Effects of the Indonesian Throughflow on the Pacific and Indian Oceans

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Abstract

Effects of the Indonesian throughflow (ITF) on the circulation and thermal structure of the Pacific and Indian Oceans are studied by comparing solutions of a near-global ocean general circulation model with open and closed Indonesian passages from 1981 to 1997.

The ITF contributes to the maintenance of model circulation system around eastern Australia and southern Indian Ocean. Blockage of ITF weakens the Indian Ocean South Equatorial Current and Agulhas Current and strengthens the East Australian Current. The ITF does not affect the Mindanao Current, but drains waters carried by this current into the Indian Ocean and thus reduces tropical-subtropical exchange in the North Pacific. Meanwhile, it helps maintain a stronger New Guinea Coastal Undercurrent and thus enhances tropical-subtropical exchange in the South Pacific. Water parcels traveling along the western boundary of the South Pacific cross the equator in the presence of the ITF, but are confined to the southern hemisphere without the ITF. The southern “exchange window” in which subducted waters can reach the tropics is wider with than without the ITF. Blockage of the ITF depresses the mean thermocline of the tropical Pacific, increases sea surface temperature (SST) in the central to eastern equatorial Pacific and thus enhances SST difference between the warm pool and cold tongue. It also raises the mean thermocline of the Indian Ocean (especially the southern Indian Ocean) and reduces SST in the southern Indian Ocean.

Blockage of the ITF reduces seasonal-to-interannual thermocline fluctuations in the central to eastern equatorial Pacific because the resulting deeper thermocline attenuates fluctuations in response to local Ekman pumping. The opposite is true in the southern Indian Ocean for interannual time scale. However, seasonal thermocline fluctuation in that area is weakened when the ITF is blocked (despite a shallower thermocline). It indicates that local Ekman pumping is not necessarily the dominant mechanism controlling seasonal thermocline variability there as previously suggested. Radiation of planetary waves from the ITF area and advection by the ITF-dependent South Equatorial Current could also be important. Blockage of the ITF also reduces interannual variability of SST in the eastern equatorial Pacific and enhances those in the tropical southern Indian Ocean and south of Tasmania.

The results indicate that the ITF plays active roles in ENSO and its decadal modulations by affecting tropical-subtropical exchanges, mean thermocline structure, mean SST
difference between the warm pool and cold tongue, and seasonal-to-interannual variabilities of thermocline depth and SST.
1. Introduction

The Indonesian throughflow (ITF) is widely known, on average, to carry warm and fresh Pacific waters through the Indonesian archipelago into the Indian Ocean. It is the only channel in the tropics through which inter-ocean exchange of water masses occurs. Gordon (1986) suggested that the ITF could be important to global ocean thermohaline circulation as it might return the North Atlantic Deep Water that upwelled and warmed in the Pacific back to the Atlantic. Godfrey (1996) discussed several aspects of ITF effects on the Pacific and Indian Ocean circulation and discussed the important impact on surface heat flux. The potential role of the ITF to the global climate system remains to be an important area of investigation.

Measuring the total transport of the ITF are difficult due to the complicated geometry in the region with many passages and because of the large variability of transport through various passages. Godfrey (1996), in his comprehensive review of ITF-related studies, discussed some of the difficulties in estimating the ITF using various methods. The estimates of total and partial ITF transports from various direct and indirect measurements roughly range from somewhat below zero (from the Indian into the Pacific Oceans) to a value close to 20 Sv (1 Sv = 10⁶ m³/s). Based on a linear inversion from global hydrographic sections using conservation principles, Macdonald (1998) obtained an estimated mean ITF transport of 10±10 Sv, which is consistent with the mean and uncertainty of various measurements. Uncertainties in estimating ITF transport cast a major difficulty in understanding physical processes associated with the ITF. Two major issues related to studies of the ITF are mechanisms controlling the mean and variability of the ITF (in terms of its transport and structure) and effects of the ITF on ocean circulation and the coupled ocean-atmosphere system of various time scales. This study focuses on the latter issue.

There have been a number of numerical modeling studies evaluating effects of the ITF on the circulation of the Pacific and Indian Oceans and on the global climate system, mostly by comparing model solutions with open and closed Indonesian passages. These modeling studies are briefly reviewed below.

Based on a global ocean general circulation model (OGCM) that has relatively coarse
resolution forced by climatological mean surface forcings that is constant in time, Hirst and Godfrey (1993) (hereafter HG93) discussed the effects of the ITF on the mean state of the Pacific and Indian Oceans by examining equilibrium model solutions with and without the ITF. The ITF is found to have an overall effect of cooling the Pacific and warming the Indian Ocean. Large changes in sea surface temperature (SST) and thus surface heat flux are found in several regions such as the Agulhas outflow and Leeuwin Current regions in the Indian Ocean and the equatorial region and Tasmanian Sea in the Pacific. The ITF is also found to strengthen the South Equatorial Current (SEC) and Agulhas Current in the Indian Ocean and to weaken the East Australian Current (EAC) in the South Pacific.

Verschell et al. (1995) used a single-layer reduced-gravity model forced by time-dependent wind during 1980-1989 to study the effects of ITF on the mean as well as low- and high-frequency (longer and shorter than 6 months) variability of upper layer thickness (a proxy for thermocline depth) in the Pacific and Indian Ocean. Changes in the southern Indian Ocean are found to be much larger than those in the Pacific Ocean. Murtugudde et al. (1998) used a multi-layer reduced-gravity primitive equation model, integrated over the period of 1980 to 1995, to address the effects of the ITF on seasonal and interannual variabilities of SST and thermocline depth of the tropical Indo-Pacific Oceans. This study also included an atmospheric mixed-layer model aiming to account for some feedback of the atmosphere to SST. SST variability in the central to eastern equatorial Pacific was not correlated with ITF transport in their model, only the difference in SST variability with and without the ITF was. Rodgers et al. (1999), using a primitive equation OGCM for the Indo-Pacific domain driven by seasonal forcings, found that the mixing ratio of thermocline waters in the equatorial Pacific with those from the northern and southern hemispheres was dependent on ITF transport.

