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Atlantic meridional overturning circulation and the Southern Hemisphere supergyre

Sabrina Speich,[1,2] Bruno Blanke,[1] and Wenju Cai[3]

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[1] The ocean's role in climate manifests itself through its high heat capacity, its own rich internal dynamics and its ability to transport vast quantities of heat and freshwater. Of particular interest is the global ocean circulation associated with the Atlantic meridional overturning (AMOC). Because observations are sparse, the detailed global structure of the AMOC remains poorly understood, particularly the pathways along which water returns to the Atlantic to compensate the export of North Atlantic Deep Water (NADW). Here we provide the first quantitative 3-dimensional global view of the AMOC using a Lagrangian reconstruction which integrates hundred of thousands water particle trajectories in an ocean model. The resulting pattern elucidates the role of the wind in structuring the pathways of the AMOC. In particular, the Lagrangian analysis reveals a strong link with the three subtropical gyres of the southern hemisphere (SH), which merge into a "supergyre" spanning the three ocean basins. The coupling between the upper ocean wind-driven circulation and the overturning in the model suggests that changes in the SH winds can alter the pathways of the AMOC, and therefore the water properties and the associated heat and freshwater transports. **Citation:** Speich, S., B. Blanke, and W. Cai (2007), Atlantic meridional overturning circulation and the Southern Hemisphere supergyre, *Geophys. Res. Lett.*, *34*, L23614, doi:10.1029/2007GL031583.

1. Introduction

[2] The Atlantic meridional overturning circulation (AMOC) is the large-scale ocean circulation of mass resulting from different air-sea forcings (exchanges of heat, freshwater and momentum) and internal dynamical processes [e.g., *Wunsch*, 2002]. In the Atlantic Ocean this circulation is characterized by the export to the Southern Ocean (SO) of North Atlantic Deep Water (NADW) replaced by an inflow of surface and thermocline waters. Nearly all work on the AMOC has focused on the sinking branch in the North Atlantic. The remainder of the global circulation related to the AMOC is still poorly known. Such an understanding is critical to determine how the AMOC may respond to and drive changes in climate. Particularly important is the definition of how water returns to the Atlantic to balance the export of NADW. Indeed, the nature of the return path determines the heat and salt transports.

[3] Although details of the structure remain poorly known, it is widely accepted that the AMOC has a global interrelation with the SO being the critical crossroad for this circulation, as it connects the major basins to the Atlantic Ocean [*Sloyan and Rintoul*, 2001].

[4] Over the last decade, several studies proposed a strong connection between the AMOC and tidal-and wind-energies [*Munk and Wunsch*, 1998; *Paparella and Young*, 2002]. Indeed, it is suggested that the overturn of the ocean must be accompanied by a SO upwelling of the deep water [*Webb and Suginohara*, 2001]. The presence of such upwelling is supported by numerous studies and some relate it to the wind forcing [*Döös and Coward*, 1997]. Winds are also responsible for at least a part of the meridional fluxes across the eastward flow of the Antarctic Circumpolar Current (ACC), which connects the SH polar region with the rest of the global ocean [e.g., *Friocourt et al.*, 2005]. The physical structure of the AMOC and its efficiency in climate regulation are affected by the nature and the existence of these exchanges through their influence on the water masses involved. In particular, they determine the return path and the properties of the associated inflowing waters, and by this they profoundly affect the heat and salt balance of the Atlantic [*Weijer et al.*, 1999]. The lack of a comprehensive understanding of the detailed structure of the AMOC makes it difficult to assess its impact on the climate system.

