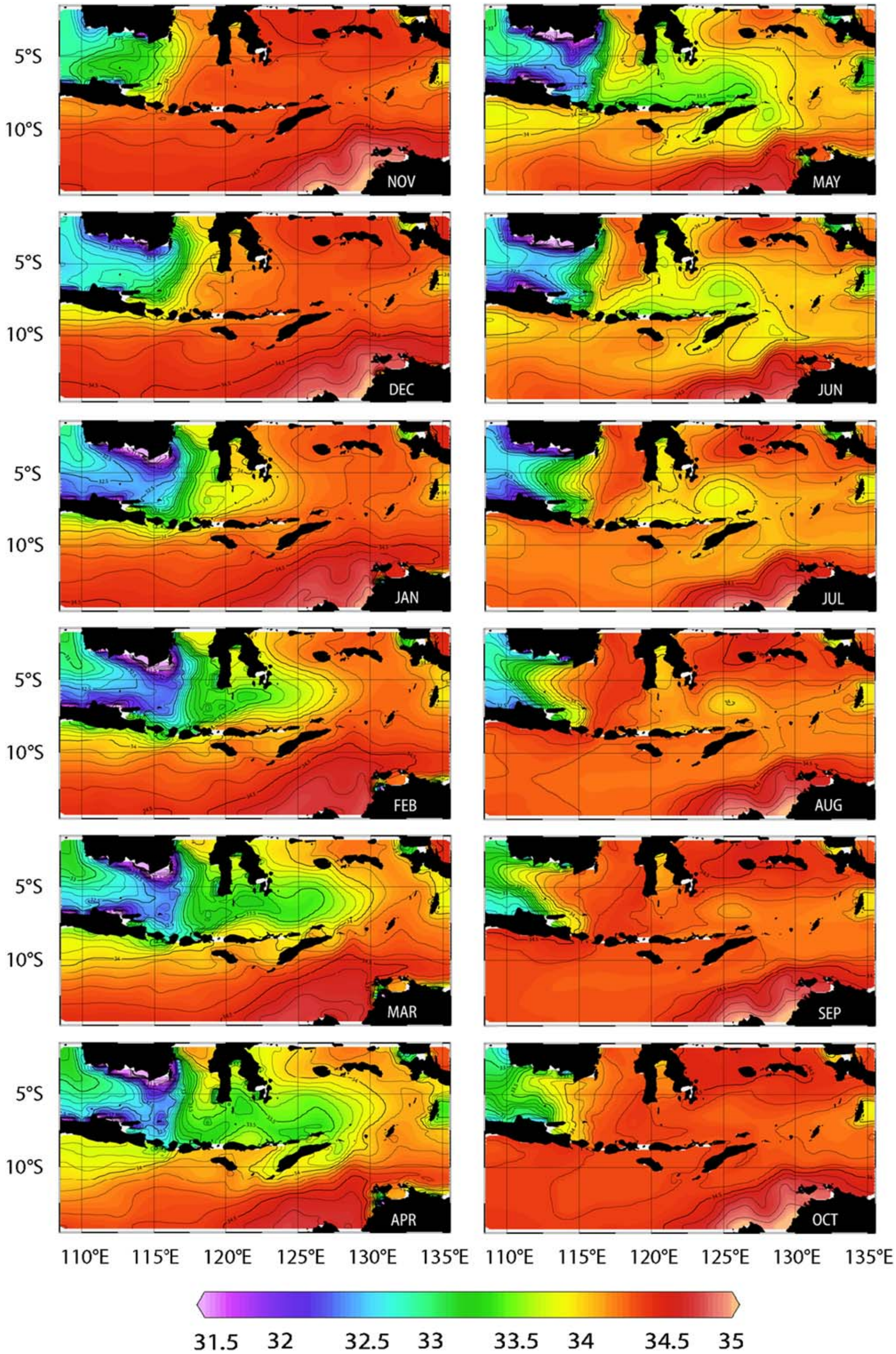

Fig. 7. Near-surface salinity (3–52 m depth averaged) in the Indonesian Seas from the KL07 model, starting in November, the end of the dry season. Months are indicated in the lower right corner.