The only modeling study that examines the effects of the ITF in a coupled ocean-atmosphere context is that by Schneider (1998), in which changes in SST due to blockage of the ITF, and subsequent changes in heat flux and wind, as well as the feedback into the ocean were discussed. He concluded that the ITF would affect the climate of the entire tropics as well as part of the mid-latitudes. However, model limitations limited the confidence in the sign of the feedback. Moreover, the short-integration time precluded an analysis of effects on interannual variability.
Although some aspects of ITF effects on the Pacific and Indian Oceans have been discussed by the previous studies, many issues need further investigation, especially those related to effects on the equatorial Pacific, tropical-subtropical exchanges, and seasonal-to-interannual variability. The objectives of this study are (1) to revisit the effects of the ITF on the mean circulation and thermal structure of the Pacific and Indian Oceans, (2) to evaluate the ITF effects on seasonal-to-interannual variability, and (3) to examine its impact on tropical-subtropical exchanges and implications to decadal modulations of ENSO. To achieve these objectives, we employed a state-of-the-art OGCM integrated over the period of 1980-1997. Model solutions with open and closed Indonesian passages are compared to highlight effects of the ITF.

This study goes beyond previous related efforts in many aspects. The period of study is longer and includes the most recent El Niño. The meridional and vertical resolutions are overall higher. The higher resolution, along with the advanced mixing schemes and relatively high-frequency forcings, improve the fidelity of the model simulation. Our analysis isolates ITF effects on seasonal and interannual time scales. As will be seen, this helps shed light on the similarity and difference in forcing mechanisms of seasonal and interannual variabilities in the Pacific and Indian Oceans. Furthermore, we address ITF effects on tropical-subtropical exchanges and their implications to decadal modulations of ENSO. The potential impacts of ignoring the ITF in models used for ENSO forecasts and diagnostics are discussed.

In the next section, model configuration and numerical experiments are described. In section 3, the performance of the model (with open Indonesian passages) are evaluated through comparisons with various observations and with other model simulations. The two model solutions, with open and closed passages, are compared in section 4 to highlight effects of the ITF on the mean state (subsection 4.1) and on seasonal and interannual variabilities (subsection 4.2). The findings are summarized in section 5.

Although blockage of the ITF creates an unrealistic oceanic state, it helps understand the influence of the ITF in maintaining the mean and controlling the variability of circulation and thermal structure in the Pacific and Indian Oceans. Describing the role of the presence of the ITF and discussing effects of blocking the ITF are philosophically the same. Moreover, comparison of model solutions with and without the ITF helps identify possible errors in the mean state and variability of regional models that ignore the ITF.
2. Model configuration and experiments

The model used is the parallel version of the primitive-equation MIT OGCM (Marshall et al. 1997a and 1997b). The spatial domain is nearly global (75S-75N). The model has a uniform zonal resolution of 1°. The meridional resolution is 0.3° in the tropics (within 10° of the equator), 1° in the extra-tropics (poleward of 22°S and 22°N), with gradual transition in between. There are 46 vertical levels with a thickness of 10 m in the upper 150 m, gradually increasing to 400 m at depth. The meridional and vertical resolutions in the tropics are chosen to ensure a reasonable representation of tropical currents and related thermal structure.

The model topography is shown in Figure 1 along with an enlargement near the Indonesian Archipelago. It is bin-averaged from the Navy’s ETOPO5 5-minute world bathymetry. The major passages of the ITF are marked in the lower panel: the westernmost Lombok Strait (near 116°E), the Flores Strait (near 120°E), the Savu Strait (near 123°E), and the easternmost Timor Passage. Two small gaps near 106°, 6°S and 143°E, 10°S are very shallow and carry little throughflow. Apart from bin-averaging from the high-resolution bathymetric map, no subjective artificial treatment is applied to the topography in this area.

The model employs two advanced mixing schemes: the so-called K-profile parameterization (KPP) vertical mixing (Large et al. 1994) and the GM-Redi isopycnal mixing (Redi 1982, Gent and McWilliams 1990). The KPP scheme parameterizes convection and wind-driven vertical mixing in the surface boundary layer by specifying profiles of vertical diffusivities. In addition, a non-local transport term permits the transfer of surface properties to the bottom of the boundary layer during convection events. The scheme thus facilitates vertical penetration of heat and momentum near the surface which would otherwise be too small with, for example, the traditional Pacanowski and Philander vertical mixing (Pacanowski and Philander 1981) or constant-mixing scheme. Another important feature of KPP, particularly important for equatorial currents, is the inclusion of a gradient-Richardson mixing term that represents shear instability mixing below the surface boundary layer. Without this term, the Equatorial Undercurrent (EUC) in the Pacific would tend to be too shallow and too strong. The GM-Redi isopycnal mixing is
considered more realistic than a simple constant horizontal mixing formulation because
the former tends to “mix” along isopycnals and to preserve the volume of a specific water
mass between any two isopycnal surfaces. In regions of steep isopycnal slope, the GM-
Redi mixing coefficients are tapered following the procedure described by Large et al.
(1997).

