

## Tasman leakage in a fine-resolution ocean model

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[1] Tasman leakage, the westward flow of thermocline waters south of Australia from the Pacific to the Indian Ocean, is one of the lesser-studied of the inter-ocean exchanges. Here, some of the properties of the Tasman leakage are inferred from Lagrangian particles integrated using the three-dimensional velocity fields of the 1/10 degree resolution OFES model. The mean Tasman leakage in this model is 4.2 Sv, with a standard deviation of 4.3 Sv. The heat flux associated with this leakage lies in the range 0.08–0.18 PW. There is large variability in the Tasman leakage on both sub-weekly and inter-annual scales, but no trend over the 1983–1997 period. Despite the large weekly variability, with peaks of more than 20 Sv, it appears that less than half of the Tasman leakage is carried within eddies. **Citation:** van Sebille, E., M. H. England, J. D. Zika, and B. M. Sloyan (2012), Tasman leakage in a fine-resolution ocean model, *Geophys. Res. Lett.*, 39, L06601, doi:10.1029/2012GL051004.

### 1. Introduction

[2] The thermocline waters of the Pacific and Indian Ocean are connected by two pathways around Australia: the Indonesian Throughflow (ITF) to the north of the continent and the Tasman leakage to the south. While the ITF has been studied and measured in dedicated programs [e.g., Gordon, 2005; Sprintall *et al.*, 2009], the Tasman leakage is much-less studied [e.g., Speich *et al.*, 2007] and many of its properties remain largely unquantified. The goal of this study is to calculate some of the most climatically relevant metrics of the Tasman leakage within a 1/10° global ocean model.

[3] Here we define the Tasman Leakage as all water which passes south of Australia on route from the subtropical Pacific to the subtropical Indian Ocean. The Tasman leakage is fed by the East Australia Current (EAC), the western boundary current of the southern Pacific Ocean. This southward flowing current, which carries up to 37 Sv at 33°S [Ridgway and Dunn, 2003], bifurcates at approximately 35°S. Most of the water then flows eastward along the Tasman Front with less than 10 Sv continuing southward, mostly in the form of eddies and filaments [Suthers *et al.*, 2011]. The Tasman leakage is the part of this southward flowing water that flows around Tasmania and reaches the Indian Ocean.

[4] There are only a few estimates of the magnitude of the Tasman leakage. Using data from repeat hydrography sections south of Tasmania, Rintoul and Sokolov [2001] estimated the baroclinic transport of the Tasman leakage to be  $8 \pm 13$  Sv.

Using a numerical model, Speich *et al.* [2002] found a somewhat smaller estimate of 3 Sv. More recently, Weijer *et al.* [2012] found a Tasman leakage of  $8 \pm 1$  Sv in the low-resolution CCSM4 model.

### 2. The Model and Methods

[5] Here, the OGCM For the Earth Simulator (OFES) output is used to study the Tasman leakage. OFES is a global high-resolution ocean-only model [Masumoto *et al.*, 2004; Sasaki *et al.*, 2008] configured on a 1/10° horizontal resolution grid with 54 vertical levels. The model has been initialized from World Ocean Atlas temperature and salinity fields, and then forced by NCEP forcing from 1950 to 2007. Here, three-day snapshots from the last 27 years (from 1980 to 2007) are used.

[6] The OFES simulation is in good agreement with observational data around Australia (Figure 1). Most of the features in the model sea surface height fields are similar, both in the mean and in variability, to the AVISO altimetry data. The dominant time scales of variability also agree to a large extent (see Figure S1 in the auxiliary material).<sup>1</sup> However, there is a tongue of relatively high variability southwest of Tasmania which is less pronounced in the altimetry, suggesting the model over-estimates the eddy activity there.