[5] The most natural way to estimate flow origins, pathways and the associated heat and freshwater transport is to follow the movement of water masses and diagnose their transformation. To date, observations are too sparse in space and time to obtain a robust Lagrangian view of the global AMOC. On the other hand, while global ocean general circulation models (OGCMs) only approximate reality, they provide consistent time-varying 3D fields. Here, we chose to reconstruct a climatological picture of the AMOC using an OGCM constrained to mimic the observed tracer climatology [*Madec and Imbard*, 1996]. By this condition the model acts as a 4D dynamical interpolator of the observed fields, much in the sense of more classical inverse models. To recover the global pathways of the AMOC we applied to the OGCM outputs a recently developed quantitative Lagrangian analysis [e.g., *Blanke et al.*, 1999, 2002]. This algorithm enables us to calculate large quantities of water-particle trajectories. Therefore, it allows robust estimates of water masses pathways and their along-track transformations.

2. General Circulation Model

[6] The simulation we analyzed was run with the ORCA OGCM [*Madec and Imbard*, 1996]. The horizontal resolu-

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[1] Laboratoire de Physique des Océans, UMR 6523, CNRS, IFREMER, UBO, UFR Sciences et Techniques, Brest, France.

[2] Now at Centre de Bretagne, Campus Ifremer, L'Institut de Recherche pour le Développement, Plouzané, France.

[3] Marine and Atmospheric Research, Commonwealth Scientific and Industrial Research Organisation, Aspendale, Victoria, Australia.

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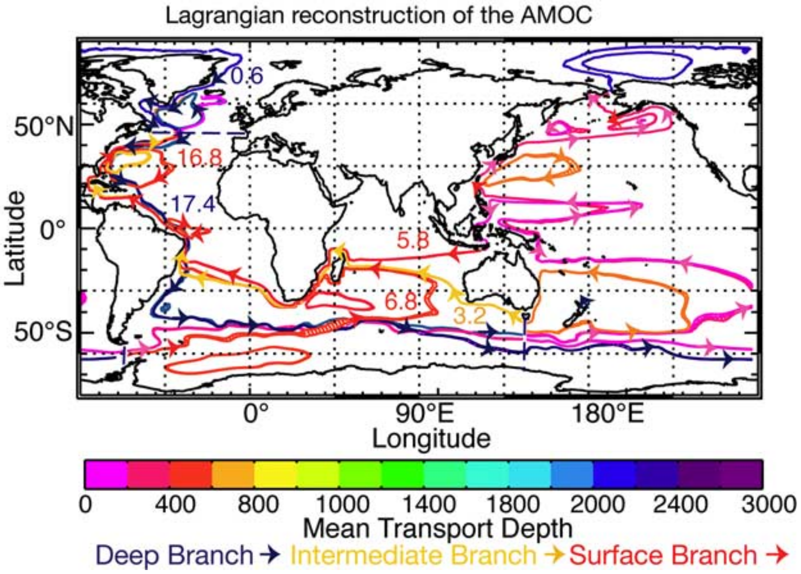

Figure 1. Lagrangian derived reconstruction of the global AMOC. Its structure is shown as median pathways between successive oceanic sections crossed by water particles. The colors indicate the mean depth of the transfer between two given sections. The AMOC is defined here as the thermocline waters (in orange, red, and pink) transformed into NADW (blue) in the North Atlantic sector. Pathways show the upper and lower branches of the AMOC. Numbers quantify the mass transfers between control sections (transports are expressed in Sverdrups 1 Sv = 10^6 m s^{-1}). 17.4 Sv of NADW flow southward from the North Atlantic and are replaced by 0.6 Sv from Bering Strait and 16.8 Sv of thermocline water flowing northward from the equator.

tion is 2° in longitude and varies in latitude from 0.5° at the equator to 2°cos(ϕ) poleward of the tropics. There are 31 levels in the vertical, with the highest resolution (10 m) in the upper 150 meters. Lateral mixing occurs only along neutral surfaces. Eddy-induced tracer advection is parameterized following *Gent and McWilliams* [1990]. Vertical mixing is computed with a 1.5 turbulent closure scheme, which provides 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 derived from the ECMWF 10-year (1979–1988) reanalyses (smoothed by an 11-day running mean).

