Pathways and Effects of the Indonesian Throughflow Water in the Indian Ocean Using Particle Trajectory and Tracers in an OGCM

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(Manuscript received 16 March 2005, in final form 19 September 2005)

ABSTRACT

The 3D pathways of the Indonesian Throughflow (ITF) in the Indian Ocean are identified using an OGCM, with a combined set of tools: 1) Lagrangian particle trajectories, 2) passive tracers, and 3) active tracers (temperature and salinity). Each of these tools has its own advantages and limitations to represent the watermass pathways. The Lagrangian particles, without horizontal and vertical mixing, suggest that at the entrance region the surface ITF subducts along the northwestern coast of Australia and then travels across the Indian Ocean along the thermocline depths. The subsurface ITF more directly departs westward and crosses the Indian Ocean. Using the passive tracers, which are mixed vertically under convection as well as horizontally due to diffusion, the ITF is shown to undergo vigorous mixing as soon as it enters the Indian Ocean and modifies its upper temperature–salinity (T–S) characteristics. Thus, the surface and subsurface ITF watermasses lose their identities.

Upon reaching the western boundary, the ITF reroutes into three distinct depth ranges, owing to the seasonal reversal of the Somali region: route 1—across the Indian Ocean just to the south of the equator (200–300 m); route 2—across the Indian Ocean to the north of the equator (100–200 m); and route 3—upwells in the Somali region and spreads all over the surface of the northern Indian Ocean. The seasonality of the Somali Current is crucial to spread the ITF along route 3 during the summer monsoon (April–October) and route 2 during the winter monsoon (November–March). The basinwide spreading is responsible for a long residence time of the ITF in the Indian Ocean to be at least 20 yr.

The effects of the ITF on the temperature and salinity are mainly accompanied with the major pathways. However, indirect effects are visible in a few spots; that is, the warm and saline feature is produced in the subsurface off the southwestern coast of Australia around 30°S caused by the eastward surface current, which is under the thermal wind relationship owing to the warm and fresh ITF component. This component also enhances vertical convection and warms the surface around 40°S. The Arabian Sea high salinity water is produced extensively with the effects of the Somali upwelling, which is originally strengthened by the fresh and warm ITF.

1. Introduction

Indonesian Throughflow (ITF) is a system of currents flowing from the Pacific to the Indian Ocean and the only low-latitude connection between the world oceans. The ITF is the major route of fresh and warm water from the Pacific to the Indian Ocean (Gordon and Fine 1996). It plays a significant role in the Indian Ocean heat budget by exchanging nearly 11 W m$^{-2}$ with the atmosphere, which amounts to up to 25% of the net air–sea heat flux of the southern Indian Ocean (Vranes et al. 2002). The annual mean volume transport of the ITF into the Indian Ocean is estimated by both observational and modeling analyses and ranges between 10 to 16 Sv (1 Sv = 10$^6$ m$^3$ s$^{-1}$; Hirst and Godfrey 1993). These uncertainties are not only due to the lack of sufficient observations over the Indonesian seas but also due to the complicated topography of the straits, which make it difficult to model (Masumoto and Yamagata 1993). Interannual variabilities of the ITF following the signals of ENSO (Murugudde et al. 1998) and Indian Ocean dynamics (Yamagata et al. 1996) are also responsible for the changes in this net volume transport. Such a large water injection modifies both water properties and ambient circulation over the Indian Ocean. To identify such effects, we would need a proper understanding of the trajectory of the ITF.

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DOI: 10.1175/JCLI4167.1

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Several studies have been done on the spreading pathways of the ITF over the Indian Ocean, although none of them provide a detailed three-dimensional track of the ITF. A probability density function analysis over the Lagrangian trajectories of the particles initialized at the ITF entrance region by Song et al. (2004, hereafter SGV) has concluded that 67% ± 5% of the ITF turns to the northern Indian Ocean at the western boundary and is eventually transmitted to the south following the annual mean Ekman transport. It is well known that the Indian Ocean undergoes dramatic seasonal reversals [Somali Current (Schott et al. 1990), Coastal Currents (Shetye et al. 1991), and Wyrtki Jet (Wyrtki 1971)] following the monsoon. These seasonal changes in circulation may be crucial in spreading the ITF in the northern Indian Ocean. The Somali Current is particularly the key to the ITF, which crosses the equator from the southern Indian Ocean to the northern region only in this western boundary current (Schott et al. 2002; Miyama et al. 2003). Thus, the seasonally spreading pathways of the ITF have to be compared to its annual mean path over the Indian Ocean and considered important in supplying additional information over the findings of SGV.

The Lagrangian particle trajectory is an appropriate tool to find the track of water mass and has been used widely (Haines et al. 1999; Miyama et al. 2003; SGV). It efficiently represents the explicitly resolved circulation. However, the main difficulty we face with the Lagrangian trajectories is that they do not represent processes such as diffusion, mixing, or turbulence. With the sufficient approximations, diffusion or turbulence can be accounted indirectly from the large-scale model velocity as done by SGV. The mixing at the immediate entrance region modifies the ITF water, and it is difficult to separate vertical velocity and the mixing further. Thus, the particle-derived trajectory has its own limitations. To identify the importance of these processes in spreading the pathways, in this study, we compare the Lagrangian trajectory with tracers, which are initialized along with the particles. These tracers are zero-buoyant and independent to any of the modeling restorations. Temperature (T) and salinity (S) are also typical tracers, which can be used to track the watermass by classical T–S analysis (You and Tomczak 1993), while the difficulty is that they adjust to the surface forcing, and hence, lose the signature of their water types. Instead, the passive tracers with zero surface forcing and restoration will keep their signature on their journey, while they undergo physical processes such as diffusion, turbulence, or mixing. Tracers are widely used in the comprehensive oceanographic study and water mass analysis (Jensen 2001, 2003).

This paper is also intended to find the effects of the ITF over the Indian Ocean. By contrasting a control model run with a “closed throughflow” run, Hirst and Godfrey (1993), Murtugudde et al. (1998), and Wajszcz (2002) have concluded that the ITF gives SST prints over the Indian Ocean at the immediate entrance region, the Somali upwelling region, and the southern Indian Ocean (south of 40°S). However, closing the channel by an artificial bridge and contrasting it with the reference run does not necessarily show only the direct effect of the ITF advection. Actually, any change in the dynamic field due to the closure will also be printed. Thus, it is important to identify whether these footprints are accompanied by the actual track or not.

The following are the goals of this study: 1) to establish a detailed three-dimensional flow pattern of the ITF over the Indian Ocean (especially the ITF entrance region at the Indonesian Straits and the Somali upwelling region where the ITF routes are significantly redirected) by following both the Lagrangian-type trajectories and the passive tracer pathways along with the temperature and salinity; 2) to determine the significance of seasonal changes in the Indian Ocean in spreading the ITF pathways; and 3) to examine the effects of the ITF on temperature and salinity over the Indian Ocean by contrasting the reference case against the “no throughflow” case and support the findings using the pathways. The following is the structure of this article. Section 2 introduces the model experiments and methods. In section 3, significance of seasonality in the spreading of pathways is described using Lagrangian trajectories, and a comparison with tracer pathways is shown in section 4. In section 5, the effects of the ITF over the Indian Ocean are described followed by the discussion in section 6. The conclusions are given in section 7.

