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Philippe Jean-Baptiste, Michèle Fieux, A. Ilahude. An eastern Indian ocean ^3He section from Australia to Bali' evidence for a deep Pacific-Indian throughflow. *Geophysical Research Letters*, 1997, 24 (21), pp.2577-2580. <10.1029/97GL02071>. <hal-03334973>

HAL Id: hal-03334973

<https://hal.science/hal-03334973v1>

Submitted on 5 Sep 2021

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An eastern Indian ocean ^3He section from Australia to Bali: evidence for a deep Pacific-Indian throughflow

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Abstract. The distribution of ^3He has been measured on an Australia-Bali transect, across the Pacific-Indian throughflow region of the Eastern Indian Ocean, in SE and NW monsoonal regimes. Additional samples were also collected directly on the main sills over which water is exchanged between the Indonesian Seas and the Indian Ocean. The ^3He data show that the South Banda Sea deep waters, between 800 and 1400 m, leave the Banda basin over the sills in the straits of Sumba, Savu, Roti and Timor and enter the equatorial Indian Ocean. The permanence of the ^3He in both opposite monsoonal regimes, and the only weak dilution of the ^3He signal between the straits and the Australia-Bali section hundreds of kilometers apart, suggest that this deep outflow is not negligible.

Introduction

^3He is enriched between 7 and 10 fold with respect to the atmosphere in submarine hydrothermal and volcanic emanations and is injected into deep ocean waters. There, it provides a unique tracer for deep circulation in a depth range where hydrographic indicators generally show nearly uniform distributions. The Pacific basin is by far the most enriched in ^3He , mainly released in large amount on the East Pacific Rise. Similarly, significant excesses are observed in the Indian ocean, mainly in the western part of the basin, over the Indian ridges system from the Gulf of Aden to the Rodriguez Triple Junction (Jean-Baptiste et al., 1990; 1992). However the magnitude of the ^3He anomaly in the Indian ocean is less than half of that in the Pacific. This interocean ^3He gradient could therefore provide a tool in tracing the flow of intermediate and deep water between the two oceans.

Water exchange via the Indonesian archipelago is of particular importance due to its potential involvement in the global thermohaline circulation (Gordon, 1986). The Indo-Pacific throughflow is mainly oriented from the Pacific to the Indian ocean, driven to a large extent by the pressure gradient between the two oceans. Therefore, most basins in the Indonesian archipelago are flushed directly or indirectly from the Pacific ocean (Wyrtki, 1961). This region presents a complex topographic structure, with islands dividing the area into many

basins connected by sills at various depths. These topographic features are of prime importance with respect to the throughflow, particularly for intermediate and deep water exchanges between the Pacific and Indian basins. Figure 1 displays the location and depth of the main passages. It shows the deep straits ($> 1000\text{m}$) which define the Pacific to Indian Ocean deep pathway. Deep Pacific water enters through the Molucca Sea and makes its way through the Lifamatola Strait (sill depth $\approx 1950\text{m}$) which is the only connection with the south. Here, it splits off in different directions. The main branch feeds the Banda Sea and flows through narrow deep passages (sill depth $\approx 2100\text{m}$) into the Savu Sea and eventually into the Indian Ocean north and south of Savu Island over sills in a depth range 1100-1300m. In the north, the deep branch that penetrates the Celebes Basin and then the Macassar Strait is stopped further south by the shallower bathymetry (depth $< 800\text{m}$). Geostrophic calculations show that the mean transport is mainly concentrated in the first five hundred meters of the water column (Fieux et al., 1994; 1996). However, long-term current measurements in the Timor Strait (Molcard et al., 1996) show that below 500 m, velocities increase again, with a maximum around 1400m depth, suggesting that deep water exchanges are also significant.

To trace the ^3He signature of the «deep» Pacific waters spilling over the Indonesian sills into the Indian Ocean, we collected samples for helium isotopes analysis during the JADE French-Indonesian project in 1989 and 1992.

