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A synthetic float analysis of upper-limb meridional overturning circulation interior ocean pathways in the tropical/subtropical Atlantic

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Synthetic floats are released in an ocean general circulation model to study fluid pathways followed by the upper limb of the meridional overturning circulation from the subtropical South Atlantic to the subtropical North Atlantic. The floats are designed to track this fundamentally three-dimensional, non-isentropic flow while sampling water properties and all terms of the equation governing the vertical component of relative vorticity. The low-resolution ocean simulations demonstrate how upper-limb flow navigates the complex, time-dependent system of wind-driven gyres. Pathways that extend into the interior North Atlantic before entering the Caribbean Sea are emphasized over the more direct western boundary route. A large number of floats are released in the southern hemisphere to verify the importance of such interior pathways in the model and document key events that occur along them. Upper limb water first approaches the equator in a modified inertial western boundary layer. Equatorial processes (visco-inertial boundary layer dynamics, upwelling, heating) are necessary to reset water properties and permit fluid to permanently cross the equator, typically requiring eastward retroflection into the EUC. After upwelling at the equator, fluid that does not advect northward or southward into the interior returns to the western boundary and turns northward in a frictional western boundary layer. The generation of negative relative vorticity by planetary vorticity advection can break the boundary layer constraint and permit retroflection into the NECC near 5°N from late spring through fall. Once in the

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interior, this fluid advects northward into the southern subtropical gyre in a flow governed by Ekman dynamics. There the fluid subducts and advects southwestward to enter the Caribbean Sea under the influence of layered thermocline dynamics. The importance of interior pathways is confirmed although we note that fluid parcels generally take complex paths and frequently make multiple attempts to enter the northern hemisphere or multiple treks around gyres.

1. INTRODUCTION

The overturning circulation of the global ocean exerts an important influence on the storage and redistribution of internal energy within the Earth's climate system. The Atlantic Ocean plays a unique role in this by virtue of the deep water formation that occurs at high latitudes. North Atlantic Deep Water formed near Iceland and Greenland flows southward as a Deep Western Boundary Current that eventually feeds the deep flows of the Indian and Pacific Oceans. This necessitates an upper ocean return flow within the Atlantic basin. The resulting overturning system of cold deep water exiting and warmer surface water entering the North Atlantic is referred to as the Meridional Overturning Circulation (MOC), and the return flow is referred to as the upper-limb of the MOC. The understanding of upper-limb pathways and associated water mass modifications that occur en route is important because these will influence the vertical stability of the flow that eventually reaches the subpolar North Atlantic. This could then influence the deep water formation rate and thus the strength of the MOC and associated net northward heat flux.

The upper-limb of the MOC cannot follow a simple path from the South Atlantic to the North Atlantic because of the angular momentum constraint imposed by the Earth's rotation and the resulting system of wind-driven gyres. Of particular interest to the present study are the paths taken by fluid parcels as they navigate from the South Atlantic subtropical gyre, across the equatorial and tropical gyres, and then into the North Atlantic subtropical gyre. It is known from previous studies that the circulation connecting these gyres must be fully three-dimensional and seasonally varying. The equator is a location of special concern because of strong upwelling and surface heating. Western boundary processes are also important. Unlike the Gulf Stream that closes the North Atlantic subtropical gyre over a continuous meridional extent of some 15 degrees latitude, the western boundary currents of the equatorial and tropical gyres generally extend along less than 5 degrees latitude and flow in opposite directions. *Munk* [1950] suggested that these features should not even be called gyres for these reasons. Moreover, these western boundary currents vary seasonally, and the North Brazil Current (NBC) that closes the equatorial gyre is unstable during the time of year when these gyres are most developed (late spring through fall). During this time, the southeastward western boundary flow of the tropical gyre acts to block the NBC, so a large fraction of the NBC retroflects and flows eastward to become the North Equatorial Countercurrent (NECC). The retroflection is unstable and eddies occasionally pinch off and migrate northward carrying a fraction of the upper-limb fluid. In addition to the gyres, upper-ocean flow also includes subtropical overturning cells that return water subducted in the subtropical North and South Atlantic back toward the equator [*Malanotte-Rizzoli et al.*, 2000; *Lazar et al.*, 2002).

