Mixing processes deduced from the Mediterranean water signature in the North Atlantic

The conservation equations of heat and salt are combined in such a way that a rather simple relation is found between the known volume flux of Mediterranean Water entering the North Atlantic and the effects of lateral and vertical mixing processes. The method is a form of inverse method in which the only unknowns are the vertical and lateral diffusivities.

A careful linear combination of conservation equations

The steady conservation equations for salt and heat can be written with respect to neutral density coordinates as

\[ \nabla \cdot (\bar{S} \nabla S) + \partial S/\partial t = \nabla \cdot (\bar{K} \nabla S) + \partial S/\partial t \]

\[ \nabla \cdot (\bar{\Theta} \nabla \Theta) + \partial \Theta/\partial t = \nabla \cdot (\bar{K} \nabla \Theta) + \partial \Theta/\partial t \]

Here the superscripts \( u \) and \( f \) refer to the upper and lower interfaces bounding each layer and \( h \) is the vertical distance (layer thickness) between these bounding density interfaces. \( D \) and \( K \) are the vertical and lateral diffusion coefficients and \( \varepsilon \) is the dianeutral velocity.

For each layer we will consider a series of control volumes bounded by the source of Mediterranean Water in the east and a series of contours of salinity and conservative temperature, \( S_0 \) and \( \Theta_0 \), (see Figure 1). We carefully take a specific linear combination of these conservation equations and form a conservation equation for the variable \( \Delta S (\Theta - \Theta_1) - \Delta \Theta (S - S_1) \) where the offset values \( \Theta_1 \) and \( S_1 \) are the volume averaged conservative temperature and salinity of the control volume, and the vertical differences \( \Delta S \) and \( \Delta \Theta \) are the area averaged differences between the values at the upper and lower interfaces bounding a density layer. The resulting equation is

\[ FQ \{ \nabla \cdot (\bar{S} \nabla S) - \Delta S (\Theta - \Theta_1) \} = \int_A \nabla \cdot (\bar{K} \nabla S) \, dA + \Delta \Theta (S - S_1) \}

Here \( A \) is the area from the Gulf of Cadiz to the salinity contour \( S_0 \) and the angle brackets indicate an area average over area \( A \). We have used the symbol \( D \) in (3) for the average of the diapycnal diffusivity at the lower and upper interfaces. \( 0.5(D^+ + D^-) \). Here \( Q \) is the volume of Mediterranean Water entering the control volume in the east and \( cQ \) is the volume flux leaving across the salinity contour \( S_0 \) in the west. We take \( c \) to be around 0.8 for fixed so that \( F \) defined as

\[ F = \frac{1}{S_0 - S_1} \frac{\int \nabla \cdot (\bar{S} \nabla S) \, dA}{\int (\nabla \cdot (\bar{K} \nabla S) \, dA)} \]

lies in the range 0.85 < \( F \) < 1.0.

Because of its careful construction, dianeutral advection \( c \) makes a negligible contribution to (3) as does the vertical gradient of the dianeutral diffusivity. Rather, the process of dianeutral mixing enters (3) only as the average of the dianeutral diffusivity at the upper and lower interfaces. In addition, this dianeutral diffusion term is proportional to the vertical curvature of the \( S-\Theta \) diagram which is much less subject to numerical noise than is traditionally involved with estimating second derivatives such as \( \nabla \cdot (\bar{K} \nabla S) \). These advantages were the motivation for forming the rather careful linear combination of the conservation equations.

Figure 1 shows five \( S_0 \) and \( \Theta_0 \) contours on the \( \gamma = 27.70 \) km \( m^{-3} \) density surface that we use as bounds for five overlapping areas on this density surface. We have eight layers in the vertical giving 40 equations of the form (3). The volume fluxes of Mediterranean Water into each of the eight layers are taken from the work of Baringer and Price (1997). Hydrographic data from the region of the North Atlantic near the Straits of Gibraltar has been taken from the atlas of Koltermann et al. (2004).

We performed least-squares fits assuming that the diffusivities \( D \) and \( K \) were constant along each layer. Figure 2 shows that there is a strong tendency for the straight lines of equation (3) on the \( D-K \) diagram from an individual layer to nearly cross at a point and this strongly suggests that the method has sufficient resolving power to be able to estimate both \( D \) and \( K \), and that these diffusivities are not constant in the vertical. In this way we performed eight such fits with five equations in each fit, and the resulting values of the diffusivities for the eight layers are shown in Figure 3.

The method seems able to distinguish between the effects of epineutral and dianeutral diffusion on the dilution of the Mediterranean Water signature in the eastern North Atlantic. Also the over-determined least-squares “inversion” gives dianeutral and epineutral diffusivities that vary smoothly in the vertical.

REFERENCES


Marine and Atmospheric Research

Castaway Esplanade, Hobart Tasmania, 7000, Australia • trevor.mcdougall@csiro.au

Wealth from Oceans

National Research Flagship