Advection and diffusion of Indonesian throughflow water within the Indian Ocean South Equatorial Current

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Abstract. Warm, low salinity Pacific water weaves through the Indonesian Seas into the eastern boundary of the Indian Ocean. The Indonesian Throughflow Water (ITW) adds freshwater into the Indian Ocean as it spreads by the advection and diffusion within the Indian Ocean's South Equatorial Current (SEC). The low salinity throughflow trace, centered along 12°S, stretches across the Indian Ocean, separating the monsoon dominated regime of the northern Indian Ocean from the more typical subtropical stratification to the south. ITW is well represented within the SEC thermocline, extending with concentrations above 80% of initial characteristics from the sea surface to 300-m within the eastern half of the Indian Ocean, with 60% concentration reaching well into the western Indian Ocean. The ITW transport within the SEC varies from 4 to 12 x 10^6 m^{3}sec^{-1}, partly in response to variations of the injection rate at the eastern boundary and to the likelihood of a zonally elongated recirculation cell between the Equatorial Counter Current and the SEC within the Indian Ocean. Lateral mixing disperses the ITW plume meridionally with an effective isopycnal mixing coefficient of 1.1 to 1.6 x 10^4 m^{2}sec^{-1}.

Introduction

The South Equatorial Current (SEC) of the Indian Ocean forms the boundary between the monsoon derived water masses of the northern Indian Ocean, marked by the evaporative conditions of the Arabian Sea and excess freshwater conditions of the Bay of Bengal (as best exemplified by their sharply different surface salinity, [Conkright et al.., 1994]), with the more typical subtropical stratification of the southern Indian Ocean. However, what particularly sets the Indian Ocean SEC apart from its cousins of other oceans is the presence of low salinity Pacific thermocline water injected at the eastern boundary, in what is usually referred to as the Indonesian Throughflow Water (ITW). The ITW is considered to be an important element in the heat and hydrological budget of the Indian Ocean [Piola and Gordon, 1986], and

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perhaps part of a large interocean network of thermohaline fluxes [Gordon, 1986]. It may also influence SST and associated ocean atmosphere coupling within the Indian Ocean, and hence of special interest to monsoon climate research.

Using the WOCE meridional WHP CTD sections and hull mounted ADCP data [Ffield, 1997] the ITW transport contribution to the thermocline of the SEC is determined as well as its meridional isopycnal mixing with Indian Ocean water.

Indonesian Throughflow Water

The ITW characteristics are defined by data obtained in the Timor Sea [Fieux et al., 1994, 1996a; Ilahude and Gordon, 1996; Gordon and Fine, 1996]. The throughflow thermocline layer is represented by a nearly isohaline profile, a product of freshwater input and strong vertical mixing within the Indonesian Seas that tends to mute the salinity stratification of the Pacific throughflow water [Ffield and Gordon, 1992; Hautala et al., 1996]. A major Pacific source is drawn from the North Pacific thermocline flowing along Makassar Strait, although the lower thermocline and deeper waters of the Indonesian Seas are dominated by South Pacific water flowing at a slower rate through the deep channels east of Sulawesi [Gordon and Fine, 1996].

The throughflow transport appears to have a seasonal signal, with maximum values occurring during the boreal summer, with essentially zero values during the boreal winter [Fieux et al., 1994, 1996b; Arief and Murray, 1996]. Meyers et al., [1995] XBT based estimate for the 1983 to 1989 yields an annual mean of 5 Sv passing through the upper 400 meters across a section between Java and Australia (Figure 4c of Meyers, 1996 using 1983 to 1994 XBT data, indicates a slightly lower annual mean) with a 12 Sv August-September maximum, and essentially zero transport in May-June and October-November. Quadfasel et al., [1996] find that of the 22 Sv transport within the upper 470 m of the South Equatorial Current in the eastern Indian Ocean in October 1987, approximately 9 Sv is derived from the ITW. Fieux et al., 1994, 1996b find 18 Sv passing into the Indian Ocean between Java and Australia in August 1989 and 2.6 Sv headed eastward in February 1992. Bray et al., [1997] further examines the Timor Sea circulation using the WHP I10 data. Meyers [1996]; Fieux et al., 1996b; Gordon and Fine, 1996, all suggest the throughflow is reduced during El Niño episodes ([Meyers, 1996] finds a 5 Sv ENSO signal of the throughflow), when sea level stands lower at the tropical Pacific entrance to the Indonesian Seas, effectively representing a northern winter analog.

