The Mid-latitude formation of Lower North Atlantic Deep Water

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The conventional "conveyor belt" interpretation of the North Atlantic circulation describes the import of warm thermocline waters and a volumetrically compensating export of cold North Atlantic Deep Water (NADW) as a single meridional overturning cell with two layers. Here we describe a more elaborate system with four layers, figure 1. In the upper cell, part of the imported warm water is made denser in the Labrador Basin and is exported at mid - depth as Upper NADW (UNADW), principally Labrador Sea Water (see papers by McCartney, Curry and Bezdek, and Curry and McCartney, this volume). The remainder of the warm water is made denser in the Nordic and Polar Seas, producing Nordic Seas Overflow Waters (NSOW). The NSOW represents a mixture of dense waters from the Nordic Seas with warm and intermediate waters entrained as the dense waters spill over the sills of the Greenland Scotland ridge system.

The NSOW is not directly exported. At mid - latitudes the NSOW encounters the dense Antarctic Bottom Water (AABW) flowing northwards from the equator. The approximately equal transports of these two convergent dense plumes upwell and combine to form the Lower NADW (LNADW), which is exported from the North Atlantic above the AABW. These upper and lower varieties of NADW, which represent the two modes of deep water exported from the North Atlantic, are separated by a Middle NADW layer which shows little export across the equator. The exported LNADW is formed by abyssal upwelling and warming of denser waters converging into the mid - latitude western North Atlantic from the equator and the Nordic Seas, while the exported UNADW is more directly produced by cooling and downwelling of the warm water.

The LNADW is characterized by a potential vorticity minimum and a dramatic transport mode in the Deep Western Boundary Current (DWBC) near $\theta = 1.8 - 2.0°C$ from about 30°N to near the equator. The low potential vorticity is traced to a source region northeast of the Bermuda Rise at the point of contact of the convergent plumes of NSOW and AABW. It appears that the intense deep circulation of the Gulf Stream system acts as a mixer for the convergent plumes and the accompanying convergent warmer deep waters to produce a homogeneous product. The deep westward return flow of the Gulf Stream transports this water towards the western boundary, with a prominent pathway south of the Bermuda Rise. We infer that this return flow is not completely a recirculation, as it often is diagrammed, but instead is a bifurcating flow, splitting into a southward DWBC component and a northward recirculation into the Gulf Stream, with the former supplying

the LNADW transport mode and low potential vorticity core in the DWBC. At the level of the LNADW and the convergent plumes the lateral circulation looks something like figure 2 (which does not explicitly show the counter - rotating deep recirculation cells to either side of the axis of the Gulf Stream but instead represents their action as a pair of egg - beaters). Crucial to this system is the involvement of LNADW recirculation: that offshore of the strong equatorward flow of the LNADW in the DWBC is a poleward interior flow of recirculating LNADW -- with a distinct admixture of South Atlantic characteristics. This is essential to achieve a mixing product that is warmer than the convergent cold plumes. The existence of these recirculations cannot be reflected in the meridional overturning circulation schematic of figure 1, as that is a zonal average field. These interior recirculations at mid and low- latitudes are well documented in the literature. Also shown on the schematic are secondary flow pathways for the LNADW: into the Newfoundland Basin and into the DWBC north of the Gulf Stream system. At both locations these pathways bring the influence of the southern components of the mixture into these higher latitude sites.

