Pathways of the Global Meridional Overturning Circulation Inferred from a Data Constrained Ocean & Sea-Ice Model

Sang-Ki Lee[1] (Sang-Ki.Lee@noaa.gov), Rick Lumpkin[1], Marlos Goes[2,1], Molly O. Baringer[1], Christopher S. Meinen[1], Shenfu Dong[1], Hosmay Lopez[2,1] and Steven G. Yeager[3]

[1]Atlantic Oceanographic and Meteorological Laboratory, NOAA, Miami, FL, [2]Cooperative Institute for Marine and Atmospheric Studies, University of Miami, Miami, FL,

[3]National Center for Atmospheric Research, Boulder, CO

Summary

Ocean tracers such as heat, salt and carbon are perpetually carried by the Global Meridional Overturning Circulation (GMOC) from their source regions and redistributed between hemispheres and across ocean basins. The GMOC is therefore a crucial component of the global heat, salt and carbon balances (Macdonald & Wunsch, 1996; Sarmiento & Le Quere, 1996; Talley, 2003, 2008). Although much has been learned during the recent decades based on observations and models (e.g., Ganachaud & Wunsch, 2000; Sloyan & Rintoul, 2001; Ganachaud, 2003; Talley et al, 2003, Lumpkin and Speer, 2007), the pathways of the GMOC, especially in the Southern Hemisphere, are relatively poorly understood because of a paucity of data and model limitations.

Here, we attempt to examine the gaps in our understanding of the GMOC and its pathways by using a surface-forced ocean & sea-ice model simulation that is constrained by long-term averaged global hydrographic data, a method known as robust diagnostic simulation (DIAG; **Figure 1**). The zonally averaged overturning streamfunctions in the Atlantic and Southern Oceans (**Figure 2**) and Indo-Pacific and Southern Oceans (**Figure 3**) are derived from DIAG. By tracing the streamfunction contours one can follow the water mass pathways of the GMOC circuit.

The derived GMOC pathways are summarized in a new schematic (**Figure5**), which highlights two important but often overlooked aspects of the GMOC pathways. First, **the heaver part of the North Atlantic Deep Water (NADW)**, which forms predominantly in the Greenland, Iceland and Norwegian (GIN) Seas, **and the lighter part of the NADW**, which forms in the Labrador and Irminger Sea, **contribute roughly equally to the southward return flow of the AMOC (Figure 2)**. Second, **the heavy-to-light water mass transformation that occurs primarily in the Indo-Pacific Oceans through diapycnal diffusion, is one of the key elements required to close the GMOC circuit (Figure 3)**, concurring with previous observation-based studies (Lumpkin and Speer 2007; Talley 2013). Finally, it is found that these pathways of the GMOC are poorly captured in the surface forced ocean & sea-ice simulation that is not constrained by hydrographic data (MODEL, **Figure 4**).

