Interannual to Interdecadal Variabilities of the Indonesian Throughflow Source Water Pathways in the Pacific Ocean

VINU VALSALA AND SHAMIL MAKSYUTOV
CGER, National Institute for Environmental Studies, Tsukuba, Japan

RAGHU MURTUGUDDE
ESSIC, University of Maryland, College Park, College Park, Maryland

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ABSTRACT

Some of the possible interannual to interdecadal variabilities of the Indonesian Throughflow (ITF) source water pathways in the Pacific Ocean are identified from an ocean reanalysis product provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) under the name Ocean Reanalysis, version S3 (ORA-S3). The data were used in an offline mode to evolve adjoint pathways of a passive tracer, which is injected from the key channels of the Indonesian straits where the ITF enters into the Indian Ocean. The adjoint pathways are simulated using interannually varying circulations for 41 yr starting from December 2000 to January 1960 with reversed currents and other physical parameters (control run). A climatological run for the 41 yr is produced with the reversed currents and other physical parameters as a monthly climatology. The adjoint pathway variability is found by subtracting the climatological run from the control run. The empirical orthogonal function (EOF) analysis carried out over the monthly differences between the tracer concentrations of the control run and the climatological run shows that the ITF is largely supplied from the northwestern tropical Pacific during a normal year, whereas the supply from the south equatorial Pacific is dominant during El Niño–Southern Oscillation (ENSO) years at a lag of 6 months. The interannual variability of the ITF source water pathways in the Pacific is largely determined by the ENSO variability and they are confined to the tropical Pacific, whereas the corresponding interdecadal variability is controlled by the meridional overturning circulations in the tropical and subtropical Pacific. The adjoint pathways hint that the ITF volume transport may have interdecadal variability; they are closely related to the variability of the subtropical cells (STCs) in the Pacific Ocean and can be quantified using the tropical convergence changes. The ITF is just an active member of the recharge–discharge of tropical warm waters at all time scales, and its role in the coupled climate variability of the Indo-Pacific needs to be assessed in that context.

1. Introduction

The Indonesian Throughflow (ITF) is a system of currents transporting waters from the Pacific to the Indian Ocean via Indonesian straits (Gordon and Fine 1996). Observational estimates prior to 2002 suggested that the ITF transports roughly 10 Sv (1 Sv = 10⁶ m³ s⁻¹) of water from the tropical Pacific to the southeastern tropical Indian Ocean (Gordon and Fine 1996; Molcard et al. 1996; Fieux et al. 1994; Gordon et al. 2003; Vranes and Gordon 2005). However, recent observations made from the International Nusantara Stratification and Transport (INSTANT) current moorings suggest a significantly higher transport: that is, up to 15 Sv (Van Aken et al. 2009; Gordon et al. 2008, 2010; Sprintall et al. 2010; Atmadipoera et al. 2009). The ITF brings relatively warm and fresh tropical Pacific water to the Indian Ocean (You and Tomczak 1993; Song et al. 2004; Valsala and Ikeda 2007), which has an equivalent contribution of nearly 11 W m⁻² surface heat flux to the tropical Indian Ocean (Vranes et al. 2002).

The ITF net volume transport exhibits interannual variability according to the El Niño/La Niña cycles [El Niño–Southern Oscillation (ENSO); Meyers 1996; England and Huang 2005]. Generally an El Niño event is followed by a weak ITF volume transport. The negative anomalies of the ITF volume transport lag El Niño by approximately...
8 months. During El Niño years, the anomalous westerlies in the central equatorial Pacific and the subsequent downwelling oceanic equatorial Kelvin waves cause the thermocline in the eastern equatorial Pacific Ocean to deepen with a corresponding shoaling in the western equatorial Pacific (Neelin et al. 1998). Note that weak trade winds and the associated warm water discharge also have the same impact on the tropical Pacific thermocline (Yu and Mechoso 2001; Wang and Weisberg 1994). This causes the elevated pressure head in the western equatorial Pacific to relax and thereby causes a decrease in the water discharge: that is, the ITF from the Pacific to the Indian Ocean (Murtugudde et al. 1998). Gordon et al. (2008) attributed the low estimates of the ITF volume transport made during 1997–98 to the largest El Niño of the century during 1997.

The ITF has a significant influence on the climate of the Southeast Asian landmasses. The coupled atmosphere–ocean climate models simulated with/without the ITF have revealed that the ITF causes significant precipitation anomalies in the rim countries of Southeast Asia as well as in the Indian Ocean (Schneider 1998; Wajowicz and Schneider 2001). For example, the above two studies employed coupled general circulation models (GCM) to investigate the role of ITF in the global climate system. They concluded that the closure of the ITF in the GCM causes (i) an increase in the surface temperature (SST) centered on 190°E in the equatorial Pacific roughly by a magnitude of 1°C and a corresponding decrease in the SST in the eastern Indian Ocean by 0.6°C, (ii) a positive sea surface height anomaly in the western equatorial Pacific Ocean of about 30 cm and a negative anomaly in the southern tropical Indian Ocean of about 25 cm, (iii) a precipitation surplus of 3 mm day⁻¹ in the western Pacific and a similar amount of deficit rainfall in the eastern Indian Ocean and western Australia, (iv) a 10–20 W m⁻² heat flux into the eastern Indian Ocean with a 10 W m⁻² efflux from the equatorial Pacific, and (iv) an eastward shift in the centers of the deep convection and warming in the central Pacific.

The ITF is driven by the pressure gradient from the Pacific to the Indian Ocean through the Indonesian Seas (Wyrtki 1987; Inoue and Welsh 1993). Godfrey (1989, 1996) put forward the theory that the depth-integrated flow around Australia can be expressed as summation of line integrals of wind stress along 44°S, around Australia can be expressed as summation of line integrals of wind stress along 44°S, where the flow is...
volume transport of the ITF almost entirely. However, it does not represent the in situ ITF water mass, because the wind-driven circulation slowly advects the water over the years through its circuitous path into the tropics and eventually forms the ITF in the western equatorial Pacific. The interannual variability in the tropical Pacific Ocean circulation and changes in the atmospheric forcing can therefore cause significant changes in the source water properties of the ITF. Previous studies have demonstrated that the net volume transport of the ITF correlates with ENSO (England and Huang 2005). However, the effect of such interannual anomalies on the source waters of the ITF and their origin are poorly known.

