Contributions of Indonesian Throughflow to eastern Indian Ocean surface variability during ENSO events

Xiaolin Jin1 | Jonathon S. Wright2

1Civil Aviation Flight University of China, Guanghan, China
2Department of Earth System Science, Tsinghua University, Beijing, China

Correspondence
Xiaolin Jin, Department of Aviation Meteorology, Civil Aviation Flight University of China, Guanghan, China. Email: jinxlin@163.com

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Abstract
The contribution of ocean transport to the transition between the Indian Ocean Dipole mode (IOD) and the Indian Ocean Basin mode (IOB) during El Niño–Southern Oscillation (ENSO) years is investigated using reanalysis products. Composite analysis suggests that the IOD–IOB transition is robust among ENSO years, with variations in the eastern Indian Ocean mixed layer playing a key role. Although this transition has typically been attributed to changes in surface heat flux in the eastern Indian Ocean, our results suggest that approximately one third of the mixed layer temperature tendency during the transition results from anomalous ocean heat transport. Enhanced surface heat flux anomalies and oceanic advection starting from October during El Niño developing years combine to warm the eastern Indian Ocean, promoting the decay of the positive IOD cold tongue and the emergence of a positive IOB pattern. The contribution of ocean advection to the IOD—IOB transition is dominated by the Indonesian Throughflow (ITF), which accounts for around 70–80% of total ocean advection contribution in the southeastern Indian Ocean (20–25% of the total warming tendency). These variations in ITF heat transport arise in large part from local wind anomalies. Southeasterly wind anomalies along the northeastern edge of an anomalous Indian Ocean anticyclone associated with El Niño intensify surface-layer heat transport into the Indian Ocean in the ITF outflow region. This change in surface transport contrasts with total ITF transport anomalies during El Niño years, as total transport is dominated by negative subsurface transport anomalies.

KEYWORDS
Indian Ocean variability, Indonesian Throughflow, ENSO

1 | INTRODUCTION
The El Niño-Southern Oscillation (ENSO) in the tropical Pacific Ocean profoundly influences the global atmospheric circulation (Lau and Nath, 1996; Alexander et al., 2002). Many studies have shown that ENSO accounts for much of the variability in the Indian Ocean (Chambers et al., 1999; Reason et al., 2000; Lau and Nath, 2003; Yang et al., 2015; Yang et al., 2017). The leading mode in the Indian Ocean on interannual time scales
is the Indian Ocean basin mode (IOB), characterized by basin-scale warming or cooling. IOB is closely associated with ENSO, with a maximum correlation of 0.91 when IOB lags ENSO by 5 months (Yang et al., 2007; Du et al., 2009). The second mode is the Indian Ocean dipole mode (IOD), characterized by a zonal dipole of sea surface temperature (SST) anomalies across the tropical Indian Ocean (Saji et al., 1999). The positive phase of the IOD corresponds to cold anomalies off the coast of Sumatra/Java and warm anomalies over the western Indian Ocean. IOD plays an important role in modulating rainfall in countries surrounding the tropical Indian Ocean (Ashok et al., 2001; Ashok et al., 2003; Saji and Yamagata, 2003b; Meyers et al., 2007).

IOD typically displays seasonal phase locking, appearing in summer, peaking in autumn, and rapidly decaying in December to be replaced by IOB (Saji et al., 1999; Du et al., 2009; Yang et al., 2015). Unlike the Pacific, the Indian Ocean thermocline is deep and flat, which is unfavorable for the Bjerknes feedback. Indian Ocean variability during the strong El Niño of 1997–98 has been extensively studied (Webster et al., 1999; Yu and Rienecker, 1999; Murtugudde et al., 2000). Yu and Rienecker (1999) attributed Indian Ocean SST variations primarily to remote forcing by ENSO. By contrast, Webster et al. (1999) argued that these variations, although coincident with the strong El Niño, were primarily caused by dynamics internal to the Indian Ocean basin. Other attempts have been made to explore the mechanisms for IOD evolution (Saji et al., 1999; Webster et al., 1999; Rao et al., 2002). Using a conceptual model, Li et al. (2003) concluded that ENSO is a key triggering mechanism for IOD. Yang et al. (2015) quantified the relative contributions of ENSO forcing and internal variability to IOD in coupled model experiments, attributing one third of IOD variance to ENSO. ENSO-related surface heat flux anomalies in the eastern Indian Ocean play a key role in IOD evolution (Du et al., 2009). In addition to ENSO forcing, Annamalai et al. (2003) suggested that the Indonesian Throughflow (ITF) helps to initiate the IOD. However, it is still unclear whether and to what extent ITF variability may impact the decay of IOD and its transition to IOB.