The model is forced at the surface by wind stress as well as heat and freshwater
fluxes. Zonal and meridional wind stresses are obtained from the reanalysis product of
the National Center for Environmental Prediction (NCEP) (Kalnay et al. 1996). The
heat flux is a blended product with the temporal mean obtained from COADS (da Silva
et al. 1994) and the temporal variability from NCEP reanalysis. The “global” mean
within the model domain, about 29 W/m², is removed from every grid point to minimize
climate drift. In addition to this imposed heat flux, model SST is relaxed to NCEP’s SST
with a spatially dependent and seasonally varying coefficient computed from the NCEP
reanalysis product in the manner described by Barnier et al. (1995). The computed
relaxation coefficients correspond to time scales of typically 30-45 days for low- and mid-
latitude and shorter for high-altitude oceans. A similar treatment is applied for the
freshwater flux where the imposed flux consists of temporal mean from COADS with the
global mean (7.7×10⁻⁷kg/m²/s) removed, temporal variability from the NCEP reanalysis,
and relaxation to Levitus’98 climatological mean salinity (Boyer and Levitus 1998) with
a time scale of 2 months. The wind stress used has a 12-hourly interval. That of heat
and freshwater fluxes is daily.

The model was first spunup for 10 years from rest with Levitus’98 climatological
temperature and salinity, forced by seasonal climatological forcings averaged from 1980 to
1997. The 10-year spinup time is much shorter than thermocline time scales for mid- and
high-latitude oceans, but is relatively sufficient for the development of circulation systems
in upper tropical oceans, which is the main focus of the present study. The relatively short
spinup time alleviates the drift of density structure in deep ocean (a common problem
for ocean models) without using relaxation of deep density to climatology which sacrifices
model dynamics. The short spinup and real-time integration period precludes the analysis
of ITF effect on global ocean circulation which involves the possible connection with
upwelled North Atlantic Deep Water (i.e. the hypothesis of Gordon 1986).
Following the spinup, two integrations are performed with forcings from 1980 to 1997, with the Indonesian passages open and closed, respectively. A similar strategy was adopted by Murtugudde et al. (1998) in which the open and closed ITF experiments were based on the same initial conditions.

3. The control run

Before discussing effects of the ITF, we first evaluate the performance of the model based on comparisons of the control run (with open Indonesian passages) with various observations and other model simulations. Figure 2 shows the spatial distribution of temporal correlation of model sea level with that obtained by the TOPEX/Poseidon satellite altimeter from 1993 to 1997. Model sea level anomalies are interpolated to the satellite tracks to facilitate the computation of correlation. Black areas indicates missing data. Reasonably good model-data correlation is seen in the tropical Pacific and Indian Oceans, especially along the equatorial wave guide, the Intertropical Convergence Zone, and South Pacific Convergence Zone in the Pacific, and along 10°S and off Java in the Indian Oceans. These are areas of active wave activities (equatorial Kelvin waves, Rossby waves, coastal Kelvin waves). The good correlation in the tropics is encouraging because it is the focus of the present study. The model under-estimates the magnitude of observed variability by approximately a factor of two (upon global average) primarily due to limited spatial resolution and accuracies of the forcing fields.

Model temperature in the upper tropical Pacific is compared with data obtained from the 75 TOGA-TAO temperature moorings from 1983 to 1997. Figure 3 shows the comparison of vertical profiles for (a) temporal average, (b) temporal variability, and (c) model-data correlation. The model's stratification is too strong comparing to the data. There is a cold bias in the model below the surface layer (primarily in the central to eastern equatorial Pacific). A sensitivity experiment (not shown) with a background (interior) vertical diffusivity that is four times as large ($10^{-5}$ m$^2$/s as opposed to $2.5 \times 10^{-6}$ m$^2$/s) results in opposite differences (very diffusive thermocline and a warm bias in the upper tropical Pacific). The findings of the present study are not affected by these differences.
because results of a previous analysis of ITF effects based on model solutions with the large background vertical diffusivity are very similar to the findings reported in this paper. The model's root-mean-squared (r.m.s) variability is close to the observed magnitudes in the upper 50 m, but is generally weaker than the observed value by 30-50% further down. The temporal correlation with the data is approximately 0.7 near the surface and the thermocline (between 100 and 150 m), and smaller at other depths.

Model-data comparisons of zonal velocities at three TAO current meter mooring locations along the equatorial Pacific are presented in Figure 4. The strength of the model's EUC is close to the observed magnitude in the western to central equatorial region (165°E and 140°W), but weaker in the eastern part (110°W). The depth of EUC core is consistent with observations. Magnitudes of the temporal r.m.s. variability of zonal velocity is about 20-60% weaker than the observations depending on location and depth. Spatial resolution, values of background viscosity, and strength of wind forcing are believed to be the primary factors contributing to the weaker variability of the simulated velocity.

Figure 5a shows 10-day averages of simulated total ITF transport as a function of time. ITF transport is defined here as the sum of depth-integrated transports through various passages (negative being from the Pacific to the Indian Oceans). The mean transport over this period is approximately 13 Sv. The partition among various straits from east to west are: 4.6 Sv for Timor Passage, 6.5 for Savu Strait, 0.4 Sv for Flores Strait, and 1.5 Sv for Lombak Strait (cf. Figure 1b). Most of the transport is accounted for by the two passages in the west. That for the Lombak Strait is in excellent agreement with current meter measurements in this strait (Murray and Arief, 1988). The relative transports simulated by the model through various passages is qualitatively consistent with the general perception of how the ITF is partitioned.

The mean value of our simulated ITF transport is well within the range of estimates inferred from various measurements, but higher than the average. It is also smaller than that simulated by OGCM of HG93, close to that simulated by the coupled model of Schneider and Barnett (1997), and larger than those simulated by reduced-gravity models of Verschel et al. (1995) and Murtugudde et al. (1998). Note that none of these model includes tidal mixing near the Indonesian archipelago, which could modify ITF transport (Field and Gordon 1992, Takaki et al. 1996). Murtugudde et al. (1998) applied enhanced
horizontal mixing to reduce ITF transport because an attempt to reduce this transport through enhanced vertical mixing was unsuccessful.