The percentage of ITW within the Indian Ocean SEC is determined by comparing the potential temperature,

salinity (T/S) data points measured during the WOCE WHP observational period of 1995, with the 'pure' Indonesia (Timor Sea) source water T/S properties and the principal water masses of the Indian Ocean (Fig. 1). The comparison is made with a simple isopycnal model: an observed T/S point at a WHP station is assumed to be composed of a linear admixture of the principal water type values along the same isopycnal. This method disregards vertical mixing which is a safe assumption within the highly stratified thermocline; it is also noted that the vertical processes would tend to reduce the thermocline salinity within the westward flowing SEC, while isopycnal mixing would act to increase salinity, as observed. The Indian Ocean principal water masses are considered to be the southern Indian Ocean Central Water (ICW), and the sharply contrasting surface layer waters of the Arabian Sea and Bay of Bengal. The Bay of Bengal surface water may pass into the throughflow by way of the South Java Current, which curls back to the west as it's waters join the SEC. The ICW component is swept into the northern Indian Ocean within the western margins of the tropical Indian Ocean providing the primary source of thermocline within the northern Indian Ocean [*You and Tomczak*, 1993; *You*, 1996], therefore the northern Indian thermocline may be considered as a diluted (with Arabian Sea, Bay of Bengal and ITW) form of ICW and not as an independent, principal water mass. As the contrast between the throughflow and principal water masses is small for water cooler than 10°C this method cannot detail with acceptable precision the throughflow percentage below the thermocline. Although the bulk of throughflow transport is believed to occur within the thermocline layer [*Wyrtki*, 1987; *Gordon and Fine*, 1996] and the SEC is weak below the thermocline, the reader is cautioned that further Pacific water may enter the Indian Ocean below the thermocline [*Fieux* et al., 1996a].
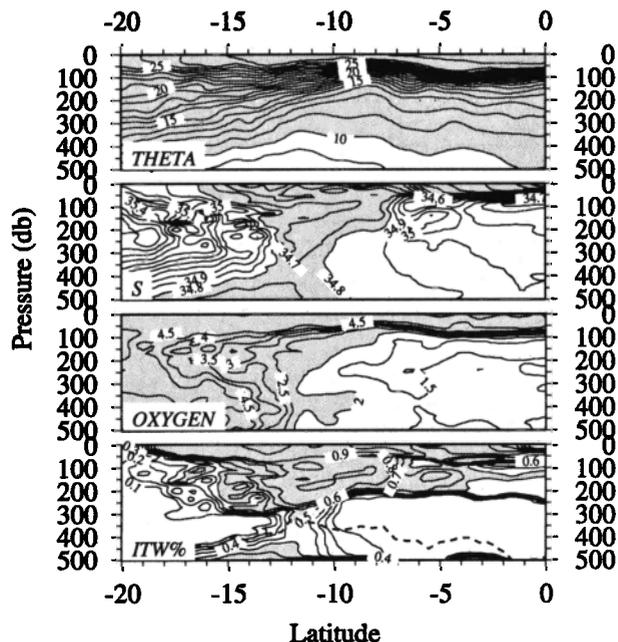
Figure 2. Temperature, salinity, oxygen and percentage Indonesian Throughflow Water along WOCE WHP section I9n (see fig. 1 of Ffield, 1997, this issue).

The I9n section, nominally along 95°E (Fig. 2) salinity divulge the presence of the ITW by the low salinity water column centered at 12°S. The sharp meridional gradient in thermocline oxygen falls immediately south of the plume of throughflow water, clearly showing the major frontal zone associated with the plume. The high percentage of throughflow water in the upper 50 m south of 15°S is most likely a consequence of southward Ekman transport characteristic of this region and the doming of the thermocline between 5° and 13°S denotes the division between southward and northward Ekman transport [*Trenberth* et al., 1990]. Southward flux of freshwater (south of 15°S) tends to balance the net evaporation of the south Indian Ocean subtropical region. North of the plume axis there is also high concentration of throughflow water. This is Indonesian water embedded with the Equatorial Counter Current (the ADCP reveals strong flow towards the east between 6° to 8°S), as part of the recirculation cell discussed below. North of 5°S the low salinity water may reflect local excess precipitation and Bay of Bengal influence and is not included in the throughflow transport values.

