GEOPHYSICAL RESEARCH LETTERS, VOL. 31, L21301, doi:10.1029/2004GL020854, 2004

Temporally integrated estimate of the Indonesian throughflow using tritium

P. Jean-Baptiste,[1] W. J. Jenkins,[2] J. C. Dutay,[1] E. Fourré,[1] V. Leboucher,[1,3] and M. Fieux[3]

Received 27 June 2004; revised 24 September 2004; accepted 4 October 2004; published 2 November 2004.

[1] Because of the high interannual and seasonal variability, transports from the various methods used to estimate the Indonesian throughflow encompass a large range of values. Here, we estimate a temporally integrated transport for the throughflow from comparison of the tritium water column inventory on both sides of the throughflow. Our approach is based on the simple idea that tritium, with a radioactive decay half-life of 12.32 yr, is well suited to infer the transit time (and consequently the mass flow) of the waters through the Indonesian archipelago. We show that the tritium budget implies a flow of 8.6 ± 4 Sv, corresponding to a transit time of 10.5 yr. This result, which represents an average over seasons and several ENSO and non-ENSO periods, shows that repeated tritium measurements on both sides of the Indonesian Seas could provide a useful method for monitoring the long-term evolution of the throughflow.

INDEX TERMS: 4825 Oceanography: Biological and Chemical: Geochemistry; 4860 Oceanography: Biological and Chemical: Radioactivity and radioisotopes; 4223 Oceanography: General: Descriptive and regional oceanography; 9340 Information Related to Geographic Region: Indian Ocean; 9355 Information Related to Geographic Region: Pacific Ocean. **Citation:** Jean-Baptiste, P., W. J. Jenkins, J. C. Dutay, E. Fourré, V. Leboucher, and M. Fieux (2004), Temporally integrated estimate of the Indonesian throughflow using tritium, *Geophys. Res. Lett.*, *31*, L21301, doi:10.1029/2004GL020854.

1. Introduction

[2] Pacific waters entering the Indonesian Archipelago follow two main routes [*Gordon and Fine*, 1996]. The western route, which is the predominant pathway, enters the Celebes Sea from the North Pacific and proceeds through the Makassar Strait toward the Flores Sea. From here, one minor branch enters the Indian Ocean through the Lombok Strait [*Murray and Arief*, 1988] while the majority of the flow enters the Banda Sea and rejoins the Indian Ocean through the Ombai and Timor straits (Figure 1). The eastern route reaches the Banda Sea through the Halmahera and Maluku Seas.

[3] There is convincing evidence [e.g., *Ffield and Gordon*, 1992; *Gordon and Fine*, 1996] for the North Pacific origin of the waters following the western route including tritium and radiocarbon tracer data [e.g., *Fine*, 1985; *Moore et al.*, 1997]. These waters are transported southward by the Mindanao current, one branch of which enters the Celebes Sea while the rest of it turns eastward into the North Equatorial Countercurrent. The origin of the waters following the eastern route into the Indonesian Seas is less certain. While the North Banda Sea communicates with the Maluku Sea and the North Pacific water masses through the Lifamatola strait, most of the South Equatorial Current (SEC) turns eastward to join the North Equatorial Countercurrent. A small fraction of the flow, however, makes it way to the Banda Sea, in agreement with salinity data, which point to the presence of South Pacific lower thermocline waters in the eastern basins [*Gordon and Fine*, 1996; *Hautala et al.*, 1996].

[4] Following the nuclear tests of the early sixties, tritium concentration in the atmosphere has increased by a factor of ~1000 relative to the natural background. Numerous studies have been published addressing the fate of this sharp tritium spike in the ocean. However, the tritium concentrations decrease nowadays only slowly through time, thus there is a more accurate use of tritium as a radioactive clock. Here, we use the radioactive property of the tracer to infer the transit time of the waters through the Indonesian Archipelago, and to calculate the intensity of the throughflow.

2. Tritium Data

[5] For this study, tritium measurements were selected on both sides of the throughflow (Figure 1). On the Pacific side, data are from the WOCE P4 zonal transect occupied in 1989. The selected stations (st. 4 and st. 5) come from the core of the Mindanao current and are representative of North Pacific waters entering the Indonesian Seas. On the Indian side, the tritium samples were obtained in 1989 during the JADE cruise downstream of the Ombai strait and in the Timor passage (Figure 1).