These and other processes provide a multitude of possible upper-limb pathways. The observational record is presently inadequate to accurately map these pathways, quantify the mass fluxes associated with them, understand the controlling dynamics, and quantify the water mass modifications that occur. Numerical model experiments are needed, and while ocean general circulation models are imperfect, they are sufficiently realistic to begin identifying and understanding the physical processes that govern upper-limb pathways, and to help guide observational strategies.

Recent improvements in numerical models, including the development of the HYbrid-Coordinate Ocean Model (HYCOM) [*Bleck,* 2002; *Halliwell,* 2003] with the addition of improved synthetic float/drifter technology, allow us to pursue a new model analysis of upper-limb pathways. We identify upper-limb pathways, along with important dynamical and thermodynamical processes that control them, in a low-resolution HYCOM simulation of the Atlantic Ocean. Because of the low model resolution, the western boundary pathway and the influence of NBC rings are not a focus of the present study. Instead, specific attention is given to fluid parcels that follow interior pathways as governed by processes resolved in the low-resolution model. In particular, upper-limb water that enters the interior via the NECC before joining the North Atlantic subtropical gyre circulation is studied in the most detail. Thermodynamical variables, along with terms of the relative vorticity balance, are interpolated to the floats to aid in our understanding of the governing processes. In doing this, we demonstrate the importance of five key processes that govern interior upper-limb pathways: (1) boundary layer dynamics, including western, surface, and equatorial boundary layers; (2) equatorial upwelling and the associated water mass modifications; (3) seasonal variability of the wind-driven tropical and equatorial gyres; (4) interior Ekman wind-drift; and (5) subtropical subduction. These processes change or reset fluid parcel vorticity in ways that permit upper-limb fluid to cross the equator and transit between gyres. Despite the limitations of low-resolution simulations, the insights gained are scientifically interesting and will aid in the interpretation of observations and in the design of high-resolution simulations.

In carrying out these analyses, we validate the use of synthetic three-dimensional Lagrangian (particle-following) floats as a tool for numerical circulation model analysis of thermohaline circulation pathways. The feasibility of using model floats to track fluid pathways have been demonstrated in earlier studies. For example, *Fratantoni* [1996] seeded the Miami Isopycnic-Coordinate Ocean Model (MICOM) with isopycnic floats to study flow pathways in the tropical Atlantic. *Malanotte-Rizzoli et al.* [2000] and *Lazar et al.* [2002] used isopycnic floats to track fluid pathways from the subtropics to the equator, seeding the flow after it had subducted. However, there are limitations to using isopycnic floats in models to track flows that are fundamentally non-isentropic. *Harper* [2000] seeded subduction regions of the global ocean near the surface with three-dimensional particle-following floats and successfully tracked fluid pathways before and after subduction. The present study demonstrates the importance of using three-dimensional particle-following floats to map pathways of upper-limb MOC fluid as it flows from the subtropical South Atlantic across the equator and into the North Atlantic subtropical gyre.

2. BACKGROUND AND GOALS

The tropical Atlantic Ocean circulation has been the subject of studies ranging from major multi-national expeditions to individual efforts. A selected few papers provide the essential backdrop for our work. We begin with the analysis of IGY hydrographic sections by *Roemmich* [1983] in which estimates of the zonally integrated mass and internal energy transports are presented at several latitudes based on geostrophic and Ekman dynamics. These quantify the MOC and show that the upper-limb transports must transition from primarily within the thermocline layer upon approaching the equator from the South Atlantic to the mixed layer upon leaving the equator to the North Atlantic. This can only occur through water mass modification as fluid is upwelled and heated. *Philander and Pacanowski* [1986a; 1986b] model the seasonally varying circulation along with meridional mass and internal energy fluxes. These analyses demonstrate a dependence upon the gyres' seasonally varying dynamic topography [*e.g., Garzoli and Katz*, 1983; *Katz,* 1987] for the storage and release of the internal energy accumulated as a result of the MOC and surface heat flux.