The motivation for investigating the ITF source water variability can be stated as follows: The water properties of the ITF have important implications for the Indian Ocean freshwater and heat budget (You and Tomczak 1993; Piola and Gordon 1984; Toole and Raymer 1985; Vranes et al. 2002; Potemra and Schneider 2007). The ITF properties are also key for the Pacific Ocean warm pool precipitation (Jochum and Potemra 2008). The properties of the ITF can be considered as a function of the properties of its source waters. For example, the observations suggest a clear partitioning of upper-thermocline low-salinity ITF waters from the lower-thermocline high-salinity waters. These clearly distinguishable properties are caused by the distinct origins of source waters in the Pacific. Therefore, a variability in the supply of these source waters could have implications for the composition of the ITF; the focus here is the impact of interannual to interdecadal climate variability on the source waters. This can potentially alter the Indian Ocean freshwater and heat budgets induced by the ITF. Therefore, it is important to clearly identify the source waters of the ITF from the Pacific Ocean supply side and assess its spatial and temporal variability. Establishing a picture of this variability is the primary focus of this study.

ITF is the only low-latitude oceanic connection between two large ocean basins. Therefore, the discharge of water from the Pacific basin to the Indian Ocean via ITF is crucial in the mass balance of these two oceans. The OGCM experiments show that, if the ITF were absent, the pressure head in the western Pacific would increase by several tens of centimeters (Hirst and Godfrey 1993; Schneider 1998), which can potentially alter the basin-scale circulation of both the Pacific and Indian Oceans. However, the above mean picture may have significant amount of interannual variability. That means that the anomalous circulation in the Pacific Ocean may show preferences to choose which water to supply to the ITF. This, in turn, may have role in determining the variability of structure and dynamics of both the basins. However, our understanding of these issues is not extensive as the fate of the ITF waters in the Indian Ocean (see Valsala et al. 2010b). Therefore, we consider that it is important at first to look at the variability of ITF source waters in the Pacific and identify what controls variability. This article endeavors to answer the following questions: (i) What are the regions in the Pacific Ocean where the ITF water originates? (ii) Does the supply of the ITF exhibit any interannual variability? (iii) What controls the ITF source waters in the Pacific and how is it linked to the Pacific Ocean circulation?

The following is the structure of the presentation of this study: Section 2 describes the method, data, and model used in this study. Section 3 describes the ITF source water variability in the Pacific from 41 yr of data and model analysis. Section 4 offers a discussion and some conclusions drawn by the paper.

2. Data, model, and methods

a. Dataset

The data and model used in this study are similar to those used in Valsala et al. (2010b). Therefore, only a brief description is included here. In this study, we used an ocean reanalysis product to find the source waters of the ITF in the Pacific Ocean. The operational ocean reanalysis product employs an optimal interpolation method for data assimilation and is provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) under the name Ocean Reanalysis version S3 (ORA-S3; Balmaseda et al. 2008). The main datasets used in the assimilation system consist of historical 4D temperature and salinity (upper 2000 m), number of mooring observations, Argo profiles, and sea surface altimetry measurements. The ocean is forced with fluxes derived from the 40-yr ECMWF Re-Analysis (ERA-40) and Enhanced Ocean Data Assimilation and Climate Prediction/ Ensemble Based Predictions of Climate Changes and Their Impacts (ENACT/ENSEMBLES) quality controlled datasets. The ORA-S3 is generated on a Hamburg Ocean Primitive Equation-Optimal Interpolation (HOPE-OI) grid. The horizontal resolution is \(1^\circ \times 1^\circ\) with an equatorial refinement: that is, the meridional resolution increases gradually toward the equator, where it is 0.3\(^\circ\) in the meridional direction. There are 29 levels in the vertical, with a typical thickness level of 10 m in the upper ocean. Vertical mixing is based on Peters et al. (1988), and the barotropic solver, originally implicit, was made explicit as described in Anderson and Balmaseda (2005). The ORA-S3 data are available at monthly intervals from 1959 to the present, but we only employ the data from 1960 to 2000 in this study.

b. Transport model

To identify the source water pathway variability of the ITF in the Pacific, we employed an offline tracer transport
model as documented in Valsala et al. (2008), Valsala (2009), and Valsala et al. (2010a,b). In this model, the circulation, temperature, salinity and other diagnostic physical parameters are used in an offline mode to evolve an advection–diffusion passive tracer. We obtained the horizontal circulation fields, temperature, salinity, mixed layer depth, freshwater flux, net surface heat flux, and sea surface height from the ORA-S3 product. Vertical velocities are computed by applying mass conservation in each level. The surface boundary exchanges freshwater with the atmosphere as evaporation and precipitation, which appear as velocities at the top cell face of the model surface grid. The free-surface kinematic boundary condition is provided by the sea surface height taken from the reanalysis data.

The seasonal surface vertical mixing is parameterized through the K-profile parameterization (KPP) scheme as in Large et al. (1994) because the mixing coefficients are not readily available from ORA-S3. In addition to a Laplacian horizontal diffusion, which is provided for computational stability, an isopycnal diffusion of Redi (1982) type and eddy-induced transport of Gent and McWilliams (1990) are also incorporated into the offline model.

In Valsala et al. (2008), this tracer transport model has been tested extensively with the simulation of chlorofluorocarbon-11 (CFC-11), in which the offline circulations and other physical parameters were derived from the Geophysical Fluid Dynamics Laboratory (GFDL) reanalysis products. However, in the present study, we have optimized the same model for ORA-S3 circulations, because it is designed to reduce spurious climate variability in the reanalysis because of the stationary nature of the observing system using an online bias correction algorithm (Balmaseda et al. 2008). Moreover, the surface salinity in the GFDL reanalysis was obscured by the freshwater flux errors (W. Anderson, GFDL, 2008, personal communication). The transport model that is optimized for ORA-S3 fields is tested for mass conservation and CFC-11 simulations, and the results are analyzed below. The limitations of the model tropical mixing reported in Valsala et al. (2008) were also eliminated in the new version of the offline model by fine-tuning in the vertical mixing parameterizations so that the model reproduces the CFC distributions realistically. The transport model has the same horizontal and vertical resolution as the ORA-S3 data. The monthly ORA-S3 output is interpolated onto a model time step of 2 h for the tracer integration.

