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Tasman leakage: A new route in the global ocean conveyor belt

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Abstract: The existence of a new route that draws relatively cold waters from the Pacific Ocean to the North Atlantic via the Tasman outflow [Sloyan and Rintoul, 2001; Rintoul and Bullister, 1999; Rintoul and Sokolov, 2001] is presented. The new route materialises with comparable magnitude and characteristics in three independent numerical realisations of the global ocean circulation. Its realism is supported by hydrographic data we have interpolated via an inverse model [Ganachaud and Wunsch, 2000]. The "Tasman leakage" constitutes a sizeable component of the upper branch of the global conveyor belt and represents an extension to the prevailing views that hitherto emphasised the routes via the Drake Passage [Rintoul, 1991] and the Indonesian Throughflow [Gordon, 1986].

Keywords: Ocean circulation, Numerical model

Tasman leakage: a new route in the global ocean conveyor belt

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Abstract. The existence of a new route that draws relatively cold waters from the Pacific Ocean to the North Atlantic via the Tasman outflow [*Sloyan and Rintoul,* 2001; *Rintoul and Bullister*, 1999; *Rintoul and Sokolov,* 2001] is presented. The new route materialises with comparable magnitude and characteristics in three independent numerical realisations of the global ocean circulation. Its realism is supported by hydrographic data we have interpolated via an inverse model [*Ganachaud and Wunsch,* 2000]. The "Tasman leakage" constitutes a sizeable component of the upper branch of the global conveyor belt and represents an extension to the prevailing views that hitherto emphasised the routes via the Drake Passage [*Rintoul,* 1991] and the Indonesian Throughflow [*Gordon,* 1986].

1. Introduction

The global thermohaline circulation (THC), sometimes referred to as the ocean's "conveyor belt", is important because it is responsible for a large portion of the heat transport from the tropics to higher latitudes in the present climate. The physical structure of THC and its efficiency in regulating climate is substantially affected by the nature and very existence of inter-ocean exchanges of water masses [*Rintoul*, 1991; *Gordon,* 1986; 1996a,b; *Houghton,* 1999]. The sources, pathways and characteristics of these exchanges are not well enough established to allow their influence on the climate system to be quantified. Over the last fifteen years, studies on the upper branch of the THC have primarily focussed on two routes that involve totally different water masses. The cold route [*Rintoul,* 1991], commencing at Drake Passage, necessitates strong heat gain and evaporation in the Atlantic basin and is therefore more susceptible to variations in the local atmospheric forcing. The warm route [*Gordon,* 1986] via the Indonesian Throughflow depends more on intermittent heat and salt advection by the Agulhas leakage and atmospheric forcings in the Indo-Pacific sector.

A recent study with one of the three models used here suggested the possibility of a third route [Speich et al., 2001]. To formally establish and describe this new pathway we now present more definitive evidence, exploiting two further models and the WOCE observational database. Furthermore, we suggest that this third route efficiently transfers subantarctic mode and antarctic intermediate waters from the Pacific to the North Atlantic through the Tasman outflow [*Sloyan and Rintoul,* 2001; *Rintoul and Bullister*, 1999; *Rintoul and Sokolov,* 2001], just south of Tasmania and north of the Antarctic Circumpolar Current (ACC).

2. Methods

The most natural approach to estimate origins and pathways of flow, and their associated heat and freshwater transport, is to follow the movement of water masses and their transformations. To date, observations are too sparse in space and time to obtain a consistent Lagrangian view of the world-scale interbasin thermohaline circulation. Alternatively, general circulation models (GCMs) of the global ocean provide coherent three-dimensional dynamical and thermodynamical fields varying in time. Here we use novel Lagrangian diagnostics [*Döös,* 1995; *Blanke and Raynaud,* 1997; *Marsh and Megann*, 2001] to trace the water masses in three very different GCMs: an eddy-permitting level model (OCCAM, *Webb et al.,* 1997), a coarser resolution level model using robust diagnostics (ORCA2, *Madec et al.,* 1998) and an isopycnic layer model (GIM, *Marsh et al.,* 2000).