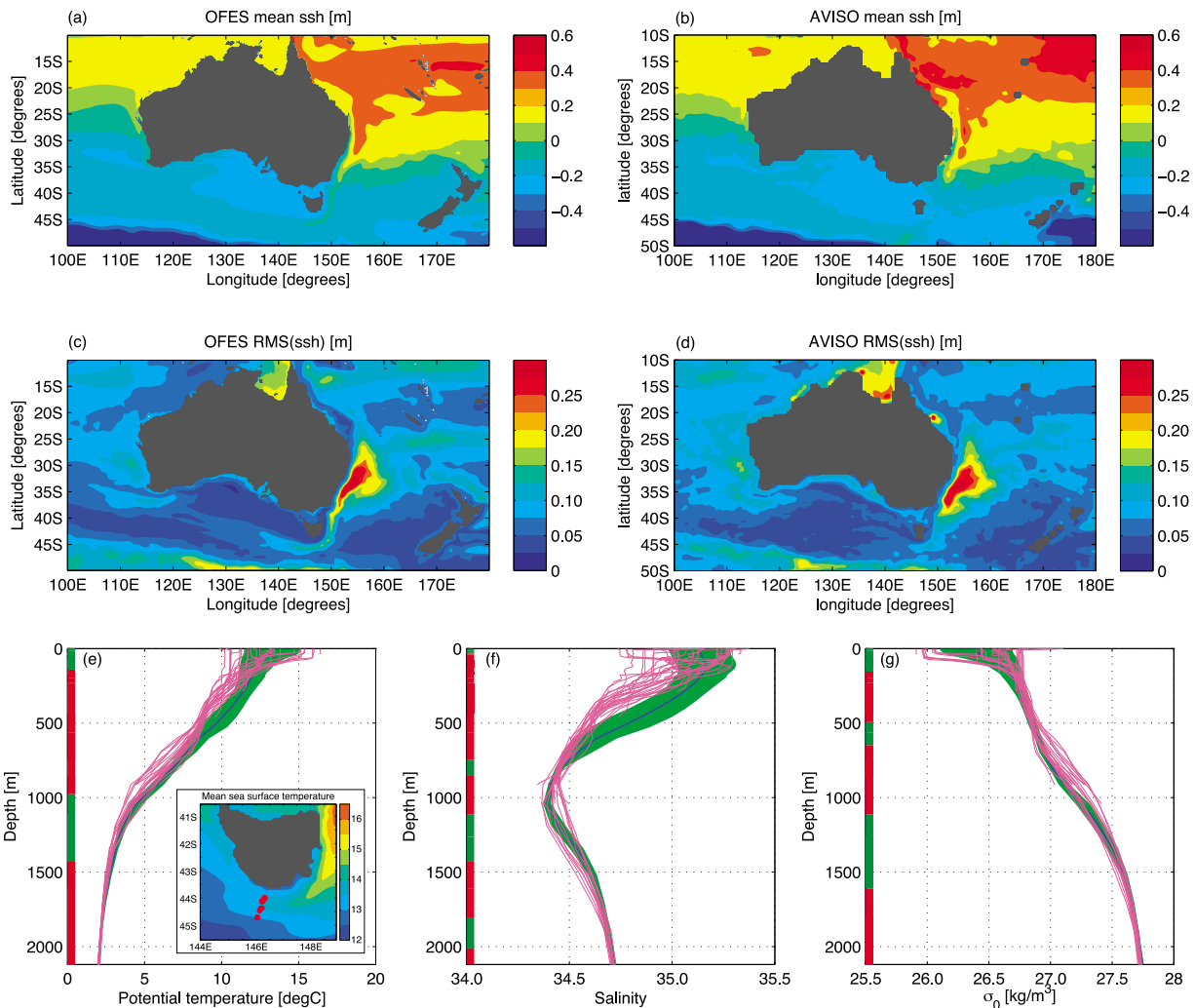
[7] As for the temperature and salinity, the model is slightly biased warm and saline south of Tasmania (Figures 1e and 1f), although these biases are largely density compensating and geostrophic velocities are very similar. For this analysis, data from 30 hydrographic stations taken between 1993 and 2001 in a  $25 \times 70$  km region southwest of Tasmania measured as part of the SR3 WOCE section [Rintoul and Sokolov, 2001] are compared to almost 7000 OFES model temperature and salinity profiles at the same locations and same months. The two-sample Kolmogorov-Smirnov test [van Sebille *et al.*, 2009; Meinen *et al.*, 2012] is used to test whether the hydrographic and model profiles could come from the same underlying distribution. This statistical test reveals that the model data is indistinguishable from the hydrography near the surface, as well as around 1200 m depth. For the other depths, however, it cannot be said with 95% confidence that the hydrography and the model are statistically identical. It appears that this bias south of Tasmania is due to subtropical water being too warm and saline and extending undiluted from the EAC in OFES (see Figure S2). A tongue of anomalously warm and salty water can be observed connecting the subtropics around Tasmania with the Great Bight south of Australia. OFES may be underestimating the interaction between subtropical and subantarctic water masses in the southern Tasman Sea [Sokolov and Rintoul, 2000], however it still provides a reasonable simulation of the leakage originating from the EAC.