Helium isotope results and discussion

A initial indication of this ^3He signature is given by the GEOSECS data set (Ostlund et al., 1978). Figure 2 displays a $\delta^3\text{He}$ vertical section in the Eastern Indian ocean based on GEOSECS stations 436 ($29^\circ 15\text{S}/109^\circ 58\text{E}$) to 442 ($1^\circ 12\text{S}/90^\circ 45\text{E}$). In addition to the well established deep maximum between 2000m and 3000m, it clearly shows a shallower core of slightly enriched $\delta^3\text{He}$ values centered around 1100m depth, reaching its maximum ($> 15\%$) at station 439 ($13^\circ 02\text{S}$), i.e., in the same zonal belt as the Indonesian throughflow. Moreover, the depth of the anomaly, which corresponds to the typical depth of the major sills at the exit of the Banda Sea, is a further suggestion of the Indonesian Seas origin of this feature.

The location of the stations sampled for helium in August 1989 and Feb.-March 1992 (i.e., in two different monsoonal regimes) is shown in Figure 1. ^3He and ^4He measurements were

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Paper number 97GL02071.

0094-8534/97/97GL-02071\$05.00

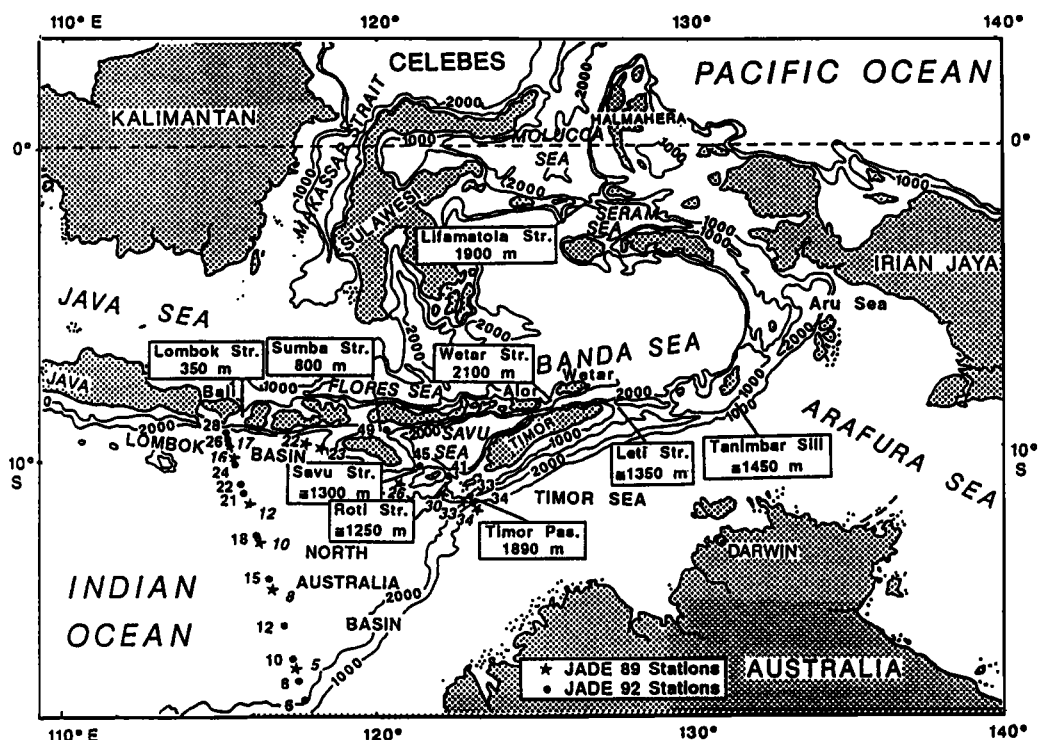


Figure 1. Map of the Indonesian region with the position and depth of the main sills defining the deep throughflow pathways (after Wyrski, 1961 and Fieux et al., 1996a) and location of the JADE 1989 (stars) and 1992 (dots) stations sampled for helium.

carried out in Saclay on a VG 3000 mass spectrometer following a routine procedure (Jean-Baptiste et al., 1992). As helium-4 concentrations are essentially constant and close to their solubility equilibrium value, helium isotopes results are expressed using the delta notation: $\delta^3\text{He} (\%) = (R/R_{\text{atm}} - 1) \times 100$, with $R = ^3\text{He}/^4\text{He}$ and $R_{\text{atm}} = (^3\text{He}/^4\text{He})_{\text{atm}} = 1.38 \times 10^{-6}$. The uncertainty in the $\delta^3\text{He}$ does not exceeding 0.4%.