c. Method

To identify the source water of ITF from the Pacific Ocean, we initialized a numerical passive tracer at the key ITF channels in the Indonesian Seas and run the offline model in adjoint mode. The ITF is tagged as a uniform tracer with a concentration of 1 unit of tracer per m$^{-3}$ right at the exit of Indonesian straits into the Indian Ocean. The injection is maintained throughout the simulation period over a small box straddling the key channels of the ITF in the Indonesian island regions. The tracer is injected in direct proportion to the vertical profile of the ITF volume transport as it is introduced into the Indian Ocean. The same tracer injection method is used in the work of Valsala et al. (2008) for identifying the ITF pathway variability in the Indian Ocean, but with forward model simulations of passive tracers. The adjoint spreading pathways of the tracer is calculated by the following simple method: the velocities from the reanalysis data are reversed in direction (i.e., eastward velocity is multiplied by $-1$ to make it westward) and the integration is carried out from the end point of the total span of the data (i.e., 2000) to the beginning point (i.e., 1960). This method is used by Fukumori et al. (2004) to find the adjoin of El Niño water pathways in the tropical Pacific. More theoretical discussion on the adjoint of the pathways derived by this method can be found in Hourdin and Talagrand (2006) and Hourdin et al. (2006). In this case, the seasonal vertical mixing and horizontal diffusions are, however, in the same direction as in the forward models, because these are irreversible processes.

Two sets of integrations are performed. In the first set, we run the model for 41 yr by reversing the circulation and the other data starting from December 2000 and ending in January 1960. Note again that the tracer is continuously injected in the key channels of the ITF throughout the integration. Therefore, the tracer propagates backward from the initialization point into the Pacific Ocean and accumulates in the domain over time. The extent of spreading of the adjoints in the Pacific Ocean is interpreted as the extent over which the ITF water is originally derived (i.e., the source region for the ITF) in the forward circulation of the ocean. This experiment is referred to as the control run. To delineate the variability of tracer adjoints due to the interannually varying circulations, we run a climatological simulation, in which the long-term monthly climatological circulation and other data were derived for the 1960–2000 period and were repeatedly used for 41 yr. In this case, for each year of the simulation, the data from December to January are used. This is referred to as climatological run. Therefore, the climatological run results in the mean adjoint of the ITF source waters. In each of these runs, the tracer concentrations, horizontal and vertical advection fluxes, vertical mixing, and isopycnal fluxes are saved on as monthly snapshots for the analysis purpose.

The interannual variability of the source water pathways of the ITF is calculated by subtracting the control run by the climatological run. Thus, a one-to-one difference between two runs will remove two aspects from
the solutions: (i) a net accumulation trend of tracers and (ii) the seasonal cycle.

d. General circulation of western equatorial Pacific

Before proceeding to present the tracer results, here we introduce a brief description of the upper-ocean general circulations in the western equatorial Pacific as resolved in the ORA-S3 data. Figure 1 (top) shows the 1960–2000 average of the surface (0–100 m) circulations as resolved in ORA-S3. The shaded values represent the magnitude of the currents (m s\(^{-1}\)) and vectors represent the annual-mean circulation. The general circulations shown here are discussed in several OGCM studies (Qiu and Lukas 1996; Lukas et al. 1991). Therefore, only a brief description is provided here.

The important features of the western equatorial Pacific general circulations are clearly captured by ORA-S3. The major circulations such as the SEC, NECC, NEC, and South Equatorial Counter Current (SEC) are comparable to observations as described in Godfrey (1996). The Halmehera eddy (HE) and Mindanao eddy (ME) represent the retroflection of SEC and NEC to the NECC.

![Figure 1](image-url)
on the annual mean. The retrofection of SEC to the NECC is considered as a major reason why the ITF is not fed by the SEC (for a review, see Godfrey 1996). In the ORA-S3 data, the ITF is fed mainly from the NECC. The ITF enters the Indian Ocean through the Lombok, Timor, and Ombai Straits. The flow through the Makassar Strait feeds the ITF to the Lombok Strait, whereas flow circulating around Borneo through the China and Java Seas also feed components of ITF to the Indian Ocean. The latter is exaggerated in the ORA-S3 data compared to the observations; however, the significance of such routes of ITF is recently being observed (Susanto et al. 2010). A flow leakage from the Torres Sea to the Timor Strait is due to the deficient representation of the topography of the ORA-S3 data. The annual-mean ITF volume transport estimated as the sum of flow through the Lombok, Timor, and Ombai Straits is 13 Sv, which is in general agreement with other OGCMs and observations that suggest a range of 10–15 Sv of ITF volume transport (see section 1 for related references).

Figure 1 (bottom: shade) shows the composite magnitude of the velocity during El Niño years. The May–December averages of the years 1965, 1972, 1977, 1982, 1987, 1991, 1993, and 1997 are used to make the El Niño composite. The vectors show the composite circulation anomaly during El Niño years with respect to a 41-yr (i.e., 1960–2000) climatology. It can be seen that the surface averaged (0–100 m) circulation during El Niño has a westward anomaly in NECC and an eastward anomaly in NEC. SECC and SEC are strengthened in the far west during El Niño years. Examining the annual-mean and El Niño anomalies of surface (0–100 m) averaged circulation gives the following general conclusions: (i) the thermocline-level ITF is fed from the northern tropical Pacific which is consistent with observational evidence of Gordon and Fine (1996), and (ii) a weakened NEC during El Niño may cause a weaker northerly supply of thermocline-level ITF, whereas the supply from the SEC during this time can be significant. In the following sections, we present the detailed variability of the supply of the source waters of the ITF.

e. Validation of transport model using CFC-11

In our study, it is extremely important to validate the model transport matrices against the observations and assess the transport errors a priori. To validate the transport matrix produced by the model, we use CFC-11 as an evaluation tool. The CFC-11 was introduced to the atmosphere by anthropogenic emission since the early 1930s. In the ocean, CFC-11 is biogeochemically inactive and hence its mass is conserved. Therefore, CFC-11 is a good marker for the deep-ocean ventilation processes. When a water mass is formed in the bottom of the surface mixed layer, it keeps the memory of CFC-11 from its last contact with the atmosphere and is then transported and mixed into the deep ocean. Thus, measuring CFC-11 in the deep waters tells us about the ventilation pathways of the ocean water masses. In an ocean modeling perspective, this property is exploited as a validation component for model transports (England 1995; Dutay et al. 2002; Valsala et al. 2008). A model that resolves a transport matrix accurately should have a CFC-11 signature close to the corresponding observations.