AMOC at 26.5°N in MODEL, DIAG, & OBS

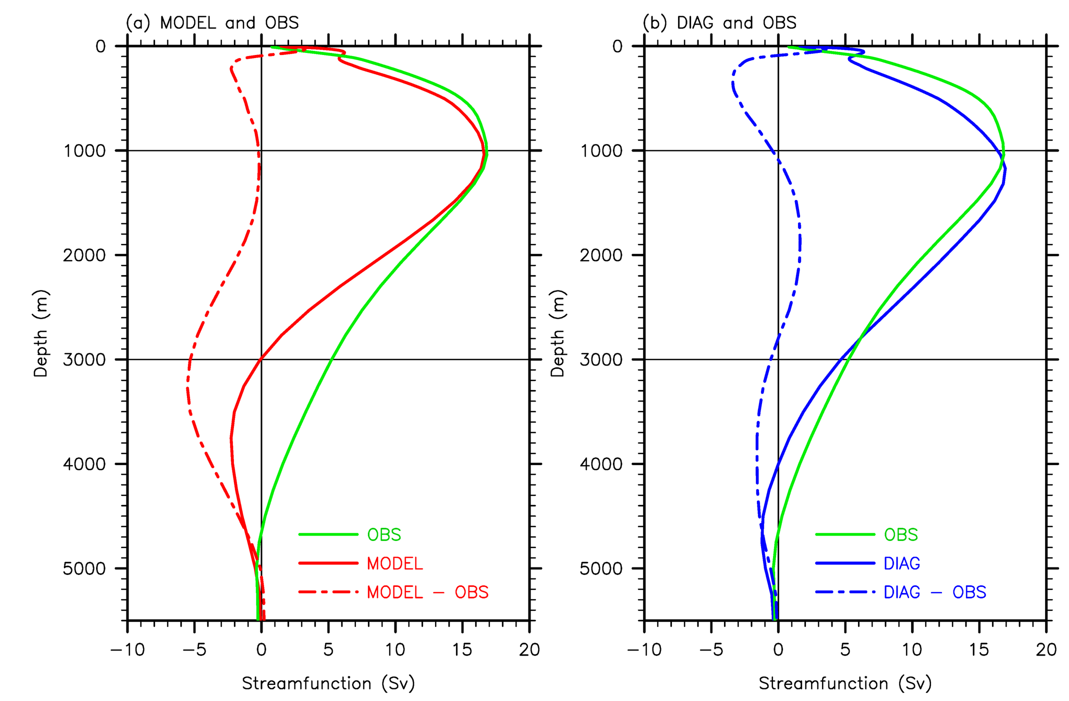

Figure 1. Current state-of-the-art GCMs suffer from several critical systematic biases in the GMOC. For example, the Atlantic Meridional Overturning Circulation (AMOC), which is the Atlantic component of the GMOC, observed at 26.5°N by the RAPID-MOC/MOCHA/WBTS array is characterized by the southward returning flow extending from about 1,000 to the ocean floor near 5,000 m (Figures 1a and 1b). **A state-of-the-art surface-forced ocean & sea-ice model, on the other hand, shows a much shallower southward returning flow** between about 1,000 and 3,700 m (Figure 1a). Previous studies showed that **this is a common symptom in many surface-forced ocean & sea-ice models as well as in fully coupled climate models** (Danabasoglu et al., 2014, 2016).

Robust Diagnostic Simulation (DIAG)

Due to these limitations (Figure 1a), it is questionable whether the current state-of-the-art GCMs are up to the task of bridging gaps in the observation-based GMOC estimates and furthering our understanding of the GMOC pathways. Therefore, in order to minimize the known limitations in GCMs, here we **utilize a surface-forced ocean & sea-ice model simulation (CESM1) constrained by long-term averaged global hydrographic data** - this technique is often referred to as a robust diagnostic simulation (DIAG) in the literature (e.g., Sarmiento and Bryan, 1984).