Water mass characteristics throughout the region, and their seasonal variability have been discussed in detail elsewhere (Fieux et al., 1994; 1996a).

The Australia-Bali section

The two $\delta^3\text{He}$ vertical sections between Australia and Bali, obtained in 1989 and 1992, are shown in Figure 3a and 3b. The first striking feature in these sections is the occurrence of a $\delta^3\text{He}$ maximum in the depth range 750-1500 m, visible on both 1989 and 1992 cruises. As mentioned above concerning the GEOSECS section located further west (Fig. 2), the depth range of this maximum corresponds to that of the main passages between the Banda Sea and the Indian Ocean. $\delta^3\text{He}$ in the Banda Sea were measured recently during the ARLINDO cruise (Top et al., 1997) and show values up to 18-20% in this depth range, i.e., the same magnitude as the maximum observed in the JADE sections, whereas typical Indian Ocean $\delta^3\text{He}$ values at this depth are much lower (8-10%). Hence the $\delta^3\text{He}$ maximum between Australia and Bali represents the signature of the Banda Sea ^3He -rich «deep» waters penetrating the Indian Ocean as part of the Pacific-Indian throughflow. Further, if we examine the shapes of individual vertical ^3He profiles, we can see that they exhibit a clear break at the depth of the ^3He maximum with a sudden departure from the typical Pacific shape, strongly suggesting a «sill effect» on the water masses vertical distribution (Fig. 4). The stations located in the northern part of the Australia-Bali section (Fig. 4b), as well as along a Bali-Timor line (Fig. 4c), display $\delta^3\text{He}$ values in excess of that of the Pacific Ocean at the same depth. The hydrographic data rule out vertical mixing over the sills as the prime cause of this feature. This enrichment agrees indeed with the observations made by Top et al., 1997 that point to additional ^3He sources in the Indonesian Seas. South of the hydrological front, between 13°S and 14°S (Fieux et al., 1994, 1996a), the water between the surface and 600m depth originates mainly (>70%) from the

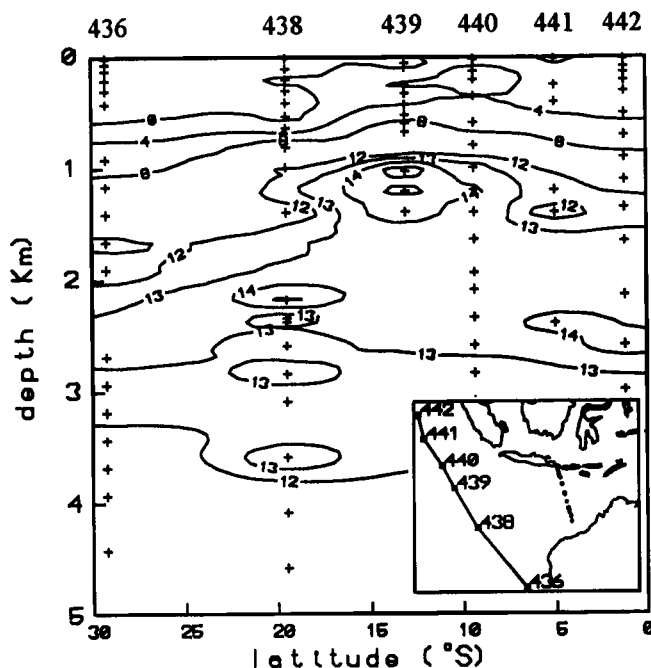


Figure 2. GEOSECS $\delta^3\text{He}(\text{‰})$ vertical section across the Eastern Indian Ocean, approximately 2000 km west of the JADE Australia-Bali transect.