[8] The Lagrangian particles are advected within the three-dimensional OFES velocity data using the Connectivity

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**Figure 1.** Comparison of mean sea surface height in (a) OFES and (b) AVISO absolute dynamic topography from altimetry. Root-mean-square sea surface height variability is also shown for (c) OFES and (d) AVISO altimetry. Profiles of (e) potential temperature, (f) salinity, and (g) potential density southwest of Tasmania show that the model is biased warm and saline in the 200–800 m depth range. These panels show 30 individual hydrographic stations as magenta lines (taken at the red dots south of Tasmania shown in the inset in Figure 1e), and the mean (solid line) and standard deviation (shaded area) from the model at the same locations and months. The red bars on the y-axis show where a statistical test gives a 95% confidence that the two data sets are not from the same underlying distribution, while the green bars depict where that test fails and the model and hydrography are thus indistinguishable.

Modeling System [e.g., *Weijer et al.*, 2012], employing a fourth order Runge–Kutta scheme. Particles are released on a meridional section south of Tasmania, at 146.4°E between 50°S and 30°S, every three days but only if the local velocity is westward. Particles are assigned a transport which is the local zonal velocity times the area of the grid box over which the particle is released and the particles are then advected both forward and backward in time. In this way, a total of  $7.5 \times 10^5$  particles are advected, for up to 27 years or until they reach one of the boundaries of Figure 2a. We only use the trajectories of those particles that originate in the Pacific Ocean and end up in the Indian Ocean, both north of 35°S.