2. Model description and method of study

a. General description

The model we used in this study is the Australian Community Ocean Model version 2.0 (ACOM), which is a modified version of Modular Ocean Model version 2 [see Schiller et al. (2002) for a detailed description of the model]. It is a primitive equation z-coordinate ocean model cast in the B-grid. ACOM adopts a hybrid vertical mixing scheme by Chen et al. (1994) by associating the Kraus–Turner-type mixing (entrainment is directly related to the surface momentum and buoyancy flux) and the Richardson number–dependent mixing (Price et al. 1986). The hybrid scheme improves the simulation of the mixed layer deepening in the strong vertical shear region (the dominant part of the Rich-
ardson number–dependent scheme) and in the high latitude due to wind stirring and convective overturning (the dominant part of the Kraus–Turner type). In the southern latitudes (south of 40°S) the effects of the ITF appear at the surface by following the convective overturning and wintertime cooling (Hirst and Godfrey 1993; Wajswie 2002).

The model domain contains both the Indian Ocean and the Pacific Ocean from 40°N–65°S, 0°–290°E with a constant resolution of 1° × 0.5° (longitude by latitude) and with 25 vertical levels (first 16 in the upper 300 m). The topography is selected from ETOPO5 to keep the straits reasonably realistic. Closed circulation around Australia is permitted. At the northern and southern boundaries, sponges are applied to the temperature and salinity taken from Levitus and Boyer (1994). Since the model domain engulfs the complete path of the ITF at the south (i.e., around 60°S), there is no requirement of additional water supply to conserve the volume as far as the ITF is concerned. However, the western side of the model domain (0°E and north of 55°S) is blocked by solid walls. Hence, the water supply from the Atlantic is explicitly set to zero. In the south of 55°S to the southern boundary (65°S), a cyclic boundary is applied at the east and the west boundaries. This regulates the strength of the Atlantic Circumpolar Current (ACC) nearly 65 Sv (south of 45°S), and thus the interior model solution of the Indian Ocean is not strongly affected by the boundaries.

The horizontal viscosity and diffusion are estimated using constant coefficients 4 × 10^5 and 2 × 10^5 m^2 s^-1, respectively. The model-produced Somali Current exceeds 2 m s^-1 on the full onset of the monsoon and is comparable with observations of Schott et al. (1990). The model Agulhas Current is 64 Sv and is comparable with the observed value of 70 Sv by Bryden and Beal (2001). The choice of higher horizontal diffusion is related with computational stability. The vertical viscosity and diffusion coefficients [which are being parameterized in Chen et al. (1994)] are given background values of 1 × 10^-6 and 2 × 10^-5 m^2 s^-1, respectively. The excessive deepening of convective mixing at the higher latitude found in the model is likely due to the weak density stratification. This large vertical diffusion offsets the underestimate of poleward heat transfer caused by the large horizontal viscosity (Bryan 1987).

The model is spun up for 20 yr (sufficient for upper 500-m evolution) forced with monthly wind stresses derived from Hellingman and Rosenstein (1983). Monthly shortwave flux is derived from Josey et al. (1999). Latent heat flux is estimated using the model SST and relative humidity data derived from the Comprehensive Ocean–Atmosphere Data Set (COADS). Longwave radiation and sensible heat flux are kept constant [refer to Schiller et al. (2002) for the estimation of heat fluxes of ACOM]. Although the SST is calculated from the heat flux, a restoring force is also applied to SST (time scale of 30 days) so that it is constrained within a realistic range near the climatology. This restoration to the climatological values is likely to produce an imprint of the ITF in the no throughflow run. Sea surface salinity (SSS) is restored to monthly climatology according to Levitus and Boyer (1994).

b. Methods and experiment cases

Throughout this paper, the climatological ocean (reference case) is referred to as CASE-Ref. Lagrangian trajectories of the ITF are produced using the instantaneous velocity fields derived from the CASE-Ref. Particles are initialized at the Indonesian Straits in a box 20°S–10°N, 110°–140°E and 0–500 m. Twenty thousand particles are uniformly initialized on the first of January (20 000 is a relatively large number and virtually equivalent to a sequential initialization in one year). Trajectories are traced for more than 20 yr, noting that the particle will not undergo vertical and horizontal mixing. Moreover, we do not make any explicit additions to the velocity field for accounting the diffusion or turbulence.

To identify the importance of vertical and horizontal mixing in spreading the ITF pathways, we released six tracers at the ITF entrance region in the CASE-Ref. These are “passive tracers” (no surface forcing and no restoration to the predefined values). Tracers are initialized at different depth levels. Tracers 1 through 5 are in order from the surface to depths with approximately 60-m vertical intervals and tracer 6 extends to the bottom. We will compare the “Lagrangian trajectories” with the “tracer pathways,” and the differences will be attributed to the reasonable physical mechanism for making such differences. All tracers are run for 5 yr.

An artificial pathway of the ITF is found from the annual mean velocity field derived from the CASE-Ref. This is meant to identify the importance of seasonality in spreading the ITF pathways in the Indian Ocean and is referred to as CASE-An. Finally, an artificial ocean with no throughflow is produced by putting a “land bridge” across the Indonesian Straits so that no throughflow is permitted. It is run for 15 yr starting from the restart of the reference case and is referred to as CASE-No. By this time, the ocean reaches another steady state adjusting to the closure of the ITF. We will contrast CASE-No with CASE-Ref to find the effects of the ITF in the temperature and salinity over the Indian Ocean.
c. Model climatology: CASE-Ref

The detailed results of ACOM2.0 simulations have been reported by Schiller et al. (2002). Figure 1 shows the model seasonal circulation of the upper 50 m of the Indian Ocean [for an excellent review of monsoon circulations over the Indian Ocean, refer to Schott and McCreary (2001) and Shankar and Vinayachandran (2002)]. Large-scale monsoon circulation features like the Summer Monsoon Current (SMC), South Equatorial Current (SEC), and Somali Current (SC) in the boreal summer and the North Equatorial Current (NEC), SEC, and reversed SC in the boreal winter are reproduced reasonably well in the model. The Southern Gear (SG; 4°N) and Great Whirl (GW; 10°N) are simulated well in the model although the former is weakly evolved. This discrepancy may be due to the high diffusion values of the model. The model Wyrtki Jet [or Equatorial Jet (EJ)] is stronger in the spring season (February–April) than that in the fall season (September–November). This is not consistent with the observations of Reppin et al. (1999). The EJ simulations of the model are reviewed in Schott and McCreary (2001), who attributed this common difference in the model studies to the discrepancy in the numerous wind datasets. Interestingly, when our model is forced with the daily scatterometer wind stress, a strong EJ is produced in the fall season.

A reasonable simulation of propagating features with about 500-km scales is important in spreading the pathways. The ITF is blended especially well at the equatorial Indian Ocean by the seasonal circulations (Haines et al. 1999). Typically, the model reproduces the westward-propagating anticyclonic vorticity north of the equator formed by the nonlinear interaction between the SMC and reflected Rossby waves from the eastern boundary (Vinayachandran and Yamagata 1998). The vorticity east of Sri Lanka (Vinayachandran and Yamagata 1998) was also well simulated. However, the recently found equatorial “Twin Gyre” by Rahul et al. (2004) is not well evolved, which is attributed to the coarse resolution of the model in simulating such a fine mesoscale feature.

The model-produced ITF seasonal transport is shown in Fig. 2. The model has two openings in the Indonesian seas representing the Lombok (300 m) and Timor (1100 m) Straits. The throughflow is permitted through the Makassar Strait, Banda seas, and Java seas (Masumoto and Yamagata 1993; Gordon and Fine 1996). Papua New Guinea is connected to Australia, and Torres Sea is closed since it is not a significantly important route of the ITF to the Indian Ocean (Wajsowicz 2002). In the model, the annual mean volume transport over the upper 300 m is nearly 6 Sv for the Timor Strait and 4 Sv for the Lombok Strait. These values are higher than the observations of Molcard et al. (1996) and Vranes et al. (2002).