[7] The experiment was designed for the recovery and study of the dynamics associated with the observed global ocean hydrology. Our analyses focus on the last year of a 10-year simulation run after addition to the model equations of a restoring term to the observed ocean temperature and salinity climatology [*Madec and Imbard*, 1996]. The relaxation time-scale is 50 days in the upper 800 m and 1 year in the deep ocean. To let the model physics recover the boundary and equatorial currents not well resolved in the observed climatology, this restoring term acts everywhere, except in the tropics, in the surface boundary layer, and in a 1000 km band around the coastal boundaries. Because of the restoring term model results are a dynamical interpolation of sparse observed fields and the resulting computed transports compare relatively well with observations (e.g., cf. discussion by *Blanke et al.* [1999, 2002] and *Friocourt et al.* [2005]). Model and method deficiencies as well as the sparsity of data used to construct the climatology we used may limit the scope of our results, but the overall consistency found in this study and previous analyses can be used to add credibility on them.

3. Results

[8] In our quantitative Lagrangian approach, water masses are represented by hundreds of thousands of elementary water particles distributed over a given initial geographical section. Because bottom waters are not so well represented in the observed climatology we used, our study is limited to the upper cell of the AMOC, that is to the surface and thermocline waters masses that transform into NADW.

[9] We computed backward in time the trajectories of the particles that represent the southward flow of NADW at 44°N in the North Atlantic (i.e., characterized by a potential density anomaly greater than 27.7 kg m^{-3}). An example of such a water-parcel trajectory is given in Animation S1 of the auxiliary material.[1] These particles originate in the downwelling of surface or subsurface waters that enter the North Atlantic either northward at 44°N or northward at the Bering Strait from the Pacific Ocean. The reconstruction of the AMOC in the rest of the ocean is obtained by integrating the same set of trajectories forward in time from 44°N. The Lagrangian computations used monthly varying velocity fields, and the results are presented as annual mean values.

[10] An objective circulation structure is obtained by calculating the 3D non-divergent transport field established by the displacement of particles marked with an individual

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2007GL031583.

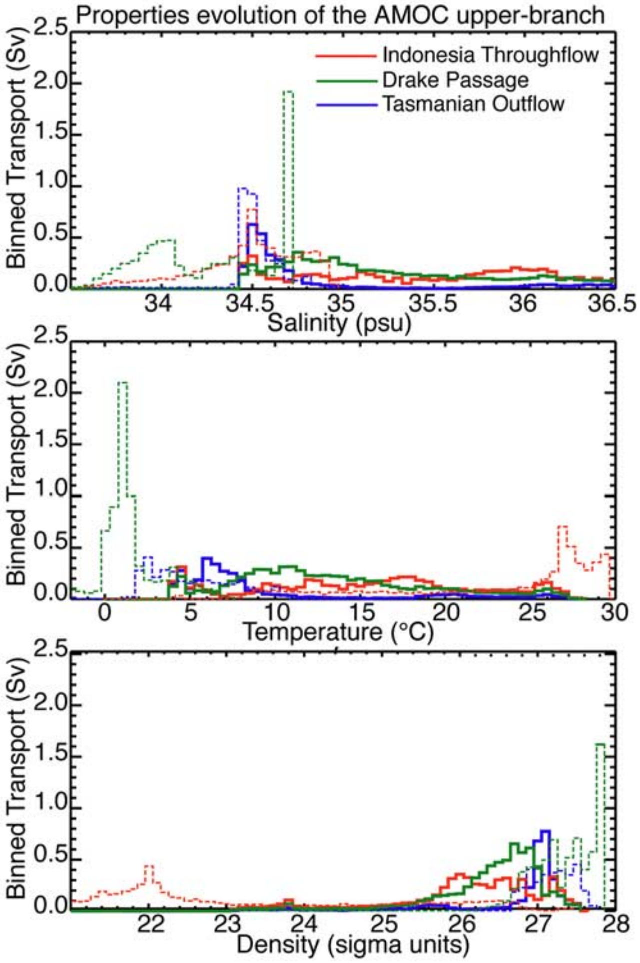

Figure 2. Binned transport of the northward-transmitted warm waters to the equatorial Atlantic with origins in the Indonesian Throughflow (red), the Drake Passage (green), and the Tasman outflow at 145°E (blue). The result is expressed as a function of (top) salinity, (middle) temperature, and (bottom) density anomaly, at the origins (dashed lines) and at the equator in the Atlantic (solid lines).