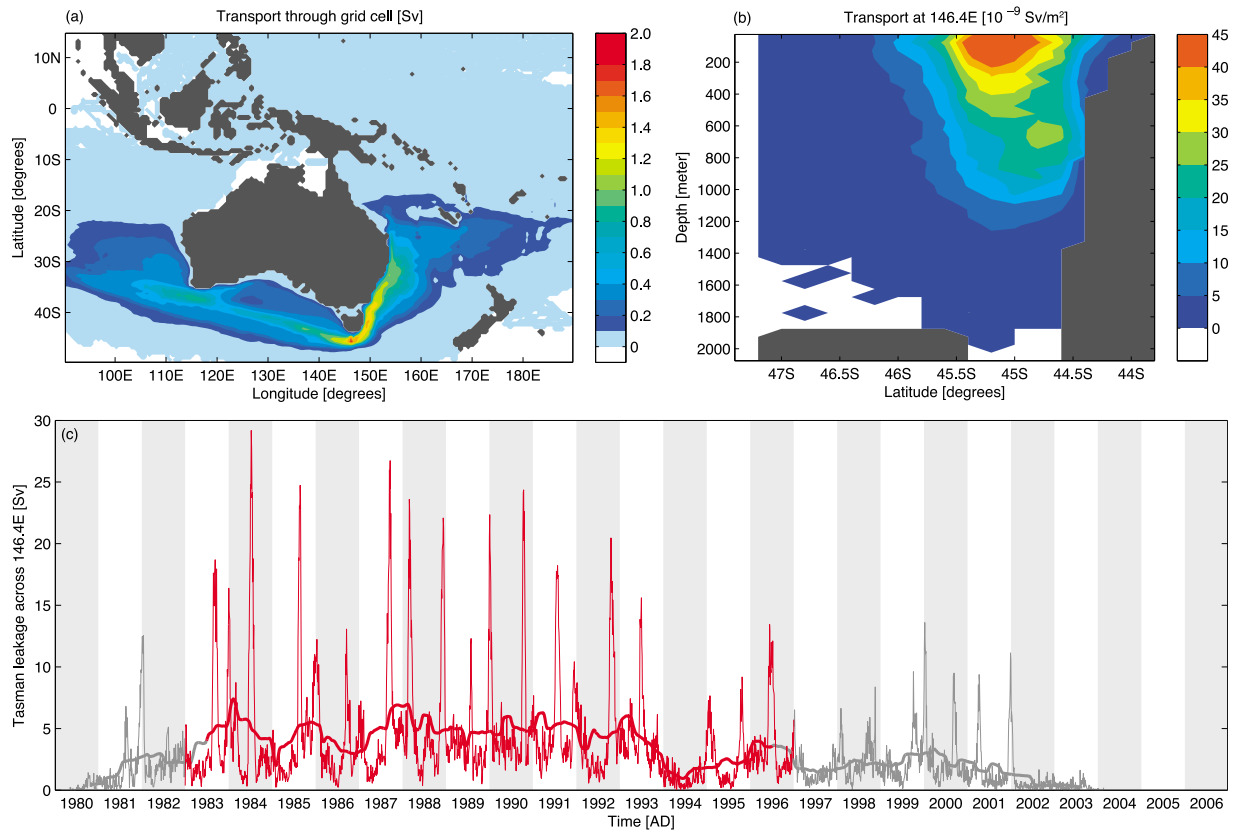
### 3. Results

#### 3.1. Pathway and Time Series of the Tasman Leakage

[9] Figure 2a shows the path taken by the Tasman leakage particles. This map is computed by adding up the transport

carried by all particles passing each  $0.5^\circ \times 0.5^\circ$  grid box. Most of the particles flow through the EAC and then flow around Tasmania in a very narrow current. West of Tasmania, the main path is still relatively narrow and in a northwest direction, although there is some recirculation in the Great Australian Bight. At the release section, more than 90% of the Tasman leakage is within the upper 1000 m, and there is a subsurface core centered around 100 m (Figure 2b). The core is not attached to the continental slope but is located some 50–100 km offshore, suggesting that the Tasman leakage does not round Tasmania in a boundary current. There is very little Tasman leakage south of 46°S, which is in agreement with the observations [*Rintoul and Sokolov*, 2001].

[10] A time series of the Tasman leakage can be computed by summing the transport carried by the Tasman leakage particles on the release section at each three-day snapshot (Figure 2c). However, there is a ramp-up effect that has to be



**Figure 2.** Overview of the Tasman leakage in the OFES simulation. (a) The transport through each  $0.5^\circ \times 0.5^\circ$  grid box for all Tasman leakage particles. (b) The transport by Tasman leakage particles on the release section at  $146.4^\circ\text{E}$ . (c) Time series of transport as the Tasman leakage particles cross the  $146.4^\circ\text{E}$  meridian. In Figure 2c the thin lines denote transport on three-day resolution, and thick lines denote one-year running-mean transport. Due to ramp-up effects (it takes the particles typically 3 and 10 years to reach the Pacific and Indian Oceans, respectively), the time series before 1983 and after 1997 should not be regarded and is thus shown in grey. Between 1983 and 1996, the Tasman leakage varies on both sub-weekly and inter-annual time scales, with peaks of more than 20 Sv. The mean during this period is 4.2 Sv, with a standard deviation of 4.3 Sv.

accounted for. Namely, particles need a certain amount of time to reach  $35^\circ\text{S}$ ; within 3 and 10 years, 90% of the particles reach the Pacific and Indian Ocean, respectively. Particles released in either the first 3 or the last 10 years should therefore not be considered in the time series and we are left with a 14 year time series (1983–1997). Note that the choice of trimming period does not greatly affect the results presented here.

[11] The mean Tasman leakage over this 14 year period is 4.2 Sv, with a standard deviation of 4.3 Sv. This is lower than the estimates of *Rintoul and Sokolov* [2001] and *Weijer et al.* [2012], but slightly larger than the estimate by *Speich et al.* [2002]. Note, however, that the Tasman leakage is here defined more stringent than in the study of *Rintoul and Sokolov* [2001], which explains the lower estimate. The time series of the Tasman leakage in OFES shows large variability at a temporal resolution of three days, ranging from less than 1 Sv to more than 25 Sv. The time-series is dominated by 15–20 multi-week events when the Tasman leakage is more than 10 Sv, alternated with longer periods when the Tasman leakage is lower than 5 Sv. These events are probably related to large eddies passing the  $146.4^\circ\text{E}$  meridian and do not possess a seasonal signal (see Figure S3).