The simulated ITF transport displays relatively large variability with a range and standard deviation of approximately 20 Sv and 3.5 Sv. The frequency spectrum of the ITF transport (Figure 5b) indicates that the dominant variability is at the annual period. Interannual and semi-annual signals are also evident. The averaged seasonal cycle (Figure 6a) has a peak-to-trough range of approximately 7 Sv with the weakest and strongest ITF occurring in January-February and July-August, respectively. The “zigzag” in the averaged seasonal transport reflects the contribution of semi-annual signal (from the Indian Ocean). The simulated seasonal variation is qualitatively consistent with that estimated by Meyers (1996) from XBT data and those simulated by Masumoto and Yamagata (1996) and Murtugudde et al. (1998).

The interannual anomaly of annual-mean ITF transport is shown in Figure 6b (solid curve) along with the model’s annual-mean Niño3 and Niño4 SST indices (dashed and dash-dotted curves). The two indices are defined as the interannual anomaly of SST averaged over the areas of (150-90°W, 5°N-5°S) and (160°E-150°W, 5°N-5°S), respectively. The correlation between interannual ITF transport and SST anomaly is 0.47 for Niño3 and 0.58 for Niño4, which are above the 95% confidence level of 0.4 and 0.43. Meyers (1996) estimated ITF transport in the top 400 m based on geostrophic calculation using repeated XBT transects across the Indian-Ocean side of the ITF (Sunda Strait to Fremantle) over the period of 1983 to 1994. He found a relatively strong ENSO signal (a range of 5 Sv) that showed a good (anti-)correlation with the Southern Oscillation Index (which is anti-correlated with the Niño3 index). In particular, the ITF is found to be stronger during the 1988-1989 La Niña and weaker during the El Niño during 1986-1987 and 1991-1994. Our result (Figure 6b) is consistent with that of Meyers (1996), but with smaller magnitude. Moreover, we also find relatively weak ITF during the El Niño of 1982-1983 and 1997-1998, which are not covered by Meyers’ study period.

The above model-data comparisons indicate that the model has a reasonable performance in simulating many aspects of the circulation in the tropical Pacific and Indian Oceans as well as the transport of ITF that connects the two.
4. Effects of ITF on circulation and thermal structure

In this section, effects of the ITF on the circulation and thermal structure of the Indo-Pacific Oceans are analyzed by comparing model solutions with open and closed Indonesian passages. The two subsections address ITF effects on the mean state and seasonal-to-interannual variabilities, respectively. The comparisons are based on the temporal mean and variability of the two model solutions for the period of 1981 to 1997. The year of 1980 was excluded from the analysis because relatively large transient adjustments occur in this year following blockage of the ITF. After this year, a smaller and relatively linear trend is seen in the solution with blockage of the ITF, with the trend in velocity field being smaller than that in thermal fields.

The time-mean quantities presented in the next subsection are referred to temporal averages from 1981 to 1997. Due to a small and relatively linear trend in the solution with blockage of the ITF, the difference in time-mean state between two solutions (with and without the ITF) is somewhat larger for the later part of the integration than it is for the earlier part. For the analysis of variability, trends in both solutions are removed because the focus of variability is on seasonal-to-interannual variability. The blockage of the ITF may create low-frequency waves which could remain the solution for longer than a year. However, this effect seems small because results of an analysis based on 1990-1997 are fairly similar to those presented in the following (based on 1981-1997).

4.1 Effects on the mean state

Mean circulation:

Effects of the ITF on the depth-averaged circulation is illustrated by the time-mean barotropic transport stream functions with and without ITF and their differences (Figure 7). The absence of the ITF causes an anti-cyclonic circulation loop around Australia and the southern Indian Ocean. This circulation extends from the Indonesian Seas, southward down the east coast of Australia, westward along the northern flank of the Antarctic Circumpolar Current to the Agulhas retroflection region, northward along the east African
coast to Mozambique, then eastward across the Indian Ocean near 10°S and back to the Indonesian Seas. There is even a small extension of the loop into the south Atlantic Ocean. This change is very similar to that reported by HG93 except that the magnitude of the change is smaller here (due to a weaker ITF in our model). The consequence of this anti-cyclonic circulation includes a weaker South Equatorial Current (of the Indian Ocean) and Agulhas Current and a stronger East Australian Current (EAC). The southward-flowing Leeuwin Current is also weaker in the top 100 m without ITF (not shown). However, this is compensated by a weaker northward flow at depth and so the change in depth-integrated transport is small.

An important aspect associated with this loop but not discussed by HG93 is the role of the ITF on the New Guinea Coastal Undercurrent (NGCC), the low-latitude western boundary current (LLWBC) in the South Pacific (near 152-155°E, 5-10°S). Zonal sections of meridional velocity across this current at 10°S with and without the ITF and their difference are shown in Figures 8a-c. The change in meridional velocity, although having a barotropic component, is depth-dependent. The largest change occurs at the core of NGCC (centered at the depth of approximately 150 m), with a 40-50% reduction in core speed. This current is an important carrier of thermocline water from the southern subtropical gyre in the Pacific to the equatorial Pacific. The absence of the ITF thus reduces tropical-subtropical exchange in the South Pacific.

In contrast, the LLWBC in the North Pacific, the Mindanao Current, is not sensitive to the ITF (Figures 8c-e) despite the fact that much of the ITF waters come directly from the Mindanao Current. This is because the wind-driven North Equatorial Current, the bifurcation of which feeds the Mindanao Current, should not be sensitive to ITF that is far downstream of it. Although the ITF does not affect the Mindanao Current, it drains much of the North Pacific thermocline water carried by this current into the Indian Ocean and thus reduces the exchange between the tropical Pacific and the northern subtropical gyre.