transport, and by computing the horizontal streamfunction associated with the vertical integration of this transport field. Figure 1 shows the reconstructed pathways of the global AMOC. To highlight both the deep and near surface routes, we drew only the "median" contour of the horizontal streamfunction. Colors represent the mean depth of the exchange between different key ocean sections. The numbers shown give the calculated mass transports for the corresponding colored branch. The total transport associated with the model AMOC is 17.4 Sv (1 Sv = 10^6 m s^{-1}). The southward flowing NADW in the Atlantic Ocean is replaced by 16.8 Sv of surface and thermocline waters coming from the South and by 0.6 Sv of Pacific water flowing across the Bering Strait.

[11] Transformation of dense waters into upper-layer water takes place mainly in the SO during one or more circumnavigations of Antarctica, as discussed by *Sloyan and Rintoul* [2001]. When transformed these waters leak into the three SH oceanic basins, with the largest fraction penetrating into the Pacific Ocean. 5.2 Sv of NADW upwells and transforms into upper waters without flowing through the Drake Passage. The rest, almost 12 Sv, recirculates mostly in the ACC and spreads within all other ocean basins before coming back to the Atlantic, south of the African continent. The direct leakage of the Drake Passage water to the South Atlantic is less than 1 Sv and is not shown on Figure 1.

[12] The mean depths calculated along the various paths of the AMOC return branch show that the leakage of circumpolar water to the Indian and Pacific subtropics occurs at different depths levels. The deepest path is located close to southern Australia and is related to the Tasman outflow [*Rintoul and Sokolov*, 2001]. Centered between 600 and 800 m, it subducts to approximately 1000 m en-route crossing the Indian Ocean. Once it reaches the Equatorial Atlantic, it carries the freshest and coolest waters of all routes. Figure 2 shows the histograms of the binned mass-transport for the different pathways as a function of T, S and density. When the properties of all the waters composing the different return pathways are compared at their origins, Drake Passage waters are the coldest, freshest and densest compared to those in the Indonesian and Tasman flows (green, red and blue dashed lines, respectively). Nonetheless, once all these waters have reached the Equatorial Atlantic, the freshest and densest contribution comes from the Tasman waters (solid lines with the same color code). Indeed, the Tasman outflow and subsequent leakage are sufficiently deep to remain isolated from water mass transformations driven by air-sea exchange. As a result, Tasman outflow lower thermocline characteristics are rather well preserved along the path to the North Atlantic. Hence, the Tasman connection turns out to be the most efficient conveyor of low thermocline fresh water to the North Atlantic. This suggest that the major input of fresh, intermediate waters into the Atlantic Ocean occurs south of Africa as already suggested in previous modeling studies [*Drijfhout et al.*, 2005] and supported by a recent application of finite-difference inverse modeling (M. Ollitraut et al., manuscript in preparation, 2007).

[13] The global AMOC we derived differs from the conventional pathways inferred from data analyses or inverse models [*Ganachaud and Wunsch*, 2000; *Sloyan and Rintoul*, 2001]. For the North Atlantic return flow, the traditional pathway usually includes only two sources of water: the Indonesia Throughflow and the direct leakage to the South Atlantic from Drake Passage, respectively referred to as the "warm route" or "cold route" [*Schmitz*, 1995]. The usual estimated partition is that the contribution from the Indonesian source lies around 6–8 Sv, whereas from Drake Passage is ~10 Sv. While our reconstruction confirms the Indonesia Throughflow as a major provider of water for the North Atlantic return flow, it reduces the significance of the direct leakage from the Drake Passage and uncovers the Tasman outflow as a key feature for the AMOC.