We have spun up the model CFC-11 using ORA-S3 data from 1930 to 1958 by repeating the 1959 forcing and then continuing from 1959 through 1999 with the interannually varying circulation. The choice of 1959 circulation for the spinup, instead of monthly climatology that could be derived from 40 yr of ORA-S3 data, was because of two reasons. (i) The inventories and growth rate of CFC-11 in the atmosphere were negligible prior to 1930 compared to its tremendous growth from 1960 and onward (Valsala et al. 2010a). Therefore, the choice of the 1959 circulation to simulate CFC-11 from 1939 to 1958 does not affect the results of our study. (ii) On the other hand, by adopting a climatology of 40 yr constructed from 1960 to 2000, it is possible that the average of long-term changes in the ocean circulation may be incorporated into the CFC-11 simulation from 1930 to 1959, which is, arguably, unrealistic. The surface flux conditions for the CFC-11 forcing were kept the same as those of Valsala et al. (2008). To validate the model CFC-11 simulations, we have compared the results of model CFC-11 from the year 1995 with the observations taken from Global Ocean Data Analysis Project (GLODAP) (Key et al. 2004). A majority of the data used in the GLODAP dataset are collected between 1990 and 1999 during the World Ocean Circulation Experiment (WOCE) period. About 80% of the total CFC-11 observations used in GLODAP dataset come from 78% of the total cruises during WOCE. Therefore, we assume that the GLODAP scenario is fairly representative of the period between 1994 and 1997.

Figure 2 shows that the ORA-S3-driven offline transport model represents a reasonable replication of the observed CFC-11. The depth-integrated CFC-11 from the observations of GLODAP (Key et al. 2004) and the model show that the regional patterns of Pacific Ocean CFC-11 inventories are reasonably represented in the model. A critical part in the transport modeling is to retain the vertical distributions of CFC-11. To illustrate the model’s capacity to resolve the vertical distribution, we have shown two vertical sections along 160° and 290°E. The shallow penetration of CFC in the tropical region and deep ventilation in the subduction zone (40°N and 40°S) are reasonably represented in the two vertical sections shown. However the vertical gradient of simulated CFC-11 is
weaker in the model, perhaps related to the coarse vertical resolution of the model. Figure 2 (right) shows the percentage error in the model CFC-11 compared to observations. This percentage is calculated as \( \frac{\text{model} - \text{observations}}{\text{observations}} \) at each grid point. The vertical integral of CFC-11 ranges over an error bar of \( \pm 10\% - 15\% \). Note that this is the maximum error produced by the model. This error drops below \( \pm 10\% \) when the vertical integration is limited to 500 m. This is obvious from the corresponding errors in the vertical sections in Fig. 2 (right). This is an important factor to note, because in the following sections we will see that majority of the ITF water originates at a depth above 800 m in the Pacific Ocean (on interannual and interdecadal time scales), where our model error is typically less than \( \pm 10\% \). In certain regions, such as at 160°E and north of 40°N, the model penetration of CFC-11 is deeper than that found in the GLODAP observations. This is the limitation of the model mixed layer depth, which is deeper than those found in the climatological estimations based on de Boyer Montégut et al. (2004). Because they are far removed from the study area, we presume that the impact of these biases on our analysis and conclusions is minimal.

3. Interannual variability of the ITF source water in the Pacific

a. Horizontal structure

In this section, we describe the ITF adjoint pathways as revealed in our tracer simulation. At first, we compared the spreading of the adjoint in the control run and in the climatological run. Figure 3 (top) shows the 41st-yr average of the ITF adjoint derived in our control simulation. The depth-integrated tracer concentration is shown. The larger values of the tracer in the ITF entrance region are related to the continuous injection of tracers. Note that the tracer distribution corresponds to the adjoint of ITF pathways; therefore, it represents the source region where the ITF is derived in the previous 41 yr. The farthest tracer points from the ITF entrance region represent the oldest ITF source water.

The adjoints at the end of the 41st-yr simulation show that the ITF is largely supplied from the northern tropical Pacific, which is consistent with the findings of Gordon et al. (2003). Interestingly, a part of adjoint stretches from 5°S, 180° to 20°S, 100°W, which shows the supply through the northwestward flow of the subtropical gyre, which must be supplied to the ITF region through the SEC as...
suggested in the Sverdrup model of Hirst and Godfrey (1993). However, partitioning of ITF sources as northern versus southern origin is difficult to achieve by analyzing Fig. 1 (top) alone. The adjoint shown in this figure is a consequence of the mean as well as interannual variability in the circulation of the Pacific Ocean.

The role of the interannually varying circulation of the Pacific Ocean on the supply of source waters for the ITF can be further investigated by monthly differences between the tracer concentrations of the control run and the climatological run. Here, we refer to the monthly tracer concentration differences between the control run and

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**Fig. 3.** (top) Depth-integrated tracer concentration at the end of 41st yr of the simulation using interannual varying circulation. (middle) Difference of the depth-integrated tracer concentration between the interannual and the climatological simulation at the end of the 41st yr. Units are in tracer per square meter. (bottom) Time series of difference of the depth integrated tracer concentration averaged over a box shown (see middle panel) in black and ENSO index in red. Both lines of (bottom) are normalized with their respective standard deviations.
the climatological run as $\Delta C$. A negative $\Delta C$ adjoint in any location of the ocean will imply that the supply of source water from that location at that time was larger in the interannual simulation than in the climatological run and vice versa.

Figure 3 (middle) shows the depth integrated $\Delta C$ at the end of 41 yr. Again the loading of the tracer is larger near the ITF entrance region because the coalescing of tracers per unit volume supplied from the different regions of the ocean at the entrance region. For instance, Fig. 3, (middle) shows that negative $\Delta C$ is located in the northwestern tropical Pacific with a maximum amplitude located around the Mindanao area. Therefore, the ORA-S3-derived pathways of the ITF source water reflect a northern origin of the ITF, which is essentially consistent with Gordon et al. (2003). On the other hand, the positive $\Delta C$ is located along the equatorial western Pacific, which depicts an entry of ITF water through SEC along the boundaries of Papua New Guinea during some years, which is close to the proposed pathway of the ITF by Godfrey et al. (1993). Figure 3 illustrates two things: (i) the interannual variability causes a preferential supply of ITF from the northern versus southern tropical Pacific and (ii) the major variability in the supply of the ITF is related to the transition of source waters from north to south than any other factor, at least on interannual scales.

