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LETTER TO THE EDITOR

The role of baroclinic eddies in mixing tritium into the oceanic gyres

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Li et al. (1984) have calculated the vertical mixing coefficient K to be 1.7 ± 0.2 cm^2 s^{-1} from the global GEOSECS tritium data. However, this calculation contains assumptions about mixed layer depth and ventillation of the thermocline which may not be justified. All the values of K were calculated below a mixed layer depth of about 75 m; the deeper one makes the mixed layer, the smaller the calculated value of K below it, and vice versa.

The mixed layer is generally thought to be isothermal and due to surface processes such as heating, cooling and wind mixing. In the tropics and summer conditions in middle latitudes, the surface layer is highly stratified, shallow (about 25 m) and easy to define. The mixed layer deepens throughout the winter in middle latitudes and becomes difficult to define. It can go down to 800 m in places and various authors' attempts to record mixed layer depth are given in Woods (1984). During the summer, a new mixed layer is formed again on top of the deep winter penetration of tracers. Deep advection away from areas of active vertical mixing is probably an important ventillation process as well.

The deep winter mixing is usually attributed to downwelling from surface cooling. However, we suggest that baroclinic eddies, growing in the horizontal temperature gradients produced by the western boundary currents, dominate the vertical mixing in the gyres. This process is visible in the winter and masked in the summer by a shallow warm mixed layer at the surface.

Thus, to simply take an annual average of mixed layer depth must underestimate the volume of sea water in close chemical equilibrium with the atmosphere. In Li et al.'s data (1984) for tritium penetration into the north Atlantic there is clearly a shallow mixed layer at 75 m and a second deep mixed layer down to about 700 m. The authors are unable to account for the latter. In the north Pacific, there is a suggestion of a second mixed layer down to 300 m, consistent with a weaker gyre.

Let us make no assumptions about the mixed layer and take the cross-section for tritium in the western Atlantic GEOSECS cruise (Ostlund et al., 1974) (Fig. 1). The exponential penetration depth is 750 m (at 30° N) and 1.3 km at 50° N. Results from the southern hemisphere are sparse but an exponential penetration depth of 250 m at 30° S is suggested.

If we make the simplifying assumption that the main release of tritium was seven years prior to the GEOSECS cruise, then from classical diffusion theory:

$$\frac{Z^2}{4Kt} \simeq 1$$

where Z is the e^{-1} depth at time t with vertical diffusivity K. This yields for K:

30° N $K \simeq 5$ cm^2 s^{-1},
50° N $K \simeq 20$ cm^2 s^{-1},
30° S $K \simeq 0.5$ cm^2 s^{-1}.

The point of this simple calculation is to show the large spatial variability in K, which can be related

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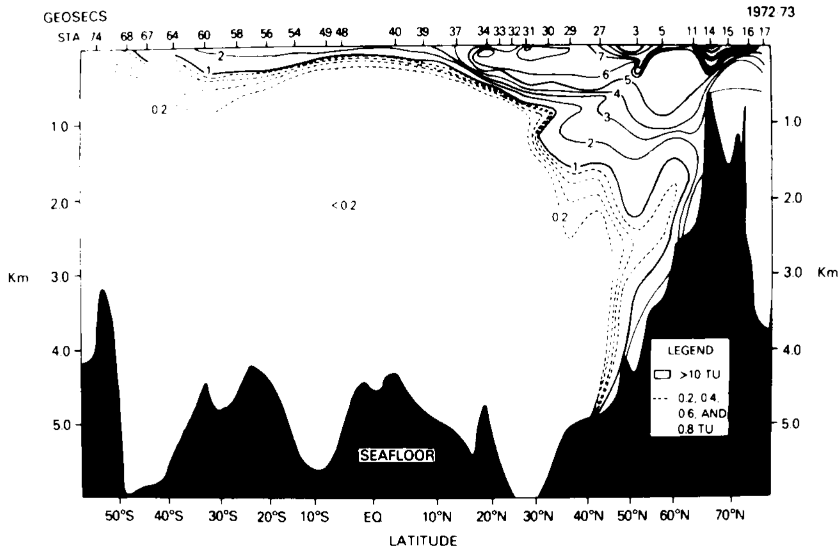

Fig. 1. Penetration of tritium into the western Atlantic, from GEOSECS data (Östlund et al., 1974).

to the dynamics of the gyre. It is well-known that tracers penetrate along isopycnal surfaces and we have proposed above that the mechanism which drives this transfer is baroclinic eddies.

Baroclinic eddies are not purely horizontal but are "tipped over" slightly so that parcels of cold, potentially dense water in the north are exchanged with warmer parcels to the south nearly along constant density surfaces. This process is known as slantwise convection (see Fig. 2). If there is sufficient knowledge of the mixing process, K can be represented by a typical vertical velocity multiplied by a vertical mixing length.

Fig. 3 (from Broecker and Peng, 1981) shows the density cross section for the same western Atlantic GEOSECS track and the $\sigma = 26.8$ surface slopes down about 600 m between 55° N and 30° N. An eddy has a typical transverse velocity of 10 cm s^{-1}. If we assume this velocity is actually directed along the isopycnal slope, this gives an estimate of 10^{-3} cm s^{-1} for the vertical velocity w, which is certainly not directly observable. The vertical velocity follows a wave-like pattern in the horizontal, so there is no net vertical mass flux.

