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Warm and cold water routes of an O.G.C.M. thermohaline Conveyor Belt

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Abstract. A global general circulation model analyzed with a Lagrangian methodology is used to describe and quantify the paths, transports, and characteristics of the "warm" waters forming the upper branch of the conveyor belt in the North Atlantic Ocean. The total transport for this branch turns out to be 17.8 Sv in the North Atlantic at 20°N: 11.8 Sv are composed of waters coming from the two classical origins, the Drake Passage and the Indonesian Throughflow, which contribute with 6.5 and 5.3 Sv respectively. The remaining 6 Sv find their origins partly in the passage between Antarctica and the Australian Continent (with 3.1 Sv) and partly in the Indo-Atlantic sector itself (*i.e.,* with 2.9 Sv). The geographical structure of the different routes emphasizes the role of the Southern Ocean and large-scale current systems in water mass transformation and distribution.

1. Introduction

The global ocean redistributes heat and salt through its thermohaline circulation: surface warm waters flow northward in the North Atlantic, cool and sink in the polar and subpolar regions, and then flow southward, enter the Southern Ocean and eventually all the ocean basins, where they upwell slowly into the upper kilometer and return to the North Atlantic with the wind-driven circulation. This circulation, known as the Great Ocean Conveyor Belt (GCB), provides a northward heat flux roughly equal to 1 petawatt and fully comparable to that transported poleward by the atmosphere.

The Southern Ocean is a crucial region for the GCB as it receives water from the Atlantic Ocean, distributes this water among the Global Ocean and gives it back to the Atlantic. The GCB is a circulation scheme that was developed over the last fifteen years [*Gordon,* 1986; *Broecker,* 1987, 1991; *Rintoul,* 1991; *Schmitz,* 1995, 1996a, 1996b]. Many open questions remain about this oceanic circulation cell. Indeed, the hypotheses on the origin of waters that return to the North Atlantic Ocean in the upper 1000m are controversial. Are these waters coming directly from the Drake Passage [*Rintoul*, 1991; *Schmitz*, 1995; *Döös*, 1995; *Macdonald and Wunsch*, 1996] or from the Indian-Pacific sector, *via* the Cape of Good Hope [*Gordon*, 1986; *Gordon et al.*, 1992]? What is the input in term of water mass characteristics: are these waters mainly surface, thermocline, subthermocline or intermediate waters? As different origins or distinct water mass contributions define different exchanges and redistributions of heat and mass, a correct evaluation of these properties is essential before any time scales related to the climate variability of this circulation can be assessed.

We chose to reconstruct a climatological picture of this circulation by using a numerical model of the global ocean whose tracer fields are constrained to remain close to the *Levitus*'s [1982] atlas. Consequently, the model acts as a dynamical interpolation of this given climatology, much in the sense of more classical inverse models [*e.g., Rintoul,* 1991; *Macdonald and Wunsch,* 1996]. Then, we interpret the model's Eulerian fields by means of a Lagrangian methodology [*Blanke and Raynaud*, 1997; *Blanke et al.*, 1999], linking together, dynamically, different oceanic sections.

2. The ocean model

The simulation we analyze was performed with ORCA, the new global configuration of the OPA Ocean General Circulation Model (OGCM) [*Madec et al.*, 1998]. The horizontal resolution is 2° in longitude and it varies in latitude from 0.5° at the equator to $2^\circ\cos(\phi)$ poleward from the tropics. In order to remove the North Pole singularity two poles are introduced in the northern hemisphere grid. The resulting stretched mesh is constructed in such a way that the anisotropy ratio always remains close to one. There are 31 levels in the vertical, with the highest resolution (10 m) in the upper 150 meters.

The model physics is as discussed in *Blanke et al.* [1999], *i.e.* lateral mixing occurs only along neutral surfaces and the vertical mixing is computed through a 1.5 turbulent closure scheme which provide a low diffusivity in and below the thermocline ($0.1 cm^2 s^{-1}$). The model is forced by a daily climatology of momentum, heat and fresh-water fluxes obtained from the ECMWF 15-year (1979-1988) reanalyses (smoothed by a 11-day running mean).