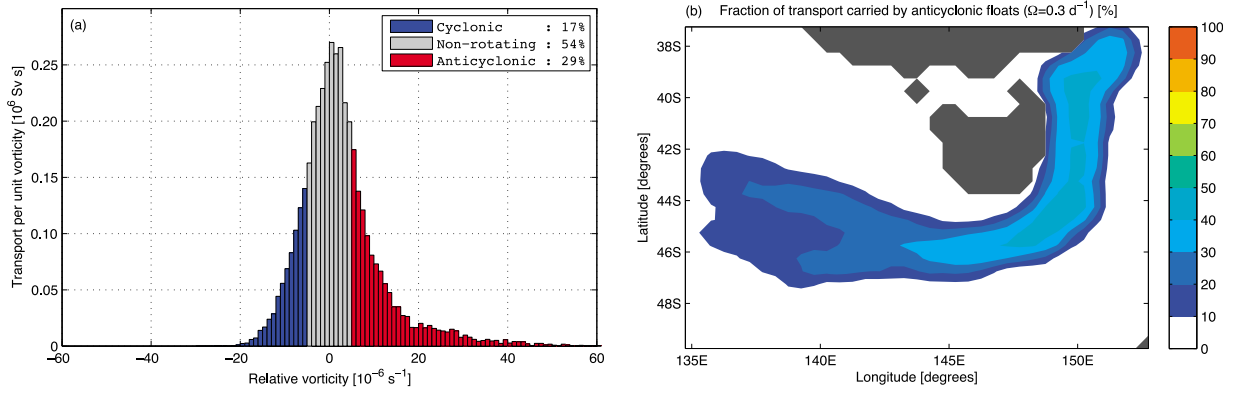
[12] There is also relatively high inter-annual variability (the thick red line in Figure 2c), with 1994 standing out in particular. In this year, the Tasman leakage dropped to nearly 0 Sv

for an extended period of time. There is no statistically significant trend in the time series. There can be a number of causes for the interannual variability. For example, *Rintoul and Sokolov* [2001, Figure 7] show that the magnitude of Tasman leakage is inversely related to the latitude of the zero wind stress curl over the Southern Ocean south of Tasmania. In OFES, there is some evidence that this relationship also holds (see Figure S4), although it is not statistically significant in the model.

### 3.2. The Heat Flux Associated With the Tasman Leakage

[13] Probably the most relevant role of the Tasman leakage in global climate is its inter-ocean heat exchange. Determining the heat flux from the Pacific to the Indian Ocean due to the Tasman leakage requires knowledge of the temperature at which the Tasman leakage water returns to  $146.4^\circ\text{E}$ . Using Lagrangian trajectories, this calculation is prohibitive, as it would require advecting Lagrangian particles throughout the global ocean until their eventual re-entry into the Pacific, possibly requiring thousands of years of model integration. It is possible, however, to estimate bounds on the heat flux (associated with zero net mass flux) carried by the Tasman leakage.

[14] *Ferrari and Ferreira* [2011] attribute heat fluxes due to particular flow features by averaging transport in temperature coordinates and then summing over ‘closed circulations’



**Figure 3.** Analysis of the amount of Tasman leakage carried by eddies, versus the amount carried by non-eddy flow. (a) A histogram showing the distribution of Tasman leakage transport across the 146.4°E meridian south of Tasmania as a function of relative vorticity. This distribution peaks around zero relative vorticity, and when eddy transport is defined as all transport with  $|\zeta| > 5 \times 10^{-6} \text{ s}^{-1}$ , then half of the transport is in non-rotating flow. (b) A loop parameter analysis of the trajectories [Doglioli *et al.*, 2006] also yields the estimate that no more than half of the transport is carried by eddies, with the eddy contribution largest on the eastern side of Tasmania.

