Interhemispheric Water Exchange in the Atlantic Ocean

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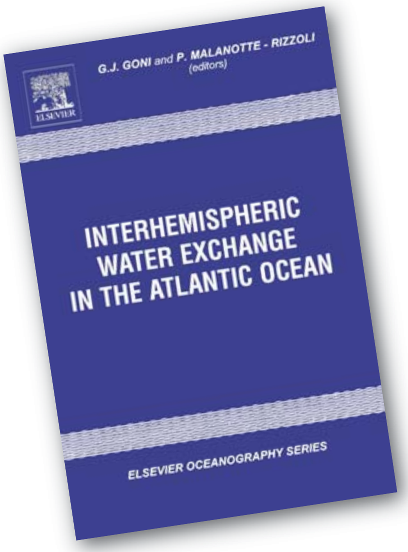

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The tropical ocean spans 82 percent of Earth's equatorial circumference (Indonesian maritime continent included). Here, where the atmosphere's opposing Hadley Cells meet to produce the rainy Intertropical Convergence Zone, the ocean is characterized by a shallow intense thermocline, regional upwelling, and zonally elongated circulation gyres, crisscrossed by Rossby and Kelvin Waves. The tropical ocean draws lots of attention by the climate community as the hot end-member of the global heat engine. There, excess heating is transferred poleward by a variety of coupled oceanic and atmospheric processes, both on the horizontal and vertical planes. Each tropical ocean basin plays a unique role in the climate system because of its particular geography. The Pacific, accounting for about half of the equatorial ocean, hosts the powerful climate presence of El Niño and La Niña, with its near global reach. The Asian Monsoon, imposing strong seasonally reversing meridional winds across the equator, dominates the Indian Ocean. The narrow Atlantic tropics, hemmed in by the jigsaw-puzzle fit of South America and Africa (making a believer in continental drift of a curious school child) holds another special place in Earth's climate system. While the Atlantic has its own "El Niño" of sorts, and plays a role in the African and American monsoons, its specific attribute is the interhemispheric water exchange across the Atlantic's tropical belt.

The Atlantic is home of a vigorous meridional overturning (full depth, vertical plane) circulation, a thermohaline circulation driven by North Atlantic Deep Water formation that runs at a clip of 15 to 20 Sv (Sv = 1 Sverdrup = 1 million cubic meters per second), with a northward flow of warm water in the upper kilometer, and a southward flow of cold water within the deeper layers. The resultant northward heat flux and its variability in Ice Age (century to millennium) time scales has stimulated a great deal of "Conveyor Belt" (a term I consider to be misleading) literature. Within the western tropical Pacific there is also northward flow in the upper kilometer of similar magnitude to that of the Atlantic; however, this northward flow across the Pacific equator is balanced mainly within the horizontal flow pattern mostly by export of warm North Pacific water through the Indonesian Seas, and hence does not impose as large a cross-equator heat flux as does the Atlantic's meridional overturning circulation.

The interhemispheric exchange of the warm water within the upper kilometer of the tropical Atlantic is the main theme of the excellent collection of research papers or chapters composing the book *Interhemispheric Water Exchange in the Atlantic Ocean* edited by G. J. Goñi and

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P. Malanotte-Rizzoli. In 19 chapters involving 55 authors, it presents us with an impressive array of results. The book covers a wide range of observational and modeling topics involving cross-equatorial transfer of water, zonal circulation, planetary waves, sea-air interaction, and meridional ocean overturning (mostly about the shallow tropical-subtropical overturning circulation). Not all papers address the main theme of interhemispheric water exchange, though all are worthwhile contributions towards understanding Atlantic tropical oceanography. Of course, the book chapters have gone through vigorous peer review, and are of uniformly high quality; however, I do have some concern that collections of articles within books do not get as much attention (citations) as articles published in standard, widely distributed journals. I hope this is not true as the Goñi and Malanotte-Rizzoli book deserves the attention of the ocean and climate science communities.