Transport through the Indonesian seas links the tropical Pacific and Indian Oceans, with the ITF contributing to the heat budgets of both basins (Godfrey, 1996; Gordon, 2005). Heat fluxes into the Indian Ocean by the ITF are approximately 0.5 to 1.0 PW (Hirst and Godfrey, 1993; Godfrey, 1996; Vranes et al., 2002), the same order of magnitude as net surface heat fluxes into the northern Indian Ocean (Webster et al., 1998). Recent anomalous warming in the Indian Ocean has been linked to enhanced heat import from the Pacific via the ITF (Lee et al., 2015; Nieves et al., 2015; Liu et al., 2016; Li et al., 2017; Zhang et al., 2018). Using reanalyses, Dong and McPhaden (2016) identified an interhemispheric gradient in Indian Ocean SST trends during the recent hiatus period, with ITF transport playing an important role. In this study, we use reanalysis data to clarify the role of the ITF in the decay of IOD events during ENSO years.

## 2 | DATA AND METHOD

We focus on ocean reanalysis products for 1958–2014, namely the European Centre for Medium-Range Weather Forecasts (ECMWF) Ocean Re-Analysis System version 4 (ORAS4, Balmaseda et al., 2013) and the GECCO2 reanalysis (Köhl, 2015) produced by the German contingent of the Estimating the Circulation and Climate of the Ocean project (ECCO, www.ecco-group.org). ORAS4 is based on the Nucleus for European Modelling of the Ocean (NEMO) ocean model with a standard horizontal resolution of 1° and 42 vertical levels. Wind stresses and other atmospheric forcings are from the ECMWF 40-year Re-Analysis (ERA-40) through December 1989, the ECMWF Interim Re-Analysis (ERA-Interim) from 1989 to 2009, and ECMWF operational analyses from 2010 onwards. ORAS4 applies a three-dimensional variational data assimilation system in a first guess at appropriate time configuration. GECCO2 is based on the Massachusetts Institute of Technology ocean general circulation model (MITgcm) with 50 vertical levels and a horizontal resolution of 1°. The background atmospheric state is from the National Centers for Environmental Prediction–National Center for Atmospheric Research Reanalysis 1 (NCEP–NCAR R1). An adjoint method has been used to adjust the model outputs for consistency with observational data. These two reanalyses have previously been used to investigate variability in the Indian Ocean (Dong and McPhaden, 2016; Jin et al., 2018). Mean ITF volume transport integrated over the upper 700 m is 10.7 Sv in both GECCO2 and ORAS4, between estimates of 11.7 Sv based on International Nusantara Stratification and Transport (INSTANT) mooring data (Sprintall et al., 2009) and 8.7 Sv based on expendable bathythermograph measurements (Wijffels et al., 2008; Liu et al., 2015). We use monthly winds from NCEP–NCAR R1 on a 2.5° grid (Kalnay et al., 1996) and monthly SST data from the NOAA Extended Reconstructed SST (ERSST) version 4 dataset at 2.0° resolution (Huang et al., 2015).

Anomalies are calculated by subtracting the respective monthly-mean climatologies for 1958–2014. All variables are mapped onto a 1° regular latitude–longitude grid using bilinear interpolation. El Niño and La Niña
FIGURE 1  Composite El Niño minus La Niña SST anomalies (shading, unit: K) and near-surface wind anomalies (vector, unit: m/s) in (a) JJA(0), (b) SON(0), (c) DJF(1), and (d) MAM (1). The parenthetical 0 and 1 indicate developing and decaying ENSO years, respectively. Differences are shown as shading or vectors when they are significant at the 95% level according to a two-tailed Student’s t test. The black box (90°–115° E, 8°–22° S) in the eastern Indian Ocean shows the domain for which the heat budget analysis is conducted. The character “AC” denotes the location of the eastern Indian Ocean anticyclone.
events are identified using the Niño3.4 index, calculated as the mean SST anomaly over the domain within 5°S–5°N and 170°E–120°W. El Niño is defined as the Niño3.4 index exceeding 0.5°C for at least five consecutive months and La Niña as the Niño3.4 index remaining less than −0.5°C for at least five consecutive months. Based on these criteria, 19 El Niño events and 18 La Niña events occurred during the 1958–2014 analysis period.