[14] Because of its intermediate depth, the Tasman route has never been invoked before as a major feature for the AMOC in inverse global calculations [*Ganachaud and Wunsch*, 2000; *Sloyan and Rintoul*, 2001], and in the mean absolute dynamical topography recently derived [*Rio and Hernandez*, 2004; *Maximenko and Niiler*, 2005]. Nevertheless, support of the existence of a Tasman Indo-Pacific

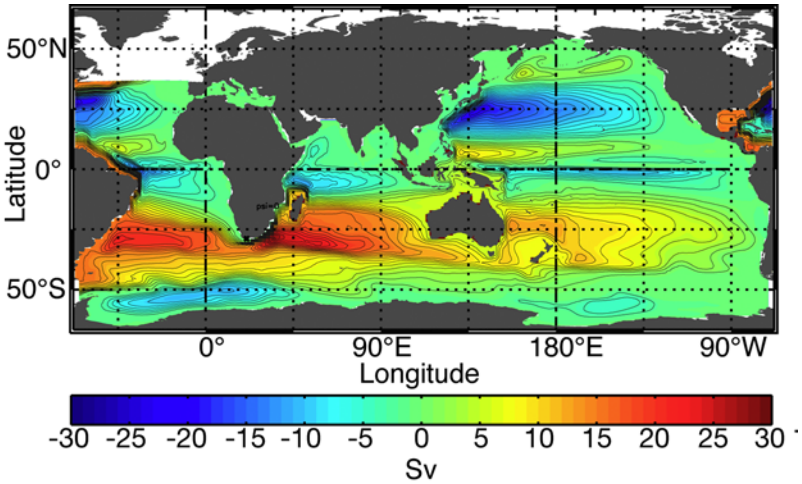

Figure 3. Horizontal streamfunction ψ of the vertically-integrated transport accounted only by the upper ocean waters transmitted northward to the North Atlantic, with origins in Drake Passage or at the same section in the North Atlantic but with a greater density. Contour interval is 1 Sv, and ψ is set to 0 over Africa. The pattern reveals the horizontal shape of the upper branch of the global AMOC. All the large-scale wind-driven structures of the ocean circulation are evident. In particular, it makes the SH subtropical supergyre appear.

connection can be found in ocean-tracer observations [*Metzl et al.*, 1990; *Fine*, 1993; *You*, 1998], in a compilation of the WOCE Indo-Pacific subsurface float data set [*Davis*, 2005], in detailed analyses of hydrological data [*Reid*, 2003; *Ridgway and Dunn*, 2007], and in a regional inverse modeling calculation [*Speich et al.*, 2002].

[15] The structure of the Lagrangian derived streamfunction for the upper to intermediate layer waters associated with the AMOC displays well organized features related to the large-scale wind forcing (Figure 3). In particular, a subtropical "supergyre" spanning all three SH basins emerges. This large cell interconnects the three basins in two ways: (1) a flow from west to east via its southern limit and parallel to the ACC, and (2) from east to west via its two northern branches: one through the Indonesian passages and the other confined to the South Pacific, which veers westward into the Indian Ocean via the Tasman outflow. This "supergyre" is an extension of the one proposed by *De Ruijter* [1982], which was originally confined to the South Atlantic and Indian basins only.

[16] Important consequence of the existence of such a supergyre is that it creates a strong dynamical barrier for meridional exchanges between the SO and the SH subtropics. This barrier is characterized by the presence of two frontal regions, the Subtropical and Sub Antarctic Fronts, (STF and SAF, respectively). These fronts are intense