The model produced annual mean volume transport of the net ITF over the upper 300 m is about 10 Sv (Fig. 2c). The seasonal transports of the ITF are in good agreement with the model simulations of Murtugudde et al. (1998), Masumoto and Yamagata (1993), and Potemra (1999). However, observations show that the
ITF transport profile vertically extends to deeper levels (300–1000 m; Molcard et al. 1996). The geostrophic transport estimated from intensive hydrographic observations suggests a weak ITF signal at 400 m (Qu and Meyers 2005). Song and Gordon (2004) noticed that, with a given net transport of 10 Sv, the more subsurface-intensified transport warms the subsurface but reduces the basinwide SST of the entire Indian Ocean. They suggested the necessity of resolving an adequate ITF profile in OGCMS. Since the SST is restored to the climatology in the present study, we expect that the basinwide ITF trajectories are not changed by the slight density difference in the vertical profile of ITF transport. The trajectories are examined with a focus on those initially given below 300 m and will be confirmed to be similar to those above 300 m.

3. Lagrangian trajectory

a. Seasonal trajectories of ITF

The instantaneous Lagrangian trajectories are shown in the Fig. 3 for the different vertical levels of initialization. Trajectories of 110 particles in 20 yr are shown with a period of one month (each dot corresponds to one month). Depth information of the particles is coded by different colors.

1) The entrance region

An important difference in the trajectories between the surface (above 60 m) and the subsurface particles at the entrance region is that the surface particles turn anticyclonic and reach the northwestern coast of Australia and subduct there (zone A in Fig. 3). The surface

Fig. 2. Seasonal cycle of volume transport above 300 m across the (a) Lombok and (b) Timor Straits. Cross-strait transport is shown. Contour intervals are 0.5 Sv degree^{-1}. (c) Seasonal cycle of net ITF above 300 m (in Sv). Negative value indicates transport into the Indian Ocean.
geostrophic transport in the southeastern Indian Ocean is anticyclonic centered at 13°–15°S [see Qu and Meyers (2005) for a recent estimate]. Also a few particles flow along the coast of Australia as part of the Leeuwin Current (Smith et al. 1991) and reach northwest Australia. After subducting, the particles turn northwestern at a greater depth (>200 m) and travel across the Indian Ocean from east to west. In contrast, the subsurface particles follow a narrow jet-like path from the entrance region and travel westward across the Indian Ocean without much deviation from the depth of initial distribution.
Following this anticyclonic and southward transport, the warm ITF cools at higher latitudes and subducts at the coast, and later, takes a deeper pathway across the Indian Ocean. In the real ocean, this subduction is enhanced by the onshore geostrophic transport, which piles up the sea level at the western coast of Australia. This onshore geostrophic current dominates the wind-driven offshore Ekman drift (Smith et al. 1991; Hirst and Godfrey 1993). It is important to notice that the cooling of the ITF surface profiles at the entrance region by the air–sea exchange potentially modifies its net heat export to the Indian Ocean. This feature is not evident in SGV, because their depth of initialization was on the \( \sigma_\theta = 24.0 \) level, which is nearly 100-m depth.

The subduction of relatively fresh and warm surface ITF at northwestern Australia suggests an enhanced vertical mixing due to the surface buoyancy flux. In a recent study, the seasonal heat budget of mixed layer in the southeastern Indian Ocean is examined using satellite observations and a high-resolution OGCM by Yan et al. (2005). In northwest Australia, the surface heat flux is controlling the seasonal variation of SST. Our particle trajectories show that, in this regime, the vertical mixing might cool the surface ITF entrained into the main thermocline. In the subsurface (>200 m), the northwestward component of the geostrophic current associated with the subtropical gyre (Schott and McCreary 2001; Qu and Meyers 2005) carries this water to the west along the main thermocline, where it meets the subsurface ITF.

The surface cooling of ITF at this zone can be substantiated by looking at the observed latent heat flux. In Fig. 4, the climatological latent heat flux (positive value for heat flux out of the ocean) compiled from COADS (da Silva et al. 1994) is shown for the two seasons along with the wind stress vectors from Hellerman and Rosenstein (1983). The latent heat flux shows an enhanced cooling in July off northwestern Australia, in a similar “shape” of the enhanced mixing zone suggested by the particle trajectories. The wind stress curl is not downwelling favorable at this region during this season.

An important question is how much of this heat release can substantiate the cooling of ITF and its subsequent subduction to the subsurface. The heat transport of the surface ITF to the Indian Ocean through the straits can be retrieved from the temperature and density observations of the World Ocean Atlas (Levitus and Boyer 1994) and the average surface transport (above 50 m) in the model as

\[
Q = C_p \int_{50}^{\infty} \rho u(\theta - \theta_0) \, dp.
\]

Here \( \theta \) is the ITF temperature profile at the opening of the straits and \( \theta_0 \) is the cooled temperature profile as observed in the subsurface of northwest of Australia (an average value over 50–100 m is used for \( \theta_0 \)). This would yield the necessary cooling of the surface ITF in order to sink to the subsurface. Also a heat release to the atmosphere over the same region is estimated from the latent heat flux in COADS, and a quantitative comparison of these two terms will help us to understand the effect of air–sea cooling in the subduction of surface ITF stream. Thus, the estimated cooling of ITF and the heat release to the atmosphere over an area off northwestern Australia (shown in Fig. 4) are given in Table 1. The necessary cooling for the subduction, especially in August while the ITF has maximum transport to the Indian Ocean, is only a half of the total air–sea cooling. This implies that the surface ITF flows southward, gradually cools in the higher latitudes, and sinks to the subsurface.

A more detailed seasonal variability in the deepening
of ITF at this pocket will be shown later using the tracer analysis. It is worth mentioning that the thermocline variability of this region is influenced by the remote wave energy propagating from the western Pacific as coastal Kelvin waves and radiating Rossby waves (Potemra 2001; Wijffels and Meyers 2004).

2) ACROSS THE INDIAN OCEAN

Both shallow and deep Lagrangian routes of the ITF show a narrow jet-like pathway bound from 8° to 20°S across the Indian Ocean from east to west. At the western boundary, most of Lagrangian trajectories turn to the northern Indian Ocean, while some turn around the northern tip of Madagascar and flow to the southern Indian Ocean through either side. The particles flowing southward along the eastern coast of Madagascar do not immediately join the ACC. They are instead entrained into the Southern Gyre (SGY) and take several loops within the gyre (see Figs. 3a,b).

At the northern tip of Madagascar, very few trajectories turn to the south compared to those in SGV. This difference may be attributable to diffusion, since our trajectories do not account for diffusion or turbulence explicitly and the particles follow a mean flow rather than a meandering path. In the real ocean, the northeastern coast of Madagascar is occupied by energetic eddies related to maritime cyclonic activities (Xie et al. 2002). These eddies play a crucial role in determining the pathways of the ITF at the western boundary of the Indian Ocean. Our tracer result will be shown later with a more southward turning of the ITF at the northern tip of Madagascar.

The particles enter the Somali region in a depth range above 500 m. Some of these deeper particles are initialized at the surface (above 50 m) in the Indonesian Straits. Thus, they are the representatives of the maximum temperature profile related with the ITF. However, the immediate turning to the south at the entrance region and the coastal subduction by the atmospheric cooling have mitigated its temperature to a lower value.

At the Somali Coast, the particles are mainly redistributed into three routes. These are 1) across the Indian Ocean just to the south of the equator, 2) across the Indian Ocean to the north of the equator, and 3) upwelling at the Somali region and intrusion into the Arabian Sea as well as the central Indian Ocean. These distinct routes are shown by selecting typical particle trajectories and are given in Fig. 3 (bottom) separately. These will be dictated as routes 1, 2, and 3 hereafter. Here, we note that these distinct routes have different depth ranges. Route 1 is always found to be at deeper depths (>200 m). Route 2 is intermediate at a depth range of 100–200 m. Route 3 is the shallowest pathway due to the upwelling at the Somali Coast. Thus, it is evident from the trajectories that the ITF pathways have a gradual downslope from the northern Indian Ocean to the equatorial region.