is supplied by the throughflow from the interior Indonesian seas. During the southeast monsoon the throughflow transport is maximum in the IAB (Meyer et al., 1995; Fieux et al., 1994, 2005), and in the exit straits (Molcard et al., 1996, 2001; Sprintall et al., 2009). The upper component of throughflow water north of 12°S in the IAB between

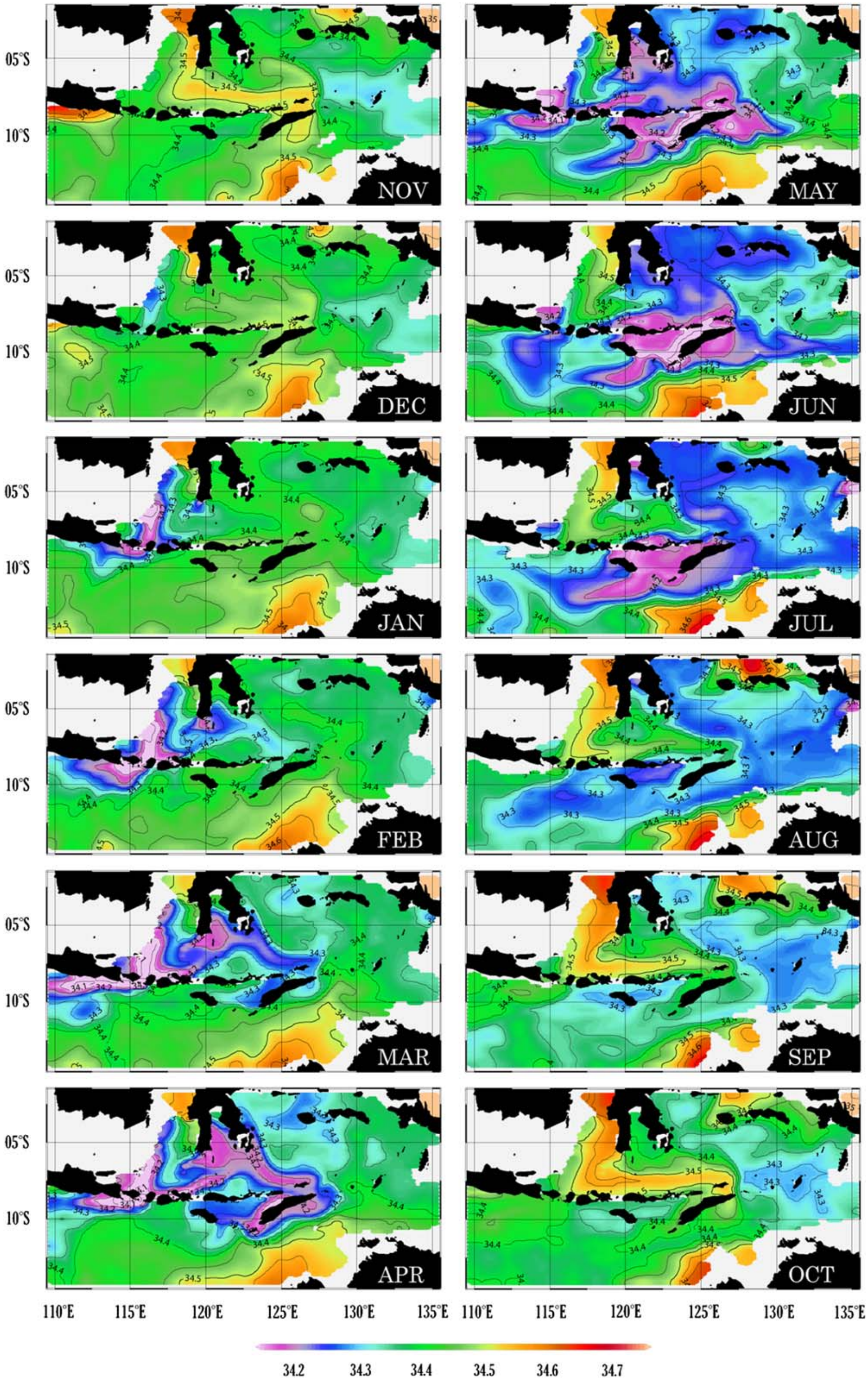

Fig. 8. Monthly salinity from the KL07 model on potential density surface 23.0 σ_θ in the Indonesian seas. Months are indicated in the lower right corner.

Java-Australia has salinity less than 34.5 (Fieux et al., 1994, 2005). Recirculation of the fresh South Java water in the northern IAB may also contribute to the salinity variation in this region (Fieux et al., 1994; Sprintall et al., 1999; Wijffels et al., 2002). For example, the salty surface layer during the northwest monsoon is persistently perturbed