In our quantitative Lagrangian approach, water masses are represented by many small water parcels. For each model, we computed, backwards in time, trajectories for hundreds of thousands of water parcels that belong to the northward flowing upper branch of the THC at the section across the equatorial Atlantic. Each trajectory is stopped when it reaches one of the sections delimiting the Indo-Atlantic sector, *i.e.* the Drake and Indonesian passages, the section linking Australia to Antarctica at the longitude of Tasmania, and the equatorial Atlantic section. The trajectories are computed using monthly varying velocity fields for ORCA2, seasonal velocity fields for OCCAM and annual mean mass fluxes for GIM.

3. Results

The Lagrangian methodology provides an accurate picture of all large-scale dynamical connections and pathways defining the warm limb of the global THC within the Indo-Atlantic sector [*Speich et al.,* 2001]. We obtain the contributions of both classical paths: the cold and the warm routes (not shown here). However, the striking new feature simulated by all three models is a pathway linking the westward flowing Tasman Current via the Indian Ocean and the Agulhas Current System (ACS) to the northward return flow of North Atlantic Deep Water (NADW) in the equatorial Atlantic (Fig. 1). Our results suggest that the Tasman contribution amounts to approximately 3 Sv (1 Sverdrup = 10^6 m^3 s^{-1}) a value that is comparable with that of the other two routes [*Speich et al.,* 2001] and represents 20 to 35% of upper branch flow. The models show that this water is not the easternmost appendix of the Indian subtropical gyre but is drawn from the Pacific Ocean. Once trapped in the Tasman outflow this water largely comprises subantarctic mode and antarctic intermediate waters (SAMW and AAIW). This corresponds well with recent observations [*Sloyan and Rintoul,* 2001; *Rintoul and Sokolov,* 2001].

Backtracking all the particles that represent this Tasman outflow to the mixed layer, we find that they essentially originate in the subantarctic zone (the equatorward side of the ACC) as SAMW (Fig. 2). These waters are then transported eastward within the ACC where they are partially modified to AAIW as has also been suggested by observations [*Sloyan and Rintoul,* 2001]. In the Pacific sector SAMW/AAIW leaves the Southern Ocean and is trapped in the subtropical South Pacific gyre system, east and west of New Zealand, renewing lower thermocline water [*McCartney,* 1982]. After a journey spanning half of the entire Pacific basin these waters return to the Southern Ocean via the East Australian Current and are then transported westward into the Indian Ocean by the Tasman outflow.

Our models suggest that, at the Pacific border, Tasman water leaking to the Atlantic has characteristics in between those of the cold and warm water routes except for salinity, which is the highest of the three routes at source section. All the water from the Tasman outflow and the Indonesian Throughflow, together with most of the water originating from the Drake Passage, come together near Cape Agulhas. The water from south of Tasmania underrides those from Drake Passage and the Indonesian Throughflow, respectively, near the ACS and further on in the Atlantic. It thus becomes the most dense, cold and fresh of the three. This occurs as the Tasman leakage is much less exposed to air/sea interactions than the other waters. It is the only route for which the majority of the water never reaches the oceanic mixed layer, with the result that temperatures and salinities are relatively unaffected in transit to the North Atlantic.

The model pathways emphasize the role of wind action in influencing the return flow to the North Atlantic. Figure 3 explicitly demonstrates that all three Southern Hemisphere subtropical gyres are intimately linked. The wind field structure of the Southern Hemisphere and the limited southern extension in latitude of the African and Australian continents compared to South America permits a subtropical «supergyre» to exist. About 3 Sv of water wrap around not only the gyres of South Atlantic and Indian Oceans [*De Ruijter,* 1982] but also that of the South Pacific. This allows the export of fresh water from the South Atlantic [*Gordon and Piola,* 1983] and the introduction of surface and lower thermocline saline Indian Ocean water around southern

Africa. Some observational studies suggest that AAIW dominates the compensation of NADW export [*de la Heras and Schlitzer,* 1999]. Until now it was thought that AAIW involved in the upper layer NADW return flow was uniquely derived from the Drake Passage. Here we suggest an important additional source for this water.