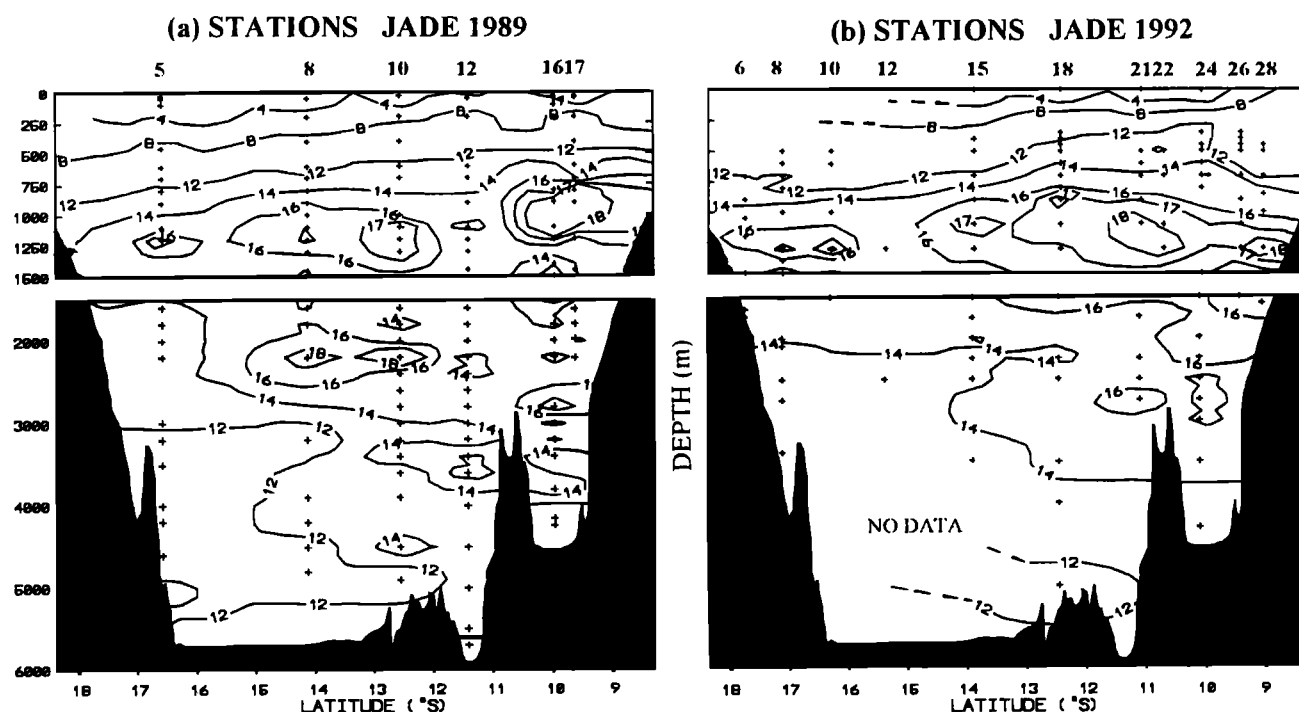


Figure 3. Australia-Bali $\delta^3\text{He}(\text{‰})$ vertical sections during the August 1989 (a) and February-March 1992 (b) JADE cruises.

Indian ocean (Fieux et al., 1994, 1996a). The $\delta^3\text{He}$ excess relative to the typical Indian ocean values may reflect the signature of the Indonesian waters (max. $\approx 30\text{‰}$) as well as the effect of vertical mixing caused by coastal upwellings over the whole area.

A closer look at the two sections also shows some differences: the latitudinal and depth locations of the main $\delta^3\text{He}$ maxima are not identical. The 1989 main ^3He tongue is centered around 800–1100 m (σ_θ range = 27.30–27.50) in the Lombok basin (stations 16 and 17), rather close to the Indonesian slope, with secondary cores further south (stations 5, 8 and 10) centered at 1200–1250 m

in the same density range ($\sigma_\theta \approx 27.45$). In 1992, the main tongue was split into two distinct cores (at stations 28 and 21–22) of the same magnitude as the 1989 core, but centered 250 m deeper (σ_θ range = 27.40–27.52). This may be related to the change in the circulation in 1992, with stronger eastward currents (carrying less ^3He) at depth in the northern part of the section (Fieux et al., 1996b). On the other hand, the southernmost core (stations 5 and 10 of JADE cruises 1989 and 1992 respectively) is at the same place in both seasons.