The mixed-layer temperature budget is evaluated as

$$\frac{\partial T}{\partial t} = \frac{Q_{\text{net}}}{\rho c_p h} - u \frac{\partial T}{\partial x} - v \frac{\partial T}{\partial y} - w \frac{\partial T}{\partial z} + R,$$

where $T$ is the layer-mean temperature, $c_p$ is the volumetric heat capacity of seawater, and $h$ is the mixed layer depth. Here, $h$ is set to a constant depth of 45 m, corresponding to the fifth level below the surface in both ORAS4 and GECCO2 and the average mixed layer depth in the southern tropical Indian Ocean. $Q_{\text{net}}$ is the net surface heat flux (positive downward), including sensible and latent fluxes as well as longwave and shortwave radiation. $u$ and $v$ are zonal and meridional oceanic current velocities within the layer, and $w$ is the vertical velocity at the base of the layer. The first four terms on the right-hand side of Equation (1) respectively represent the contributions of net surface heat flux, zonal advective heat flux, meridional advective heat flux, and vertical advective heat flux into the upper layer. The final term, $R$, is a residual term collecting the effects of convection and horizontal/vertical diffusion (see also Zhang and Delworth, 2015). We have also conducted heat budget analyses with variable mixed-layer depth. Results are
similar to those obtained assuming fixed mixed layer depth, indicating that our results are robust to this choice.

3 | RESULTS

3.1 | The composite IOD–IOB transition

Figure 1 shows composite El Niño minus La Niña SST anomalies for distinct three-month periods between summer (June–August) of the ENSO developing year, referred to as JJA(0), and spring (March–May) of the ENSO decaying year, referred to as MAM(1). The parenthetical “0” or “1” denotes ENSO developing (0) or decaying (1) years, respectively. As variations in the Indian Ocean during La Niña years are qualitatively opposite to those during El Niño years, we focus mainly on variations during El Niño years. The zonal dipole of SST anomalies in the Indian Ocean appears in JJA(0) and peaks in SON(0), with positive anomalies in the west and negative anomalies in the east during El Niño years (Figure 1a,b). This dipole structure corresponds to the positive phase of IOD. After November(0), SST anomalies in the eastern Indian Ocean decay but those in the western Indian Ocean maintain their sign. Almost the entire tropical Indian Ocean basin becomes warmer than normal by January(1) of El Niño years, marking the IOB positive phase.

Sign changes of SST anomalies during the IOD–IOB transition primarily occur in the southeastern Indian Ocean, highlighting the role of eastern tropical Indian Ocean variability in the decay of IOD and the development of IOB. Observational data likewise show larger SST variance in the eastern pole than in the western pole during both IOD phases, suggesting that the IOD index is determined mainly by the state of the eastern Indian Ocean (Saji and Yamagata, 2003a; Hong et al., 2008b).
The importance of eastern Indian Ocean SST also manifests in asymmetry between the positive and negative phases of IOD, with SST anomalies having larger magnitudes in the positive phase (Hong et al., 2008a; Zheng et al., 2013; Yang et al., 2015). Zheng et al. (2010) attributed this asymmetry to nonlinear thermocline feedback in the eastern Indian Ocean.