Strammer, Fischer, Brandt, and Schott discuss the upper kilometer circulation and its variability. They present a useful schematic of the seasonal surface circulation in which five bands of alternating zonal currents are shown between the South and North Equatorial Currents, including some that are mainly undercurrents. It is a pretty complicated circulation pattern, accounting for the difficulty in tracing the pathways that ultimately accomplish the interhemispheric transfer of water. Schematics of the tropical Atlantic circulation included in many of the book's contributions are rich in names and arrows, making it difficult for the casual reader to know what elements of the circulation to focus on. The unambiguous interhemispheric transfer is shown along the western boundary where the North Brazil Current passes into the northern hemisphere before retroflection (curling) into the ocean interior to feed the North Equatorial Counter Current and Equatorial Undercurrent. The retroflection shares a trait common to other retroflection of the world's oceans, notably the Agulhas retroflection—as large pools of one ocean's water drift into a neighboring ocean, each "pool" annualized contributes around 1 Sv of interocean transport. At the northern tip of the North Brazil Current retroflection, South Atlantic upper layer water breaks away as eddies, or what are more often referred to as "rings," and drifts into the northern hemisphere, contributing to the meridional overturning circulation. However, even the part of the North Brazil Current that "retroflects" into the interior appears to be lost to the South Atlantic's subtropical gyre, as there is no clear pathway back to the South Atlantic gyre (maybe some return within the surface Ekman Layer).

Halliwell, Weisberg, and Mayer track the circuitous three-dimensional Lagrangian paths of "synthetic" floats, seeded in the South Atlantic subtropical gyre of a HYCOM model (30°S to 70°N), as they maneuver across the complicated, seasonally variable equatorial and North Brazil Current environment. Before entering the Caribbean Sea, many floats first extend and upwell into the interior of the northern tropics of the Atlantic rather than pass quickly into the Caribbean along a western boundary route. But, as the authors point out, this may be sensitive to the coarse 1.4° horizontal resolution of the model. Hazeleger and de Vries investigate trajectories within a higher-resolution OCCAM model (0.25° horizontal grid), specifically to track the Equatorial Undercurrent waters after they upwell along the equator. Some of the upwelled water takes part in the shallow tropical-subtropical overturning cell, and part gets caught up in the deeper meridional circulation cell associated with the North Atlantic Deep Water formation— about two-thirds is drawn into the latter. The word "complicated" is clearly evident in describing the trajectories. One wonders how the results of models can be tested in the real world. I suppose if the model agrees with what observations scientists have, then one must assume that it has a good chance of being right for those attributes that can't easily be observed—at least let's hope so.

A powerful tool for studying ocean circulation and its variability is the satellite altimeter. Chapters by Mayer, Baringer, and Goñi and by Buehner, Malanotte-Rizzoli, Busalacchi, and Inui investigate ways to extend the usefulness of satellite-altimeter-derived sea level variability by incorporating *in situ* data or by its assimilation into a model to tell us more of the full circulation. Vianna and Menezes investigate the surface circulation variability from 1995 to 2000. They show that the eastward flowing North Equatorial Counter Current draws its water from two sources: (1) the southern side is supplied by the North Brazil Current, which introduces South Atlantic water; and (2) the northern side is composed of North Atlantic subtropical water injected by the North Equatorial Current. Vianna and Menezes contribute to the main theme of the book by noting that the equatorial current exhibits quasi-standing waves that lead to northward transport in three specific longitude windows along the western tropical Atlantic.