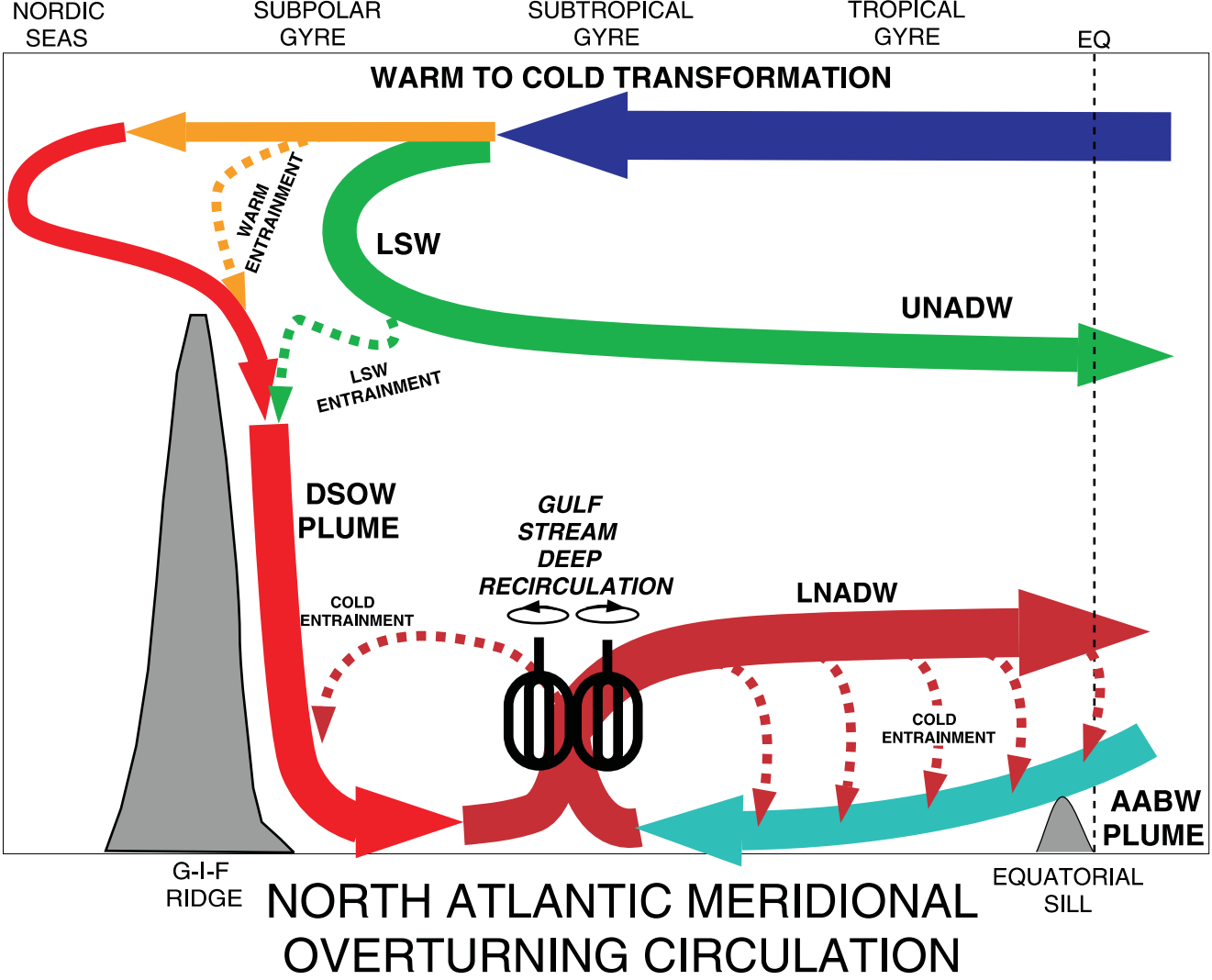
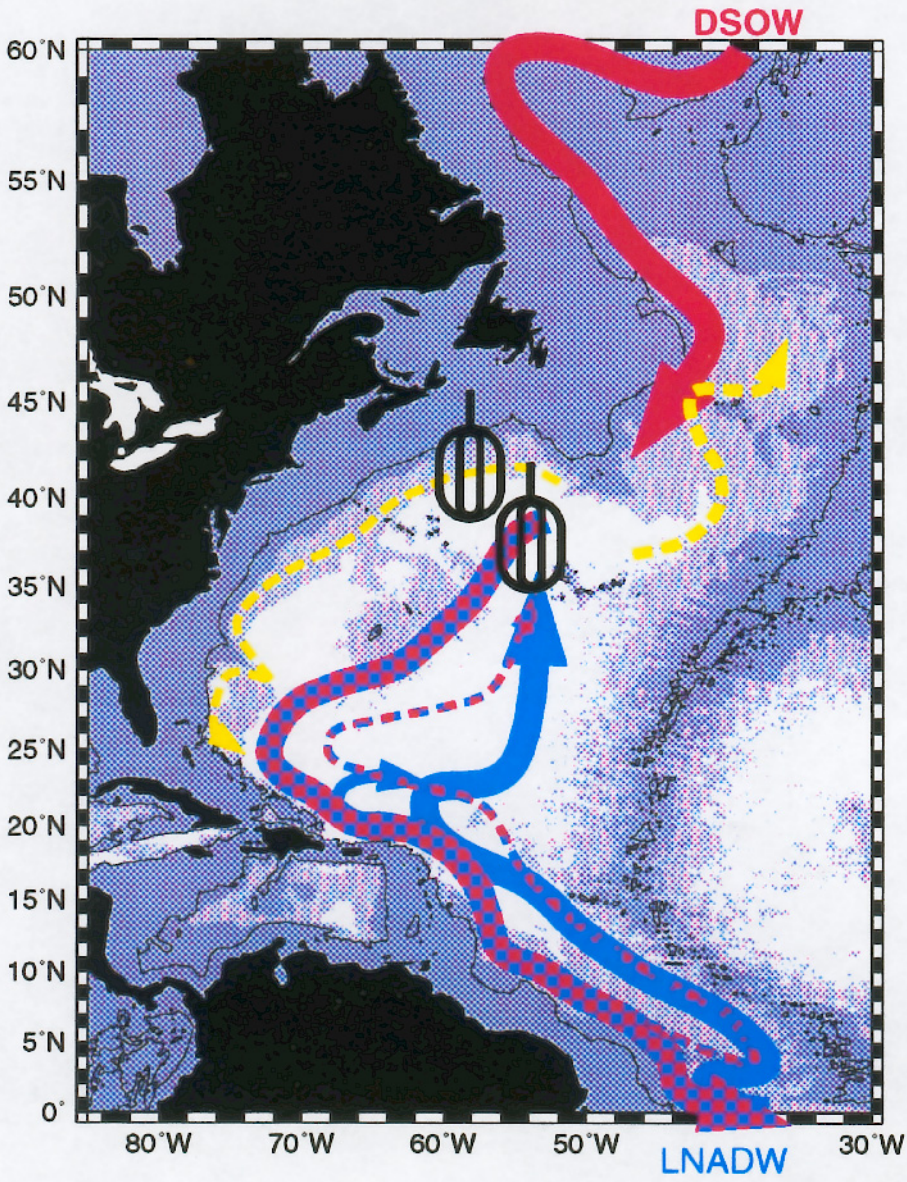


Figure 1. Schematic of the meridional overturning circulation of the North Atlantic Ocean, emphasizing the counterrotating deep recirculations of the Gulf Stream System acting to mix the convergent plumes of cold DSOW from the north and AABW from the south with overlying warmer deep waters to produce a homogeneous LNADW that dominates the deep water export from the North Atlantic.


DSOW
60°N
55°N
50°N
45°N
40°N
35°N
30°N
25°N
20°N
15°N
10°N
5°N
0°
80°W
70°W
60°W
50°W
30°W
LNADW