The prominent variability in the tropical Pacific Ocean dynamics is related to the ENSO. Therefore, we calculated an El Niño composite of $\Delta C$ from the same years as given in section 2c. We found that the composite of the vertical integral of $\Delta C$ essentially has the same features as the $\Delta C$ map at the end of 41 yr as shown in Fig. 3 (top). Therefore, the prominent $\Delta C$ variabilities close to the western tropical Pacific are essentially driven by the ENSO dynamics in the tropical Pacific Ocean. To elucidate the temporal variability of this spatial pattern, here we show a time series of area averaged $\Delta C$ over a box defined by $10^\circ$N–$10^\circ$S, $145^\circ$E–$115^\circ$W, as shown Fig. 3 (top). The time series (Fig. 3, bottom) illustrates that the adjoint pathway variability close to the western tropical Pacific is indeed related to El Niño because there is a significant correlation between $\Delta C$ variability and ENSO (ENSO index is shown as red line in Fig. 3, bottom). A detailed correlation analysis of interannual variability of the ITF adjoint pathways and its relation to El Niño is given in the following sections.

**DOMINANT MODES OF HORIZONTAL TRACER DISTRIBUTION**

The $\Delta C$ at the end of 41 yr reflects only the major differences in the ITF source water pathways. However the monthly $\Delta C$ adjoints oscillate in time and space according to the variability of Pacific Ocean circulation. To find the prominent pattern of $\Delta C$ oscillation in time and space, we applied empirical orthogonal function (EOF) analysis to the monthly $\Delta C$ patterns. The $\Delta C$ pattern is detrended before computing the EOFs.

In this subsection, we present the EOF analysis carried out over the depth-integrated $\Delta C$ patterns in order to depict the horizontal variability of the ITF source water pathways. In a separate section below, we also present the EOF analysis carried out over the vertical sections of $\Delta C$ patterns.

Figure 4 shows the first three EOFs of the depth-integrated $\Delta C$ concentrations and their respective principle components (PCs). The EOFs are multiplied with an average standard deviation of the first three PCs, and all the PCs are normalized with their respective standard deviations. The units of EOFs are in tracer m$^{-2}$.

The dominant mode of $\Delta C$ oscillation is visible in EOF-1. This is similar to the $\Delta C$ at the end of 41st yr as shown in Fig. 3 (bottom). The EOF-1 suggests that the dominant mode of ITF source water pathway oscillation is essentially confined to the western Pacific, spreading to the north by northwest into the Sulu, Philippine, and South China Seas and east to the dateline over much of the deep tropics and in southeast into the South Pacific convergence zone. Here, we note that the large EOF loading near the entrance region of the ITF reflects the coalescing of water from various regions into the entrance region before exiting to the Indian Ocean. The PC-1 shows the time variability of EOF-1 with both high-frequency (i.e., interannual) as well as low-frequency (i.e., interdecadal) characteristics. The EOF-1 and PC-1 together suggest the following points: (i) the most dominant variability of ITF source water origin in the Pacific is between the northern tropical Pacific and southern equatorial Pacific; (ii) this variability exists both on interannual and interdecadal time scales; and (iii) the EOF-1 explains 50% of the interannual variability of the source water pathways in the Pacific Ocean, indicating that the interannual variability exerts a dominant control on ITF source water variability.

The EOF-2 shows a negative loading oriented at the core of NEC (see Fig. 1, top) sandwiched by two positive loadings, one in the Philippine basin and other in the HE region. Some part of the positive loading also extends down to $10^\circ$S through the northern coast of Papua New Guinea. Therefore, the EOF-2 suggests that the positive loading of EOF-1 is strengthened toward the Halmahera region rather than in the core of NEC. The PC-2 exhibits only interannual oscillations. EOF-2 explains 14% of the interannual variability of the ITF source water pathways in the Pacific Ocean.

EOF-3 explains only 7% of the total interannual variability. The oscillation of EOF-3 has a complex pattern.
EOF–1

EOF–2

EOF–3

PC–1, Var=50%

PC–2, Var=14%

PC–3, Var=7%

Fig. 4. First three EOFs of the ΔC concentrations and their respective PCs (black lines) and ENSO index (red lines). EOFs are multiplied by the average standard deviation of first three PCs. Units of EOFs are in tracer per square meter. PCs and ENSO index are normalized (nondimensional) to fit into a common y axis.
with several positive and negative polarities all over the western tropical Pacific Ocean. This is likely the intra-seasonal waves impinging on the western boundary during ENSO events driven by the westerly wind bursts. The PC-3 also shows interannual variability.

We calculated the correlation of first three PCs with the normalized ENSO index (red lines, where positive refers to El Niño, in Fig. 4). The correlation of PCs with ENSO index at zero lag, however, is found to be relatively weak. A close examination of PCs and ENSO index shows that some individual peaks correlate well each other if appropriate lags are applied. We calculated a lead–lag correlation between the PCs and ENSO index, and the results are shown in Fig. 5.

The maximum correlation between PC-1 and ENSO index occurs at a lag of 6 months (i.e., PC-1 lags ENSO by 6 months). The correlation is at maximum at a 6-month lag with a coefficient of 0.45 (correlation at 95% significance level is 0.41). The correlation weakens as the lag increases or decreases from 6 months. At zero lag, the correlation is not statistically significant. The correlation is also insignificant when PC-1 leads the ENSO index.

The correlation of PC-2 with ENSO also displays similar behavior as that of PC-1 with ENSO. The maximum correlation of PC-2 with ENSO is found at a lag of 5 months (i.e., PC-2 lags ENSO by 5 months). The combination of correlation coefficients between PC-1 and PC-2 with the ENSO index reveal the following points: (i) the first and second dominant variability in the source water pathways of the ITF in the Pacific has a 6-month lag correlation with ENSO and (ii) a total of 64% (sum of variances of first two EOFs) of interannual variability of ITF source water supply occurs at an approximate lag of 6 months with ENSO.

The combined analysis of EOF-1, EOF-2, PC-1, and PC-2 and correlation with ENSO index lead to the conclusions that (i) during El Niño years increased, supply of the ITF source water is found in the south equatorial Pacific; (ii) during La Niña years, on the contrary, increased supply of the ITF source water is found in the northwestern tropical Pacific; (iii) the ITF source water supply from the equatorial Pacific peaks 6 months after an El Niño event; (iv) the EOF-1-type ITF source water variability (i.e., originating in the northern tropical Pacific or the south equatorial Pacific) has both interannual and interdecadal components.