To further demonstrate the effect on tropical-subtropical exchanges, we performed simulations of trajectories of water parcels subducted in the subtropical north and south Pacific using time-mean velocity fields with and without ITF. Figure 9 is an example of the exchanged parcels (i.e. those arriving at the tropics rather than recirculating within
subtropical gyres) initially released at 24°N and 24°S at 50 m. Trajectories for recirculating parcels are plotted. The simulation period is 9 years. The color of a trajectory segment indicates the depth of the particle. In both hemisphere, the parcels roughly follow the thermocline en-route to the tropics. Those that arrive at the equatorial Pacific eventually upwell to the surface and travel poleward following the Ekman flows.

In the presence of the ITF, many “exchanged” parcels from the North Pacific (panel a) that travel along the western boundary are split into two branches: one that turns eastward into the EUC and another that goes into the Indian Ocean. Blockage of the ITF causes the latter branch to join the EUC (panel b). In the South Pacific, with ITF open, parcels carried by the NGCC cross the equator and go around the Halmahera Eddy before turning east into the equatorial Pacific (panel c). When the ITF is blocked, they are confined to the southern hemisphere and join the EUC directly. Blockage of the ITF also reduces the zonal extent of the “exchange window” within which subducted parcels can arrive at the tropics (east of 127°W and 110°W at 24°S with and without ITF, respectively). The above results suggest that the contribution of North and South Pacific thermocline waters to EUC waters would be different with and without ITF, consistent with the finding of Rodgers et al. (1999).

In summary, the ITF regulates the relative magnitudes of tropical-subtropical exchanges in northern and southern hemispheres: its presence reduces (enhances) the influence of the northern (southern) subtropical gyre and thus contribute to decadal modulations of ENSO. Models that do not account for ITF would exaggerate the effect of the northern Pacific and under-estimate the role of the southern Pacific. Tropical-subtropical exchange rates inferred from such models are subject to biases due to the missing ITF effect.

Response of circulation in the tropical Pacific is more baroclinic and so cannot be revealed by the depth-integrated flow shown in Figure 7. The difference in of zonal flow in the equatorial region without and with ITF (Figure 10a) is characterized by eastward tendency near the surface and in the EUC (east of the dateline) and westward tendency in between. Such a layer structure continues at greater depth, reflecting the highly baroclinic nature of equatorial flow. The change in vertical velocity in this region (Figure 10b) shows a general downwelling tendency (reduced equatorial upwelling). The change of zonal flow
away from the equator (not shown) is less baroclinic, with eastward tendency from and above the thermocline and small westward tendency at depth.

Figure 11 shows the difference in horizontal velocities without and with ITF at 5 and 95 m. The length of arrows have been scaled by the square root of velocity magnitude to provide a better visualization of small vectors. However, the direction of the velocity vectors (i.e., ratio of zonal and meridional velocities) are preserved. The vectors are mapped from the original grid to a reduced $3^\circ \times 1^\circ$ grid to avoid overlap of arrows. A general eastward tendency is seen over most of the Pacific at both depths. The eastward “flow” turns poleward near the eastern boundary. The change is larger between $5^\circ$N and $5^\circ$S. Near the equator, the tendency is westward to the west of the EUC (east of 140$^\circ$W at this depth), reflecting the baroclinic structure shown in Figure 10a.

HG93 reported a “two-layer” adjustment of tropical Pacific circulation with eastward and westward tendencies above and below 500 m when the ITF is closed and with downwelling connecting the two (their Figure 21 with the sign reversed because it is closed -open). Our findings are similar to theirs in terms of the general eastward tendency in the upper tropical Pacific. However, the highly baroclinic adjustment of zonal flow near the equator found in our model was not shown by HG93.

**Mean thermal structure:**

The change of circulation due to blockage of the ITF has widespread influence on subsurface temperature, most notably in the tropical Pacific and southern Indian Ocean (Figure 12). The general warming of the tropical Pacific and cooling of the Indian Ocean is consistent with the fact that the heat transport between the Pacific and Indian Ocean is cut off (approximately 0.6 PW, 1 PW = $10^{15}$W).

The warming in the tropical Pacific can be explained by the general eastward tendency of horizontal velocity which turns poleward near the eastern tropical Pacific (as discussed earlier). Such a tendency advects warmer waters in the western tropical Pacific towards the east and spreads them poleward in the eastern tropical Pacific. The downwelling tendency near the equator also help depress isotherms and create warming (at a fixed depth). The very large change near the EAC and smaller change near the Kuroshio are
because of shifts in turning latitudes of these currents: the EAC extends farther south and
the Kuroshio not as north. In the Indian Ocean, the general cooling is due to the reduced
heat advection from the Pacific. The larger cooling in the southern Indian Ocean is due
to the weaker SEC, Agulhas Current, and Leeuwin Current and the reduced difference of
horizontal temperature between the ITF channel and these areas.

In most of areas, the change in subsurface temperature is generally larger near the
thermocline. Consequently, the mean thermocline depth is depressed and raised in the
tropical Pacific and Indian Ocean, respectively. This is illustrated in Figure 13 by the
depth of the 20°C isotherm, D20 (a proxy for thermocline depth in the tropics). The
change is the largest in the southern Indian Ocean and the eastern equatorial Pacific.
That for the latter region is substantial considering the shallowness of thermocline in
there.