The equivalent eddy diffusivity is given by

$$K = \overline{w^1 z^1} = 0.5\ (10^{-3}\ \text{cm s}^{-1} \times 600\ \text{m})$$
$$= 30\ \text{cm}^2\ \text{s}^{-1}.$$

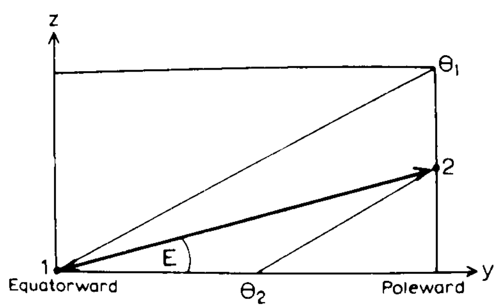

Fig. 2. Height-latitude cross section (in this case for the atmosphere) showing potential temperature increasing equatorward and upwards. Even though the system is stable for vertical convection, potential energy can be converted to kinetic energy if parcels of fluid are exchanged along the solid black arrow.

(The factor of 0.5 comes from averaging over a horizontal wavelength.)

Thus, we see quite good agreement between the values for the vertical eddy diffusivity at 50° N, calculated from independent data sets on the same cruise. The baroclinic calculation also implies a horizontal transfer coefficient. We have assumed that water in the deep thermocline is in direct contact with the atmosphere in regions of outcropping isotherms found in the gyres.

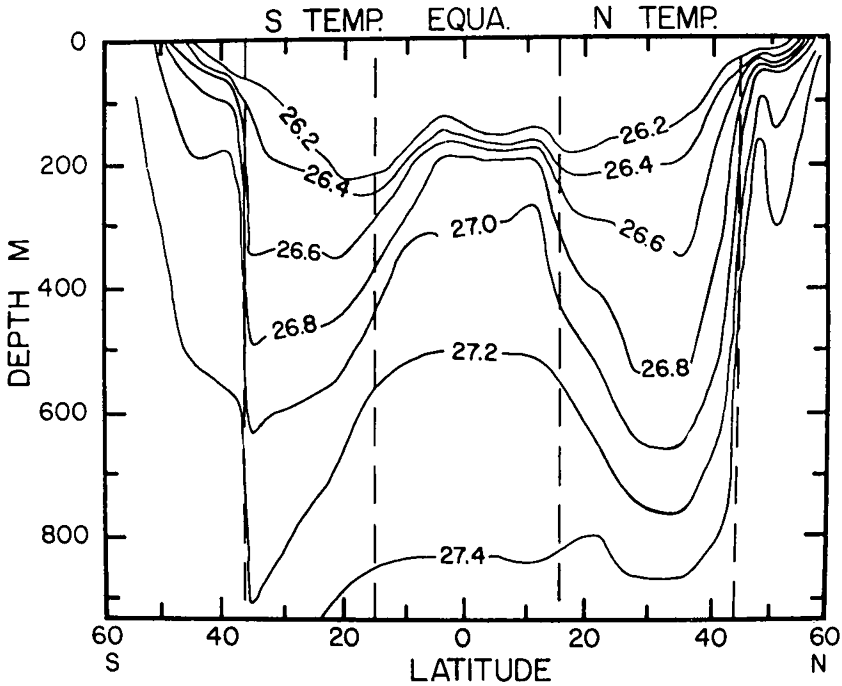

Fig. 3. Potential density cross-section for the western Atlantic GEOSECS track (Broecker and Peng, 1981)

Thus, we propose three mixing regimes for the Pacific and Atlantic Oceans in the northern hemisphere:

15° N–40° N	remnants of earlier convection or weak baroclinic eddies to the south of the gyre;
40° N–50° N	strong baroclinic eddies;
50° N–70° N	thermohaline circulation, due to cold water downwelling in the Norwegian Sea.

The tritium cross section obtained from the recent transient tracer experiment (Östlung, 1983) supports this hypothesis. The penetration of tritium directly into the gyre is not much deeper than in the GEOSECS data, consistent with eddies growing in the top kilometre of the western boundary current. However, the penetration of tritium into the polar sea is much deeper, with evidence of recirculation under the gulf stream (Jenkins and Rhines, 1980).

The oceans of the southern hemisphere provide an interesting challenge in this problem. The lack of gyres suggests weak penetration and shallow mixed layers. However, the circumpolar current is thought to be baroclinically unstable. This current is also cold, experiences high wind stress and is biologically very active; it could be providing the missing sink for anthropogenic CO_2. Li et al.'s data (1984) for the southern oceans do not immediately suggest this. However, observations were sparse and a zonal average at 45° S, rather than a latitudinal average, would be interesting to see.

Conclusion

This brief study shows why box models of the ocean, however refined, have not adequately modelled vertical transports. Insufficient attention has been paid to efficient middle latitude transfers by baroclinic eddies. This eddy mixing can be treated with a vertical mixing coefficient or, for time scales of over 10 years, by assuming a much deeper mixed layer. This is consistent with box model results of CO_2 uptake by the ocean, which require an "unrealistically deep" mixed layer (Bacastow and Björkström, 1981) to produce the observed airborne fraction of anthropogenic CO_2.

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