DIAG: Atlantic & Southern MOC in Density Coordinate

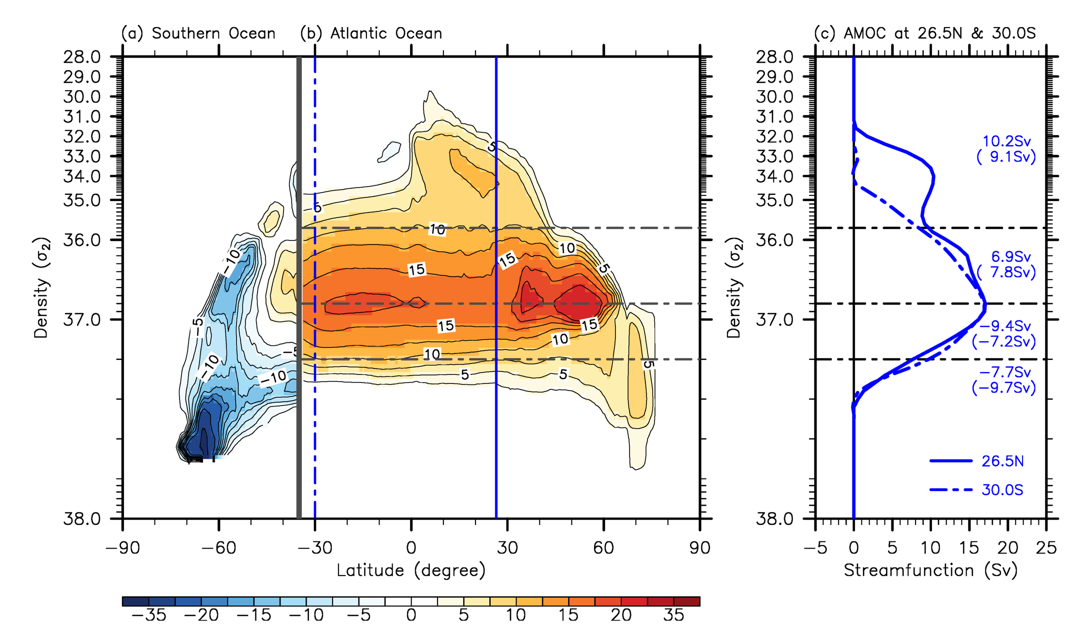

Figure 2. The surface water that participates in the tropical Atlantic upwelling and the subtropical shallow overturning cell (σ_2 < 35.7) is known to originate largely from the Indian Ocean via the Agulhas leakage (e.g., Gordon, 1996; Beal et al., 2011). At 26.5°N, about 10.2 Sv of the warm surface water is transported northward. Antarctic Intermediate Water (AAIW) that forms at the surface mixed layer in the southeast Pacific, and is modified in the southwest Atlantic, is an important source of intermediate depth water (σ_2 = 35.7 ~ 36.8) (e.g., McCartney, 1977; Talley, 1996). At 26.5°N, the northward transport of intermediate depth water is about 6.9 Sv (Figure 2c). Two distinctive sinking regions are readily identifiable. One is centered at around 60 - 65°N where the lighter portion of NADW (i.e., upper NADW, σ_2 = 36.8 ~ 37.1) is formed, mainly in the Labrador and Irminger Seas. The other is located north of around 70ºN where heavier NADW (i.e., lower NADW, σ_2 > 37.1) is formed in the GIN Seas. In total, about 17.1 Sv of NADW is carried southward through the AMOC return flow across 26.5°N (i.e., transport below σ_2 > 36.8).

Tracing the streamfunction lines back to the formation areas indicates that **lower NADW formed in the GIN Seas and upper NADW formed in Labrador and Irminger Seas contribute roughly equally to the southward AMOC return flow** (about 7.7 Sv and 9.4 Sv, respectively at 26.5°N).