The experiment was developed in order to recover and study the dynamics associated with the observed global ocean hydrology. Our analyses are carried out over the last year of a 10-year simulation in which a restoring term to the *Levitus'* [1982] climatology was added to the potential temperature and salinity equations [*Madec and Imbard*, 1996]. The relaxation has a time scale of 50 days in the upper 800m and 1 year in the deep ocean. This restoring acts everywhere except in the tropics, in the surface boundary layer, and in a 1000 km neighbourhood of the coastal boundaries. This way, the model physics is able to recover the boundary and

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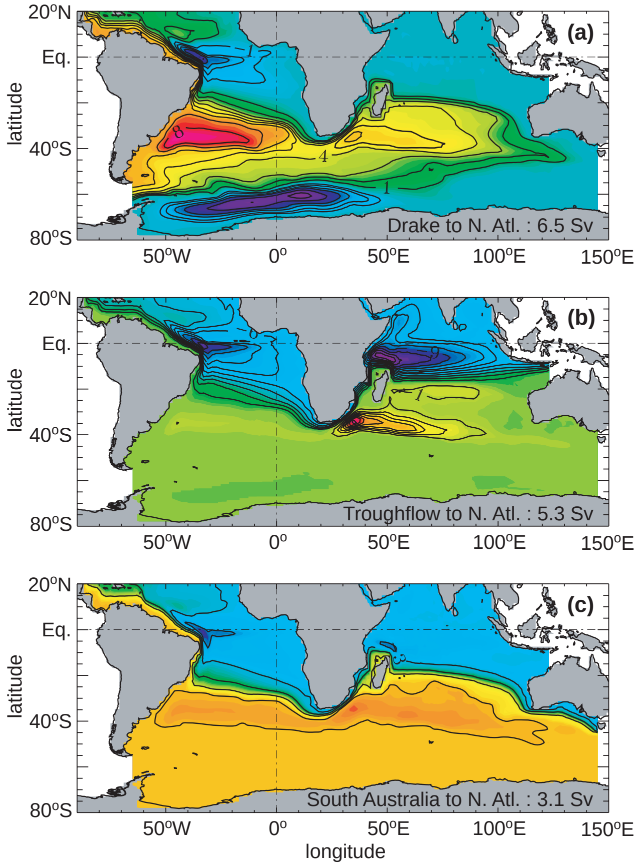

Plate 1. Horizontal streamfunction related to the vertically-integrated transport of the northward-transmitted warm waters to the North Atlantic (0-1200m) with origins a) in the Drake Passage b) in the Indonesian Throughflow c) South of Australia.

equatorial currents not well resolved in the Levitus' climatology. The computed transports compare rather well with observations (cf. discussion in *Blanke et al.,* 1999).

3. The Lagrangian methodology

A natural and convenient way to trace ocean water masses is to follow their pathways. This is something still difficult to achieve with observations, even though there is a true effort of the scientific community to use real floats to track water movements. In the meantime, ocean models, despite the fact they only approximate reality, compute time-varying three-dimensional velocity fields that can be used for Lagrangian diagnostics.

In our approach, individual trajectories are computed with a mass-preserving algorithm [*Blanke and Raynaud,* 1997; *Blanke et al.*, 1999]. Due to water mass incompressibility, we assume that individual particles conserve their infinitesimal mass along their trajectory. As a current can be entirely determined from the particles composing it, with well defined characteristics (position, velocity and tracers), the transport of a given water mass can be computed from its own particles and their associated infinitesimal transports. Following *Döös* [1995], quantitative conclusions are obtained by using a large number of particles, sufficient to insure the numerical stability of the transport estimates. We have used individual transports that are always less than 10^{-2} Sv. It ensures an overall error of the computed water mass transports less than 0.1 Sv.

The Lagrangian computations are achieved with a monthly varying velocity field as the results showed to be sensitive to a time sampling larger than one month.

4. Results

In order to determine the origin of the water composing the upper branch of the GCB, we trace backward in time the northward flow crossing the 20°N section of the Atlantic Ocean (NATL hereafter) and decompose it according to its origins at the limits of the Indo-Atlantic region: NATL itself, the Indonesian Throughflow (I-TFL), the section between Australia and Antarctica (S-AUS), and the Drake Passage (DRAKE).