[6] The tritium vertical profiles are shown in Figure 2. On the Pacific side, the subsurface maximum is typical of the lateral ventilation of the mid and low latitudes by isopycnal advection of northern Pacific waters that are more enriched in tritium [*Fine et al.*, 1981, 1987]. This maximum is removed by the strong vertical mixing in the Indonesian thermocline [*Ffield and Gordon*, 1992] and is no longer apparent in the waters exiting the Indonesian Seas.

3. Tritium Budget

[7] The tracer vertical distribution shows that bomb tritium is essentially restricted to the upper 1500 meters of the water column. This water depth also corresponds to that

---

[1] Institut Pierre Simon Laplace/Laboratoire des Sciences du Climat et l'Environnement, Gif-sur-Yvette, France.

[2] Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA.

[3] Institut Pierre Simon Laplace/Laboratoire d'Océanographie Dynamique et de Climatologie, Université Paris VI, Paris, France.

0094-8276/04/2004GL020854

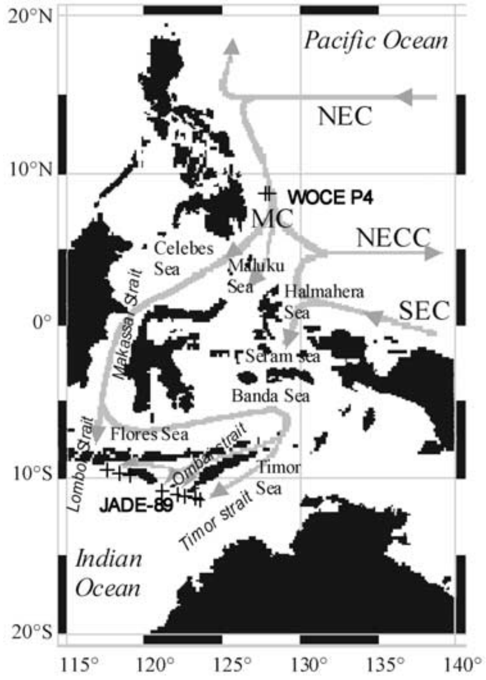

Figure 1. Location of the hydrographic stations and schematic diagram of major currents: NEC: North Equatorial Current, SEC: South Equatorial Current, NECC: North Equatorial CounterCurrent, MC: Mindanao Current.

of the deepest sills over which Indonesian waters spill into the Indian Ocean [e.g., *Jean-Baptiste et al.*, 1997; *Gordon et al.*, 2003a]. Therefore, in the following, this depth is chosen as the reference level H for calculating the change in the water column tritium inventory between entrance and outlet of the Indonesian Seas.

[8] The tritium budget of the Indonesian Seas can be written by balancing the four following terms:

- the tritium flux entering from the north
- the net tritium flux exchanged at the air-sea interface
- the amount of tritium removed by radioactive decay
- the tritium flux leaving the Indonesian Seas to the Indian Ocean

(N.B. since tracer concentrations are very low at H = 1500 m, the tritium flux across the reference level is neglected).

[9] The waters leaving the Indonesian Seas in 1989 (i.e., the year of the tritium measurements on the JADE cruise) entered the Indonesian Seas from the north in the year (1989-τ), where τ is the mean transit time of the waters through the Indonesian archipelago. Hence, the amount of tritium entering the system per unit of time for the year (1989-τ) will be equal to $\int_0^H q_{in}(z) \times C_{in}^{1989-\tau}(z)dz$, where $q_{in}(z)dz$ is the flow entering the Indonesian Seas per unit of time between depth z and $z + dz$ and $C_{in}^{1989-\tau}(z)$ is the tritium concentration at depth z. In a similar way, the amount of tritium leaving the Indonesian seas in 1989 through the Ombai and Timor straits will be equal to $\int_0^H q_{out}(z) \times C_{out}^{1989}(z)dz$. Hence, the tritium budget can be expressed by the following equation:

$$\int_0^H q_{out}(z) \times C_{out}^{1989}(z)dz - \exp(-\lambda\tau)\int_0^H q_{in}(z) \times C_{in}^{1989-\tau}(z)dz - A_0\Phi_{EP}\exp(-\lambda\tau_{EP}) = 0 \qquad (1)$$

where Φ_{EP} is the net tritium flux added by rain/vapor exchange at the surface (area A_0). The term $\exp(-\lambda\tau)$ accounts for the tritium decay of the waters during their transit time τ through the Indonesian archipelago while $\exp(-\lambda\tau_{EP})$ accounts for the decay of the tritium added by rain/vapor exchange at the surface, with a characteristic decay time τ_{EP} ($\tau_{EP} < \tau$). At this stage, we neglect the leakage through the Lombok strait as well as the minor South Pacific component, the influence of which are examined next.