The correlation of PC-3 with ENSO shows a maximum correlation at zero lag (Fig. 5). This indicates a local response of oceanic circulation in response to ENSO-related wind anomalies in the ITF entrance region. However, EOF-3 shows that this local variability of the ITF source water is relatively minor (only 7% of variance).

b. Vertical structure

In this section, we show the vertical structure of the ITF source water variability as revealed from our tracer
analysis. This is essential to consider, because the depth-integrated features do not necessarily imply a variability in the supply of source water at various depths. However, the depth-integrated $\Delta C$ represents the mean horizontal patterns of the ITF source water variability.

To isolate the effect of source water variability in the vertical, we again employ EOF analysis on $\Delta C$ concentrations averaged over a zonal section from 160°E to 100°W. The choice of this zonal section for averaging is made from analyzing EOF-1 and EOF-2, which show zonally oriented patterns of ITF source water variability. The western edge for this zonal average is limited to 160°E to avoid the large loading of the tracer near the ITF entrance region.

Figure 6 shows the first three EOFs and their respective PCs of these zonally averaged vertical $\Delta C$ concentrations. The depth range shown is only down to 1400 m because the tracer concentration loading below this depth was negligible. The vertical sections clearly demonstrate the importance of baroclinic currents on the supply of ITF source water. For instance, in the equatorial region, two cores of EOF-1 loading are visible, one at the surface and another at a depth of 800 m. A distinct EOF-1 positive loading at 40°N at a depth of 200 m is also noticeable. In the upper 200 m, the positive loading of EOF-1 is sandwiched between two regions of negative loading.

The PC-1 for the vertical mode also shows both interannual as well as interdecadal oscillations. The smoothed line (thick black) running over PC-1 in Fig. 6 (top) shows the filtered cycle at a period of above 9.5 yr. The thin black line in Fig. 6 (top) shows the difference between PC-1 and the 9.5-yr filtered PC-1. Therefore, the EOF-1 of the vertical section shows a clear interdecadal variability in contrast to the depth-integrated EOFs shown in the previous section. However, the correlation of PC-1 with the ENSO index (red line) has an approximate zero lag, which is a reflection of the fact that zonal averaging of the $\Delta C$ over 160°E–100°W represents an average response in the east–west direction. The following are conclusions from the comparison of EOF-1 and PC-1 of depth-integrated $\Delta C$ concentrations of Fig. 4 with that of the vertical section of $\Delta C$ of Fig. 6: (i) the variance explained by the EOF-1 of the latter is lower at 42%, (ii) the PC-1 of the latter is strongly modulated by an interdecadal signal, and (iii) the EOF-1 of the latter reflects the mode of interdecadal oscillation in the ITF source water supply rather than the interannual signal.

The EOF-2 of the vertical section of $\Delta C$ has a maximum of negative loading at 350-m depth centered on 5°S. A positive loading is more surface trapped centered on 20°N. The PC-2 is correlated with ENSO at an approximately zero lag. The EOF-2 of the vertical distribution of $\Delta C$ has a similar implication as that of the depth-integrated $\Delta C$, as presented in Fig. 4 (middle). Both the EOFs show that, during an El Niño year, the ITF is supplied from south equatorial Pacific. This supply is stronger at a depth of 300 m in the zonal average.

The EOF-3 has a complex vertical structure with an interdecadal time scale. However, the variance explained by this mode is only 10%.

The comparison of EOF-1, EOF-2, and EOF-3 and the respective PCs shown in Fig. 6 reveals the following points: (i) EOF-1- and EOF-3-type responses are spread relatively wide in the meridional as well as vertical directions, whereas their respective PCs have prominent interdecadal variability; (ii) EOF-2-type responses are mostly focused between 20°S and 20°N and confined above 400 m, whereas its PC shows much shorter timescale interannual variability; and (iii) the shorter timescale variability of the ITF source waters in the Pacific are driven by the equatorial dynamics, whereas tropical to midlatitude dynamics determine interdecadal variability of the ITF source waters.

c. Dominant modes of normalized tracer distribution

An important difference between the EOFs of the depth-integrated horizontal distributions of $\Delta C$ and that of the vertical distribution of $\Delta C$ is that a low-frequency variability is more obvious in the latter than in the former. This difference is likely because of the following two facts: 1) the time scales associated with the ITF source water supply are expected to be different at different depths, and that is reflected in the latter, and 2) the large loading of tracers at the mouth of ITF entrance region related to ENSO is averaged out in the latter analysis because of a zonal average applied to $\Delta C$. In other words, once the dominant short time-scale variability near the mouth of the ITF entrance region is eliminated from the EOF, we could resolve the spatial structure of large timescale variability.

To reduce the large loading of concentrations near the ITF entrance region and to facilitate a visual contrast of the large-scale space and time variability of the ITF adjoint pathways, we normalized the $\Delta C$ concentrations at each grid point with the corresponding standard deviations derived from 41 yr. Further, the EOF analysis is carried out with this normalized $\Delta C$ in order to highlight the low-frequency variability that is relatively less obvious in the analysis presented above.

Figure 7 represents the first three EOFs of normalized $\Delta C$ and their respective PCs. In this case, the large EOF loading close to the mouth of the ITF entrance is eliminated and the patterns are stretched to the entire Pacific. The corresponding PCs show that the high-frequency variability is removed and they only represent interdecadal oscillations of the ITF source water supply. Figure 7 illustrates that the supply of the ITF from the subtropical
Fig. 6. First three EOFs of the ΔC concentrations averaged from 160°E to 100°W and their respective PCs (black lines) and ENSO index (red lines). EOFs are multiplied by the average standard deviation of the first three PCs. Units of EOFs are in tracer per meter cubed. PCs and the ENSO index are normalized (nondimensional) to fit into a common y axis. (top right) The smoothed line (thick black) running over PC-1 shows the filtered cycle at a period of above 9.5 yr, and the thin black line shows the difference between PC-1 and the 9.5-yr filtered PC-1.
Fig. 7. First three EOFs of the normalized and depth-integrated ΔC concentrations and their respective PCs (black line) and ENSO index (red line). PCs and ENSO index are normalized (nondimensional) to fit into a common y axis.
Pacific has a clear interdecadal variability. The EOF-1 of normalized $\Delta C$ resembles the corresponding EOF of the vertical section of $\Delta C$ as shown in Fig. 6. The EOF-2 of normalized $\Delta C$ shows more stretched patterns in zonal and meridional directions. The EOF-2 has similar features as that of EOF-3 of the vertical section of $\Delta C$. For instance, the meridional extent of negative EOF-2 loading of Fig. 7 can be seen from $10^\circ$ to $40^\circ$N with a maximum amplitude at $140^\circ$W. The depth at which this EOF maximum occurs is at 400 m as seen in Fig. 6 (bottom). The positive loading of EOF-2 in Fig. 7 is in the southern subtropical Pacific with a maximum amplitude near $140^\circ$W. The depth at which this EOF maximum occurs is at 200 m as seen in Fig. 6 (bottom). Therefore, the subtropical thermocline waters are slowly advected around the gyres before becoming contributions to the formation of ITF on interdecadal time scales.

