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Significance of the vertical profile of the Indonesian Throughflow transport to the Indian Ocean

Qian Song and Arnold L. Gordon

Department of Earth and Environmental Sciences, Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York, USA

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[1] Using an ocean general circulation model, we find that the vertical profile of the Indonesian Throughflow (ITF) transport is important in regulating the stratification and surface heat fluxes of the Indian Ocean. With the same total ITF transport, a thermocline-intensified ITF, relative to a surface-intensified ITF, not only cools the surface layer of the Indian Ocean while warming the Indian Ocean below the thermocline, but also induces negative temperature anomalies at the sea surface throughout the Indian basin. As a consequence of this surface effect the net heat gain of the Indian Ocean is increased. The results suggest that it is necessary to properly represent the vertical profile of ITF transport within ocean and climate numerical models. *INDEX TERMS:* 4255 Oceanography: General: Numerical modeling; 4231 Oceanography: General: Equatorial oceanography; 4572 Oceanography: Physical: Upper ocean processes; 4215 Oceanography: General: Climate and interannual variability (3309); 4512 Oceanography: Physical: Currents. **Citation:** Song, Q., and A. L. Gordon (2004), Significance of the vertical profile of the Indonesian Throughflow transport to the Indian Ocean, *Geophys. Res. Lett.*, *31*, L16307, doi:10.1029/2004GL020360.

1. Introduction

[2] The effects of the Indonesian Throughflow (ITF) on the Indian Ocean have been studied using numerical ocean models [e.g., *Hughes et al.*, 1992; *Hirst and Godfrey*, 1993, hereinafter referred to as HG; *Godfrey*, 1996; *Murtugudde et al.*, 1998; *Wajsowicz*, 2001; *Lee et al.*, 2002] and coupled climate models [e.g., *Schneider*, 1998; *Wajsowicz and Schneider*, 2001]. Most of these studies focus on the effects of the opening and closing of the Indonesian Passages, and do not explicitly consider the effects of such secondary characteristics of the ITF as the vertical profiles of the ITF temperature, salinity and transport, on the Indian Ocean. *Wajsowicz* [2001], by forcing the same ocean model with two wind stress climatologies, obtain different vertical profiles of ITF transport, as well as different profiles of ITF temperature and salinity and different total transport of ITF in the upper 300 m. Thus, it is impossible in those model runs to isolate the impacts of the variation of the vertical profile of ITF transport on the Indian Ocean. Mooring measurements in the Makassar Strait [*Gordon et al.*, 1999, 2003] suggest that the transport of ITF peaks within the thermocline, rather than at the sea surface. *Gordon et al.* [2003] suggest that it is important for climate models to simulate correctly the vertical structure of the ITF in discussing the effects of the ITF on the climate system. The objective of this study is to investigate the significance of the vertical profile of ITF transport to the Indian Ocean using an ocean general circulation model (OGCM).

2. Numerical Model

[3] The numerical model used in this study is the Lamont Ocean Atmosphere-Mixed-Layer (AML) Model. It is a primitive equation OGCM with z-coordinates. The model configuration is the same as that by *Song et al.* [2004] (description of model details therein). The model domain is 50°S–30°N and 0°–150°E. The zonal resolution is 0.5° in the tropics and decreases gradually to 1.7° in extratropics. The meridional resolution is about 0.8° in the Somali Current and the Leeuwin Current regions, and falls off to 1.2° for the most of the ocean. There are 28 layers in the model with 10 m resolution in the upper 100 m. The model is forced by the monthly wind stress climatology from the National Center for Environmental Prediction (NCEP) [*Kalnay et al.*, 1996]. Surface heat fluxes are internally computed by coupling the ocean model to an advective AML [*Seager et al.*, 1995]. The sources of other forcing data are: the International Satellite Cloud Climatology Project (ISCCP) monthly climatological solar radiation corrected by Earth Radiation Budget Experiment data [*Seager and Blumenthal*, 1994]; ISCCP monthly climatological cloudiness data; and NCEP monthly wind speed climatology. The sea surface salinity is restored to Levitus monthly climatology [*Levitus*, 1994] with a restoring time scale of one month. Sponges are applied in the region north of the Makassar Strait and near the southern boundary. Temperature and salinity in the sponge layers are restored to Levitus seasonal climatology, with a restoring time scale of six months. Lateral mixing of temperature and salinity are accomplished by the *Griffies* [1998] implementation of the eddy parameterization scheme of *Gent and McWilliams* [1990]. The coefficient for both the isopycnal diffusion and the eddy-induced transport is set to be 400 m^2 s^{-1}. For vertical mixing, convective adjustment and Richardson number dependent mixing of *Pacanowski and Philander* [1981] are used. In addition, a uniform background vertical diffusivity of 10^{-1} m^2 s^{-1} for momentum and 10^{-5} m^2 s^{-1} for temperature and salt is used everywhere.