In the past, appropriate modeling studies have been accomplished in order to assess the relative importance of Southern Hemisphere winds on the THC [*Cox*, 1989; *Toggeweiler and Samuels*, 1995; *Rahmstorf and England*, 1997]. Due to the sensitivity of such models to different boundary conditions, their results do not resolve the question completely. Despite the fact that the simulations we used were not designed to solve this issue, our Lagrangian diagnostics suggest that the Southern Hemisphere winds influence the pathways and therefore the water masses forming the return flow to the North Atlantic. This would imply that the Southern Hemisphere wind forcing is strongly related to the freshwater transport into the South Atlantic and, following *Rahmstorf* [1996], to the dynamical regime and stability of the THC.

Observations indicate that lower thermocline Pacific waters penetrate the Indian Ocean through the South Australian Passage [*Metzl et al.,* 1990; *Fine,* 1993; *Toole and Warren,* 1993; *You,* 1998]. But a more quantitative evaluation of water mass transfer and destiny has been lacking until now. Analysis of water mass properties and dynamic heights suggested a northwestward flow of AAIW from the south of Australia to the northern part of the subtropical gyre [*You,* 1998]. This indeed reinforces previous hypotheses which assert that a fraction of AAIW observed in the Indian Ocean originates south of Australia [*Fine,* 1993; *Talley,* 1998]. Here we compute the net transports across hydrographic lines at 32°S, 115°E and 145°E from the most recent global hydrographic inverse model [*Ganachaud and Wunsch,* 2000] (Fig.4). There is strong evidence for an intense westward flow of AAIW and SAMW south of Australia at both 115°E and 145°E. The entrance of these waters into the Indian Ocean is difficult to localize due to a strong eddy field at 32°S. Nevertheless, the large scale tendency of AAIW/SAMW cumulated transport at 32°S, eastward of 50°E, is a general northward motion of these waters, coinciding well with the eastern branch of the subtropical gyre. A recent analysis on neutral surfaces [*You,* 1998] suggests such a pathway for AAIW between 95°E and 110°E.

4. Conclusions

We draw the following conclusions from this study. Both our model results and observations indicate that the Tasman outflow is an important feature, allowing an efficient Pacific to Indian lower-thermocline water exchange. The Tasman leakage is a sizeable element of the global THC. Due to the preserved water mass characteristics along its path from south of Tasmania to the equatorial Atlantic, the Tasman leakage may play an important role in the THC response to climate change. In particular, the corresponding upper branch transport of SAMW and AAIW raises the possibility that recent freshening of these waters [*Rintoul and England,* 2002; *Wong and Bindoff,* 1999] – consistent with climate model predictions of an intensified hydrological cycle under global warming [*Manabe et al.,* 1991; *Murphy and Mitchell*, 1995; *Gordon and O'Farrell,* 1997] – could ultimately impact convective activity in the North Atlantic.