DIAG: Indo-Pacific & Southern MOC in Density Coordinate

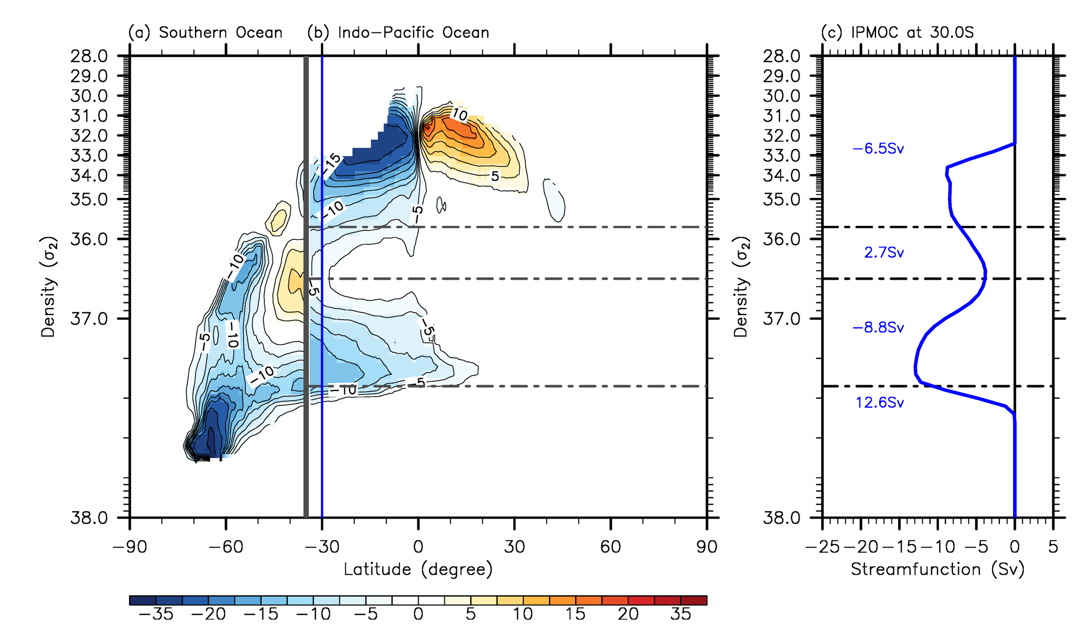

Figure 3. The southward flow of NADW into the Southern Ocean is the major source of the local water mass in the Southern Ocean known as Circumpolar Deep Water (CDW), which carries high salinity water from the Atlantic close to the surface in the Southern Ocean. AABW forms near the Antarctic continent, becomes lighter north of 60 ºS and then is exported into the Indo-Pacific Oceans. At 30°S, about 12.6 Sv of AABW (σ_2 > 37.17) is exported into the Indo-Pacific Oceans (Figure 3c). The abyssal water mass that enters the Indo-Pacific Oceans ultimately transforms into Indian Deep Water and Pacific Deep Water (IDW and PDW, σ_2 = 36.5 ~ 37.17) through diapycnal mixing (e.g., Talley 2013). A smaller portion of PDW directly supplies cold and freshwater to the equatorial Pacific upwelling system (3.8 Sv). IDW and the rest of PDW are carried back to the Southern Ocean (8.8 Sv at 30°S) to form upper CDW, which also originates to a lesser degree from upper NADW in the South Atlantic (Figures 2a and 2b). Upper CDW in part transforms into AAIW (σ_2 = 35.7 ~ 36.5) in the surface mixed layer in the southeast Pacific and is transported back into the Atlantic and Indo-Pacific Oceans (e.g., Talley, 2013). AAIW reenters the Pacific Ocean (2.7 Sv) and along with PDW supplies cold and fresh water to the equatorial Pacific upwelling system (6.5 Sv).

This heavy-to-light water mass transformation (i.e., from AABW to surface & thermocline water) that occurs primarily in the Indo-Pacific Oceans is a key step required to close the GMOC circuit.