[4] Three experiments are performed: NOITF (no ITF); ITF10 (10 Sv ITF); ITF10TH (10 Sv ITF but with more thermocline-intensified transport profile) (Figure 1). In NOITF, the Indian Ocean and the Pacific (which is the sponge layer in the present model setup) are isolated by a land bridge. In ITF10 the vertical profile of ITF transport is developed by model physics given the surface forcing and

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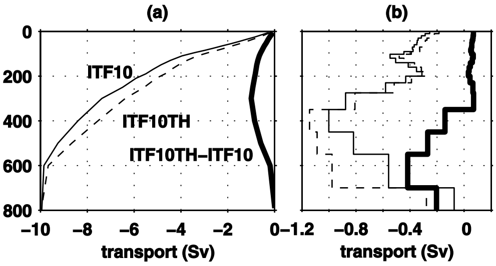


Figure 1. (a) ITF transport stream functions integrated from the surface downward and (b) ITF transport of each layer in the model across 2°S through the Makassar Strait (Figure 2) in the model runs. Positive values indicate northward transport.

parameterization in the model. The different vertical profile of ITF transport in ITF10TH from that in ITF10 is achieved by employing an artificial force in the Timor Passage (the rectangle marked with a cross sign in Figure 2). The force is positive (eastward) in the upper 300 m and negative (westward) between 300–1000 m, which restricts and reinforces the westward flow in the upper 300 m and between 300–1000 m, respectively. The vertical profiles of ITF temperature and salinity within the Indonesian Seas are virtually the same between ITF10 and ITF10TH, due to the sponge layer north of the Makassar Strait. In all the experiments the model is initiated from Levitus climatology and run for 25 years. The climatologies presented in this study are computed by taking average over the last 5 years.

3. Results

3.1. Effects of the ITF

[5] There are two means by which the ITF can affect the Indian Ocean stratification. One is by the direct effect of horizontal advection of the ITF water properties in the Indian Ocean. The ITF water as viewed on isopycnal surfaces is fresher and hence cooler than the waters in the Indian Ocean [e.g., *Song et al.*, 2004]. Thus, the spreading of the ITF water along isopycnals in the Indian Ocean acts to freshen and cool the Indian Ocean along isopycnals, as shown on the surface of σ_0 = 25.0 (Figure 2; see also Figure 3b), but the effects are conspicuous only in the latitude band between 5°S–15°S and become weaker with distance from the Indonesian Seas as the ITF water is mixed with the warmer and saltier waters in the Indian Ocean along its westward advective route within the South Equatorial Current (SEC).