Mean thermocline depth reflects heat content and is widely considered to be an impor-
tant precondition for longer term variation of ENSO behavior. Changes in the mean depth
or property of the thermocline in the equatorial Pacific by anomalous water mass origi-
nating in the subtropics was hypothesized to cause decadal variations in ENSO behavior
(e.g., Deser et al. 1996, Gu and Philander 1997). Decadal changes of dominant frequency
and magnitude of interannual variations due to difference in mean slope and depth of
the thermocline have been demonstrated by relatively simple coupled ocean-atmosphere
models of the tropical Pacific (Kirtman and Schopf 1998, Fedorov and Philander, 2000).
The contribution of ITF to the maintenance of thermocline structure thus implicates its
potential role in ENSO.

The ITF could affect the coupled ocean-atmosphere system more directly through its
effect on SST. Figure 14 shows the time-mean SST with and without the ITF and their
difference. Blockage of ITF results in (1) warmer equatorial SST in the central to eastern
Pacific and thus an enhanced SST gradient between the warm pool and the cold tongue,
and (2) a general cooling of the southern Indian Ocean south of the SEC, west of the
Leeuwin Current, and near the Agulhas retroflection region.

The change in the southern Indian Ocean resembles the pattern of change in subsurface
temperature presented in Figure 12. The similarity suggests that a dominant process is
responsible for changes in surface and subsurface temperatures in that region. This is the
reduced horizontal advection of heat associated with the weakening of the SEC, Agulhas
Current, and near-surface Leeuwin Current along with the reduced horizontal difference of temperature between the ITF channel and the southern Indian Ocean. Vertical mixing, such as convection discussed by HG93, would also contribute at higher latitudes. The changes of SST near the EAC and Kuroshio in mid-latitude Pacific are also similar to those of subsurface temperature. They are again caused by shifts in the turning latitudes of these current mentioned earlier.

In contrast, the surface warming in the central to eastern equatorial Pacific and off the South American coast is different from the pattern of subsurface warming. This surface warming is associated with several processes due to blockage of the ITF: (1) the weakened westward advection of waters in the cold tongue towards the warm pool (Figure 10a), (2) reduced upwelling of subsurface water (Figure 10b), and (3) vertical mixing with warmer subsurface water (Figure 12a).

The change in zonal SST gradient is important to ENSO because it affects the wind field which would then feedback to the ocean. Whether the feedback is positive or negative (i.e. whether the change in wind field would reduce or enhance the ITF-induced change in zonal SST gradient) remains to be investigated. Based on a coupled model simulation, Schneider (1998) found that a positive feedback between surface wind and SST initially caused by blockage of the ITF was possible.

The pattern of SST response to ITF is somewhat similar to that presented by HG93 in the Indian Ocean and western Pacific (their Figure 13d, upto 160°W only). Near 160°W, SST difference in our model is close to 0.5°C whereas it is only 0.25°C in HG93. Judging from the difference in surface heat flux with and without ITF presented by HG93 (their Figure 1b), the maximum SST difference in the eastern equatorial Pacific (not presented) appears to be about 0.5°C, which is smaller than the 1°C difference seen in our model. The larger response of SST to ITF in the equatorial Pacific in our study is attributed to the finer resolution (both meridionally and vertically) and more sophisticated mixing schemes in our model, both of which are important to the simulation of tropical circulation and thermal structure (especially the EUC).

Warming in the central to eastern tropical Pacific due to blockage of ITF was also reported by Murtugudde et al. (1998) and Rodgers et al. (1999), both with a magnitude of approximately 1°C. However, that in the former has a maximum magnitude between
140°W and 110°W along the equator (their Figure 10) whereas that in the latter is the largest off the South American coast (their Figure 13). The warming pattern we found has local maxima in both of these areas. The differences in SST response is believed to be caused by differences in the relative contributions of horizontal advection, vertical advection, and vertical diffusion which are all important to the heat balance in this region.

There are also other differences between ours and previously reported SST response. For instance, the change of tropical SST in our model is more confined to the equatorial region than that reported by Murtugudde et al. (1998); we do not find the large changes in SST in the interior of South Pacific (upto 0.6°C) and northeast Pacific (over 1°) reported by Rodgers et al. (1999).

4.2 Effects on seasonal-interannual variability

Thermocline depth variability:

Figures 15a and b illustrates the r.m.s. variation of D20 with the Indonesian passages open and closed for time scales longer than 1.5 years (contributed primarily by interannual signals). The difference between the two is shown in Figure 15c (the difference between r.m.s. variation of D20, not the r.m.s. variation of the difference in D20). The interannual variability in thermocline depth in the eastern equatorial Pacific (Niño3 area) is smaller without ITF. This can be explained in terms of a deeper thermocline experiencing smaller depth variations in response to the same magnitude of Ekman pumping (wind forcing is identical for both model runs). In contrast to the Pacific, the interannual variability of thermocline depth in the southern tropical Indian Ocean is generally larger with blockage of the ITF due to a shallower rather than deeper thermocline. These changes suggest that local Ekman pumping is the dominant mechanism controlling interannual variations of thermocline depth in the tropical Pacific and Indian Oceans.

The r.m.s. variability for the annual band is presented in Figure 16 in a way similar to the interannual band discussed above. There are two local maxima of thermocline
variability in the southern tropical Indian Ocean (60°E and 90E, 10S). The presence
of these two local maxima have been captured by XBT data (Masumoto and Meyers
1998). The amplitude of these two maxima in the model (approximately 15 m) is smaller
that shown by Masumoto and Meyers (1998) (20-30 m). Both maxima have a clear
signature in sea level data (e.g. GEOSAT data shown by Perigaud and Delecluse 1992,
TOPEX/Poseidon data shown by Fu and Smith, 1996).