MODEL: Atlantic, Indo-Pacific & Southern MOC in Density Coordinate

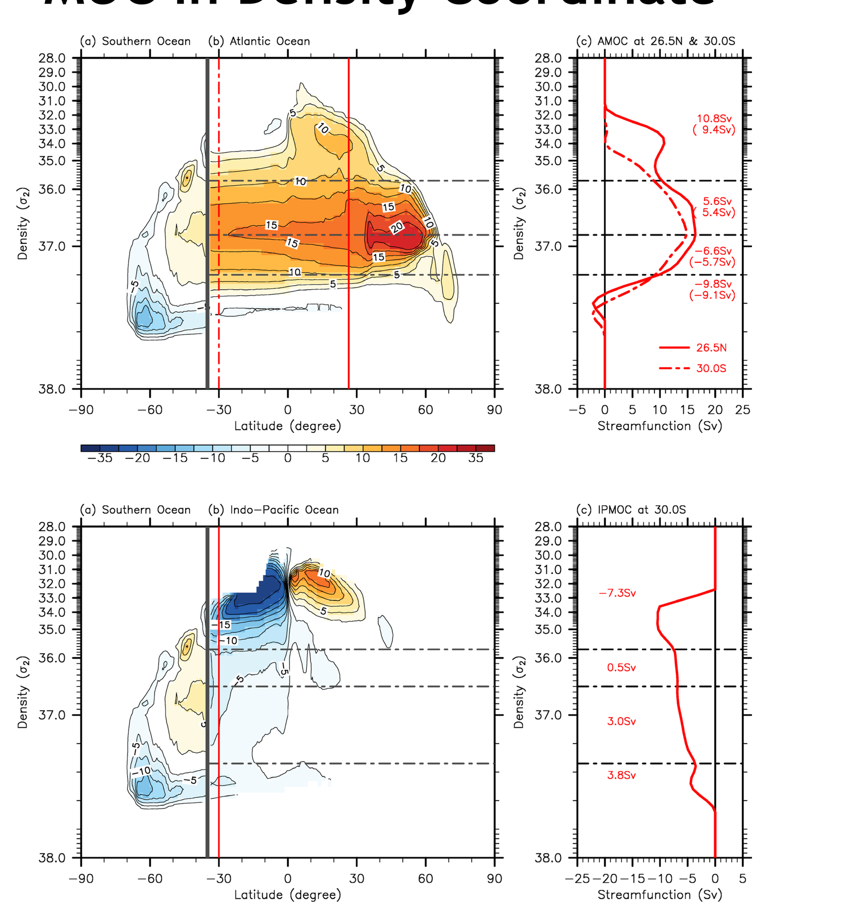

Figure 4. The GMOC pathways are poorly captured in MODEL. For example, **the southward return flow of the AMOC in MODEL originates predominantly from the Labrador and Irminger Seas, while lower NADW formed in the GIN Seas contributes very little.** NADW at 35°S is also much lighter than lower CDW at that latitude, indicating a weak linkage between the two compared to DIAG. Additionally, much less volume of abyssal water enters the Indo-Pacific Ocean in MODEL from the Southern Ocean, and it is also much heavier, compared to DIAG. But, more importantly, **the heavy-to-light water mass transformation in the Indo-Pacific Oceans, which is a critical component required to close the GMOC circuit, is almost completely missing in MODEL.** This suggests that **MODEL is not reproducing realistic pathways of the GMOC.** Thus, a series of intensive investigations is needed to further explain these shortcomings in MODEL and explore if other GCMs participating in CORE2 and CMIP5 also show these symptoms.