[6] The second means by which the ITF affects the Indian Ocean is more indirect. The injection of ITF water at various depths leads to an alteration of the circulation (i.e., velocity field) and through the thermal wind relation, to distortion of the isopycnal surfaces of the Indian Ocean (see HG for detailed discussion). In our model, as also shown in the HG model, the ITF causes higher depth-integrated steric height throughout the Indian basin. Since the steric height is inversely related to density, increase in steric height implies density is lower in ITF10 than in NOITF, which is evident throughout the water column (Figure 3a). The largest density difference between ITF10 and NOITF occurs in the upper 200 m between 10°S and 20°S where the background density gradient is the greatest. Associated with the ITF-induced negative density is the positive temperature difference between ITF10 and NOITF (Figure 3c), which has maximum in the southern subtropical Indian Ocean. The sea surface temperature (SST) of the Indian Ocean is also warmer in ITF10 than in NOITF, which results in less net ocean heat gain in ITF10 than in NOITF (Figure 5). Note that the negative temperature difference between ITF10 and NOITF within the thermocline between 5°S–15°S (domain of the SEC) is a manifestation of the direct spreading effect of the ITF water properties.

3.2. Effects of the ITF Transport Profile

[7] The effects of the variation of the vertical profile of ITF transport on the Indian Ocean are studied by comparing the experiments ITF10TH and ITF10. The ITF transport profile change (from ITF10 to ITF10TH) does not cause noticeable change in the Indian Ocean by the means of direct spreading of the ITF water as the ITF transport difference between the two runs within the thermocline is small (∼0.4 Sv between σ_0 = 24 – 26.5). However, the ITF transport profile change significantly alters the potential density and temperature fields by the means of shifting isopycnals vertically. Because of more ITF transport in the

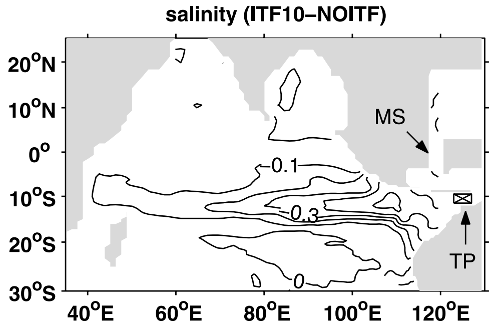


Figure 2. Salinity difference between ITF10 and NOITF on the potential density surface of σ_0 = 25.0. Potential temperature difference has similar pattern (not shown). MS and TP represent the Makassar Strait and the Timor Passage, respectively.

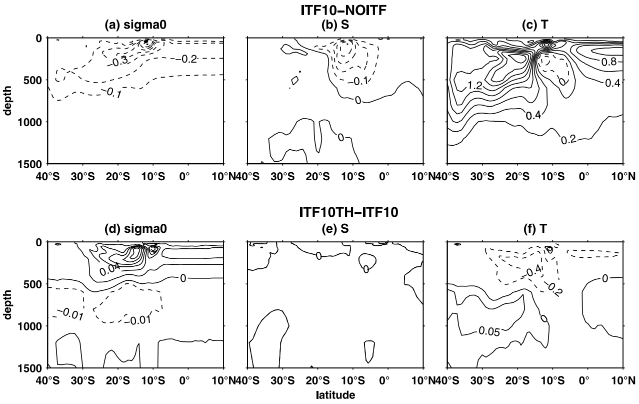
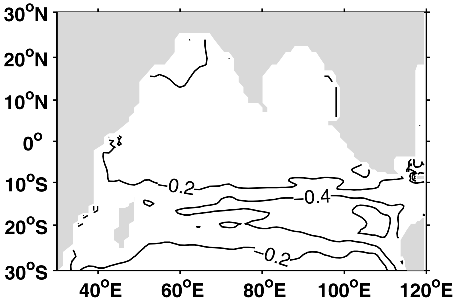


Figure 3. Difference along 95°E of (a) (d) potential density, (b) (e) salinity and (c) (f) potential temperature among model runs.

