A revised view of the Thermohaline Circulation

The thermohaline circulation of the ocean is often described in terms of downwelling sites in the Nordic and Labrador Seas with upwelling, produced by mixing due to breaking internal waves, throughout the rest of the ocean. Theoretical estimates[1,2] of the diapycnal (cross density surface) mixing coefficient required to do this give values near 10^{-4} m^2s^{-1}, an order of magnitude larger than most observed values[3,4]. The discrepancy has been explained as due to localized regions of high turbulence5 caused by the interaction of currents and topography. However the efficiency with which the energy input from the winds and tides is utilized has to be high for this mechanism to work. Here we consider a revised view of the thermohaline circulation in which there is significant upwelling due to Ekman divergence in the Southern Ocean, and show that the required diapycnal mixing is closer to observed values and that lower conversion efficiencies are required.

The two most widely reported[1,2] calculations of the vertical mixing needed to account for the abyssal stratification of the oceans hypothesise that 25 or 30 Sv, made up of both Deep and Bottom Waters, is injected at depths near 4000m and that this is mixed upwards to depths near 1000m by turbulent mixing. Both conclude that the spatially averaged dyapicnal diffusivity is 10^{-4} m^2s^{-1}. Observations of turbulence[3] and dye-diffusion[4] in the deep ocean indicate that there exists a background diapycnal diffusivity of 10^{-5} m^2s^{-1}, with much larger values being found in localized regions near rough topography[5]. The background value is consistent with mixing due to the internal wave field, and the larger values are consistent locally with the generation of additional internal waves by the interaction of currents with topography. Such waves quickly break giving increased diffusivity.

However it is not obvious that internal wave generation and breaking is enough to raise the total diffusivity by an order of magnitude. A source of power is also needed, the actual amount depending on the efficiency with which the whole process changes the potential energy of the water column. If the efficiency is 20%, normally considered a maximum for the final stage of breaking internal waves[6], then the power requirement[2] is 2.1 TW. This is just possible given current estimates of the energy input from the wind and tides but the figure does not allow for losses at other stages in the conversion process.

A contrasting view of the thermohaline circulation has come from low[7] and high resolution[8] computer model studies of the ocean circulation. These show that between 9 and 12 Sv of deep water is brought to the surface by Ekman suction in the Southern Ocean. This is driven northwards in the surface Ekman layer and is reduced in density primarily by surface freshening. The model results also emphasize earlier observations[9] that in the primary regions of Bottom Water formation around Antarctica, the near surface water masses have the same density as North Atlantic Deep Water. Thus it is not necessary for the Bottom Water to be mixed through the whole depth of the water column, only up to the level of the Deep Waters.

If we adopt this alternative view of the thermohaline circulation, then we need only consider the vertical mixing of the main Deep Water mass, North Atlantic Deep Water, whose flux is estimated to lie between 14 and 17 Sv[10]. Taking the larger of these two values and the smaller of the two model based estimates of upwelling, leaves a maximum of 8 Sv to be mixed vertically within the ocean. The 10^{-5} m^2s^{-1} background term can upwell 3 Sv, leaving 5 Sv to be upwelled by localized regions of intense mixing. If this view is corrrect then the vertical mixing coefficient, averaged over the whole ocean, is less than 3 x 10^{-5} m^2s^{-1} and, assuming 20% efficiency, the total amount of energy required is less than 0.6 TW.

These revised values are consistent with existing observations of mixing within the ocean. They emphasise the importance of the Southern Ocean and imply that although further research is needed on the localised mixing regions, there is no reason to expect that these control the thermohaline circulation.

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