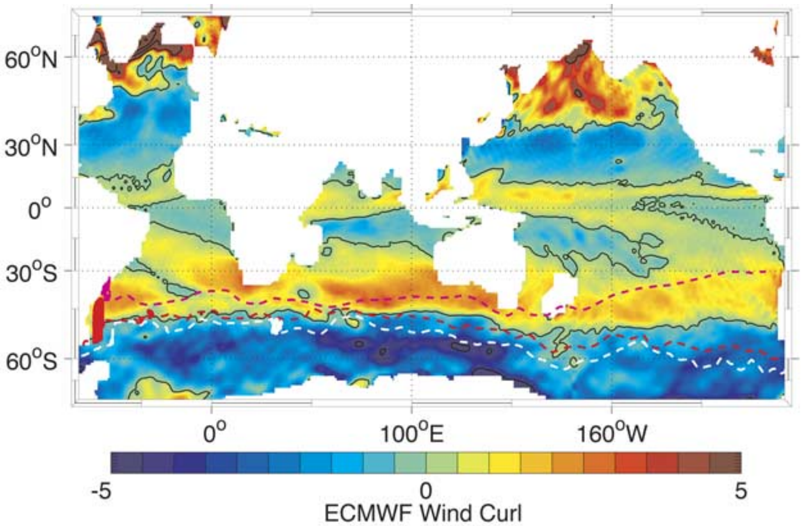

Figure 4. Wind stress curl (N m^{-3}, scaled by a factor 10^{-7}) for the ECMWF 10-year annual mean climatology. The locations of the ACC fronts given by *Orsi et al.* [1995] are superimposed: STF in magenta, SAF in red, and PF in white. Differences in position between the oceanic fronts and the maximum wind-curl and zero-curl lines likely result from the influence of the local bathymetry on ocean circulation and from the bias towards SH summer values of the hydrological data used.

circumpolar dynamical structures arising from the spatial distribution of the SH positive subtropical wind-curl that encroach on the SO, well south of Africa and Oceania (Figure 4). The STF coincides with the latitude of the maximum positive wind-curl whereas the SAF coincides with the southern limit of the positive subtropical wind-curl. Only SO waters north of both fronts can penetrate easily into the subtropical region. In the SH Atlantic sector, these fronts expands without intercepting land. Hence, meridional exchanges are mostly prevented and only less than 1 Sv of water flowing from Drake Passage enters directly into the South Atlantic. The most important fraction of the connection to the North Atlantic must first flow eastward to the East Indian Ocean (~3 Sv) where the STF borders on the South Tasman Rise and the Campbell Plateau, or the Pacific (~8 Sv) where it comes across the American continent. Hence, the SH wind structure affects the global AMOC by organizing the water pathways and properties that return to the North Atlantic Ocean.

4. Conclusions

[17] Because the AMOC pathways connect different regions of air-sea interaction, variations in their structure may influence the water masses they convey, and their associated heat and fresh-water transport. Resulting large differences in terms of climate impact ask for a thorough knowledge of the structure of the global ocean circulation, and, in particular, of the AMOC. Moreover, the evidence that the "supergyre" plays a significant part in the AMOC implies that the winds not only provide a means for the NADW to upwell and transform, but they also organize the path of the AMOC return-flow. In this way they affect the properties of the water masses that reach the North Atlantic to compensate for NADW formation and spreading. For the present climate, the Tasman route is the largest conveyor for the freshest and densest waters. Because advection of water masses affects heat and freshwater transports, variations of the wind pattern could affect the dynamical regime and stability of the AMOC [*Rahmstorf*, 2002; *Weijer et al.*, 1999]. Hence, in a changing climate, trends of the SH winds could represent an additional process to which the AMOC is sensitive [*Cai*, 2006].

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B. Blanke, Laboratoire de Physique des Océans, UMR 6523, CNRS, IFREMER, UBO, UFR Sciences et Techniques, 6 avenue Le Gorgeu, F-29238 Brest Cedex 3, France.

W. Cai, CSIRO Marine and Atmospheric Research, Private Bag No. 1, Aspendale, Victoria 3195, Australia.

S. Speich, Centre de Bretagne, Campus Ifremer, IRD, Technopole de Brest-Iroise - Site de la Pointe du Diable, F-29280 Plouzané, France. (speich@univ-brest.fr)