Interhemispheric exchange is also accomplished within the Antarctic Intermediate Water layer at 800 to 1100 m depth, defining the base of the thermocline. Schmid, Garraffo, Johns (E. not W.), and Garzoli investigate this with observations and modeling (MICOM), providing a useful new schematic of circulation at the intermediate depths. The predominately zonal flow at this level is broken only by the meridional flow along the western boundary. They find, as do Jochum and Malanotte-Rizzoli (using a MOM model), that the intermediate water layer along the equator is dominated by planetary waves rather than strong, persistent zonal flow. Both papers question the interpretation of the sparse observations at intermediate depths as evidence of robust zonal currents of intermediate water along the equator. These papers suggest caution, as these currents may be transient features associated with seasonal Rossby waves. França et al. use the altimeter data to study planetary, equatorial-trapped waves.

Snowden and Molinari look into the observations of the Atlantic's shallow subtropical overturning cells, the circuit that connects the subtropical convergence to the equatorial upwelling. They provide a useful schematic and table of transports in the western tropical Atlantic in density layers. Snowden and Molinari report that the northward transport of water less dense than σ_0 26.8 (approximately warmer than 11°C) across the equator at 44°W is slightly over 20 Sv. The Atlantic equatorial upwelling is fed by the South Atlantic cell; the North Atlantic cell has limited reach into the Equatorial Counter Current near 5°N.

Five chapters explicitly study what I consider to be the central theme of the book: the North Brazil Current and its spin-off rings, which entrap a central core of South Atlantic surface and thermocline water. The rings appear in a variety of forms, differing in their vertical profile; some are surface intensified, others more apparent at depth. Goñi and Johns (W. not E.), using ten years of altimeter data, find an eddy-generation rate of 3 to 7 rings per year (average of 5 per year), without an obvious seasonal signal. Only 7 out of the 52 rings identified entered into the Caribbean Sea, the rest shirt around the Lesser Antilles. They find that the number of rings coincide with warmth of the regional sea surface temperature. W. Johns, Zantopp, and Goñi, using observational information gathered during the 20-month (November 1998 to June 2000) North Brazil Current Ring Experiment, report that 25 percent of the rings had little sea surface expression, hence were missed by the altimeter. While not as common as the surface-intensified rings, each of these deeper-reaching rings delivers twice the amount of South Atlantic water into the North Atlantic Ocean (annualized: 1.7 Sv vs. 0.8 Sv). The authors estimate a production rate of 8 to 9 rings per year, yielding an annualized interhemispheric transport of 9.3 Sv. While the rate of formation of rings has no seasonal signal, the rings' form does, with larger, deeper-reaching (>400 m) rings occurring from November into February. Thus, the interhemispheric transport accomplished within the rings has a seasonal cycle—greater in late fall and winter—even if the ring numbers don't. Garzoli, Ffield, and Yao, using data from an array of 14 inverted echo sounders, detect 11 eddies during the North Brazil Current Ring Experiment period. These eddies have a mean diameter of 390 km, transporting waters northward at 8 Sv annually, with a total heat transport of 0.54 PW. The MICOM model results reported by Garraffo, W. Johns, Chassignet, and Goñi agree remarkably well with the observations.

The varied observational methods and model data in these papers reveal a fairly consistent picture of the North Brazil Current Rings, their size and form, the volume of water and heat they transport, and their place in the Atlantic's meridional overturning circulation. The rings account for about 50 percent of the upper limb of the meridional overturning circulation and 50 percent of the estimated cross equatorial heat flux. The balance, as required to compensate the southward deep limb, takes a longer route into the North Atlantic, following along the North Brazil Retroflection into the North Equatorial Counter Current, curling back to the western boundary with the North Equatorial Current. Of course, there may also be some leakage closer to the South American coast, more directly feeding flow into the Caribbean Sea. Besides the obvious importance of the rings to the climate system, they have substantial local ecosystems, such as reported for Barbados by Cowen Sponaugle, Paris, Fortuna, Lwiza, and Dorsey.

The Elsevier Oceanography Series has a long tradition of offering to the community fine topical collections. The book, 68th in the series, gives us a very nice collection of papers, covering many aspects of the tropical Atlantic circulation and interhemispheric transport. Although have no doubt, many ocean and climate mysteries remain to be solved in the tropical Atlantic Ocean.