The first two EOFs of normalized $\Delta C$ represent a total of 57% of the interdecadal variability of the ITF source water supply from the subtropical Pacific. The EOF-3 of normalized $\Delta C$ shows complex patterns of meridional supply of the ITF source waters; however, such variability explains only 6% of the total variability.

The combined analysis of EOFs and PCs of raw $\Delta C$ and normalized $\Delta C$ reveals the following points: (i) the interannual variability of the ITF source water supply is driven by seasonal dynamics of ENSO in the western tropical Pacific and (ii) the interdecadal variability of the ITF source water supply is controlled by exchange of thermocline water masses between the tropical and subtropical Pacific via the meridional cells such as the subtropical cells (STCs; see next section).

d. Relation between interannual to interdecadal variability and the ITF source waters

In this section, we present extended analysis of interannual and interdecadal variability of the ITF source waters. A striking result from the above analysis is that the ITF source water is preferentially chosen from different parts of the Pacific Ocean: namely, the northwestern tropical Pacific and the south equatorial Pacific. In addition, this selection process is dependent on the time scale under consideration. In other words, the south equatorial Pacific waters feed the ITF on a shorter interannual time scale, whereas a broader midlatitude water feeds the ITF on interdecadal time scale. The former can be explained by the ENSO-related surface ocean circulation anomalies, as illustrated in Fig. 1. However, to explain the latter component, we must consider the large-scale meridional overturning circulation variability in the tropical and subtropical equatorial Pacific.

Early findings on the communications between the deep tropics and the subtropics were evoked in the context of "loading the gun" for ENSO as a recharge mechanism (Wyrtki 1987), but seminal work on the tropical–subtropical exchanges as STCs (zonal-mean meridional circulations that transport warm tropical waters out of the tropics near the surface, which gets subducted and transported back to the deep tropics in the pycnocline) was reported by McCreary and Lu (1994). This established a framework for potential relations between interannual and interdecadal modes of climate variability in the Pacific. That a decadal mode existed with a pattern similar to ENSO, albeit with a much broader meridional scale, was shown by Zhang et al. (1997). Another important player in advancing the tropical–subtropical and extratropical communications and the potential role of extratropical variability was the simple model proposed by Gu and Philander (1997) for surface temperature anomalies getting subducted and propagating into the tropics below the surface to alter properties of equatorial upwelling waters and thus changing the amplitude and/or frequency of ENSOs on decadal and longer time scales. Many studies followed to argue that such temperature anomalies, were they to survive the journey to the tropics, would not be large enough in amplitude to affect coupled climate variability (Kleeman et al. 1999). An alternative view was offered whereby changes in the strength of the STCs would result in anomalous advection of mean temperatures from the extratropics as opposed to the advection of temperature anomalies by mean currents as proposed by Gu and Philander (1997). Powerful observational evidence for the slowdown of the STCs was offered by McPhaden and Zhang (2002), providing support for anomalous advection of mean temperatures as a potential mechanism for decadal variability in the Pacific. The measure of STC proposed by McPhaden and Zhang (2002) is to simply compute the convergence of waters into the tropics: that is, the difference of meridional volume transport in the pycnocline across $9^\circ$N and $9^\circ$S. Here, we refer to this tropical convergence as the transport convergence (TC).

We have calculated the structure of TC as manifest in our tracer analysis. Here, the TC is calculated as mentioned above: namely, the differences of meridional $\Delta C$ tracer fluxes between $9^\circ$N and $9^\circ$S and averaged zonally over $160^\circ$E–$100^\circ$W and over a depth of 0–800 m. We are clearly integrating well below the pycnocline for TC because the analysis of vertical variability of $\Delta C$ indicates that ITF is reaching to these depths for extracting its source waters. Figure 8 (top) shows the TC and ENSO index and they are correlated with each other on interannual time scales. In Fig. 8 (top), the TC is shown only for those cycles with a period below 9.5 yr. Clearly, the relation is not valid at the end of the period, indicating that there may be other factors at play. A mid-1990s regime
shift was suggested by Chavez et al. (2003) centered on the North Pacific, although a much more widely reported mid-1970s shift (Mantua et al. 1997) does not display any change in the relationship between ENSO and TC. The impact of recharge for a large event such as the 1997/98 ENSO event on the ITF pathways is not clear; again, however, a similar event during 1982–83 does not disrupt the covariability of the two time series in Fig. 8 (top). Further investigation is needed on the interactions between the interannual and interdecadal modes of variability, and the relation between the two remains an open issue and is beyond the scope of this study (Rodgers et al. 2004).

On the other hand, Fig. 8 (bottom) shows the TC filtered for cycles with periods longer than 9.5 yr. Figure 8 (bottom) also shows the PC-1 of Fig. 6, but filtered to include only low-frequency cycles longer than 9.5 yr. The TC and PC-1 are oppositely correlated, meaning that the interdecadal TC variability controls the ITF source water supply in the Pacific Ocean on interdecadal time scales. Figure 8 (bottom) also shows 9.5-yr or above cycles of ITF volume transport as calculated from ORA-S3. Figure 8 reveals that interdecadal ITF volume transport may also be controlled by interdecadal TC variability. For instance, the correlation between TC and PC-1 of Fig. 8 is maximum (−0.8) at a lag of 38 months on interdecadal time scales (i.e., TC lags PC-1). On the other hand, the correlation between TC and ITF as shown in Fig. 8 is maximum (0.6) at a lag of 20 months on interdecadal time scales (i.e., TC lags ITF). However, the PC and ITF shown in Fig. 8 are correlated (maximum correlation coefficient is −0.48) at zero lag on interdecadal time scales. All these correlations are above 95% confidence interval. The relation at these lower frequencies appears to be more consistent than at the interannual time scales (Fig. 8, top), again raising questions about the interactions between the two time scales and their impact on the origin of ITF source waters.