[10] The tritium flux exchanged at the surface, Φ_{EP}, which is the sum of two terms, 1) the rain component, PC_p, and 2) the tritium fluxes exchanged at the air-sea interface by the evaporation process [*Weiss and Roether*, 1980], is given by:

$$\Phi_{EP} = PC_p + EC_p\frac{h}{\alpha(1-h)} - EC_s\frac{1}{\alpha(1-h)} \qquad (2)$$

where E, P are the evaporation and precipitation per unit area and unit of time (Table 1), h is the relative humidity of the air above the interface (h ≈ 0.75), α is the isotopic fractionation factor (α ≈ 1.1) and C_p, C_s are the tritium concentration in the rain water and at sea surface respectively (the tritium content of water vapour is assumed in isotopic equilibrium with that of rain). Available data (Table 1) indicate that this evaporation/precipitation process is of minor importance here, representing ~1% of the total throughflow and less than 5% of the tritium budget. A full calculation shows that neglecting this component of the tritium budget affects the final results by ~2% only. Therefore, for the sake of simplicity, we skip this term to concentrate on the important terms of equation (1).

4. Volume Transport of the Throughflow

[11] For calculating the integrals in equation (1), we examined three different cases, assuming (1) a constant

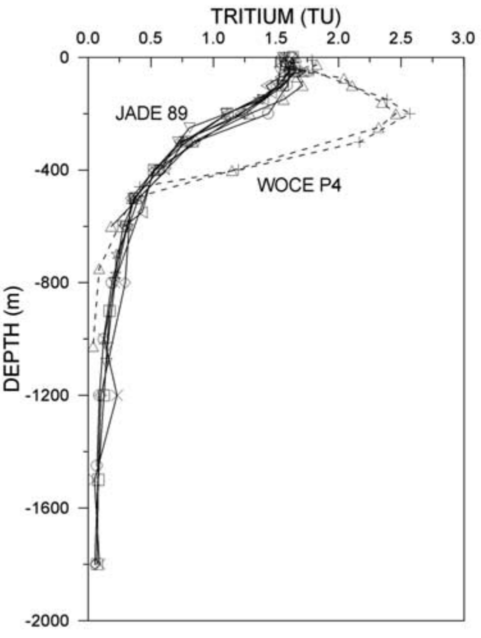

Figure 2. Tritium vertical profiles at the entrance (dotted line WOCE P4) and the exit (solid line JADE-89) of the Indonesian Seas (2-sigma error between 0.01 and 0.05 TU).

Table 1. Value of the Parameters Used to Compute the Tritium Budget[a]

Parameter	Name	Value	Reference
Indonesian Seas surface area	A_0	$(2.2 \pm 0.2) \times 10^6$ km^2	*GEBCO* [1984]
Surface area at 1500 m depth	A_{1500}	$(1.6 \pm 0.1) \times 10^6$ km^2	*GEBCO* [1984]
Tritium in precipitation (73–89)	C_p	6 ± 0.5 to 2 ± 0.1 TU	*IAEA* [1990]
Sea surface tritium in 1973	C_s	3.4 ± 0.2 TU81	*Broecker et al.* [1986]
Sea surface tritium in 1989	C_s	1.7 ± 0.1 TU	this work
Precipitation rate	P	2.2 ± 0.2 m/yr	*Hulme* [1994]
Evaporation rate	E	1.0 ± 0.2 m/yr	*Hulme* [1994]
Reference level	H	1500 m	-
Tritium inventory (WOCE P4)	I_{in}	993 ± 56 TU.m	this work
Tritium inventory (JADE 89)	I_{out}	699 ± 84 TU.m	this work

[a]The uncertainty on tritium inventories are derived from the analytical uncertainty on each measurement.