thermocline and less above the thermocline in ITF10TH than in ITF10, the vertical distance between isopycnals are reduced and the isopycnals are elevated above the thermocline. The reverse is true for isopycnals below the thermocline. The resultant density differences between ITF10TH and ITF10 show a well-organized structure (Figure 3d): higher density above 500 m and lower density below 500 m in ITF10TH. The temperature difference between ITF10TH and ITF10 (Figure 3f) has similar pattern, with maximum centered at about 20°S. Horizontally the temperature difference between ITF10TH and ITF10 expands throughout the Indian basin (Figure 4a), with larger magnitudes in the eastern Indian Ocean between 10°S–30°S. Worth mentioning is the magnitudes of the temperature difference between ITF10TH and ITF10, whose maximum is over 0.4°C, about 25% of the maximum temperature difference between ITF10 and NOITF (Figures 3c and 3f). It is significant given that the difference of ITF transport between ITF10TH and ITF10 is about 1 Sv (Figure 1), which is only 10% of the net ITF transport (10 Sv) in both ITF10 and ITF10TH.

[8] The heat content of the upper 500 m in ITF10TH is less than that in ITF10 throughout the Indian Ocean, with larger magnitudes south of 10°S in the eastern Indian Ocean (not shown). More importantly, the SST of the Indian basin north of 30°S is cooler in ITF10TH than in ITF10 (Figure 4b). The SST difference has maximum along the west coast of Australia (~0.2°C), where strong vertical mixing associated with the southward flowing Leeuwin Current brings the subsurface cooling signal to the surface (HG). As a consequence of the surface cooling in ITF10TH, there is more net surface heat flux into the ocean, in particular, along the west coast of Australia. The net heat gain of the Indian Ocean from the atmosphere in ITF10TH is 0.02 PW more than that in ITF10 (Figure 5), which is 25% of the difference of net ocean heat gain north of 30°S between ITF10 and NOITF.

(a) T 250m (ITF10TH–ITF10)



(b) SST (ITF10TH–ITF10)

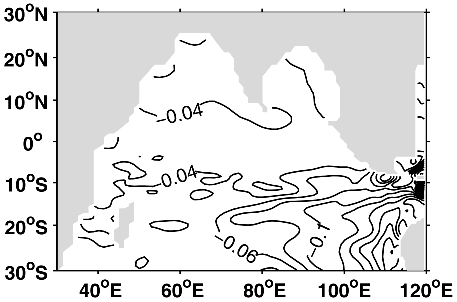


Figure 4. Difference between ITF10TH and ITF10 of (a) potential temperature at 250 m and (b) SST.

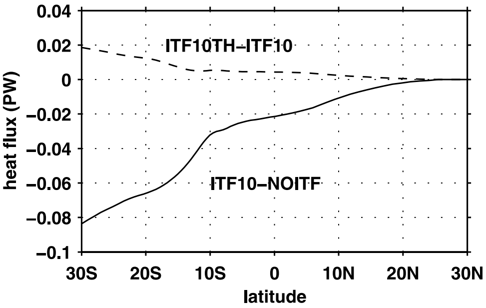


Figure 5. Difference of net heat gain of the Indian Ocean (integrated from 30°N southward) between model runs. Positive values indicate ocean heat gain.

4. Conclusions

[9] The result of this study shows that the ITF transport profile is important in regulating the Indian Ocean stratification and surface heat fluxes. It also suggests that when considering the effects of the ITF on the Indian Ocean, it is not adequate to only compare two scenarios (one with the ITF and the other without), which neglects other important ITF characteristics, such as the vertical profile of its transport. Large quantitative discrepancies among previous model studies in terms of the effects of the ITF on the Indian Ocean maybe partly due to different ITF characteristics, including the vertical profile of ITF transport, in different models. In addition, *Potemra et al.* [2002] show that the vertical structure of ITF transport has large temporal variability, which according to the result of this study could have significant impacts on the Indian Ocean.

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A. L. Gordon and Q. Song, Lamont-Doherty Earth Observatory, Columbia University, 61 Route 9W, Palisades, NY 10964, USA. (qsong@ldeo.columbia.edu)