Rapid cross-density ocean mixing at mid depths in Drake Passage measured by a tracer release

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Diapycnal mixing (across density surfaces) is an important process in the global ocean overturning circulation [1-3]. However, mixing in the interior of most of the ocean is thought to be ten times weaker[4] than that required to close the global circulation by the downward mixing of buoyancy[1]. Some of this deficit is made up by intense near-bottom mixing occurring in restricted "hot spots" associated with rough ocean floor topography [5,6], but this leaves open the question of how the mid-depth waters, 1000-3000 m, are returned to the surface, whether by cross-density mixing or by along-density flows [7]. Here we show, using an open ocean tracer release, that diapycnal mixing of mid depth (~1500 m) waters undergoes a sustained 20-fold increase as the Antarctic circumpolar current (ACC) flows through Drake Passage. We ascribe this to turbulence generated by the deep-reaching ACC as it flows over rough bottom topography there. Scaled to the entire circumpolar current, the mixing we observe is compatible with a Southern Ocean upwelling ~20Sv, where cross-density mixing contributes a significant fraction, (20-30%) of this total. The great majority of the diapycnal flux is the result of interaction with restricted regions of rough bottom topography.

The tracer, 76 kg of trifluoro methyl sulphur pentafluoride (CF_3SF_5) [8], was released within +/- 3m depth of neutral density $\gamma_n = 27.906$ kg m^{-3} in February 2009, as part of the DIMES project ("Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean", see http://dimes.ucsd.edu). The release location (figure 1) was near 58°S, 107°W, about 2000 km upstream of Drake Passage in the ACC between the Subantarctic and Polar Fronts, and at a depth of about 1500 m [9], in the upper circumpolar deep water mass (UCDW). The vertical and horizontal dispersion of the tracer was measured one year later, in the region 57°-62°S and 105°- 85°W, between the release site and Drake Passage[9]. The vertical turbulent diffusivity integrated over that period was found to be 1.3 ± 0.2 x 10^{-5} m^2s^{-1}, which is typical for the interior of the ocean far from boundaries. It is smaller by a factor of 10 than the diffusivities ~10^{-4} m^2s^{-1} which on average would be required to close the abyssal overturning circulation by down-mixing of buoyancy alone[1,2]. `

From December 2010 to April 2011 two further surveys of the eastern part of the tracer patch were carried out as it flowed through Drake Passage, yielding five meridional sections through the patch (locations shown in Figure 1). Mean vertical profiles of the sections are shown in Figure 1, lower panel. The profiles are plotted against neutral density, and also mapped against a depth scale that represents the average γ_n vs depth profiles for the stations occupied in April 2011. The dotted line shows the "target" density on which the release was made.

The surveys can be used to constrain diapycnal diffusivities both in the Eastern Pacific and the Drake Passage sectors of the ACC. The growth in the second moments of the profiles in Figure 1 can be used to estimate diffusivity averaged over the period since release[4]. These estimates are given in Figure 2, with 95% confidence intervals found from the statistics of individual profiles (see figure legend, and supplementary information for details). The estimates obtained by averaging over the path from the release point to section E and F east of Drake Passage, are two to three times larger than those confined to the Pacific sector, indicating a large increase in the rate of cross-density mixing as the tracer is advected through Drake Passage. This is consistent with the idea that the rough bottom topography which dominates eastward of about 70°W greatly influences mixing rates. Since the tracer has resided in the high diffusivity region for only a comparatively short time (a conservative estimate would be a quarter of the total time since release, assuming no increase in eastward velocity in Drake Passage) the observed broadening of profiles implies that the tracer experiences a rate of diapycnal mixing about an order of magnitude greater in Drake Passage than in the eastern Pacific.