velocity with depth, (2) an exponentially decaying vertical flow $q(z) = q_0 \exp(-z/z_0)$ with $z_0 = 166$ m (corresponding to 70% of the throughflow between the surface and 200 meters depth [*Fieux et al.*, 1994]), or (3) a velocity profile with a triangular shape and a maximum transport at 200 m as determined by *Gordon et al.* [2003b] from current measurements. The various methods lead to throughflow values which are identical to within 6% percent, so we conveniently use the constant flow approximation where the integrals can be expressed simply as $Q_{in} \times I_{in}(1989\text{-}\tau)/H$ and $Q_{out} \times I_{out}(1989)/H$ (where Q_{in} and Q_{out} are the mean flow integrated over the depth H and I_{in}, I_{out} are the tritium water column inventories). Hence, equation (1) can be rewritten as follows:

$$Q_{out}\, I_{out}(1989) - Q_{in}\, I_{in}(1989 - \tau)\exp(-\lambda\tau) = 0 \qquad (3)$$

[12] As we neglect the E-P mass balance, the mean water flow leaving the system per unit of time Q_{out} equals Q_{in} and represents the value Q of the throughflow. The transit time τ is linked to the volume flow Q by the relation $\tau = AH/Q$, where A is taken as the mean of the surface area at depth z = 0 (A_0) and depth z = H (A_{1500}). Thus, equation (3) becomes:

$$I_{out}(1989) - I_{in}(1989 - AH/Q)\exp(-\lambda AH/Q) = 0 \qquad (4)$$

which can be solved numerically for the throughflow Q. The numerical values used in the computation are summarised in Table 1 with their respective uncertainties.

[13] $I_{out}(1989)$ corresponds to the JADE-89 tritium inventory at the exit of the throughflow (Table 1). $I_{in}(1989\text{-}\tau)$ poses a specific problem due to the lack of historical tracer data in the western tropical Pacific (GEOSECS data do not extent beyond 170°E in this region). Thus, the determination of the temporal change in the tritium inventory at the entrance of the Indonesian Seas appears here as the main source of uncertainty. Since tritium was first deposited in the high and temperate northern latitudes and subsequently transferred to the low latitudes by the oceanic circulation, the decay-corrected tritium inventory in the tropical Pacific may have been steadily increasing over the whole period of interest. Van Scoy and her colleagues [*Van Scoy et al.*, 1991] have shown that between the GEOSECS survey (1973–1974) and their 1985 study, the 20% loss of decay-corrected tritium (TU81) in the Pacific subpolar gyre was indeed essentially balanced by a similar gain in the tropics. Figure 3 displays our best-estimate of the temporal change in the decay-corrected water column tritium inventory at the entrance of the Indonesian Seas from the start of the tritium fallout to 1989, based on the extrapolation of 1973–74 GEOSECS Pacific tritium inventory distribution [*Broecker et al.*, 1986]. This leads to a mean transit time τ of 17.7 years, which corresponds to an intensity of the throughflow of 5.1 ± 0.8 Sv. (NB. a linear trend between 1963 and 1989, which obviously would constitute a lower bound, would correspond to an upper limit of the throughflow Q_{max} = 11.7 Sv). If we take into account the additional uncertainties corresponding to the propagation of the individual error bars indicated in Table 1, the overall uncertainty is of the order of 30%.

[14] The above water and tritium budgets do not take into account the water leaking through the Lombok Strait (Q_{LB}), estimated at 1.7 ± 1.2 Sv [*Murray and Arief*, 1988]. If (1-β) represents the fraction of the throughflow which exits through the Lombok Strait (with $\beta = 1 - Q_{LB}/Q_{in}$), then the above water and tritium balance equations are valid for βQ_{in}. Hence, the revised value of the throughflow Q* will be equal to previous value Q divided by β, which is exactly equivalent to $Q^* = Q + Q_{LB}$, giving Q* = 6.8 Sv.

[15] As indicated earlier, the South Pacific component of the throughflow has also been neglected so far, on the basis of observational evidence which indicates that the throughflow is mostly composed of North Pacific waters. Because of the low tritium content of the South Equatorial Pacific waters, and of the strongly declining tritium concentration across the thermocline, the tritium inventory of the low

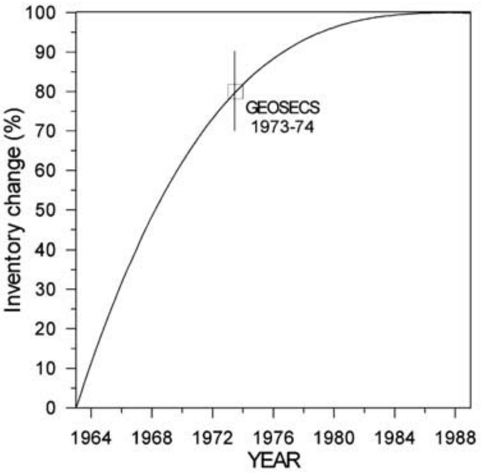

Figure 3. Estimate of the tritium inventory change (decay-corrected to 1981) at the entrance of the Indonesian Seas between the start of the tritium injection and the year 1989 (in % of the 1989 value).