Near-surface wind anomalies during El Niño years relative to La Niña years are also shown in Figure 1. Southeasterly anomalies appear over the eastern tropical Indian Ocean in JJA(0) and intensify during SON(0), marking the northeastern flank of an anomalous anticyclone centered northwest of Australia. This anomalous anticyclone is induced by remote ENSO forcing and maintained by local air-sea interactions (Wang et al., 2003). Southeasterly wind anomalies near the ITF outflow region enhance ocean advection from this region into the eastern Indian Ocean, potentially warming the eastern Indian Ocean. Using observations, Sprintall et al. (2009) suggested that southeasterly winds over the eastern Indian Ocean contribute to modulating ITF transport. Warming via ITF surface transport in the eastern Indian Ocean can erode the positive IOD and promote the advent of IOB, assuming warm SST anomalies persist in the west. ITF transport is among the factors that can trigger IOD (Annamalai et al., 2003). Our results suggest that this transport may also damp IOD under the influence of ENSO-related wind anomalies. To further test...
this hypothesis, we calculate correlations between ITF upper-layer heat transport and SST anomalies during SON(0) of ENSO years. The correlation distribution is characterized by the IOD pattern (not shown), implying that ITF anomalies modulate SST variance in the cold tongue region. Correlations of upper-layer ITF heat transport with SST anomalies in the eastern Indian Ocean range from around 0.3 to more than 0.6 (area-weighted means: 0.42 in GECCO2, 0.48 in ORAS4), suggesting that 10–40% of SST variance in this region is associated with anomalous upper-layer heat transport via the ITF.

3.2 Contributions of horizontal advection

To further assess how ocean horizontal advection contributes to the IOD–IOB transition during ENSO years, we conduct a heat budget analysis focusing on the surface-layer heat budget in the southeastern Indian Ocean (90°–115°E, 8°S–22°S). Figure 2 shows composite heat budget anomalies in this region during El Niño and La Niña years based on GECCO2 and ORAS4. During El Niño years the positive IOD peaks in boreal autumn. Positive temperature tendencies start in October(0), eroding negative SST anomalies in the eastern Indian Ocean and facilitating the transition from positive IOD to positive IOB. The primary contributors to positive temperature tendencies are anomalous surface heat fluxes and ocean advection, both of which change from negative (cooling) to positive (warming) in October(0). The contribution of vertical advection is relatively small. Ocean horizontal advection accounts for around one third of the anomalous temperature tendency during the period from October(0) to March(1), in line with the 10–40% estimate for ITF contributions outlined above. The evolution of SST anomalies during La Niña years (Figure 2b,d) is qualitatively opposite to that during El Niño years, although the IOB signal is stronger during El Niño years. Despite discrepancies between the reanalyses, both the timing of sign changes and the relative magnitudes of key terms are similar between GECCO2 (Figure 2a,b) and ORAS4 (Figure 2c,d). This consistency indicates that the results are robust to differences in the underlying models, data assimilation systems and surface forcings applied to produce these two reanalyses.

The role of surface heat flux anomalies in the IOD–IOB transition has been investigated in previous studies (Klein et al., 1999; Webster et al., 1999; Yu and Rienecker, 1999; Shinoda et al., 2004; Tokinaga and Tanimoto, 2004). During El Niño developing years, negative SST anomalies in the eastern Indian Ocean inhibit atmospheric deep convection and associated cloud cover, resulting in larger incoming solar radiation fluxes at the ocean surface. Changes in the atmosphere represent a negative feedback mechanism (Wu and Kirtman, 2005) that damps the SST anomaly, contributing to IOD decay toward the end of the calendar year. Our heat budget results support that surface flux anomalies play the leading role in IOD decay, as indicated by previous studies (Klein et al., 1999; Shinoda et al., 2004). However, ocean advection contributions are comparable to those of surface heat flux during IOB development.

To elaborate on horizontal advective contributions to SST variations in the eastern Indian Ocean, heat transport anomalies across each boundary of the analysis domain (Figure 1) are shown in Figure 3. The total heat transport anomalies are dominated by transport across the eastern boundary, especially during the October(0) to March(1)-transitional period. Heat transport across the eastern boundary is fed by the ITF, which conveys warm water from the western Pacific Ocean to the Indian Ocean. ITF anomalies account for 89 ± 5% of the horizontal advection contribution to eastern Indian Ocean temperature changes in GECCO2, and 67 ± 11% in ORAS4. Heat transport anomalies change sign in October(0), consistent with the advent of southeasterly wind anomalies over the ITF outflow region in October(0) of El Niño years. After March(1), ITF-fed warming of the eastern Indian Ocean decreases as the wind anomalies weaken. Consistency between variations in the ITF contribution and variations in anomalous southeasterlies over the outflow region suggests that winds over the Indian Ocean play a key role in modulating surface-layer ITF transport during El Niño years (see Section 3.3). Wind anomalies also impact evaporation; however, using the method of Xie et al. (2010), we find that wind-related latent heat flux anomalies have only a marginal impact on the heat budget in the eastern Indian Ocean during the IOD-IOB transition. Heat transport anomalies across the northern and southern boundaries are smaller and effectively offset each other, indicating that meridional anomalies play little role in the IOD–IOB transition. Although heat transport across the western boundary also contributes little to the transition, this transport accounts for large negative anomalies during JAS(0) of El Niño years and may thus help to form the IOD cold tongue. Results based on GECCO2 are in good agreement with those based on ORAS4.