In the deeper layers, the $\delta^3\text{He}$ anomaly tends to decrease toward values typical of the deep Indian Ocean, with a marked

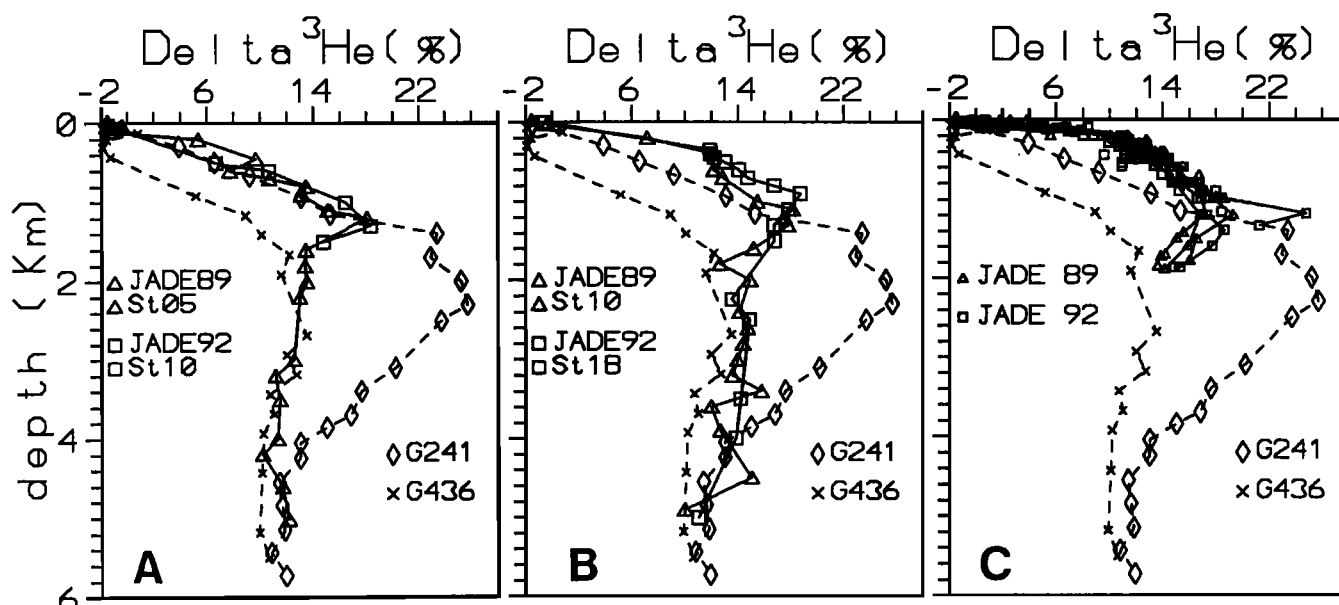


Figure 4. Selected $\delta^3\text{He}(\text{‰})$ vertical profiles from the JADE cruises south (a) and north (b) of the 13–14°S hydrological front (Fieux et al., 1994, 1996a) and along the Bali-Timor line (c). Typical profiles (dashed lines) from the central Pacific and Indian Oceans are shown for comparison: GEOSECS st. 241 (4°33'N–179°00'E) and st. 436 (29°15'S–109°58'E).