Perigaud and Delecluse (1992) suggested that annual Rossby waves contribute to these
variations, but did not explain why there were local maxima in mid-ocean. Masumoto
and Meyers (1998) argued that the two maxima were the result of zonal variation in
the strength of Ekman pumping and the resultant Rossby waves. Wang et al. (2000)
suggested that the superposition of basin-scale “local response” to zonal mean Ekman
pumping (standing waves) and Rossby waves forced by zonal anomaly of Ekman pumping
(propagating waves) could explain the two local maxima and the minimum in between.

The magnitudes of these two maxima in D20 are reduced when ITF is blocked, with
the reduction being more pronounced northeast of Madagascar. We have also examined
seasonal variabilities in model sea level with and without ITF and found the same be-
havior. The weakening of seasonal variation is opposite to that for interannual signals in
the same region, which is enhanced when the ITF is blocked. This difference indicates
that local Ekman pumping, which controls the interannual variability, is not necessarily
the dominant maintenance mechanism for the annual variation (otherwise the variability
should increase like the interannual signals). Two other mechanisms could be at work:
(1) radiation of planetary waves originating from the throughflow area (locally generated
or transmitted from the Pacific), and (2) advection of planetary waves by the SEC of
which strength and potential vorticity structure depends on the ITF heavily. Both of
these would affect the superposition of propagating and standing waves and thus modify
the magnitude and location of the maxima (and minima for that matter). Either way,
it reflects the contribution of the ITF to annual thermocline variability in the southern
Indian Ocean. An effort is being made to isolate the relative contribution of these two
effects. The results will be reported in a separate paper.

In addition to the effects on the magnitude of thermocline depth variation, the ITF
also affects the location of maximum thermocline variability at different time scales. For
the annual band, the locations of the two maxima in the southern tropical Indian Ocean are shifted eastward when the ITF is blocked, resulting in a dipole pattern in the difference associated with each local maximum (Figure 16c). In the eastern equatorial Pacific, the pool of maximum variability is also shifted eastward both for the annual and interannual bands, leaving dipole-like patterns in the difference in r.m.s. variation. These shifts imply that waves reflected from the Pacific side of the Indonesian archipelago (equatorial Kelvin waves) and those transmitted through the Indonesian Seas or generated on the Indian-Ocean side of the Indonesian coast (Rossby waves) could affect the locations of maximum thermocline variability (as well as the magnitude of the variability as discussed earlier).

**SST variability:**

The interannual SST variability with and without ITF and their difference are shown in Figure 17. The magnitude of r.m.s. variability in the central to eastern equatorial Pacific becomes smaller when the ITF is blocked. The maximum reduction is about 0.2°C, close to 15% of the total. The opposite is true for the tropical Indian Ocean but with a larger magnitude. These changes can be explained by the ITF-induced change in thermocline depth: a deeper thermocline (as well as an isotherm above the thermocline) would reduce the influence of subsurface temperature on SST in response to Ekman pumping, vice versa. Therefore, the ITF not only affects the mean SST, but its interannual variability as well. In our model, relaxation of SST would reduce the difference with and without the ITF. The impact of the ITF on interannual variability in coupled ocean-atmosphere models remains to be investigated.

Murtygudde et al. (1998) found that the difference in Niño3 index of interannual SST anomaly with and without the ITF is correlated with the Niño3 index itself. The same is true for Niño4 index. No interpretation was offered for this correlation. We performed a similar analysis and found a very similar correlation. Our result offers a simple explanation. The blocking of the ITF reduces the magnitude of interannual SST anomaly in the central to eastern equatorial Pacific. Therefore, a warm (cold) event would be not as warm (cold), and thus the correlation between Niño index and the difference of Niño indices with and without ITF.
The largest response of interannual SST to blockage of the ITF occurs downstream of the EAC off the southeast corner of Australia. The location of maximum interannual variability is shifted from east to south of Tasmania. This is due to the strengthening of EAC which allows it to extend farther downstream as discussed earlier. In addition, the magnitude of interannual variability becomes twice as large (0.5°C versus 1°C) when the ITF is blocked. The lack of interannual variability along the EAC when the ITF is present is consistent with the finding of Ridgway and Godfrey (1995) based on hydrographic data. The enhancement of interannual variability and the warming of SST near the EAC discussed earlier (cf Figure 14), both being the largest geographically, imply that the ITF has an important contribution to the regional climate near southeastern Australia.

5. Summary and Conclusions

A near-global OGCM is used to investigate effects of the ITF on the circulation and thermal structure of the Pacific and Indian Oceans. Model solutions over the period of 1981 to 1997 with open and closed Indonesian passages are compared to highlight the effects on mean state and seasonal to-interannual variability. The model employs advanced mixing schemes and has overall higher meridional and vertical resolutions than those used in previous studies. The time period of study is also the longest and includes the most recent El Niño event.

The ITF is found to affect the loop of circulation around East Australia and the southern Indian Ocean. In particular, absence of the ITF weakens the Indian Ocean SEC and Agulhas Current and strengthens the East Australian Current. The southward-flowing Leeuwin Current is also weaker in the upper 100 m without the ITF, accompanied by a weaker northward subsurface flows. The response of circulation in the tropical Pacific to blockage of the ITF is characterized by (1) a general eastward flow off the equator above the thermocline, (2) a highly baroclinic flows near the equator with eastward flows near the surface and along the EUC but westward flow between the surface and EUC and below the EUC, and (3) downwelling along the equator.

The ITF does not affect the low-latitude western boundary current in the north Pacific
(the Mindanao Current), but it drains the North Pacific thermocline water carried by this current into the Indian Ocean. This reduces the tropical-subtropical exchange in the North Pacific. Meanwhile, the ITF helps maintain a stronger low-latitude western boundary current in the South Pacific (NGCC), and thus enhances tropical-subtropical exchange of thermocline water in the South Pacific. Simulation of the trajectories of water parcels initially subducted at mid latitudes indicate that waters parcels carried by NGCC can cross the equator in the presence of the ITF, but are confined to the southern hemisphere without the ITF. The “exchange window” in which subducted water parcels can reach the tropics is wider with than without the ITF.

