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Interactive comment on "What Fraction of the Pacific and Indian Oceans' Deep Water is formed in the North Atlantic?" *by* James W. B. Rae and Wally Broecker

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The manuscript, "What Fraction of the Pacific and Indian Oceans' Deep Water Is Formed in the North Atlantic?" by Rae and Broecker, draws attention to a basic ocean circulation question that deserves revisiting due to the range of answers in the literature. Rae and Broecker rightfully identify the definition of a water mass as being a subtle issue, where the properties of seawater are not completely reset at the sea surface in many cases. Physical oceanographers have estimated the fraction of North Atlantic Deep Water (NADW) in the deep Pacific through observations (Johnson 2008), models (Primeau 2005), and model-data syntheses (Gebbie & Huybers 2010, DeVries

and Primeau 2011), and they appear to agree to first-order that the amount of NADW by volume (or mass) is less than 50%. Those studies, however, each have their own definition of a water mass, they have not published rigorous error estimates (although sensitivity studies have been done), and they have not pinpointed which dataset is most important to constraining NADW. This manuscript can contribute by giving perspective about what definition of "formation" is most useful and by being explicit about the purpose of water masses in geochemical studies. It appears that at least some of the discrepancies in the estimate of NADW in the deep Pacific can be attributed to differing definitions, and thus it is hoped that this manuscript can add some clarity to the cross-disciplinary discussion.

Rae & Broecker use phosphate-star to "determine the contributions of NADW and AABW to the ventilation of the deep Pacific and Indian Oceans." Whether the contribution is that of some tracer flux or a seawater flux is ambiguous in this introduction. Lines 78-80 (L78-80) hypothesize that "the relative amounts of deep water produced in the two source regions" could be established from phosphate-star. The term 'deep water production' seems to imply some flux of seawater is the goal. If this goal were stated explicitly, e.g., estimation of 1) the net flux of water into a density class due to air-sea exchanges (i.e, water-mass transformation), 2) the downward mass transport in that density class, or 3) the downstream horizontal mass transport out of a "formation region", a model experiment could be designed where the deep Pacific phosphate-star value is compared to these physical quantities.

An important message is the inherent sensitivity in water-mass decompositions due to the subjective choice of endmember values. Lines 121-126 demonstrate the sensitivity of the composition of the deep Pacific to the Southern Ocean endmember. This finding corroborates the analysis of Johnson (2008) in his paragraphs 32-40, and the discussion on page 1711 of Gebbie and Huybers (2010). Note that Gebbie and Huybers (2010) attempt to eliminate making any subjective choice of endmember values by defining all surface patches to be distinct water masses, but that method has other sensitivities such as to the reconstruction of missing bottom water pathways.

The authors present a counterargument to a 75/25 AABW/NADW decomposition of the deep Indo-Pacific. They reason that a AABW flux into the deep Indo-Pacific that is three times the NADW flux of 16 Sv is unreasonably large. I believe there are a number of unstated assumptions in this case, such as: 1) the flux of tracer into the Indo-Pacific is accomplished by the advection of tracer by a meridional overturning cell, and 2) no flux of tracer occurs by smaller-scale gyre or eddy motions. In addition, the 16 Sv of NADW presumably applies to the flux into the deep Indo-Pacific basins. The given citations for the 16 Sv of NADW, however, refer to the strength of the mid-depth overturning cell in the Atlantic. Do the authors assume that the entirety of NADW formed in the Atlantic makes it to the Southern Ocean and then turns northward to fill in the Indo-Pacific? If some NADW is lost along the way, then the AABW flux into the Indo-Pacific would become less than the hypothesized 48 Sv.

There is good evidence that much of the 16 Sv of NADW that is formed in the North Atlantic does not make it to the Indian and Pacific Oceans. Water is irretrievably lost due to vertical mixing processes, as evidenced by the decreasing concentrations of NADW as one moves south in the Atlantic and eastward in the Southern Ocean. As mentioned by Rae and Broecker, some NADW is the upwelled in the Southern Ocean and becomes the precursor to AABW. Deep wintertime mixed layers suggest some modification of these waters, and hence a "loss" or "renewal" of NADW into a new water mass. As suggested by the authors, this renewal is partial and not complete. Also, much of the upwelled NADW returns northward to become Antarctic Intermediate Water, which also decreases the NADW flux into the deep Indo-Pacific. Such rates of loss are quantified in the model of Primeau and Holzer (2006) and are significant, but should be highlighted with observations or inverse methods as well. If the NADW loss is great enough, the 75/25 AABW/NADW deep Pacific ratio would be tenable.