Route 1 flows to the east, across the Indian Ocean to the south of the equator, following the annual mean South Equatorial Gyre (SEG). In the eastern Indian Ocean, these particles turn to the south and reach the subduction zone (30°S), where they subduct. After subduction, these particles take a deeper route, across the Indian Ocean to the west and exit through the Agulhas region. However, some of the particles in route 1 do not undergo subduction, instead they join the South Equatorial Current (i.e., 15°S) and recirculate into the northern Indian Ocean at the western boundary. Thus, they repeat the same route or take a route at a different depth.

Route 2 is being flushed in the equatorial region due to the seasonally varying currents. At the southern tip of Sri Lanka, these particles intrude into the Bay of Bengal by following the intrusion of the SMC. These are the main pathways of the ITF into the Bay of Bengal. In a model study with buoys in the Bay of Bengal traced backward for six years, Jensen (2003) showed a pathway stretching back to the Somali region and suggested that these watermasses might be partially derived from the ITF. In our analysis, we can confirm that the ITF watermass reaches up to the Bay of Bengal following route 2. In the Bay of Bengal, these particles are brought to the surface due to cyclonic vorticity and associated open-ocean upwelling at the eastern coast of Sri Lanka during the summer monsoon (Vinayachandran and Yamagata 1998). Thus, apart from the Somali upwelling region, the ITF upwells to the surface in the east to Sri Lanka and is the major pathway of route 2 particles to the surface. After upwelling, the particles flow northward along the coast and reach the northern part of the bay. They are trapped there by the seasonally reversing coastal currents for a longer time. The ventilation time of these particles from the Bay of Bengal is several years (>20 yr; You and Tomczak 1993). The age of the ITF in the Bay of Bengal is estimated to be
more than 20 yr by SGV, and it is consistent with our results.

The ITF along routes 2 and 3 crosses the equator following the annual mean southward Ekman transport and the shallow meridional overturning circulations of the equatorial region. Our particles change depth across the equator (Figs. 3a,b), indicating the shallow overturning stated by Miyama et al. (2003). To illustrate the cross-equatorial ITF pathways from north to south, we elucidate trajectories of two particles separately in Fig. 5. These particles are originally traced from the ITF entrance region, however only necessary parts of their pathways are shown, where they cross the equator from north to south. The trajectories in the $y$–$z$ plane are also shown in Fig. 5. The shallow meridional overturning during the summer monsoon season is overlaid as vectors in this $y$–$z$ plane. The meridional section is averaged zonally over 7.5°, one either side of the position where the particles cross the equator. The shallow meridional overturning in the equatorial Indian
Ocean reverses its direction seasonally, with a northward (southward) surface (subsurface) current in the summer monsoon and southward (northward) surface (subsurface) current in the winter monsoon (Schott et al. 2002; Miyama et al. 2003). It is clear that the particles undergo this overturning pathway as they eventually cross the equator.

To illustrate the percentage concentration of particles crossing the equator from north to south after upwelling at various pockets (Somali coast, Arabian coast, and Bay of Bengal) in 20 yr of our trajectory, the equator-crossing particles (from north to south) are counted and shown as a zonal section at the equator from 60° to 100°E in Fig. 5 (bottom). Almost every particle crosses the equator in a shallow range above 100 m, as is explained by the overturning pathways. The total concentration is obtained by integrating this section zonally, and it is 38% of particles in routes 2 and 3. This is the relative concentration crossing in 20 yr, and all the particles in routes 2 and 3 will be crossing the equator following the same pathway in a longer time. The residence time for Bay of Bengal particles is more than 20 yr.

After crossing the equator, some of these particles reach the western Indian Ocean by following the SEC and reenter the northern Indian Ocean along the Somali Current, while the majority undergoes subduction at the subduction zone (20°–30°S). The subductive pathways take an anticyclonic route at the subduction zone, return to a northwest direction, and rejoin the southern gyre (see Figs. 3a,b). These particles flow to the south of the ITF jet and eventually exit via the Mozambique channel. This is a well-known trajectory.

b. Seasonal uptake of the ITF via the Somali Coast

The particles of route 3 upwell at the Somali Coast. The Somali upwelling is not along the entire stretch of the Somalia Coast but is concentrated on the northern flank of the individual gears called SG (0°–4°N) and GW (8°–10°N; Schott et al. 2002). On counting the number of particles crossing the 50-m depth upward and downward at the Somali upwelling zone, SGV have concluded that there are two zones of upwelling (one is at the Somali Coast and the other is along the equator) and one zone of downwelling between the two. After upwelling at the Somali Coast, the particles eventually turn to the east and spread all over the northern Indian Ocean exhibiting mostly chaotic seasonal pathways. In addition to the Somali region, the minority of particles upwell along the Arabian Coast and intrude into the Arabian Sea following the coastal currents (Shetye et al. 1991).

The seasonally reversing Somali Current needs further attention in evaluating the uptake and the rerouting of the ITF into the northern Indian Ocean. The vertical structures of the observed seasonal currents along the Somali Coast (Schott et al. 1990) are as follows: during the summer monsoon, the surface current is strongly northward, and during the winter monsoon, the current in the surface level reverses by keeping a northward subsurface component. Our model reproduces the seasonal cycles of the Somali current reasonably well and in good agreement with the observations of Schott et al. (1990).

We have conducted a separate experiment of particle release immediate to the southern Somali region following the main pathways of the ITF. This experiment enables us to navigate the particles along the Somali coast depending on the season. The particles are released so that they reach the Somali coast in April (for summer monsoon) and November (for winter monsoon). The region of particle release for this experiment is shown in the box in Fig. 3a. To get a quantitative assessment of the uptake of the ITF to the northern Indian Ocean along the Somali coast, we count the number of particles in a 2° × 2° bin and integrate them over an area representing the Somali region. It is noted that this area is confined to the north of the equator. The integration is also carried out vertically into 0–50 and 100–200 m for representing routes 3 and 2, respectively. The results for the two seasons (summer and winter) are shown in Fig. 6.

The seasonal trajectory analysis shows that route 3 is prominent during the summer monsoon, whereas route 2 is prominent during the winter monsoon. During the summer monsoon, the Somali Current is northward and strongest in the full onset of the monsoon (July–August). In Fig. 6, as the monsoon approaches, the surface uptake of the ITF gradually increases (line A). A sudden increase in the surface concentration during the full onset of monsoon is clearly evident from line A. Simultaneously, the concentration of particles in the subsurface level (100–200 m; line B) decreases. This is well explained by the upwelling of the particles at the Somali coast since they disappear from the subsurface level. Thus, during the summer monsoon, the uptake of the ITF to the northern Indian Ocean and its immediate upwelling cause route 3 to be dominant.

In the winter monsoon the situation is the opposite. Here, the surface current changes direction and flows southward along the Somali coast, however, the subsurface current keeps a northward component. The particle concentration at the surface level is reduced during the winter monsoon, while in the subsurface level, the particles intrude into the northern Indian Ocean along the Somali Coast and do not show up to
the surface because of the coastal downwelling. This causes route 2 to be prominent during the winter monsoon.

c. Annual mean field trajectory: CASE-An

In a similar study, Haines et al. (1999) found the annual component of the ITF spreading pathways over the Indian Ocean in a limited ocean model basin. They concentrated on the trajectories of the Indian Ocean by the initialization of particles at the southern boundary (around 30°S) and the ITF entrance region and concluded that the annual component dominates over the seasonal pathways. However, there is a possibility to renew information by examining a three-dimensional trajectory. The annual mean circulation field derived from CASE-Ref is used to find differences in the trajectories of the ITF from the velocity field including the seasonal cycle.