The salinity and percentage of the Indonesian throughflow on a representative sigma-0 surface (24.0, roughly the 100 m depth, Fig. 3) reveal the westward advection and dilution of the low salinity throughflow water within the SEC. The break in the 34.6 isohaline near 95°E may denote uneven injection of ITW or eddy variability in meridional mixing process. The plume spreads zonally across the Indian Ocean, with increased meridional spreading on reaching the rough topography between the Seychelles and Madagascar. The data suggests that the 20% ITW concentration contour may pass southward of 20°S along the coast of Madagascar, but such detail at the lower concentration levels requires a mixing model better suited to the western Indian Ocean T/S values.
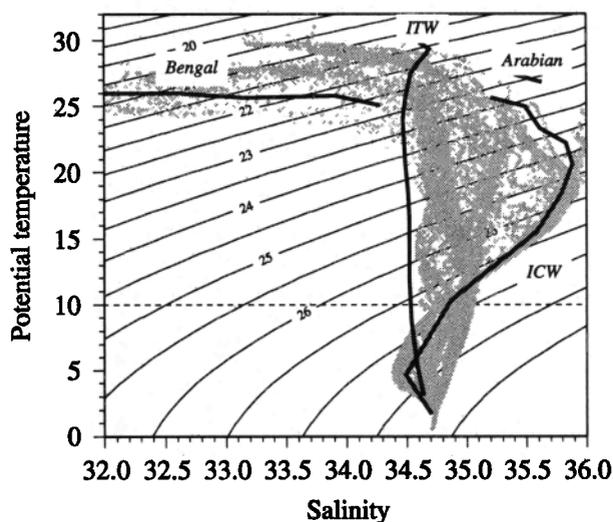

Figure 1. Potential Temperature Salinity relationship of the Indonesian Throughflow Water and principal Indian Ocean Water masses which mix along isopycnal surfaces with the Indonesian throughflow water. The Indonesian throughflow T/S characteristics are defined by data obtained in the Timor Sea (Ilahude and Gordon, 1996).
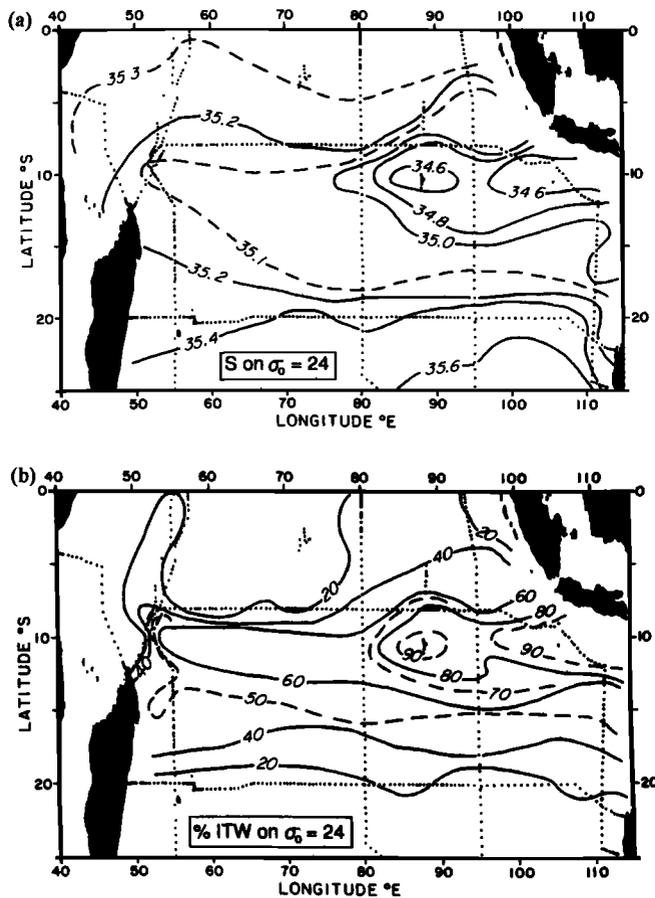
Figure 3. Distribution of salinity (3a) and percentage of Indonesian Throughflow Water (3b) on the 24.0 Sigma-0 surface, roughly at 100-m depth. The dots show the positions of the WOCE WHP CTD stations used to construct the contour field.

Geostrophic Transports

The net westward geostrophic velocity field between 5° to 20°S (6.5°S to 20°S for WHP I7, to avoid the shallow platform of the Seychelles; Table I) which includes the SEC, is determined by two reference methods: a 3000 db zero velocity and the ADCP measured velocity perpendicular to the WHP section, averaged between stations at 200 m (below the Ekman layer). The 3000 db zero reference values may provide for the more stable, climatic values; the ADCP represents the transport field at the time of measurements, including the high frequency and non-geostrophic features. The net westward flow of the SEC increases towards the west, presumably as more water joins the SEC from the north of 5°S and south of 20°S, from 11 to 15 Sv across 95°E to 23 to 36 Sv across 55°E, in agreement with the findings of *Donguy and Meyers* [1995] based on XBT analysis.