3.3 Reconfiguration of the ITF during ENSO events

Our results indicate that anomalous ocean heat transport into the eastern Indian Ocean via the ITF increases starting from October(0). Together with changes in surface heat flux, this increased ocean heat transport favors decay of the positive IOD cold tongue by
warming the eastern Indian Ocean. This result is counterintuitive at first glance because ITF transport is known to decrease under El Niño and increase under La Niña (Meyers, 1996; England and Huang, 2005; Liu et al., 2015; Feng et al., 2018). We hypothesize that the influence of enhanced ITF heat transport on SST arises not only from an increase in mass transport but also from redistribution of near-surface advection within the ITF outflow region during ENSO events. Increased heat transport into the eastern Indian Ocean is confined mainly to the upper layer.

During El Niño years, an anomalous anticyclone appears off the western coast of Australia in October–November and persists through March (1). Southeasterly wind anomalies along the northeastern flank of this anticyclone impinge on the ITF outflow region (Figure 1b,c). The surface flow of warm water into the southeastern Indian Ocean should increase in response to these anomalous southeasterly winds. To evaluate this hypothesis, Figure 4 shows climatological mean currents averaged over the upper 45 m (Figure 4a), along with anomalies during El Niño years (Figure 4b) and La Niña years (Figure 4c). Westward currents in the ITF outflow region are enhanced during El Niño events, especially near 10°S. Northward anomalies are also evident off the coast of western Australia during El Niño years. The ITF also feeds the Leeuwin current (Gordon, 2005), so that these northward anomalies imply an increase in the proportion of ITF outflow that enters the eastern Indian Ocean rather than the Leeuwin current. Indeed, previous studies have shown that the Leeuwin current is diminished during El Niño years due to reduced input from the ITF (Pariwono et al., 1986; Pearce and Phillips, 1988). The surface current anomalies demonstrate a westward diversion of near-surface ITF outflow into the eastern Indian Ocean, as expected for southeasterly surface wind anomalies in this region. This reconfiguration enhances heat transport into the eastern Indian Ocean, thereby contributing to the IOD–IOB transition.

Using INSTANT mooring data from 2003 to 2006, Sprintall et al. (2009) calculated variations in transport across the full depths of the straits, and linked these variations to equatorial surface wind anomalies over the Indian and Pacific Oceans. Surface transport anomalies evolved in tandem with wind anomalies over the Indian Ocean during El Niño events. Anomalous southeasterly winds over the eastern Indian Ocean intensified ITF transport in the uppermost 150 m as El Niño matured, while transport in the subsurface layer (below 150 m depth) was substantially reduced. Output from coupled model simulations also suggests that local wind anomalies play a critical role in modulating ITF upper layer transport (Potemra and Schneider, 2007), with enhanced ITF transport in the upper 100 m and reduced subsurface and total ITF transport during El Niño events. As opposed to local wind driving of variations in upper ocean ITF transport, the subsurface transport anomalies are driven mainly by remote effects, including divergent winds over the Indo-Pacific basin and Kelvin waves (Potemra et al., 2003; Potemra and Schneider, 2007).