Blockage of the ITF cuts off the heat transport from the Pacific to the Indian Ocean. This causes an overall warming and cooling in the tropical Pacific and southern Indian Ocean. The effect is generally larger near the thermocline, resulting in a deepening and shoaling of the thermocline in these two oceans, respectively. Meanwhile, SST is lower in the southern Indian Ocean (most notably in areas south of the Indian Ocean SEC, west of the Leeuwin Current, and near the Agulhas retroflection region) primarily due to smaller horizontal advection of heat and mixing with cooler subsurface temperature. In the central to eastern tropical Pacific, SST is warmer due to horizontal spreading of warmer water towards the east, reduced equatorial upwelling of subsurface water, and vertical mixing with warmer subsurface water.

The ITF also affects seasonal-to-interannual variability of thermocline depth and SST in the Pacific and Indian Oceans. When the ITF is blocked, thermocline depth variabilities on seasonal and interannual time scales are both reduced in the central to eastern Pacific because the deeper thermocline attenuates fluctuations in response to local Ekman pumping. Opposite to the effect on the Pacific, interannual thermocline variation in the southern Indian Ocean is enhanced by a shallower mean thermocline due to blockage of the ITF. Seasonal thermocline variation in this area, however, is actually reduced in the absence of the ITF despite the shoaling of the thermocline. This indicates that local Ekman pumping is not necessarily the dominant mechanism controlling the seasonal variability of thermocline fluctuation in the southern Indian Ocean as previously suggested (otherwise seasonal variability would also be enhanced like the interannual variability). Radiation of planetary waves from the Indonesian throughflow area and advection by the ITF-dependent SEC could also be important.
The ITF helps maintain the magnitude of interannual SST variability through its effect on the thermocline depth, which in turn regulates the intensity of subsurface temperature influence on SST in response to Ekman pumping. The absence of the ITF reduces the magnitude of interannual SST variation in the equatorial Pacific and enhances that in the southern Indian Ocean and south of Tasmania.

Our results indicate that ITF plays an active role in ENSO and its decadal modulations by affecting tropical-subtropical exchanges in both hemisphere, mean thermocline depth, SST difference between the warm pool and cold tongue, and seasonal-to-interannual variability of thermocline and SST fluctuations. In the mean time, our findings highlight limitations in using models without ITF for ENSO diagnostics and forecasts. Models that excludes the ITF are subject to biases in mean thermocline structure, mean zonal SST difference, and seasonal-to-interannual variabilities. Applications of Pacific-domain models that excludes the ITF to study decadal modulations of ENSO is also limited because the relative contribution of the northern and southern subtropical gyres to the tropical Pacific is not accurate (over-estimate of the exchange in the north and under-estimate in the south). Our results also indicate that ITF poses a difficulty in the design of an observing system used to monitor tropical-subtropical exchanges because the highly variable ITF is needed to close the mass and heat budgets.

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Figure captions

Figure 1. Model topography (a) and its enlargement near the Indonesian Archipelago (b).

Figure 2. Temporal correlation of sea level anomalies simulated by the model with those measured by TOPEX/Poseidon for the period of 1993-1997.

Figure 3. Vertical profile of time-mean temperature (a) and its standard deviation (b) averaged over the 75 TOGA-TAO temperature mooring locations between 1983 and 1997 for model (solid) and TAO data (dashed) as well as the model-data correlation (c).

Figure 4. Comparison of time-mean zonal velocity and its standard deviation with TAO current meter data at 165°E, 140°W, and 110°W, along the equator for 1983 to 1997.

Figure 5. Time series of the simulated total transport of the Indonesian throughflow (a) and the corresponding frequency spectrum (b).

Figure 6. The averaged seasonal cycle (a) and interannual anomaly (b) of the simulated Indonesian throughflow along with Nino3 and Nino4 SST indices. The dashed curves in (a) represent one standard deviation.

Figure 7. Time-mean barotropic stream function with the Indonesian passages open (a), closed (b), and their difference (c). The unit of contour levels is Sv.

Figure 8. Time-mean zonal sections of meridional velocities with open and closed Indonesian passages and their difference (closed-open) across the New Guinea Coastal Undercurrent (upper) and Mindanao Current (lower). The unit of contour levels is cm/s.

Figure 9. Simulated trajectories of water parcels subducted in the subtropics and eventually arriving at the tropics. Panels a-d correspond to exchanges in the North and South Pacific with and without ITF, respectively.
Figure 10. Zonal sections of the difference in zonal (a) and vertical (b) velocities without and with ITF along the equator. Units of contour levels are cm/s and m/day, respectively.

Figure 11. Difference of horizontal velocity without and with ITF at 5 (a) and 95 m (b).

Figure 12. Difference of temperature without and with ITF at the depths of 50 (a) and 150 m (b). The unit of contour levels is °C.

Figure 13. Time-mean depth of the 20°C isotherm, D20, (a proxy for thermocline depth) with the Indonesian passages open (a), closed (b), and their difference (c). The unit of contour levels is meter.

Figure 14. Differences in SST without and with ITF averaged from 1981 to 1997 (a) and over 1997 only (b). The unit of contour levels is °C.

Figure 15. Root-mean-squared variation of D20 with the Indonesian passages open (a), closed (b), and their difference (c) for interannual signals. The unit of contour levels is meter.

Figure 16. Root-mean-squared variation of D20 with the Indonesian passages open (a), closed (b), and their difference (c) for the annual period. The unit of contour levels is meter.

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