(i.e., those circulations which have a zero mass transport). We average the volume transport in OFES across 146.4°E south of Tasmania in temperature coordinates. The closed circulation encompassing westward flowing leakage waters yields a heat flux of 0.08 PW (see Figure S5). This method implies, however, that the westward flowing Tasman leakage water undergoes the smallest possible transformation before returning eastward and is thus a lower bound on the heat flux. If we assume that the Tasman leakage water is mixed evenly throughout all the eastward flowing water-masses, then the closed circulation due to Tasman Leakage is more spread out in temperature coordinates. This yields a westward heat flux of 0.18 PW, which can be considered an upper bound on the Tasman leakage heat flux (although a larger heat flux is thermodynamically possible).

### 3.3. The Amount of Leakage Carried By Eddies

[15] The time series of the Tasman leakage in Figure 2c reveals a highly intermittent transport, with peaks up to five times larger than the mean. This is suggestive of an eddy-component to the Tasman leakage, and knowing how much of the leakage is carried by eddies is important when devising a monitoring program. Traditional approaches of determining eddy contributions to a flow rely on Reynolds decompositions. However, because we only want to consider that part of the flow south of Tasmania which links the Pacific and Indian Oceans, a Lagrangian approach is more suitable here.

[16] One way of estimating the eddy contribution to the Tasman leakage is to use the relative vorticity  $\zeta$  of the water in which the particles are advected. A histogram of  $\zeta$  on the release section (Figure 3a) shows that the transport peaks at zero relative vorticity. The distribution is skewed, however, with more transport carried within strongly anti-cyclonic waters than within strongly cyclonic waters. Following van Sebille *et al.* [2010], who used the same approach for Agulhas leakage, eddies can be classified using a  $\zeta_{crit} = 5 \times 10^{-6} \text{ s}^{-1}$ , where cyclonic water has  $\zeta < -\zeta_{crit}$ , anti-cyclonic water has  $\zeta > \zeta_{crit}$  and all other water is taken to be non-rotating. With this classification, more than half (54%) of the transport occurs in non-rotating waters, whereas only 29% and 17% is carried within anti-cyclones and cyclones, respectively. These

numbers of course depend on the choice of  $\zeta_{crit}$  but the shape of the distribution in Figure 3b suggests that a substantial amount of the Tasman leakage is carried in non-rotating water.

[17] Another way to investigate how much of the Tasman leakage is carried by eddies is to compute, along each of the trajectories, the spin parameter  $\Omega$ , as discussed by Doglioli *et al.* [2006]. A larger  $|\Omega|$  means stronger spinning of the particle along its trajectory, which suggests eddy-trapping. When this spin parameter is calculated for all trajectories (using the same choices for parameters as Doglioli *et al.* [2006]), it appears that almost everywhere around Tasmania less than half of the leakage is carried by anti-cyclones (Figure 3b). The amount carried by cyclones is nowhere larger than 10% (not shown). The largest fractions of eddy transport are found to the east of Tasmania, and once the particles round the south of the island, the amount of eddy-transport quickly drops to less than 30%.

## 4. Summary and Conclusions

[18] Using Lagrangian trajectories in the high-resolution OFES model, we have studied the Tasman leakage. We find that the magnitude of Tasman leakage as it crosses the 146.4°E meridian south of Tasmania is highly variable, both on sub-weekly and inter-annual time-scales. The mean leakage is 4.2 Sv, which is smaller than but not insignificant compared to the 15.0 Sv of Indonesian Throughflow reported by Sprintall *et al.* [2009]. The associated heat flux of Tasman leakage is between 0.08 and 0.18 PW, which is about one third of the heat flux due to Indonesian Throughflow in the OFES model calculated using the same method (0.3–0.5 PW). Hence, studies of the inter-ocean exchanges between the Pacific and Indian Ocean should consider the Tasman leakage, also because the Tasman leakage exhibits large inter-annual variability.

[19] Two distinct analyses of the eddy contribution to the Tasman leakage corroborate each other, both suggesting that less than half of the Tasman leakage is carried by eddies. When one considers that OFES seems to overestimate sea surface height variability around Tasmania (Figure 1c), at least 50% of the Tasman leakage in the real ocean might thus be carried outside of rings. This result is important when designing

possible Tasman leakage monitoring programs, as it discounts methods based on counting eddies from altimetry.

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