thermocline South Pacific waters is quite small, representing about 5% of the total tritium input (Schlosser, Index of data, available at http://whpo.ucsd.edu/data/onetime/pacific/p09, 2004). Hence, as far as tritium is concerned, the South Pacific component acts primarily as a diluting agent. Therefore, the tritium balance equation remains valid if the water balance equation is replaced by $Q_{out} = Q_{in} + Q'_{in}$ where Q'_{in} is the South Pacific component of the throughflow.

[16] The ratio Q'_{in}/Q_{in} of the South to North Pacific contribution to the throughflow is not known precisely. While all studies point toward the flow through the Makassar strait being derived directly from the North Pacific, the origin of the waters following the eastern route is more complicated. Based on a one-dimensional diffusion model, *Hautala et al.* [1996] concluded that Banda Sea T-S data imply an increasing contribution of the South Pacific waters with depth, from ~10% in the upper 250 meters to 70–90% below 500 m. If one assumes in a rather conservative way that at least half of the throughflow takes place in the upper 500 m, and that the transport through the Makassar Strait represents at least 50% of the total transport, then their results suggest a maximum Q'_{in}/Q_{in} ratio of ~0.4. On the other hand, model simulations [*Nof*, 1996; *Morey et al.*, 1999] point to a ratio of about 0.1. With a ratio Q'_{in}/Q_{in} between 0.1 and 0.4, our best estimate of the total Indonesian throughflow (including Lombok Strait) becomes 8.6 ± 4 Sv. This value, which corresponds to a mean transit time of 10.5 years, represents the volume flow averaged over a period of time spanning several ENSO and non-ENSO periods, thus smoothing out the seasonal as well as much of the interannual variability, which are responsible for a substantial part of the differences among the transports in the literature.

5. Discussion and Concluding Remarks

[17] Considering the wide variety of methods and the large temporal variability of the flow, a critical review of the literature data is beyond the scope of the present study; see *Godfrey* [1996] and *Gordon and McLean* [1999] for reviews. Although historical data provide a large range of results ranging from a 1.5 Sv up to almost 20 Sv [*Godfrey*, 1996], the "prevailing wisdom", as stated by *Gordon and McLean* [1999], based on both experimental data and models, nowadays seems to point to 5–10 Sv average throughflow. The respective measurements published over the last years, both upstream and downstream, do converge substantially: Hautala and co-workers [*Hautala et al.*, 2001] estimated a mean 2 years (1996–97) transport of 8.4 ± 3.4 Sv using pressure gauge pairs and repeated ADCP sections. This value is consistent with the Gordon et al. value of 9.3 ± 2.5 Sv [*Gordon et al.*, 1999] which is a mean from Nov. 1996 to July 1998 using long-term moored instruments. Hence, recent studies appear to have narrowed the range significantly. Nevertheless, these results still suffer from not fully covering the decadal variability of ENSO.

[18] The present estimate of 8.6 ± 4 Sv is an attempt to close that gap using the tritium budget within the Indonesian Seas. The uncertainty remains large however, mainly because the tritium data history in the Western Pacific is not detailed enough to fully constrain the tritium inventory change. Our tracer study, which constitutes a complementary approach to both physical and modeling work, interestingly confirms most recent estimates from current meters measurements, and shows that the method is suitable and useful to estimate the mean volume transport through the Indonesian Seas.

[19] **Acknowledgment.** We acknowledge the support of IFRTP, BPPT, LIPI and French Embassy in Jakarta.

References

Broecker, W. S., T. H. Peng, and H. G. Ostlund (1986), The distribution of bomb tritium in the ocean, *J. Geophys. Res.*, *91*, 14,331–14,344.

Ffield, A., and A. L. Gordon (1992), Vertical mixing in the Indonesian thermocline, *J. Phys. Oceanogr.*, *22*, 184–195.

Fieux, M., C. Andrié, P. Delecluse, A. G. Ilahude, A. Kartavseff, F. Mantisi, R. Molcard, and J. Swallow (1994), Measurements within the Pacific-Indian oceans throughflow region, *Deep Sea Res., Part I*, *41*, 1091–1130.