North-South ^3He gradient however (lower values in the south). It is best explained by the influence in the north of the northern Indian ocean deep waters ($\delta^3\text{He} \approx 14\%$ - Ostlund et al., 1987) and in the south, of the younger circumpolar deep waters with a lower $\delta^3\text{He}$ (typical $\delta^3\text{He}$ values in the deep Southern Ocean below 3000m, are the order of 7-8% - Jean-Baptiste et al., 1991). The 1989 section exhibits two marked $\delta^3\text{He}$ anomalies between 2000 and 3000 meter depth, one at station 16 close to the continental edge, up to 18%, and a larger one noticeable at stations 8 and 10. These features are not present in the 1992 data set, pointing to their transient nature. The depth at which these transient anomalies are seen is incompatible with a pulsed outflow from the Indonesian Seas and the other available hydrographic tracers do not show any indication of a deep Indonesian Seas water signature associated with this ^3He anomaly. Hence, we favor a transient volcanic ^3He input originating from the Indonesian edge. Indonesia is situated on an active boundary where the Indian plate is subducted under the Asian plate and the entire region is characterized by widespread volcanic activity. Transient releases of energy and volcanic volatiles at plate boundaries, i.e. the so-called «megaplumes», have been observed on several occasions on the East Pacific Rise as well as in the West Pacific and are likely to be a rather usual phenomenon in submarine volcanic areas. Nevertheless, the comparison of the 1989 and 1992 sections shows that the geographical contour of the 14‰ isoline is almost identical in each of the two data sets. Therefore the present observation suggests, in agreement with measurements of the ^3He deep ocean distribution over the last two decades, that the deep ^3He field is globally at a steady-state but is fed to some extent by transient ^3He inputs. In the Australia-Bali section, this transient input may also contribute to the observed north-south ^3He concentration gradient.

^3He vertical distribution above the sills

$\delta^3\text{He}$ vertical profiles on a Bali-Timor transect are displayed in Figure 4c. This track intersects the main passages where possible deep outflow from the Indonesian Seas toward the Indian Ocean may occur, including Sumba, Savu, Roti and Timor Straits. The profiles show increasing $\delta^3\text{He}$ values with depth and display a maximum in the 1000-1300 m range consistent with the ^3He enriched layer observed further west in the Australia-Bali section. Salinity and oxygen values of 34.60 psu and $\approx 100\text{mM}$, characteristic of the Indonesian intermediate waters (Fieux et al., 1996a), are associated with this maximum. The $\delta^3\text{He}$ value of the maximum is fairly homogeneous along most of the transect, mostly in the 17%-18% range, with slightly decreasing values towards the northwest (see also Top et al., 1997). Only station 45, situated inside the Savu Strait shows increased values, up to 25%. This value exceeds by several percent those measured in the Banda Sea (Top et al., 1997) and indicates additional ^3He inputs in the Savu Sea itself. Comparison of 1989 and 1992 profiles, at two different seasons, shows much similarity and points to the steadiness in direction of the deep throughflow throughout the year.

Conclusion

The study of the ^3He distribution at the exit of the Pacific-Indian throughflow shows that the South Banda Sea deep waters, between 1000 and 1400 m, spill into the tropical Indian Ocean over the sills of the Savu, Roti and Timor straits. The

permanence of this overflow in the NW and SE monsoonal regimes, and the only weak dilution of the ^3He signal between the straits and the Australia-Bali section hundreds of kilometers apart, suggest that this deep overflow is not negligible. The magnitude Q of this deep contribution to the throughflow can be estimated from the diffusive smoothing time of the ^3He signal between the Savu-Timor straits and the Australia-Bali section (distance $\Delta d \approx 500\text{km}$), giving $Q \approx 2LK_v(\partial C/\partial z)/(\Delta C/\Delta d)$ where K_v is the vertical mixing coefficient ($K_v < 1\text{cm}^2/\text{s}$), L is the length of the Australia-Bali section, $(\partial C/\partial z)$ and $(\Delta C/\Delta d)$ are the ^3He vertical and horizontal gradients. This crude calculation falls in the range 0.1-1 Sv, representing several percent of the total throughflow.

Acknowledgments. We acknowledge the support of IFRT, INSU-CNRS, CEA, BPPT, LIPI and French Embassy in Jakarta. We also thank the captain and crew of the RV Marion-Dufresne for their kindness and competence.

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(Received March 31, 1997 ; revised June 27, 1997 ; accepted July 8, 1997)