The contribution of the ITW to the SEC transport is determined by combining the percentage of throughflow water with the geostrophic transport values. The throughflow transport across 95°E is 4 to 6 Sv, increasing to 11 to 12 Sv at 80°E. Dropping to 6 to 10 Sv at 55°E which may be due to meridional loss of throughflow water on proceeding westward. The variability may also reflect

seasonal variations in the injecting of Pacific water at the Indian Ocean eastern boundary, though transport similarity of the I8 one time and repeat sections representing a 6 month difference of injection time at the eastern boundary, argues against a seasonal cycle origin. The introduction of the Indonesian throughflow into the SEC is expected to vary interannual (ENSO) scales, with the throughflow relaxing during El Niño episodes. However comparison to the southern oscillation index does not reveal a relationship to the throughflow transport. There may be changes in the throughflow component due to changes in the subtropical gyre circulation of the southern Indian Ocean or of a recirculation cell within the equatorial current system, which advects throughflow water southward across 5°S between 95°E and 80°E. The ADCP from I9 section (95°E) does show strong southward flow in the upper 400 m across 5°S [*Hacker. personal communication*, 1997]. The existence of an equatorial recirculation is also supported by the 1990 JEXAM drifter tracks [*Michida and Yoritaka*, 1996] as well as the WOCE Indian Ocean drifters, and is the NRL model run forced by ECMWF winds [*Hacker, personal communication*, 1997]. Additionally the zonal section I2 along 8°S indicates weak northward geostrophic flow (upper 400 m) within the thermocline of the western Indian Ocean, with southward transport in the east. Thus a zonally elongated circulation cell formed between the SEC and Equatorial currents may recirculate throughflow water between 80°E and 90°E.

Isopycnal Mixing

Attenuation of the low salinity signal of the throughflow water as it spreads towards the western Indian Ocean is the consequence of lateral mixing. Vertical mixing would not lead to a reverse signal, as the salinity is low in the surface water and in the intermediate water at the base of the thermocline. Fitting a parabolic curve to the salinity versus latitude along isopycnals characteristic of the upper 400 m and balancing the meridional eddy diffusion against zonal advection (using a mean characteristic geostrophic zonal flow for the upper 400-m of 10 cm,/sec) requires an isopycnal mixing coefficient of 1.1 to 1.6 x 10^4 m^{2}sec^{-1} (Table I). Independent estimates of the diffusivities in the Indonesian plume are derived from the WOCE drifter array using *Taylor's* [1921] single particle theory. The WOCE Indian Ocean surface drifter array over the range of the plume gives diffusivities that range from 0.4 to 2.4 X 10^4 m^{2}sec^{-1} the meridional direction with an areal average of 1.3 X 10^4 m^{2}sec^{-1}. This value should decrease somewhat with depth in proportion to the decrease in velocity but will be augmented by shear dispersion in the horizontal [*Rhines and Young*, 1982; *Dewar and Flierl*, 1985]. These Ky values may be considered to be a rather large number, but perhaps not unreasonable in the strong horizontal shears of the equatorial current system.

Table 1. Transport in Sv (10^6 m³/sec) of the South Equatorial Current (SEC) and of the Indonesian throughflow component within the SEC across meridional sections obtained by the WOCE Indian Ocean Expedition of 1995. The transport values are from 5°S to 20°S (6.5°S to 20°S for I7 and I7r to avoid Seychelles), for the upper 400-m.

WHP Section Number	Time of data collection	Time at Timor Sea origin (SEC=10cm/sec)	SEC transport 3000 db (upper 400m)	SEC transport 200 ADCP (upper 400m)	throughflow transport 3000 db (upper 400m)	throughflow transport 200 ADCP (upper 400m)	Ky (m^2s^{-1}) (SEC= 10cm/s)
I9	February '95	December '93	15	11	6	4	1.31 x 10^4
I8	March '95	September '93	17	15	12	12	1.56 x 10^4
I8 repeat	October '95	March '94	27	30	11	11	1.50 x 10^4
I7	August '95	February '93	23	36	6	9	1.06 x 10^4
I7 repeat	April '95	October'92	25	30	8	10	1.06 x 10^4

References

Arief, D., and S. Murray, Low frequency fluctuations in the Indonesian throughflow through Lombok Strait, *J. Geophys. Res.*, 101(C5), 12455-12464, 1996.