The total northward flow through NATL is 40.4 Sv. A large fraction of it, 25.5 Sv, comes from NATL itself. It is a recirculation within the Indo-Atlantic domain, with only 2.9 Sv of these 25.5 Sv crossing the equator and 1.3 Sv entering the Indian Ocean before going back to NATL. It is thus mainly associated with the North Atlantic subtropical gyre.

The mass flux that originates outside the Indo-Atlantic sector amounts to 14.9 Sv. Two origins are defined in the literature respectively as the *cold* route (from the Drake Passage, 6.5 Sv in the model) and the *warm* route (from I-TFL, 5.3 Sv). Interestingly, the model suggests an additional source for the upper branch of the GCB, with waters coming from the Pacific, south of Australia, for a total of 3.1 Sv. This latter contribution was never considered in the classical pictures of the global thermohaline circulation [*Gordon*,, 1986; *Broecker,* 1991; *Rintoul,* 1991; *Gordon et al.*, 1992; *Schmitz,* 1995, 1996a, 1996b]. Nevertheless the inversions performed by *Metzl et al.* [1990] in the Indian Ocean always produced a westward flow in one or more of the subsurface layers. Evidence of a westward flow of Intermediate Water south of Australia is also documented by *Reid* [1986], *Fine* [1993], and *Rintoul and Bullister* [1999]. *Ganachaud*'s [1999] inversion confirmed its presence between the sea surface and 1200m. Numerical simulations may produce a westward current south of Tasmania [*Döös*, 1995]. Though the transport we associate to this origin is smaller

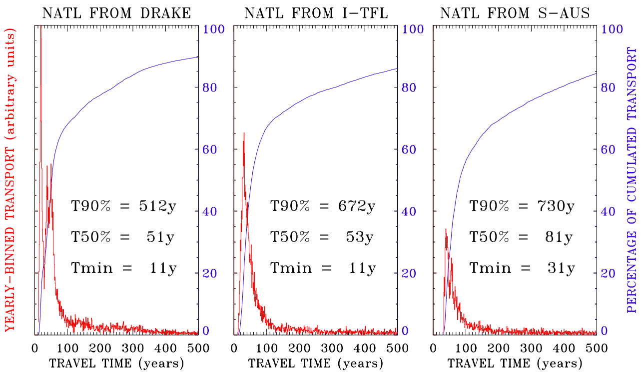

Plate 2. Yearly binned transport (in red) and time integrated transport (in blue) as function of travel times for the northward-transmitted warm waters to the North Atlantic (0-1200m) with origins a) in the Drake Passage b) in the Indonesian Throughflow c) South of Australia.

than the other two Pacific "gates", its magnitude is still comparable. Our results do not prove sensitive to the surface forcing as we obtain the same origins with different atmospheric fields [*Hellerman and Rosenstein*, 1983; *Esbensen and Kushnir*, 1981]. By adding together the 14.9 Sv coming from the Pacific with the 2.9 Sv flowing from NATL and crossing the equator, we obtain a mean value of 17.8 Sv for the thermohaline return flow across NATL.

The depth-integrated structure of the routes associated to the three different origins is shown in Fig.1. The waters coming from DRAKE take two different circuits to the North Atlantic: a direct route through the Atlantic and a longer journey that includes a detour in the Indian Ocean. In the first case, water flows from DRAKE northward in the Atlantic through the Malvinas Current, then is captured by the South-Atlantic subtropical gyre, crosses the basin eastward till it reaches the Benguela Current (BC) and veers north-westward; it reaches the coast of South America (at about 23°S) and continues northward as a boundary current, crosses the equator and reaches the NATL section (a recirculation cell appears in the equatorial band as discussed by *Blanke et al.,* [1999]). A smaller part recirculates in the South-Atlantic subtropical gyre before flowing northward in the boundary current, and crossing the equator. This pathway accounts for 2.3 Sv. In the second case, 4.2 Sv of water from DRAKE follow a more zonal path, continuing eastward within the Antarctic Circumpolar Current system. They reach the Indian Ocean where they follow the Indian subtropical gyre. Waters entering the Indian Ocean in its eastermost area veer south-westward only north of Madagascar and flow in the Mozambique Channel before entering the Agulhas Current System (ACS). Waters entering the Indian basin in its central and western parts are trapped in the ACS more rapidly and stay south of Madagascar, with some possible recirculation before flowing back to the Atlantic through the ACS. Then, all the flow turns back in the Atlantic within the BC. A portion of it undergoes the recirculation of the South-Atlantic subtropical gyre before crossing the equator in the western-boundary current, and reaching the NATL section. Evidence of this "Indian escape" for waters coming from DRAKE and reaching NATL has been documented by *Gordon et al.* [1992]. The separation of these two pathways from DRAKE occurs at about [50°W, 50°S].