From the annual mean trajectories shown in Figs. 3c,d, we note that at the entrance region, the annual mean pathways do not alter much from the seasonal pathways. It is quite obvious that the annual mean surface circulation is anticyclonic in the southeastern Indian Ocean. Also the immediate southward flow along the coastal shelf at the entrance region is related to the prevailing Leeuwin Current, which flows annually southward (Smith et al. 1991).

In the southern Indian Ocean the annual mean pathways do not provide any additional information over the seasonal pathways, as expected. The annual mean circulation has a well-defined subtropical anticyclonic gyre in the southern Indian Ocean. Following the westward drift in this subtropical gyre, the majority of the annual mean pathways turn northward along the Somali coast. At the Somali coast, the dominance of the GW in the annual mean circulation field causes the particles to upwell to the surface. The main difference between the annual mean flow and the seasonal flow is that the trajectories are well smoothened in the Northern Hemisphere and chaotic paths do not exist. In addition, the particles along the annual mean pathways stay shorter in the northern Indian Ocean and cross the equator at the eastern boundary without wide distribution. Thus, the seasonality has a significant role not only to spread the pathways but also to keep the ITF much longer in the northern Indian Ocean. The ventilation time is increased by the seasonality.

The intrusion of the ITF into the Bay of Bengal is also visible in the annual mean trajectories. The spreading of annual mean trajectories in the eastern equatorial Indian Ocean is associated with the vortices due to the Wyrtki Jet reflection at the eastern boundary, which dominates in the annual level. This is consistent with the findings of Han et al. (1999) that the semianual spectrum of the Wyrtki Jet contains higher power and dominates the annual equatorial currents over the Indian Ocean. This annual domination of vorticity plays an important role in the intrusion of the ITF into the Bay of Bengal.

4. Tracer

The tracers are initialized at the same domain as the particles at the Indonesian Straits. Here, we also released the tracers only once (in January). These are passive tracers, with no surface forcing, equivalent to a dye of each color. Tracers are set to evolve with the same time step as those of the model integration (900 s). The horizontal diffusion coefficient is chosen as the same value as that used for temperature and salinity (i.e., $2 \times 10^3$ m$^2$ s$^{-1}$). It is run for not more than 15 yr.
However, we opt for discussion concerning the first 4-yr integration results. The discernible route of the ITF shown by the tracer fades in a longer integration time as it spreads all the way in the Indian Ocean by diffusion and mixing.

a. The entrance region

At the entrance region, the surface tracer subducts at the northwestern coast of Australia. This is in confirmation with the particle trajectories. However, the tracers are found well mixed vertically in the entrance region, which is not seen in the particle trajectories because particles cannot undergo diffusion. The vertical structures of the evolution of tracer 1 (distributed initially at 0–60 m) and tracer 2 (distributed initially at 60–120 m) at the entrance region are shown in Fig. 7, corresponding to a point representative of the western coast of Australia (23°S, 110°E). Mixing and subduction cause tracer 1 to deepen at the entrance region. Tracer 2 mixes with tracer 1 during the austral winter. In the real case, this mixing modifies the upper T-S structure of the ITF and also causes the mixed layer to deepen further. The surface cooling of the ITF profiles at the northwestern coast of Australia implies a subsequent heat release to the atmosphere. The mixing at the entrance region peaks during the boreal summer, when the ITF volume transport is maximum. The mixing is likely enhanced by the shear instability of the upper layer (Chen et al. 1994) in addition to the surface momentum flux. The critical limit of the gradient Richard-

![Fig. 7.](image_url)
son number, \( R_g = [(g/\bar{\rho}) \cdot (\partial \bar{\rho}/\partial z)][(\partial U/\partial z) \cdot (\partial U/\partial z)]^{-1} = (N/f_s) = 0.25 \), for the mixing depends on the ambient density stratification \( (N) \) and vertical velocity shear \( (f_s) \). The surface shear within the upper 30 m at the ITF entrance region is noted to be about a velocity difference of 8 cm s\(^{-1}\) in this upper layer during the boreal summer. This strong shear is found to dominate over the density stratification and results in a value of \( R_g < 0.25 \).

A typical feature found in the tracer at the entrance region is the upwelling along the southern Java–Sumatra coast, which contributes to bring the subsurface tracers to the surface. In Fig. 8e, tracer 5 (initialized at 300 m) is shown after four years of integration.

Fig. 8. Tracer integration after 4 yr. Tracer 1 (initialized at 0–60 m) and tracer 2 (initialized at 60–100 m) are shown in log scale for (a),(b) the surface and (c),(d) 100 m separately. (e) Tracer 5 (raw values) for the surface. (f) The vertical structure of tracers (sum of first four tracers) along 90° (shaded) and 60°E (contours) (raw values).
The higher concentration of tracer 5 in the surface level stretching from the southern Java–Sumatra coast shows the upwelling, which brings the subsurface tracer to the surface. The upwelling along the southern Java coast migrates westward by following the seasonal migration of the wind stress (Susanto et al. 2001). The higher concentrations of tracer 5 in the surface, along the western side of the southern Java–Sumatra coast, are attributed to this migration of upwelling.

b. Across the Indian Ocean

1) Advection

The tracer pathways across the Indian Ocean after four years of integration is shown in Fig. 8. The surface and subsurface (100 m) pathways of tracers 1 and 2 are shown in Figs. 8a,b and Figs. 8c,d, respectively. The meridional section of the sum of the first four tracers is also shown for (Fig. 8f) 60° and 90°E. The advective pathways of the tracer are generally in agreement with the particle trajectories. However, the pathways spread more widely. After subduction at the western coast of Australia, tracer 1 advects across the Indian Ocean at a deeper depth. This is evident by the appearance of tracer 1 at the 100-m level across the Indian Ocean in Fig. 8c. However, the tracers do not maintain a jet-like path like the particles, whereas they spread across the latitudes to the south. This is true for tracer 2 along the 100-m level as well (Fig. 8d).

The north–south separation of the tracers at the western boundary shows that the majority of the ITF turns to the northern Indian Ocean after bifurcating nearly at 11°S. This is in confirmation with the particle trajectories. The difference between tracer fluxes across two sections, each one representing the northward and southward component, is shown in Fig. 9a. The fluxes across sections A and B are found along the line shown in Fig. 9b, and the difference is taken between A and B, in which a positive value shows a major northward flux. It can be seen that, from the surface to 250 m, northward flux is the dominant component, with a maximum value located around 100 m. This is true throughout the year, although a small seasonal variability can be seen. In Fig. 9b, the annual mean flow field above 250 m is shown as vectors. The strong northward circulation causes the tracer to advect more into the north than escaping to the south.

The majority of tracer 1 (and also tracer 2) upwells at the Somali region and equatorial region. In a longer integration (>10 yr), tracers show up on the other upwelling zone, for instance, coastal Arabia and east of Sri Lanka in the Bay of Bengal. These regions are in confirmation with the particle trajectories. However there are exceptions, where the tracers show their presence in the sea surface in which the particles were absent. One typical region is a band extending from the western coast of Australia to the east coast of Madagascar bound between 20° and 30°S (Figs. 8a,b). The necessary mechanism for such features could be attributed to the planetary waves and will be interpreted in section 4b(3).

2) Diffusion

The deviation of tracer pathways from the particle trajectories can be partially attributed to the diffusive process. The effect of horizontal as well as vertical diffusion in the tracer pathways is found to be important at the ITF entrance region. The presence of tracer 2 in the sea surface well beyond the entrance region (Fig. 8b) can be explained by the vertical diffusion. Another region noted is the Mozambique channel where tracers 1 and 2 can be seen in the surface level (Fig. 8a).
addition to this, the horizontal diffusion causes the jet axis to spread out of the SEC, and so the tracers can escape from the main stream and flow to the south across the latitudes.