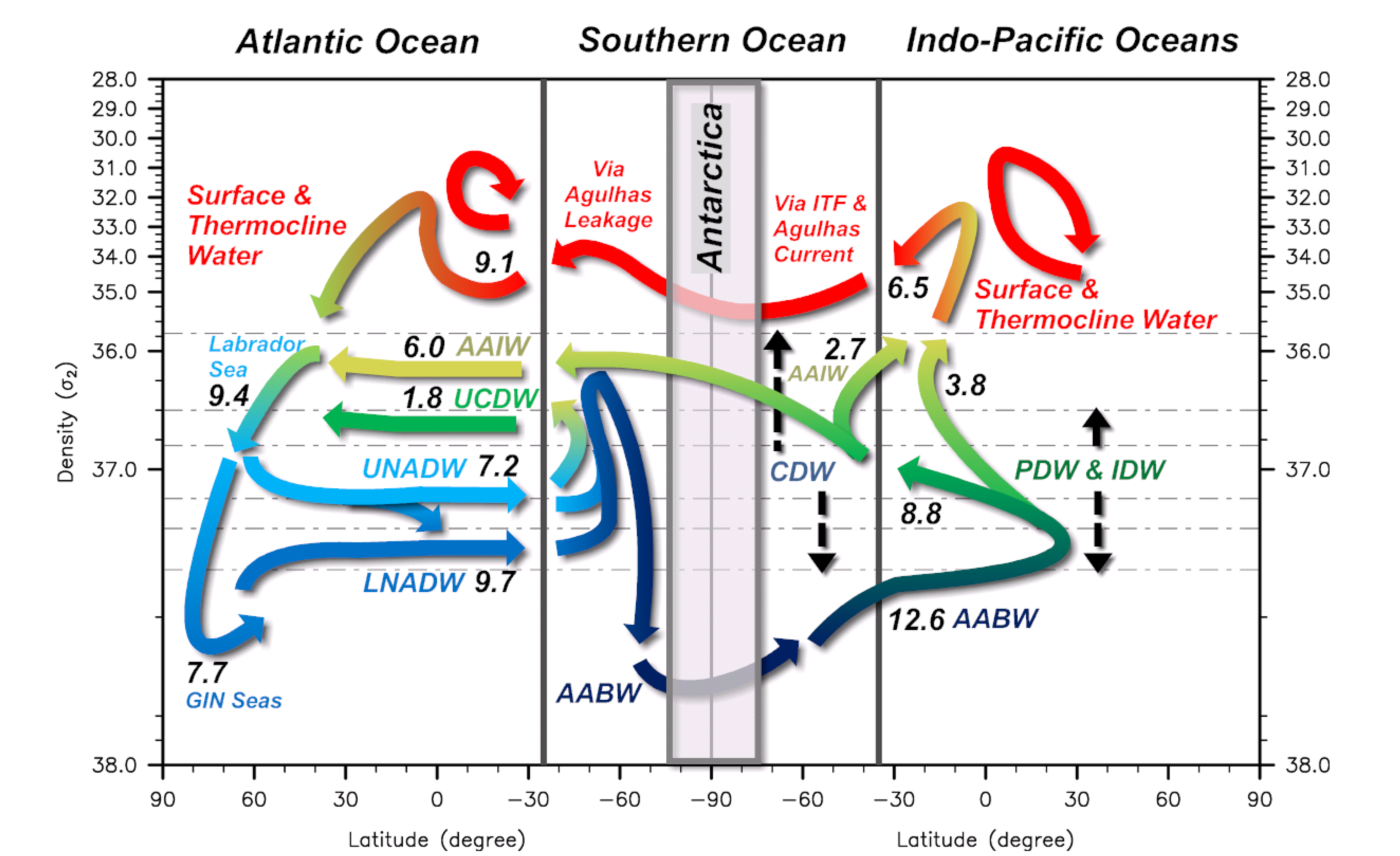

Figure 5. A summary schematic of the GMOC pathways based on DIAG. Color indicates approximate density ranges of the water masses involved. Volume transports are in Sv units. AABW denotes Antarctic Bottom Water; AAIW denotes Antarctic Intermediate Water; CDW denotes Circumpolar Deep Water; PDW and IDW denote Pacific Deep Water and Indian Deep Water, respectively; UCDW denotes upper Circumpolar Deep Water; UNADW and LNADW denote upper and lower North Atlantic Deep water, respectively; ITF denotes Indonesian Throughflow; GIN Seas denote Greenland, Iceland and Norwegian Seas. Black dotted lines indicate the density ranges of CDW, IDW and PDW

Pathways of GMOC inferred from DIAG

A summary schematic of the GMOC derived from DIAG is shown in Figure 5. The schematic flows and the associated volume transport estimates are based on a multi-year average from DIAG, as opposed to previous observation-based estimates, which are primarily based on analyses of a limited number of snapshot sections. Thus, to the extent that DIAG is reproducing realistic circulation, **this new schematic should be closer to a representation of the modern era time-average circulation.**

The GMOC is characterized by deep convection in three major sinking sites: the Labrador and Irminger Seas, GIN Seas and around Antarctic continent. Upper and lower NADW that form mainly in the Labrador and Irminger Seas and GIN Seas, respectively, are carried southward across the Atlantic basin to feed CDW in the Southern Ocean. A large portion of CDW upwells to the near-surface in the Southern Ocean and then eventually sinks near the Antarctic continent to form AABW, the heaviest major water mass in the global ocean. AABW in turn becomes lighter within the Southern Ocean, and then is exported predominantly into the Indo-Pacific Oceans.

The abyssal water imported into the Indo-Pacific Oceans is in turn transformed into IDW and PDW via diapycnal mixing. A portion of these deep water masses in the Indo-Pacific Oceans is then exported back to the Southern Ocean to feed upper CDW. Upper CDW reenters the Atlantic and Indo-Pacific Ocean as AAIW. In the Pacific Ocean, AAIW and PDW supply cold and fresh water to the equatorial Pacific upwelling system to produce equatorial Pacific surface water, which eventually reenters the Atlantic Ocean via the Indonesian Throughflow and the Agulhas leakage. The surface and intermediate depth water masses in the Atlantic Ocean later sink in the Labrador and Irminger Seas and GIN Seas to produce NADW, closing the GMOC.

Acknowledgement: This work was supported by NOAA's Climate Program Office, Climate Variability and Predictability Program (award #: GC16-207) and by NOAA's Atlantic Oceanographic and Meteorological Laboratory.