As the assumptions in the authors's counterargument were not explicit, they may be misinterpreted here. Instead, they may be considering a deep box for the global ocean

such that the NADW input is indeed $\sim$16 Sv or nearly so. Johnson (2008, Paragraph 43) illustrates a global scaling relationship in this framework, where the product of the water mass formation rate and its residence time is proportional to the global water mass volume. In his calculation, the global water mass volume of AABW is about 1.7 times larger than NADW (with a range of 1.4 to 2.4). Note that this ratio is very likely to be smaller than the value of 3 that would have been expected from the deep Pacific Ocean (=75/25), due to the high fraction of NADW in the Atlantic. Furthermore, it is still possible for the AABW and NADW formation rates to be identical, so long as the residence time of AABW is 1.7 times larger than NADW. As AABW is deeper than NADW, it is less easily brought to the surface and its residence time may plausibly be larger. The numerical model of Primeau (2005) suggests 829 and 683 years for the age of Southern Ocean and high-latitude Atlantic waters, respectively: a ratio greater than 1 that helps explain the lower NADW water-mass fractions. (I have not been careful with distinguishing ages and residence times here.) Do radiocarbon observations confirm this prediction?

Rae and Broecker suggest defining AABW by the shelf water properties so as not to introduce any NADW components by dilution on their descent of the continental slope. Consider the case of defining AABW as the Weddell Shelf Water (WSW), as was done by Johnson (2008). As he states, "This experiment can be thought of as an attempt to quantify the influence of this locally ventilated component of AABW through the global ocean." The global ratio of AABW to NADW volume in this instance is reduced to about 1.3, where the decrease in the ratio is consistent with the arguments of Rae and Broecker. The "AABW" volume still exceeds the NADW volume in this sensitivity experiment, however. In addition, because the AABW/NADW ratio is low in the Atlantic, this requires the ratio to actually be greater than 1.3 in the deep Pacific.

There is an additional issue in using WSW seawater properties to characterize "AABW" in the global ocean. Johnson (2008) find a decrease of AABW volume in the global ocean to 23% of the total volume, and a decrease of the volume of NADW to 17%.

Apparently these two water masses are no longer capable of describing as much of the world ocean. I hypothesize that WSW is "too specific"; in other words, there are other Antarctic waters being formed that have properties not well described by WSW. It is an open question to what extent this reflects shelf waters from elsewhere around Antarctica or the products of open-ocean deep convection such as the opening of the offshore Weddell Polynya. Johnson's experiment suggests that other contributors to Antarctic Bottom Water are important in describing tracer properties and could increase the amount of the world ocean that is identified as being Antarctic in origin.

The preceding paragraph emphasizes what I believe to be a basic metric against which water masses should be judged: how well can they describe the spatial variation of seawater properties? The clouds of points in the left panels of Fig. 9 suggest that a 2-water mass description of the deep ocean cannot describe much of the variability, as seawater properties would be limited to a line on a property-property diagram. A test is hereby proposed: 1) decompose the deep ocean into 2 constituent water masses using phosphate-star and the "best" Southern Ocean endmember, 2) take the partial equilibration of surface waters into account when calculating the appropriate endmembers for other tracers such as salinity, and 3) determine how well other tracer distributions can be described by this water-mass decomposition. In particular, can deep Pacific salinity reflect values similar to those around Antarctica, as observed, if it has a high percentage of NADW?

Lines 137-139 state that Gebbie and Huybers (2010) exclude the endmember values most characteristic of the ventilation of the Southern Ocean interior. In that work, 2806 surface patches are included along with tens of patches that are on the AABW shelf. The visualizations in that work are formed by averaging an entire region of ocean south of the ACC, but the actual diagnostics were performed on a higher-resolution grid.

Signed: Geoffrey (Jake) Gebbie

References:

DeVries, T., and F. Primeau, 2011: Dynamically and observation- ally constrained estimates of water-mass distributions and ages in the global ocean. J. Phys. Oceangr., 41, 2381–2401.

Gebbie, G., and P. Huybers, 2010: Total matrix intercomparison: A method for resolving the geometry of water-mass pathways. J. Phys. Oceanogr., 40, 1710–1728.

Johnson, G. C., 2008: Quantifying Antarctic Bottom Water and North Atlantic Deep Water volumes. J. Geophys. Res., 113, C05027, doi:10.1029/2007JC004477.

Primeau, F., 2005: Characterizing transport between the surface mixed layer and the ocean interior with a forward and adjoint global ocean transport model. J. Phys. Oceanogr., 35, 545–564.

Primeau, F., and M. Holzer, 2006: The ocean's memory of the atmosphere: Residence-time and ventilation-rate distributions of water masses. J. Phys. Oceanogr., 36, 1439–1456.

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