On the basis of this information, plus a seasonal Sverdrup streamfunction analysis, *Mayer and Weisberg* [1993] hypothesize a composite annual cycle to accommodate across-equator and inter-gyre exchange in a manner consistent with a cyclonic tropical gyre negating a continuous western boundary current (NBC). The hypothesis depends on different processes acting at different locations during different times of year to influence the upper-limb transports (e.g. inertial boundary layer dynamics at the equatorial western boundary during late spring/summer and interior Ekman transports near the NECC ridge/trough region during late fall/winter). These processes force a significant fraction of upper limb fluid to flow into the ocean interior within the NECC during late spring through fall when internal energy is stored at that latitude, and to then flow northward in the near-surface wind-drift during the following winter when internal energy is released to higher latitudes. Since key processes governing this interior pathway hypothesis are reproducible in low-resolution ocean simulations, verification of this hypothesis is a particular focus of the present analysis. According to *Schott et al.* [1998], up to one-quarter of the upper limb flow on annual average follows a pathway that extends into the interior North Atlantic, either flowing eastward in the NECC or flowing directly northward from the equator. Based on water property analysis, *Schmitz and Richardson* [1991] and *Schmitz and McCartney* [1993] also find that upper-limb pathways must include an interior route. Eulerian analysis of Atlantic Ocean simulations by the Navy Layered Ocean Model [*Fratantoni et al.*, 2000] has recently been employed to estimate upper-limb fluxes following different pathways. That study also demonstrates the likely importance of interior pathways.

Annual mean flux estimates along different pathways consistent with these and other studies are summarized in Figure 1. We follow the observational synthesis by *Schott et al.* [1998], who subdivide the MOC upper-limb flow approaching the equator from the southern hemisphere into three vertical layers: surface ($\sigma_\theta < 24.5$), thermocline ($24.5 < \sigma_\theta < 26.8$), and intermediate ($\sigma_\theta > 26.8$ and above 1000 m). The intermediate layer contributes a substantial fraction of the upper-limb flow, but it follows the western boundary and does not contribute significantly to interior North Atlantic pathways. The thermocline layer flow does contribute to interior pathways, but only after upwelling into the surface layer at the equator, consistent with the asymmetry described by *Roemmich* [1983]. The 4 Sv annual mean northward surface layer flow in the interior, which represents the interior pathway flows of interest to this study, consists of about equal contributions of fluid entering from the western boundary region via the NECC

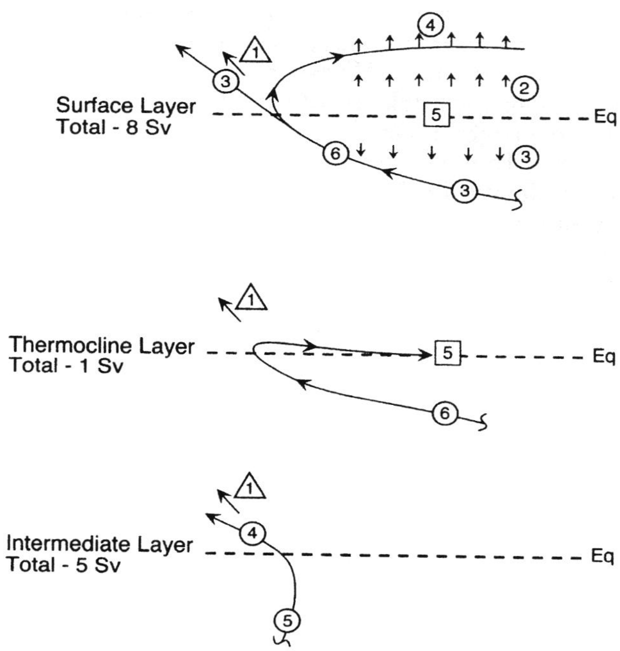

Figure 1. Schematic diagram of the upper limb transport contribution of fluid approaching the equator from the south within three vertical layers: surface layer (σ_θ<24.5, top), thermocline layer (24.5<σ_θ<26.8, middle), and intermediate layer (σ_θ>26.8 and above 1000 m, bottom). Circled numbers are horizontal fluxes in Sverdrups. Numbers in squares indicate vertical upwelling fluxes while numbers in triangles indicate horizontal fluxes within North Brazil Current eddies. All fluxes represent annual averages.