A sensitivity experiment is carried out, with different choices of horizontal diffusion coefficients \( (A_h) \) for the tracers. This will provide information about the spreading of tracers depending on horizontal diffusion. In this experiment, the tracers are uniformly initialized, from 60 to 210 m, at the ITF entrance region. Six tracers are initialized, each with different values of \( A_h \) ranging from \( 2 \times 10^3 \) to \( 6 \times 10^4 \) m² s⁻¹. The noticeable difference in the pathways between the tracers with minimum \( A_h \) (TR-min) and maximum \( A_h \) (TR-max) are explained here.

The tracer values of TR-min and TR-max are compared, across the various latitudes in the southern Indian Ocean. Since the TR-max spreads faster than the TR-min, the analysis is done at the fourth year of the output. By this time, both tracers occupy the southern Indian Ocean. The tracer concentrations are integrated over an area of 50° to 90°E and surface to 250 m. They are compared between TR-max and TR-min, as given in Table 2. It can be seen that the “diffusive erosion” of TR-min, over 25° to 35°S, is reduced to a factor of about 0.78 compared to that of TR-max. The factor decreases away from the ITF jet, which shows that the tracer with larger horizontal diffusion spreads far away from the main ITF jet. However, a major mechanism of spreading is advection, which works in common between the two cases.

3) Effects of Planetary Waves in Spreading the ITF Pathways

The annual Rossby wave in the southern tropical Indian Ocean (STIO; Periguad and Delecluse 1992; Masumoto and Meyers 1998) is examined for its significance in spreading the ITF pathways in our tracer analysis. Since the tracer evolves following linear dynamics and nonlinear wave propagation, it is apparent to show the propagation of planetary waves (Jensen 2003). In Figs. 10a and 10b, the surface pattern of tracer 2 (initialized at 60–120 m) after two years of integration is shown for September and March, respectively. It can be seen that the subsurface tracer has upwelled at the southern Java–Sumatra coast and reached to the surface. Note that the long-term decaying trend of the tracer is filtered out along with the subseasonal cycle using a Cosine–Lanczos filter, and only the annual component is retained. The phase shift between the surface patterns from Fig. 10a to Fig. 10b during the six months clearly shows the propagation of an annual Rossby wave. The phase propagation shown by the tracer is slightly shifted to a southwest direction rather than along the latitudes. The STIO Rossby wave is locally reinforced at 70°E and switches its sign (Murtugudde and Busalacchi 1999).

A time–distance section along a line drawn in Fig. 10b is shown in Fig. 10c. The section has a slight angle with respect to the latitude, which seems to be the apparent direction of phase propagation shown by the tracers. The propagation of an annual Rossby wave is evident. The Rossby wave shown by the tracer is analyzed for its meridional and zonal wavelengths. At 15°S and 90°E, the zonal wavelength is 4070 km and meridional wavelength is 1320 km. The annual Rossby wave that propagates exactly westward with these wavelengths corresponds to a phase speed of 13 cm s⁻¹. This is in a good agreement with the longwave approximation of the STIO Rossby waves suggested by Periguad and Delecluse (1992) and Masumoto and Meyers (1998). The annual Rossby waves propagating with southward components could be retrieved, although the numerical solution does not confirm such modes within the limited time–space distribution.

A typical feature found in tracer 1 (tracer 2 as well) at the surface level is a band of higher concentration stretching northwestward across the Indian Ocean from the western coast of Australia bound to 25°S (Figs. 8a,b), as noted in section 4b(1). This is, likely, a signature in a similar manner to the annual Rossby wave. The vertical motion associated with planetary waves can generate isolated patterns of tracer concentrations, at any particular depth, as observed in our solutions. However, a confirmation of this requires additional modeling experiments and research with this focus is underway.

In general, the basinwide distributions of the tracers are in good agreement with the particle trajectories. This agreement between the particles and tracers shows that it is the gradual advection following the large-scale circulation that determines the “basinwide pathway” of the ITF in the Indian Ocean. However, the processes
such as diffusion and mixing are important regionally, for example, the entrance region and the Mozambique channel.

5. No throughflow run: CASE-No

In this section we will concentrate on the effects of the ITF on temperature and salinity over the Indian Ocean following the major pathways of the ITF and contrasting the CASE-Ref with CASE-No. An artificial wall is placed across the Indonesian Straits by allowing no net throughflow. The artificial wall may permit the Kelvin wave originated in the eastern equatorial Indian Ocean (Sprintall et al. 2000) to pass through the Indonesian Archipelago and propagate poleward along the western coast of Australia. Except for this, the artificial wall is not expected to directly change anything in the model circulation. The run is produced for 15 yr from the restart point of CASE-Ref. After a few years of integration, the upper ocean (<500 m) reaches another equilibrium although the deeper level is still evolving, and does not affect the upper-ocean properties. An average of the last five years is used as CASE-No.

a. Difference in dynamic height

A contrast between CASE-Ref and CASE-No may yield all the possible impacts of the ITF over the hydrodynamics of the Indian Ocean. However, it results in both “direct effects” (due to the direct advection of the ITF) and “indirect effects” (due to the modification of the basinwide dynamics by the closure). The reason for the indirect effects is subjected to the large-scale
modification of the dynamic field in the Indian Ocean caused by the closure of relatively fresh and warm ITF. Figure 11 shows the dynamic height of CASE-Ref and CASE-No with respect to 500 m. The southern latitudes, where the ITF is flowing as a jet across the Indian Ocean, are elevated in CASE-Ref. This is related to the obvious freshwater at the ITF core. In the northern Indian Ocean, the dynamic height is relaxed in CASE-No compared to CASE-Ref. This difference is attributed to the lack of accumulation of the relatively fresh ITF in the upper 500 m. This relaxation of the dynamic height due to the closure of the ITF certainly implies a modification in the consequent basinwide structures. Therefore, the contrast between CASE-Ref and CASE-No in any field will also reflect these indirect effects. We will make use of the pathways of the ITF to categorize these effects.

b. Difference in temperature

Figure 12 shows the temperature difference for the surface and subsurface of (CASE-Ref − CASE-No). The significant SST “anomalies,” which are used here for the difference of CASE-Ref and CASE-No, are seen over the 1) entrance region, 2) Somali upwelling zone, 3) equatorial upwelling zone, and 4) south of 40°S. These regions are consistent with the findings of Wajsowicz (2002). In the regions 1, 2, and 3, the ITF pathway shows its presence at the surface. Thus, these can be concluded as the regions of the direct effects of the ITF on SST over the Indian Ocean, whereas, region 4 is not a representative surface pathway wherein the ITF travels at a deeper level (>400 m). Wajsowicz (2002) concluded that the winter time cooling and mixing bring the deeper ITF anomalies to the surface. Hirst and Godfrey (1993) suggested that the convective overturning at these latitudes decreases as a result of the closure of the ITF. Strikingly, our model mixed layer depth (MLD) has a distinct seasonal cycle for CASE-Ref and CASE-No at these latitudes. In the austral summer, the MLDs of CASE-Ref and CASE-No are comparable with each other. In the austral winter, the MLD of CASE-Ref increases by 50% compared to CASE-No. The reason is that the relatively fresh ITF at a deeper level in these latitudes enhances the convective overturning. Thus, the ITF gives pertinent SST anomalies at 40°S during the austral winter.