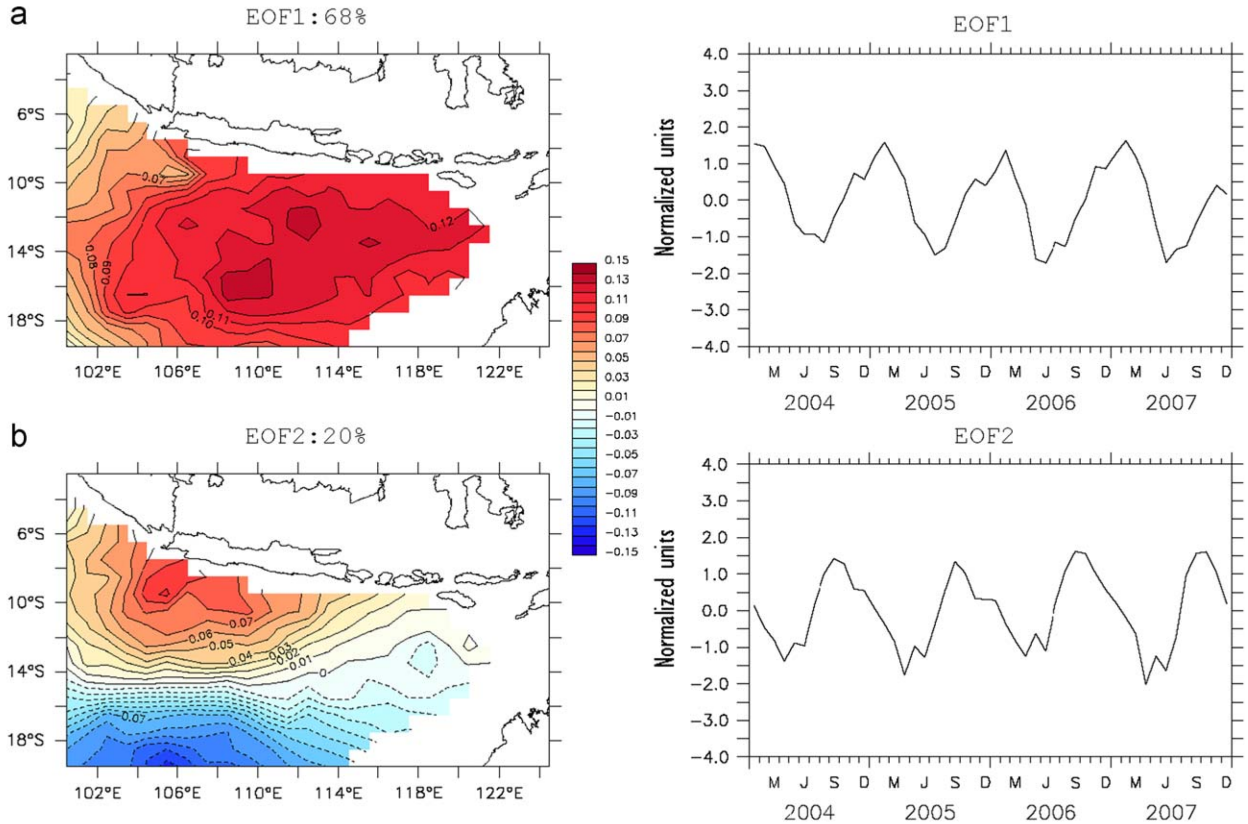

Fig. 9. Spatial pattern and temporal variation of the EOF (a) mode 1 and (b) mode 2 of the salinity anomaly averaged over the upper 50 m in the Indo-Australian Basin (IAB). Contour interval is 0.01. The EOF time series are normalized by the standard deviation.

by weak freshwater in the upper 50 m in December (Fig. 10b), and this is probably related to the circulation of the fresh South Java Water.

As shown in the data and model results (e.g. Figs. 5 and 6), the freshening of the near-surface and thermocline waters in the outflow straits are evident during transition-1 around April–June. This freshwater is derived from the fresh Java Sea water with phase lags of several months through each exit strait. The different timing in the export of freshwater through each outflow strait may result in a longer freshening episode within the IAB reservoir (Fig. 10). Freshwater fills the upper 200 m of the IAB from transition-1 (April–June) through the southeast monsoon (July–September), with a minimum around July–August. Saltier Indian Ocean water is found in the IAB during the northwest monsoon, with a peak in February (Fig. 10), due to a relaxation of throughflow transport.

5. Conclusion

We have described the characteristics and variability of ITW at the outflow straits (Lombok, Ombai, Timor) using INSTANT CTD data collected during cruises between 2003 and 2005, complemented with *T–S* output from a numerical model and Argo profiling data to assess the larger spatial and temporal context of the changes found in the straits. This more precise description offers one necessary step to assess the impact of the ITF on the heat and freshwater fluxes as it flows into the Indian Ocean.

Each outflow strait features a distinct variant of ITW. Lombok Strait, with the shortest conduit to the Pacific via Makassar Strait, has a much stronger North Pacific water signature. In contrast, Timor Passage, with the longest conduit to the Pacific via the Flores Sea and Banda Sea features ITW that is strongly modified from the inflow waters. Below ~1400 m depth in the Timor Passage, upper IDW is dominant, which corroborates a deep inflow/outflow, as observed from the INSTANT velocity data in this passage (Sprintall et al., 2009). All these ITW features largely confirm what has been found in previous studies.

Water masses present in both Ombai and Lombok Straits suggest changing sources during the annual cycle. North Pacific water at thermocline and intermediate depths is found during the peak of both the northwest and southeast monsoons in agreement with previous studies. However, during the April–June monsoon transition, there is a large freshening by the Java Sea water, that is not only confined to the near-surface as reported before, but extends to thermocline depths, and therefore acts to attenuate the signature of the North Pacific waters. The freshening deepens throughout the thermocline layer as the ITW progresses along the pathway from the Java Sea. The freshening is maximum in Ombai Strait, where