4. Discussion and conclusions

Several features of the ITF source water pathways in the Pacific Ocean on interannual to interdecadal time scales are presented in this study. We have used a novel approach of tracer modeling, using offline reanalysis ocean currents to delineate the pathways of the ITF source waters.
The results presented here are consistent with previous findings based on the observational and modeling of general circulation of the ocean. Our study points out that the depth integrated ITF is largely contributed from the northwestern tropical Pacific in a normal year. However, our analysis indicates an important exception for this supply, where the source region for the waters is switched from the northwest to south equatorial Pacific and this occurs during El Niño years. This feature agrees with the Sverdrup model predictions of the Godfrey et al. (1993), albeit only during El Niño years. Upon reconsidering the ITF water properties such as fresh and warm North Pacific water in the upper thermocline, Godfrey (1996) reconsidered the Sverdrup model and concluded that the Sverdrup model for ITF around Australia fails at the northern part of Irian Jaya at about 2°N, where the annual-mean wind stress curl gets to zero. Therefore, according to the Sverdrup model, the SEC approaching the Indonesian landmasses must exit via the straits as ITF. However, to satisfy the observed water mass properties of the ITF in the upper thermocline, Godfrey (1996) argued that the SEC must be retroreflecting to the east by the NECC and Equatorial Undercurrent and then back to the Indonesian island regions through the NEC. Our study points out that, even if such a pathway exists, it is modified during El Niño years such that the SEC can directly feed the ITF. EOF-1 and EOF-2 in Fig. 4 provide evidence for this direct pathway.

The source waters of ITF suggested by the tracer analysis were verified using the subsurface salinity anomalies in the ITF entrance region. In this case, we examined two key trajectories, with each representing the source water pathway during El Niño and La Niña years. These trajectories are chosen from the spatial pattern of EOF-1 (Fig. 4). We examined the interannual salinity anomalies averaged over 50–100-m depths along these trajectories, and results are shown in Fig. 9. The anomalies are shown as Hovmöller plots along the two trajectories (the trajectories are illustrated in Fig. 9, bottom). Figure 9 (left) represents the pathway of salinity anomalies from the south equatorial Pacific to the ITF straits. Figure 9 (right) represents the pathway from the northwestern Pacific to the ITF straits. Both trajectories share a
common pathway within the ITF channels, which is shown as color shades in Fig. 9. Here, we note that the signs of the anomalies are not the focus here, but only their propagation into the ITF channels is considered. During El Niño years, the central to western equatorial Pacific experiences a negative salinity anomaly, whereas below 10°S experiences a corresponding positive anomaly prior to the development of El Niño (Maes et al. 2002; Ballabrera-Poy et al. 2002).

The period 1997–99 is shown to illustrate the pathways of salinity anomalies into the ITF straits during an El Niño year (as an example) from two origins in the western Pacific. The passive tracer analysis revealed that the ITF source water supply from the south equatorial Pacific peaks 6 months after the El Niño event. The subsurface salinity anomalies from April 1998 propagate into the ITF entrance channel in approximately 6 months (Fig. 9, top left: thick white arrows). During this time, there is no apparent propagation of subsurface salinity anomalies from northwestern Pacific to the ITF channels (Fig. 9, top right). On the other hand, during a La Niña event (represented from 1974 to 1976), the salinity anomalies from the ITF straits retreat to the south equatorial Pacific (Fig. 9, middle left: thick white arrows), whereas the propagation from northwestern Pacific into the ITF channels are dominant (Fig. 9, middle right: white thick arrows). Therefore, the tracer results presented in this study are consistent with the subsurface salinity anomalies.

One important finding of this study is that the extent of ITF source water regions can extend as far away as the midlatitude Pacific Ocean and as deep as 1400 m. The study also concludes that the larger extent of the ITF source water causes the interdecadal variabilities in the ITF. On the other hand, the shorter interannual variability due to ENSO is confined to the tropical regions and above a depth of about 600 m.

The apparent correlation between ITF source water pathways and ENSO shows a lag of 6 months. This should be compared with the lagged correlation between ITF volume transport and ENSO, as identified in other studies (see section 1 for related references). Previous studies that looked at the effect of ITF in the global climate system focused only on the mean state of the oceanic and atmospheric circulations. For example, Schneider (1998) identified that closure of the ITF in a coupled model causes SST warming the equatorial Pacific near the east of the dateline by 1°C. However, our study points out that, once we consider the interannual variability, the effect of ITF could be much different from the above mean picture. Moreover, there could be effects related to interannual to interdecadal changes in the ITF pathways. Therefore, we require a coupled model with significantly longer integrations to separate the effects of ITF in the global climate system on interannual and interdecadal time scales.

The ITF carries warm and freshwater of the northwestern tropical Pacific to the Indian Ocean. Previous studies have reported that the magnitude of sea surface height contributed by the ITF could be as large as tens of centimeters in the western tropical Pacific. Therefore, the ITF has a potential to modify the Pacific Ocean circulation, assuming that sea level changes of this magnitude can in fact be caused by the ITF. Adding to this significant dynamic change, our results show that, if the region of the ITF influence varies from year to year, its effects on general circulation can be much different than inferred in previous studies based on ITF closed and open experiments. In conclusion, we can state that the ITF has the potential to influence not only the mean state of the Pacific Ocean but also its interannual variability. This should also be viewed in the context of ongoing Indian Ocean sea level changes (Han et al. 2010). More detailed studies with coupled climate models are required to assess the impacts of the ITF at interannual and other longer timescale climate variabilities (see, e.g., Santos et al. 2010). Our study at least hints to such possibilities of ITF-induced modification in the Pacific Ocean general circulation and climate variability.

The conclusions drawn in this paper are as follows: 1) the ITF source waters in the Pacific are supplied from the northwestern tropical Pacific in a normal year, whereas the supply from south equatorial Pacific is dominant during El Niño years; 2) the supply from the south equatorial Pacific peaks after 6 months from El Niño events; 3) the interannual variability in the supply of source waters of the ITF in the Pacific is controlled by the seasonal dynamics of the tropical Pacific Ocean related to El Niño; 4) the corresponding interdecadal variability, however, is controlled by the mass exchanges between the tropical and subtropical Pacific through the subtropical cells (STCs); and 5) the deep thermocline waters from the subtropical Pacific are fed to the ITF on interdecadal time scale, whereas much shallower tropical waters are fed on interannual time scales. The study offers an important linkage between possible interdecadal variability of the ITF volume transport and recharge–discharge mechanisms of STCs in the Pacific Ocean.

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