The subsurface temperature difference between CASE-Ref and CASE-No shows the direct impact of the ITF advection over the Indian Ocean. The anomaly extends as a belt bound to the ITF core from east to west across the Indian Ocean. The anomaly band is similar to tracer 2 (Fig. 8d) at these depths. The contribution of tracer 1 (or surface ITF) in the subsurface temperature is also important at 100 m, although it depends on the mitigation of its temperature signature at the western coast of Australia by winter cooling and subduction. The axis of the jet (ITF core across the Indian Ocean) shown by the temperature anomaly is shifted more southward than shown by tracer 2. An important difference between the temperature and the tracer is that the former is restored to the surface forcing. In the western Indian Ocean, the temperature difference at 100 m shows a positive value in the Mozambique channel. This is consistent with the presence of tracer 2 at these depths. At a deeper level (150 m), the temperature anomaly shows the subductive zone of tracer 1 extending from the northwestern coast of Australia. At 400-m depth, the anomaly is found to spread

Fig. 11. Dynamic heights with respect to 500 m for the (a) climatological model ocean (CASE-Ref) and (b) no throughflow run (CASE-No) are shown separately. Contour interval is 0.05 m. Values greater than 1.3 m are shaded gray. Values less than 1.05 m are shown as dotted contour. (Please note that dotted contour is not negative.)
into the southern Indian Ocean and is in confirmation with the return pathways of the ITF at these depths.

The indirect effects of the ITF in the SST anomaly are further discussed with explanations on the convection. Apart from the other world oceans, the Indian Ocean scenario is quite different at the southern latitudes. The warm ITF entering at the Indonesian Straits flows across the Indian Ocean and returns to the Pacific along the ACC confined to the north of 50° S. Thus the relatively warm ITF in the tropical southern Indian Ocean at a deeper depth enhances the thermohaline circulation as well as increases convective overturning in the southern portion where the warm and fresh ITF meets the relatively more saline and colder Antarctic water.

This deep convection is more apparent from the time series of the tracers along 40° S and is shown in Fig. 13. The solid (dashed) line represents the annual cycles of the zonally averaged tracer 2 along 40° S at 10 m (100 m). The tracer concentrations on both levels become identical when convective mixing occurs, as is evident during the austral winter. The increased vertical convection at these latitudes is indeed the mechanism that brings the deep ITF anomalies to the surface. Thus, the SST anomalies induced by the ITF at region 4 can be interpreted as the indirect effect of the ITF due to the modification in deep convection.

c. Difference in salinity

The salinity prints of the ITF over the Indian Ocean are shown in Fig. 14 for the surface and subsurface (100, 150, and 400 m). At the surface, the fresh ITF extends from the entrance region to the west. It is the coastal upwelling along the Sumatra coast that brings the subsurface ITF to the surface and advects to the southwestern direction. The core of freshwater extending from the Sumatra coast is evident in the salinity anomaly and is consistent with the presence of deeper-level tracers at the surface (Fig. 8e). The signature of the ITF in the salinity field at this region would also correspond to similar prints in the temperature field. However, a similar feature in the temperature field is not present in this region. The heat flux is adjusted to the climatological SST either in CASE-Ref and CASE-No so that the difference becomes minor.

In the northern Indian Ocean, the surface salinity anomaly shows a basinwide east–west contrast. In the eastern Indian Ocean, the surface is occupied with
freshwater, whereas in the western region the surface anomaly is more saline. In the Bay of Bengal, the ITF upwells to the east of Sri Lanka, and the presence of the freshwater anomaly is justifiable. The dynamic topography (Fig. 11) shows that the closure of the ITF relaxed the basinwide steric height in the northern Indian Ocean. In contrast relatively stronger upwelling occurs due to the ITF. However, the high salinity anomaly found in the Arabian Sea cannot be directly related to the ITF. It is the Arabian Sea High Salinity Water (ASHSW; Prasad and Ikeda 2002), which is strengthened as the ITF enhances Somali upwelling. If the ITF is closed, the weakened upwelling in the Somali region in CASE-No might truncate the seasonal spreading of the ASHWM.

A high salinity belt along 40°S in the surface level is not a footprint of the ITF water. In CASE-Ref, the low salinity ITF water tends to flow out meridionally across the southern latitudes. The closure of this freshwater influx reduces the meridional overturning and results in a saline anomaly. This is an indirect effect of the ITF.

In the subsurface level (100 m), the ITF is visible as
the low salinity band similar to tracer 2. This indicates the direct effects of the ITF advecting the salinity. Unlike the temperature anomaly the axis of the salinity anomaly at 100 m is the same as that of tracer 2. A saline anomaly extending from the southwestern coast of Australia across the Indian Ocean can be found in the subsurface levels (continuously in 100, 150, and 400 m). Neither the particle trajectories nor the tracer pathways support the presence of the ITF along this band, and hence, it is not the direct effect of the ITF water. In the climatological ocean (CASE-Ref), the dynamic height is elevated in the ITF core across the Indian Ocean (Fig. 11a). This strengthens the eastward geostrophic component in the surface level and a westward counter component in the deeper level (figure not shown) due to the thermal wind relations. This east–west overturning shifts the relatively high saline surface water of the central southern Indian Ocean toward the Australian coast, subducts there, and appears as a print of the saline anomaly at 100, 150, and 400 m. This is an indirect effect of the ITF.

6. Discussion

Our method to picture the three-dimensional pathways of the ITF using the Lagrangian trajectories and tracers enables us to categorize the various physical processes responsible for the spreading of the ITF in the Indian Ocean. The Lagrangian trajectories keep track of the ITF for a much longer time and give us a fundamental view of the three-dimensional flow. On the other hand, the tracers, which spread all over the ocean after several years of integration, potentially show the importance of diffusion, mixing, and turbulence in spreading the pathways in the real ocean. Distinct pathways of the surface and subsurface (>60 m) ITF are revealed by initializing particles at every 15-m interval from the surface in the entrance region above the thermocline depths.

Using the pathways revealed from our experiments, we portray a schematic view of three-dimensional pathways of the ITF in the Indian Ocean as shown in Fig. 15 (top). The distinct pathways are shown in different colors according to the depth ranges. The return pathway from the north of the equator to the south is shown as a dashed line. In Fig. 15 (bottom), the meridional structures of the ITF revealed from the Lagrangian particle trajectories and tracers are shown along 60°E. The shaded values show the number of particles counted in $2^\circ \times 2^\circ \times 50$ m bins. The cores of the individual routes (routes 1, 2, and 3) can be seen as large numbers of particles in the shaded values. The contours show the sum of all six tracers. In the northern Indian Ocean, the ITF resides along a downslope from the north to the equator owing to the northern upwelling zones (Somalia, Arabian Coasts, and Bay of Bengal). We notice that the meridional section of tracer pathways also has a similar depth-oriented distribution of the ITF. Thus, the redirection of the ITF into the distinct routes (routes 1, 2, and 3) in the Somali region is a major cause of the distinct depth ranges of the ITF.

The mixing and subduction of the surface ITF profile in the entrance region tells us that the upper-level heat input of the ITF into the Indian Ocean may release back to the atmosphere. In a coupled general circulation model, Schneider (1998) and Wajsowicz and Schneider (2001) have noticed a strengthened wind over the ITF entrance region due to the closure of the ITF. Thus, the release of heat into the atmosphere at the immediate entrance region has influence on the atmospheric pattern, which may in turn affect the ocean. However, the surface corrections for temperature and restoration of salinity to the climatological values may contaminate our “anomaly” fields of CASE-Ref — CASE-No. Moreover, CASE-No is run with climatological forcing, which has the influence of the ITF. The tracers upwell in the southern Java—Sumatra coast and may shed light on the role of the ITF in the evolution of the Indian Ocean dipole mode (IOD). The ITF contains the ENSO-related oceanic signal (Murtugudde et al. 1998) and is a useful component to connect ENSO and IOD through the ocean.