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SPEICH ET AL.: TASMAN LEAKAGE

Figure 1. Horizontal streamfunction, for three different GCMs simulations, related to the vertically-integrated transport of the northward transmitted warm waters to the equatorial Atlantic with origins south of Tasmania, at 145°E. Displayed are "Tasman leakage" contributions from **a**, GIM. **b**, ORCA2. **c**, OCCAM. Contour interval is 1 Sverdrup (1 Sv = 10^6 m s^{-1}), the value *y* = 0 has been set in Tasmania. The three models agree on the order of magnitude of transport intensity (3.5 Sv for GIM and 3.2 for ORCA2 and OCCAM) and trajectory pathways. Tasman waters flow westwards remaining close to the South Australian plateau. They leave the southwestern tip of the Australian continent to cross the Indian Ocean northwestwards as part of the northern branch of the Indian subtropical gyre. They reach the African continent and flow southwards east and west of Madagascar. At the retroflection point they escape from the ACS to the South Atlantic. They cross the South Atlantic at the northern flank of the subtropical gyre. On the western side of the basin they continue by flowing northwards to the equator within the North Brazil Current. The only noticeable difference between model streamfunctions concerns the intensity of Tasmanian water recirculation around the subtropical gyres of the South Atlantic and Indian Oceans. GIM exhibits no such recirculations.

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Figure 2. Fields of vertical velocity (10^{-6} m s^{-1}) through the base of the mixed layer obtained by backtracking Tasman leakage particles. The traced isolines correspond to surface density values (s anomaly units) relative, for each grid point, to the time of the year when mixing layer depth is maximum. **a**, GIM. **b**, ORCA2. **c**, OCCAM. Despite the differences between models, the three simulations give the same indication, that is the largest portion of Tasman leakage water appears to originate in the Subantarctic Zone, principally in the Indian and Pacific sectors of the Southern Ocean. This region is where the largest fractions of the global SAMW and AAIW are formed [*McCartney,* 1982; *Marsh et al.*, 2000]

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Figure 3. Horizontal streamfunction displaying the complete Atlantic-to-Atlantic Tasman water roundtrip, shown here for

ORCA. Contour interval is 1 Sv, the value ψ = 0 has been set in Tasmania. The patterns reveal a horizontal view of the quasi-total THC cell. Indeed, being part of the global conveyor belt, Tasman waters are originally exported southwards from the Atlantic in a deep western boundary current as North Atlantic Deep Water (NADW). NADW leaves the South Atlantic for the Southern Ocean, joining the ACC to flow eastwards and eventually entering the Indian or Pacific Oceans during the first or a successive circumnavigation around Antarctica. The large value of the streamfunction in the subpolar region attests that a sizeable portion of TAS waters have travelled many times around Antarctica before being injected in the South Pacific subtropical gyre system and subsequently into the Tasman outflow. Likewise, in this picture, all the large-scale wind-driven structures of the present-day global ocean circulation emerge: the subtropical gyre systems, the ACC, and the Indian and Pacific tropical patterns. This suggests that the wind play a significant role in the structure of the THC upper branch. In particular, the South Atlantic, Indian and South Pacific subtropical gyre systems seem intimately connected. In the figure, 3 Sv of water wrap around the three local subtropical gyres. This interbasin subtropical supergyre is the physical mechanism that permits Tasman leakage. The supergyre does not extend through the Drake Passage as the American continent is located too south with respect to the wind curl maximum and thus it blocks a westward connection.