To assess whether ORAS4 and GECCO2 accurately reproduce these depth-dependent compensating changes in ITF transport, Figure 5 shows meridional cross-sections of volume transport anomalies in SON(0) of El Niño and La Niña years across the 115°E meridional transect. Increased ITF transport into the southeastern Indian Ocean during El Niño years (Figure 5a) is confined to the upper 150 m north of about 14°S, with large negative anomalies below. Transport anomalies during La Niña years (Figure 5b) are qualitatively opposite to those during El Niño years, with reduced transport into the southeastern Indian Ocean in the surface layer near 10°S and enhanced transport below. This result illustrates how wind-driven intensification of ITF surface transport contributes to warming the IOD cold tongue and facilitating the transition from positive IOD to positive IOB during El Niño years. Surface-layer advective warming of the southeastern Indian Ocean occurs despite reductions in total ITF transport during El Niño years, as the latter arise from decreases in subsurface transport (below about 150 m) that more than offset the enhanced surface-layer transport.

4 | CONCLUSIONS AND DISCUSSION

In this study, we have examined the IOD–IOB transition during ENSO years and investigated the mechanisms behind this transition. Composite analysis of all ENSO events during 1958–2014 reveals robust and qualitatively opposite evolutions during El Niño and La Niña. SST anomalies characterizing the positive (negative) IOD mode develop in boreal summer and autumn of El Niño (La Niña) developing years. This pattern decays rapidly toward the end of the calendar year and is replaced by basin-wide warm (cool) anomalies characteristic of the positive (negative) IOB mode. The key region for this transition is the eastern Indian Ocean surface layer. We therefore examine the mechanisms behind the IOD–IOB transition by applying a heat budget analysis to the uppermost 45 m of the southeastern Indian Ocean.

Both net surface heat flux and horizontal ocean advection contribute substantially to the IOD–IOB transition. Anomalies in net surface heat flux are associated
with negative atmospheric feedback to the SST anomalies and have been examined in detail by previous studies (e.g., Klein et al., 1999; Shinoda et al., 2004; Du et al., 2009). Ocean advection accounts for around one third of the total mixed layer temperature tendency in the eastern Indian Ocean during the IOD–IOB transition, with changes in ITF transport into the eastern Indian Ocean playing the dominant role. Remote ENSO forcing induces an anomalous anticyclone in surface winds over the southeastern Indian Ocean during El Niño years and an anomalous cyclone during La Niña years. Wind anomalies along the northeastern side of this circulation anomalously redistribute surface heat transport in the ITF outflow region. Southeasterly near-surface wind anomalies during El Niño years intensify westward surface currents near 10°S and diminish southward currents along the western coast of Australia, diverting more warm water westward into the eastern Indian Ocean. The vertical profile of ITF transport shows opposing variations in the surface (upper 150 m) and subsurface (deeper than 150 m) layers. The increase in surface ITF heat transport into the southeastern Indian Ocean during El Niño years is an important contributor to the transition from positive IOD to positive IOB despite decreases in subsurface and total ITF transport into the Indian Ocean.

Although ocean reanalyses are widely used, budgets based on these data are complicated by the effects of data assimilation and unresolved mixing (Wenzel et al., 2001; Burgers et al., 2002; Bell et al., 2004; Balmaseda et al., 2013; Fu, 2013). Imbalances in the heat budgets based on both ORAS4 and GECCO2 are evident in Figure 2. Although these imbalances are a necessary side effect of observational data assimilation, the results should still be validated against different approaches or data sources. Moreover, although the IOD-IOB transition during La Niña years is qualitatively opposite to that during El Niño years, the evolution of SST anomalies is not strictly symmetric between El Niño and La Niña years. For example, the magnitude of IOB-related SST anomalies in the eastern Indian Ocean is larger during El Niño decaying years than during La Niña decaying years (Figure 2). This and other asymmetries of ENSO-related SST anomalies in the Indian Ocean deserve further investigation.

In addition to the direct effects of surface wind stress, Gordon et al. (2003) suggested that anomalous winds could modulate ITF transport through salinity-driven changes in buoyancy. Several recent studies have highlighted the role of the ITF in redistributing heat between the Pacific and Indian Oceans (Lee et al., 2015; Nieves et al., 2015; Li et al., 2017), emphasizing the need to more fully characterize and understand this current and its behaviors. Our results reveal that ITF outflow plays an influential role in the IOD–IOB transition during ENSO years, in which wind forcing modulates ITF heat transport into the southeastern Indian Ocean. This conclusion further underscores the importance of this complex current system in climate variability and change.

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ORCID
Xiaolin Jin https://orcid.org/0000-0002-5799-1066

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