Some of the complex pathways, related to STIO Rossby waves, require further attention. The Rossby wave signature found in our tracer experiments suggests a possible spreading of the ITF pathways associated with it. The tracers have to be analyzed separately, for the geostrophic and ageostrophic components associated with these Rossby waves, and its significance in spreading the ITF pathways. It is also important to determine the vertical level, where the maximum velocity associated with these internal modes is located. In a 1&½ layer reduced gravity model with a 200-m layer thickness, Perigaud and Delecluse (1992) and Masumoto and Meyers (1998) have shown that the first baroclinic mode can substantiate the STIO annual signals. The seasonal and interannual variabilities of these Rossby waves and the associated ITF pathways give an interesting theme to study.

Since our model domain does not include the Atlantic Ocean completely, it is fair to point out the impacts of this limitation on our trajectory results shown here. We start with the discussion that the Agulhas retroreflection region (18°~22°E), where the Indian Ocean water exchanges with the Atlantic as pinched-off eddies (Boebel et al. 2003; Pichevin et al. 1999), is embedded...
in the model domain. The recent estimation of KAPEX-RAFOS float experiments near the Cape of Good Hope suggests an interocean exchange of mass flux through the Agulhas rings, though a precise estimation is unavailable yet (see issue on “Interocean Exchange around Southern Africa,” Deep-Sea Res. II, 2003, Vol. 50, No. 1).

We discuss whether our particle trajectories shown in the southwestern Indian Ocean are falsified by lack of its exchange with the Atlantic. The model Agulhas current is 64 Sv, which is close to the reality of 70 Sv, across a section along the Lowered Accoustic Doppler Current Profiler (LADCP) observation in Bryden and Beal (2001). In 20 yr of the numerical experiments, as the particles exit through the Agulhas Current, they immediately turn eastward and join the subtropical gyre without reaching the retroflection rings. In an additional sensitivity experiment, trajectories for 50 yr (produced with the monthly output of the 20-yr model solutions) show particles reaching the Agulhas rings, after circulating several loops in the subtropical gyre. Thus, we strongly suggest that the exchange with the Atlantic

Fig. 15. (top) Schematic view of the 3D pathways of the Indonesian Throughflow in the Indian Ocean as revealed from the particle trajectories and tracers. The cyan, blue, and red lines represent the depths 200–300, 100–200, and 0–100 m, respectively. The values labeled represent the percentage of particles on individual routes. The return pathway form north of the equator to the south is shown as dashed lines. (bottom) The meridional distribution of particles and tracers along 60°E. Shaded values are the number of particles counted in 2° × 2° × 50 m bins. Contour lines represent the tracer concentrations. The equatorward slope in the existence of ITF in the northern Indian Ocean is consistently evident from both the particles and tracers.
might take a longer time scale (longer than 20 yr), and the trajectories shown in this study for the first 20 yr are not falsified in the southern Indian Ocean. This is consistent with the results of SGV, whose trajectories recirculate into the Indian Ocean at the Agulhas retroflexion region on their 50-yr solutions. It is noted that, since a more realistic “pinching-off” may be crucial for exiting the ITF to the Atlantic, a fine-resolution model is required to resolve such trajectories.

Here, we note that the Atlantic exchange of the Indian Ocean water is not crucial in determining the spreading pathway of the ITF within the Indian Ocean. Comparison of our results with previous watermass tracing studies (Miyama et al. 2003; Jensen 2003), which included the Atlantic exchange, show that the spreading pathways of the ITF within the Indian Ocean, especially the major northward turning at the western Indian Ocean and the rerouting into distinct depth ranges, are determined by the Indian Ocean interior circulation.

7. Summary

For the first time, detailed three-dimensional trajectories of the ITF in the Indian Ocean are examined using a set of tools in an OGCM. They are 1) Lagrangian particles, 2) passive tracers, and 3) active tracers (temperature and salinity). The Lagrangian trajectories, devoid of diffusion and mixing, suggest that at the entrance region the surface ITF advects to the south and subducts at the northwestern coast of Australia, while the subsurface ITF (>60 m) advects across the Indian Ocean bound to 10°–20°S. At the western Indian Ocean, the particles bifurcate, and the majority advect to the northern Indian Ocean along the Somali coast. We note that, at the Somali coast, the ITF is redirected into three distinct depth ranges: route 1—across the Indian Ocean to the south of the equator (200–300 m); route 2—across the Indian Ocean to the north of the equator (100–200 m); and route 3—upwells in the Somali region and coastal Arabia and spreads all over the surface. Route 1 is associated with the South Equatorial Gyre, which is dominant throughout a year. Among the pathways that enter the northern Indian Ocean, route 2 is dominant during the winter monsoon (November–March), when the surface Somali Current is southward. In contrast, route 3 is dominant during the summer monsoon (April–October), when the Surface Somali Current is strongly northward, and is the most chaotic pathway owing to the seasonally reversing currents in the Indian Ocean.

The particles in route 2 upwell in the Bay of Bengal and reach the surface. The cross-equatorial pathways from north to south of routes 2 and 3 are followed by the annual mean southward Ekman transport linked by a shallow meridional overturning at the equator. Upon reaching the south, these particles undergo subduction in STIO, return to the west, and exit through the Mozambique channel.

On accounting for the diffusive processes and mixing in the passive tracers, they have revealed that the ITF undergoes vigorous mixing as soon as it enters the Indian Ocean and potentially modifies its upper T–S characteristics. The ITF subduction at the northwestern coast of Australia shows a consequent heat release to the atmosphere. On the way of its advection across the Indian Ocean to the west, the ITF undergoes diffusive erosion across the latitudes south of the main jet. In addition to this, the STIO annual Rossby waves are found to be responsible for spreading the ITF away from the main jet. These annual signals cause the thermocline ITF to interact with the surface. At the western boundary the northward component of tracer flux dominates over the southward component throughout the year.

The effects of the ITF on the temperature and salinity over the Indian Ocean are accompanied with its major pathways. In the southern Indian Ocean, the direct advection is responsible for the thermocline signature of the ITF. However, the ITF anomaly appears at the surface at 40°S, which is not accompanied by the major pathway and is due to the large-scale modification in the convective overturning, as proved with the tracers. The southern Java–Sumatra coastal upwelling causes the subsurface ITF to reach the surface, as evident in the tracer analysis. The subsequent surface salinity print of the ITF is clearly seen in this region.

The ITF resides in a shallow region of the northern Indian Ocean, owing to the major upwelling zone in the north, and gradually deepens toward the equator. This feature is consistently shown in the particle trajectories as well as tracer pathways. The ITF spreads in 20 yr almost everywhere over the thermocline depths in the Indian Ocean. The other side of interpretation is that the surface route of the Global Conveyor Belt, which is injected by the ITF into the Indian Ocean, is significantly modified in the Indian Ocean during its stay.

Acknowledgments. We sincerely acknowledge the financial support from the Ministry of Education, Science, Sports and Culture through the Center of Excellence (COE), Graduate School of Environmental Earth Sciences, Hokkaido University. The first author is also supported by the Mitsubishi Trust Yamamura Memorial Scholarship Foundation, Tokyo. The model and technical notes are provided by the CSIRO, Marine

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Research, Australia. The comments received on the presentation of this work on the Indian Ocean Modeling Workshop held at the International Pacific Research Center (IPRC), Hawaii, during December 2004, helped to improve the manuscript. S. Godfrey, A. Schiller, Q. Song, and N. Schneider are acknowledged for their comments, and R. Wajszowicz for her comments, in the earlier stages of this work. Comments from anonymous reviewers greatly helped to improve the quality of manuscript. T. Ikeda is acknowledged for proofreading. Ferret software (NOAA/PMEL) is used for plotting.

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