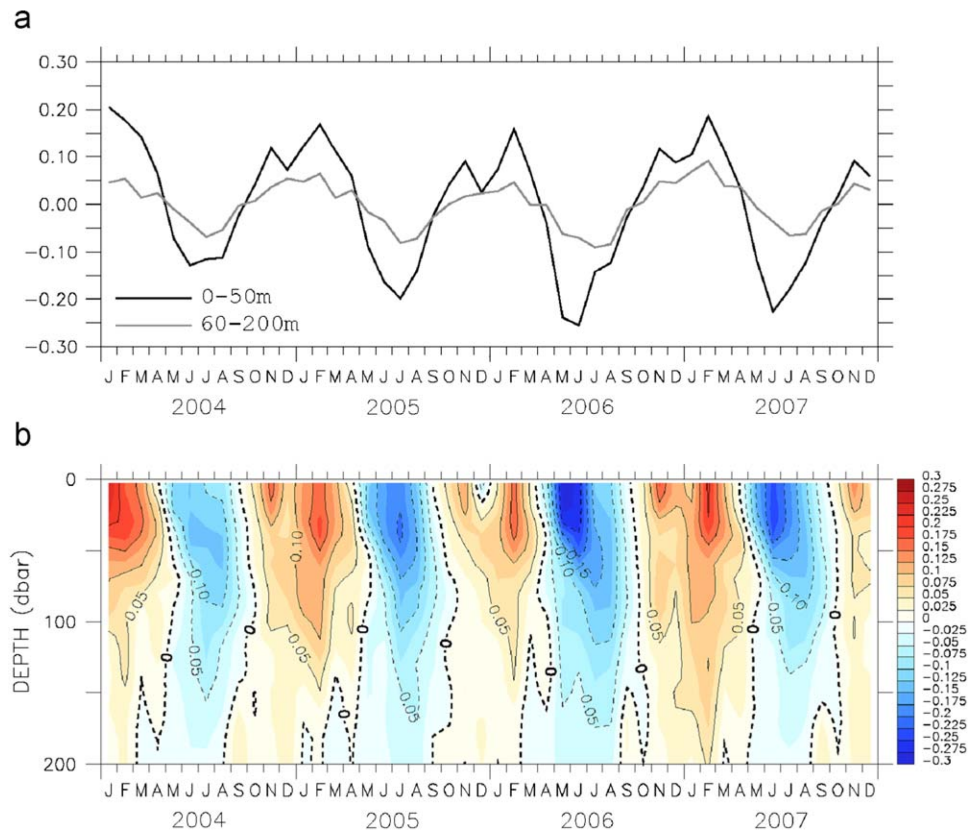

Fig. 10. Time series of the monthly average (a) 0–50 m (black line) and 60–200 m (gray line) EOF1 salinity anomaly, and (b) EOF1 salinity anomaly in the upper 200 m of the IAB (see Fig. 1 for sample box), determined from Argo data between 2004 and 2007.

intermediate water of SPSLW origin also appears, drawn to the strait through the eastern throughflow pathway.

Model results from KL07 suggest that excess precipitation and river run-off in the Java Sea supplies the near-surface very freshwater to the outflow straits, but with an advective phase lag between 1 and 5 months. During the dry southeast monsoon, the surface freshwater is flushed out of the internal seas through the straits to the Indian Ocean, but is partially mixed down into the main thermocline by the strong tidal mixing in the region. In this way the excess precipitation over the internal seas is distributed into the thermocline of the South Indian Ocean. Here, the salinity anomaly in the IAB has a strong seasonal fluctuation of the fresh layer at the surface and thermocline depths from the transition-1 to the southeast monsoon period. The freshening of this layer lasts much longer than previously estimated, and is related to the different phase lags between the IAB and the outflow straits.

Acknowledgements

Strong support and fruitful cooperation for the INSTANT program from Drs. Indroyono Soesilo, head of the Center Research for Marine Affairs and Fisheries (BRKP) Jakarta are highly acknowledged. Stimulating discussions with Dr. A.G. Ilahude onboard the BJ8 are much appreciated. We thank captains and crews of RV *Baruna Jaya VIII* and *I* for their valuable support and keen interest. We are very grateful to Dr. Suharsono and Mr. Hadikusumah of P2O-LIPI, Dr. Y.S. Djajadihardja of BPPT, Dr. Irsan S. Brodjonegoro, Dr. Duto Nugroho of BRKP, and Prof. T. Arimoto of TUMST for using their CTD archives data. ARGO profiler data were obtained from GDAC of Scripps Institution of Oceanography, University of California San Diego. The authors thank the anonymous reviewers, whose comments helped to improve the manuscript. AA has received beneficial French BGF scholarship and partly from the Ministry of National Education of Indonesia. JS contribution is supported by the National Science Foundation Award OCE0725476.

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