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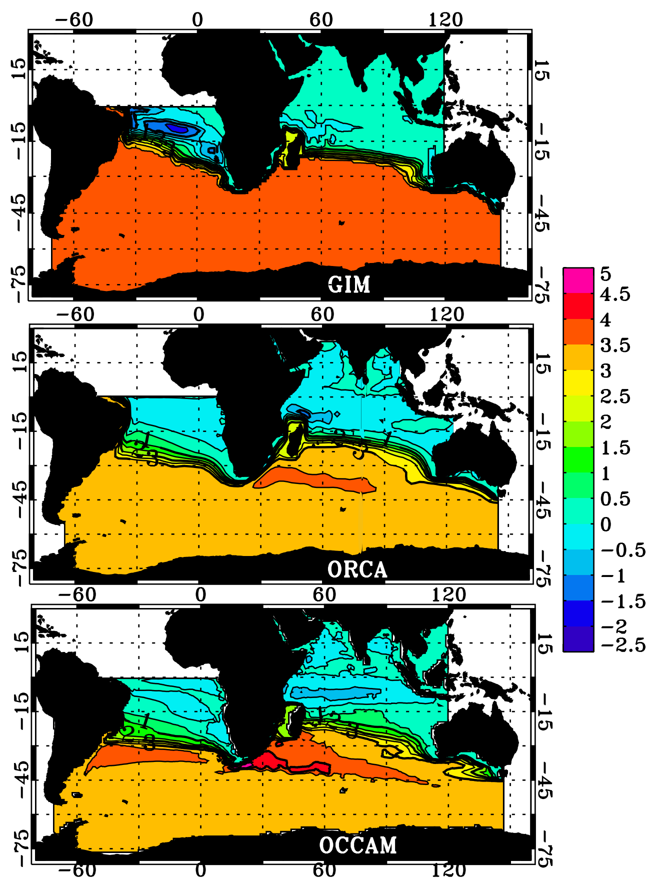
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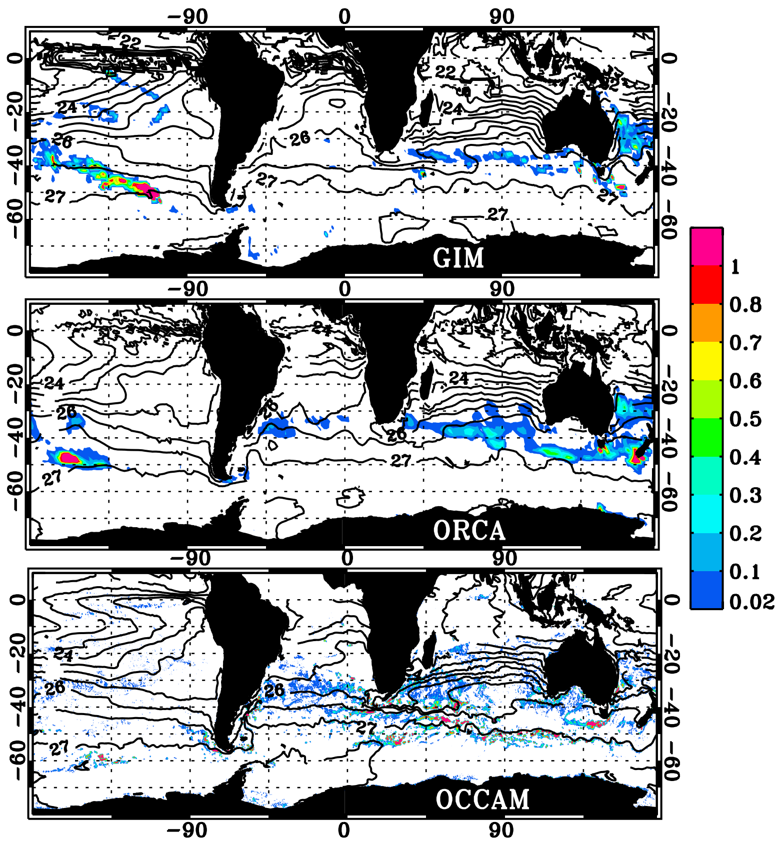

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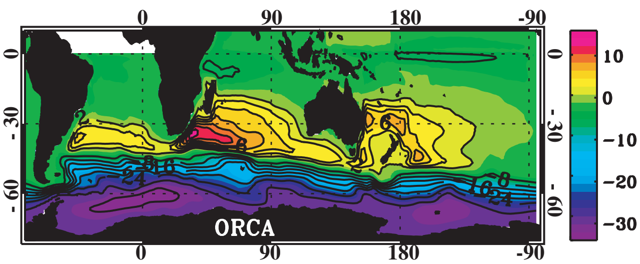
0.1
0.02



0
90
180
-90
0
- 30
- 60
10
0
−10
−20
−30
ORCA