Bray, N.A., S.E. Wijffels, J.C. Chong, M. Fieux, S. Hautala, G. Meyers, and W.M.L. Morawitz, Characteristics of the Indo-Pacific throughflow in the eastern Indian Ocean, GRL WOCE Indian Ocean Issue, Geophys. Res. Lett., this issue, 1997.

Conkright, M., S. Levitus, T. Boyer, D. Bartolacci, and M. Luther, Atlas of the northern Indian Ocean, *NOAA/NODC*, Washintgon, DC and Univ. of South Florida, St. Petersburg, FL, 1994

Dewar, W. K., and G. R. Flierl, Particle trajectories and simple models of transport in coherent vortices, *Dyn. Atmos. Oceans*, 9, 215-252, 1985.

Donguy, J., and G. Meyers, Observations of geostrophic transport in the western tropical Indian Ocean, *Deep-Sea Res.*, 42(6),1007-1028, 1995.

Ffield, A.. Introduction to the GRL WOCE Indian Ocean Issue, Geophys. Res. Letters, in press, 1997.

Ffield, A., and A. Gordon, Vertical mixing in the Indonesian Thermocline, *J. Phys. Oceanog.*, 22(2), 184-195, 1992.

Fieux, M. R. Molcard, and A. G. Ilahude, Geostrophic transport of the Pacific-Indian Oceans throughflow, *J. Geophys. Res.*, 101(C5), 12421-12432, 1996b.

Fieux, M., C. Andrie, E. Charriaud, A. G. Ilahude, N. Metzl, R. Molcard, and J. Swallow, Hydrological and chlorofloromethane measurements of the Indonesian throughflow entering the Indian Ocean, *J. Geop. Res.*, 101(C5), 12433-12454, 1996a.

Fieux, M., C. Andrié, P. Delecluse, A. G. Ilahude, A. Kartavtseff, F. Mantisi, R. Molcard, and J. C. Swallow, Measurements within the Pacific-Indian Ocean Throughflow Region, *Deep Sea Res.*, 41(7), 1091-1130, 1994.

Gordon, A. L., and R.A. Fine, Pathways of water between the Pacific and Indian Oceans in the Indonesian Seas, *Nature*, 379, 146-149, 1996.

Gordon, A. L., Interocean Exchange of Thermocline Water, *J. Geophys. Res.*, 91(C4), 5037-5047, 1986.

Hautala, S., J. Reid, and N. Bray, The distribution and mixing of Pacific water masses in the Indonesian Seas, *J. Geop. Res.*, 101(C5), 12375-12389, 1996.

Ilahude, A. G., and A. L. Gordon, Thermocline Stratification Within the Indonesian Seas, *J. Geophys. Res.*, 101(C5), 12401-12409, 1996.

Meyers, G., Variations of Indonesian throughflow and El Niño-Southern Oscillation, J. *Geophys. Res.*, 101(C5), 12255-12263, 1996.

Meyers, G., R. Bailey, and A. Worby, Volume transport of Indonesian throughflow, *Deep-Sea Res .*, 42(7), 1163-1174, 1995.

Michida, Y., and H. Yoritaka, Surface currents in the area of the Indo-Pacific throughflow in the tropical Indian Ocean observed with surface drifters, *J. Geop. Res.*, 101(C5), 12475-12482, 1996.

Piola, A., and A. Gordon, On Oceanic Heat and Freshwater Fluxes at 30°S, *J. Phys. Ocean.*, 16(12), 2184-2190, 1986.

Quadfasel, D., A. Frische, and G. Cresswell, The circulation in the source area of the South Equatorial Current in the eastern Indian Ocean, *J. Geophys. Res.*, 101(C5), 12483-12488, 1996.

Rhine, P. B., and W. R. Young, Homogenization of potential vorticity in planetary gyres, *J. Fluid Mech.*, 122, 347-367, 1982.

Taylor, G.I., Diffusion by continuous movements, *Proc. London Math. Soc.*, Ser. 2, Vol. 20, 196-212, 1921.

Trenberth, K., W Large, and J. Olson, The mean annual cycle in global ocean wind stress, *J. Phys. Oceanog.*, 20(11), 1742-1760, 1990

Wyrtki, K., Indonesian through flow and the associated pressure gradient, *J. Geophys. Res.*, 92, 12941-12946, 1987.

You, Y., and M. Tomczak, Thermocline circulation and ventilation in the Indian Ocean derived from water mass analysis, *Deep-Sea Res..*, 40(1), 13-56, 1993.

You, Y. Dianeutral mixing in the thermocline of the Indian Ocean. Deep-Sea Res. 43(3):291-320, 1996.