Fine, R. A. (1985), Direct evidence using tritium data for throughflow from the Pacific into the Indian Ocean, *Nature*, *315*, 478–480.

Fine, R. A., J. L. Reid, and H. G. Ostlund (1981), Circulation of tritium in the Pacific Ocean, *J. Phys. Oceanogr.*, *11*, 3–14.

Fine, R. A., W. H. Peterson, and H. G. Ostlund (1987), The penetration of tritium into the tropical Pacific, *J. Phys. Oceanogr.*, *17*, 553–564.

General Bathymetric Chart of the Oceans (GEBCO) (1984), General bathymetric chart of the oceans, Can. Govt. Publ. Cent., Ottawa.

Godfrey, J. S. (1996), The effect of the Indonesian throughflow on ocean circulation and heat exchange with the atmosphere: A review, *J. Geophys. Res.*, *101*, 12,217–12,237.

Gordon, A. L., and R. A. Fine (1996), Pathways of water between the Pacific and Indian oceans in the Indonesian seas, *Nature*, *379*, 146–149.

Gordon, A. L., and J. L. McLean (1999), Thermohaline stratification of the Indonesian seas: Model and observations, *J. Phys. Oceanogr.*, *29*, 198–216.

Gordon, A. L., R. D. Susanto, and A. Field (1999), Throughflow within the Makassar Strait, *Geophys. Res. Lett.*, *26*, 3325–3328.

Gordon, A. L., C. F. Giulivi, and A. G. Ilahude (2003a), Deep topographic barriers within the Indonesian seas, *Deep Sea Res., Part II*, *50*, 2205–2228.

Gordon, A. L., R. D. Susanto, and K. Vranes (2003b), Cool Indonesian throughflow as a consequence of restricted surface layer flow, *Nature*, *425*, 824–828.

Hautala, S. L., J. L. Reid, and N. Bray (1996), The distribution and mixing of Pacific water masses in the Indonesian seas, *J. Geophys. Res.*, *101*, 12,375–12,389.

Hautala, S. L., J. Sprintall, J. T. Potemra, J. C. Chong, W. Pandoe, N. Bray, and A. G. Ilahude (2001), Velocity structure and transport of the Indonesian throughflow in the major straits restricting flow into the Indian Ocean, *J. Geophys. Res.*, *106*, 19,527–19,546.

Hulme, M. (1994), Validation of large-scale precipitation fields in general circulation models, in *Global Precipitations and Climate Change*, edited by M. Desbois and F. Désalmand, *NATO ASI Ser., Ser. I*, *126*, 387–406.

International Atomic Energy Agency (IAEA) (1990), Environmental isotope data n°9, *IAEA Tech. Rep. Ser. 311*, Vienna.

Jean-Baptiste, P., M. Fieux, A. Dapoigny, and A. G. Ilahude (1997), An eastern Indian Ocean ^{3}He section from Australia to Bali: Evidence for a deep Pacific-Indian throughflow, *Geophys. Res. Lett.*, *24*, 2577–2580.

Moore, M. D., D. P. Schrag, and M. Kashgarian (1997), Coral radiocarbon constraints on the source of the Indonesian throughflow, *J. Geophys. Res.*, *102*, 12,359–12,365.

Morey, S. L., J. F. Shriver, and J. J. O'Brien (1999), The effects of the Halmahera on the Indonesian throughflow, *J. Geophys. Res.*, *104*, 23,281–23,296.

Murray, S. P., and D. Arief (1988), Throughflow into the Indian Ocean through the Lombok Strait, January 1985–January 1986, *Nature*, *333*, 444–447.

Nof, D. (1996), What controls the origin of the Indonesian throughflow?, *J. Geophys. Res.*, *101*, 12,301–12,314.

Van Scoy, K. A., R. A. Fine, and H. G. Ostlund (1991), Two decades of mixing tritium into the North Pacific Ocean, *Deep Sea Res., Part I*, *38*, S191–S219.

Weiss, W., and W. Roether (1980), The rate of tritium input to the world oceans, *Earth Planet. Sci. Lett.*, *49*, 435–446.

J. C. Dutay, M. Fieux, E. Fourré, P. Jean-Baptiste, and V. Leboucher, IPSL/LSCE, CEA-Saclay, F-91191 Gif-sur-Yvette, France. (pjb@lsce.saclay.cea.fr)

W. J. Jenkins, Woods Hole Oceanographic Institution, Woods Hole, MA, USA.