The NATL flow coming from I-TFL crosses the Indian basin westward till the African coast north of Madagascar. Part of this water veers northward, trapped in the Somali Current, and follows a clockwise recirculation. The rest of it flows southward along the African coast in the Mozambique Channel. The whole flow passes around the African continent, first by joining the ACS (where some strong recirculation appears), then by following the BC. It crosses the South-Atlantic Ocean and flows northward toward NATL in the same way as the waters from DRAKE. The waters coming from the Pacific south of Tasmania cross the Indian Ocean as a trapped flow in the northern branch of the South Indian subtropical gyre, enter the Mozambique Channel and are captured by the ACS. In the Atlantic, they have a behavior equivalent to the NATL waters originating from DRAKE and I-TFL. If we add all the Indian water contributions to NATL (including the recirculating 1.3 Sv from NATL and the 4.2 Sv from DRAKE) we find a total of 13.9 Sv for the *warm* route. The *cold* "direct" route from DRAKE to NATL is only 13% of the modelled GCB upper branch (2.3 of 17.8 Sv).

The travel time of each particle is easily diagnosed in our Lagrangian computations. Yearly-binned and cumulated transmitted transports are presented as a function of time in Fig. 2. The shortest travel times are 11 years for both DRAKE and I-TFL, and 31 years for S-AUS. More than 50% of the transport is transmitted in less than 100 years. For all three routes, at least one peak of transport is evident. Each peak turns to be linked to either a direct path, or one or several recirculations. For example, the three peaks at years 19, 29 and 58 found for the DRAKE origin characterize the median transit-time for the direct DRAKE-NATL path, the DRAKE-NATL path with recirculation in the South Atlantic, and the DRAKE-Indian Ocean-NATL journey, respectively.

5. Conclusions

We used the monthly three-dimensional circulation computed by an OGCM, in equilibrium with the observed climatological hydrology in the ocean interior, to investigate the upper branch of the GCB. The thermohaline circulation was evaluated by means of a quantitative Lagrangian analysis. We diagnose four distinct origins for the water masses reaching the North Atlantic Ocean at 20°N, for a total transport of 17.8 Sv. Two of them, DRAKE and I-TFL, have almost equivalent contributions (6.5 and 5.3 Sv respectively), and correspond to the classical *cold* and *warm* routes. The other two are more original and correspond to a remote flow from the passage between Australia and Antarctica (3.1 Sv) and an internal contribution of the Indo-Atlantic sector (2.9 Sv).

Only 2.3 Sv of the 6.5 from DRAKE flow directly to NATL while the rest first enters the Indian Ocean before coming back to the Atlantic basin with the ACS. Therefore, the modelled ACS appears as the major provider of water for NATL (13.9 Sv: 4.2 Sv from DRAKE, 5.3 Sv from I-TFL, 3.1 Sv from S-AUS and 1.3 Sv from NATL itself). Our results are consistent with the early findings of *Gordon* [1986] in terms of significant contribution to the GCB of water coming from the Indian Basin, and they emphasize the role of the Indo-Atlantic "connection" hypothesized by *Gordon et al.* [1992].

The inferred water paths strongly support the key role of the Southern Ocean in permitting interbasin exchanges of water masses. Our results reexamine the classical *warm* versus *cold* route representation. Of course, as they arise from the integration of low resolution model and data fields, they are intented only as a qualitative indication of potential pathways. The structure of the resulting routes points out the substantial role played by large-scale recirculation cells in the upper GCB branch and, therefore, in water mass transformations and distribution.

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