To obtain a more quantitative estimate of the mixing rate in Drake Passage, we solved the advection-diffusion equation for the tracer on a two-dimensional (longitude and depth) domain divided into two sub-regions, east and west of 67°W, this being approximately the longitude of the Phoenix Ridge, which marks the western extent of the seafloor mountains in Drake Passage. Vertical and horizontal diffusion and horizontal advection velocities in the two sub-regions were adjusted to give the best fits to the mean profiles B-F of Figure 2 (see supplementary information for full details). Uncertainties in the fitted parameters were estimated from the variation of the chi-square statistic in parameter space around its minimum value[10]. The best values estimated for the diapycnal diffusivity in Drake Passage and in the Eastern Pacific were respectively $(3.6 \pm 0.6) \times 10^{-4}$ $m^{-2}s^{-1}$ and $(1.78 \pm 0.06) \times 10^{-5}$ $m^{-2}s^{-1}$, where uncertainties are 2-σ. Our conclusion is that diapycnal diffusivity in the UCDW through Drake Passage, O(2km) above the bottom, averages ~20 times the values immediately to the west in the Pacific sector of the ACC. The measurements at the eastern exit of Drake Passage were made towards the leading edge of the tracer patch. This might introduce systematic errors, biasing the mixing rate low because vertical shear has narrowed the extent of the tracer distribution, or high if more rapidly advected tracer also experiences higher vertical diffusivity than average. We estimate that such systematic errors should be contained within confidence intervals broadened by a further factor of ~1.5.

Elevated cross-density mixing has been observed in the vicinity of mid ocean ridges[5,6], caused by breaking of internal waves generated by bottom currents interacting with the rough topography[6]. The view that substantial diapycnal mixing occurs in restricted areas by such interaction is now widely accepted. While the driver for near-bottom currents at the mid-ocean ridges is internal tides, recent work suggests that in the Southern Ocean the main source of mixing is the deep-reaching extension of the ACC and associated mesoscale eddies, which dominate bottom flow[11-14]. These can generate lee waves by interaction with bottom topography, which may subsequently break, producing turbulence[15]. Globally, it has been estimated that 0.2TW (~20% of the wind energy put into the surface ocean) may be dissipated by such interaction[16], much of it in the Southern Ocean[15]. The great majority of the energy goes into the layer within a kilometre of the bottom, and the diapycnal mixing induced there is likely to be of considerable importance in the modification of the deepest water masses. This forms the return path for the lower limb of the meridional overturning circulation, (MOC), supporting a flux ~10 Sv (1 Sv = 10^6 m^3s^{-1}) of Antarctic bottom water [16]. By contrast, the layer studied by the tracer release is 2-3 km from the bottom over most of the area, except in the restricted zones where it contacts the continental slope at the Northern limit of Drake Passage, or close to the peaks of the highest submarine mountains. Our measurements suggest that even these limited sources of high dissipation are sufficient to produce substantially elevated average mixing rates.

Profiles of turbulent dissipation made at the same time as tracer measurements during DIMES also show a substantial increase between the southeast Pacific and Drake Passage above the rough topography[17]. The rates of mixing we measured in the UCDW appear to scale, very approximately, with the input of power into lee wave radiation. Using the calculations of ref 13, we find that the energy density of lee wave generation in the ACC between the tracer release and our section D (Fig 1) averages 0.6 mW m^{-2}, whereas in Drake Passage between sections D and E/F it is ~20 mW m^{-2}, so a factor ~30 greater, comparable to the enhancement of 20-fold in diapycnal mixing rates. Applying the implied scaling factors to the average lee wave energy dissipation under the entire ACC (~3mW m^{-2}, again from ref 13) suggests diapycnal mixing of $(0.6 - 1) \times 10^{-4}\ m^2\ s^{-1}$ for the upper circumpolar deep water as a whole, concentrated over regions of rough topography such as Drake Passage, the Scotia Sea, Crozet-Kerguelen and the Southeast Indian Ridge. This mixing rate is in the range of values found by Zika et al [18] to be compatible with a Southern component meridional overturning of order 20Sv, given observed temperature and salinity distributions. We estimate (see supplementary information) that such a mixing rate will contribute about 3-6Sv to this overturning at the density level of deepest UCDW, where the tracer was released. Our measurements support the view therefore that ~20-30% of the Southern component of the overturning circulation at mid-depths is sustained by diapycnal processes, with the remainder being accomplished by isopycnal transport[19]. Virtually all of the diapycnal component is excited over the restricted regions of rough bottom topography below the ACC, by interaction of the deep-reaching current with the sea floor.

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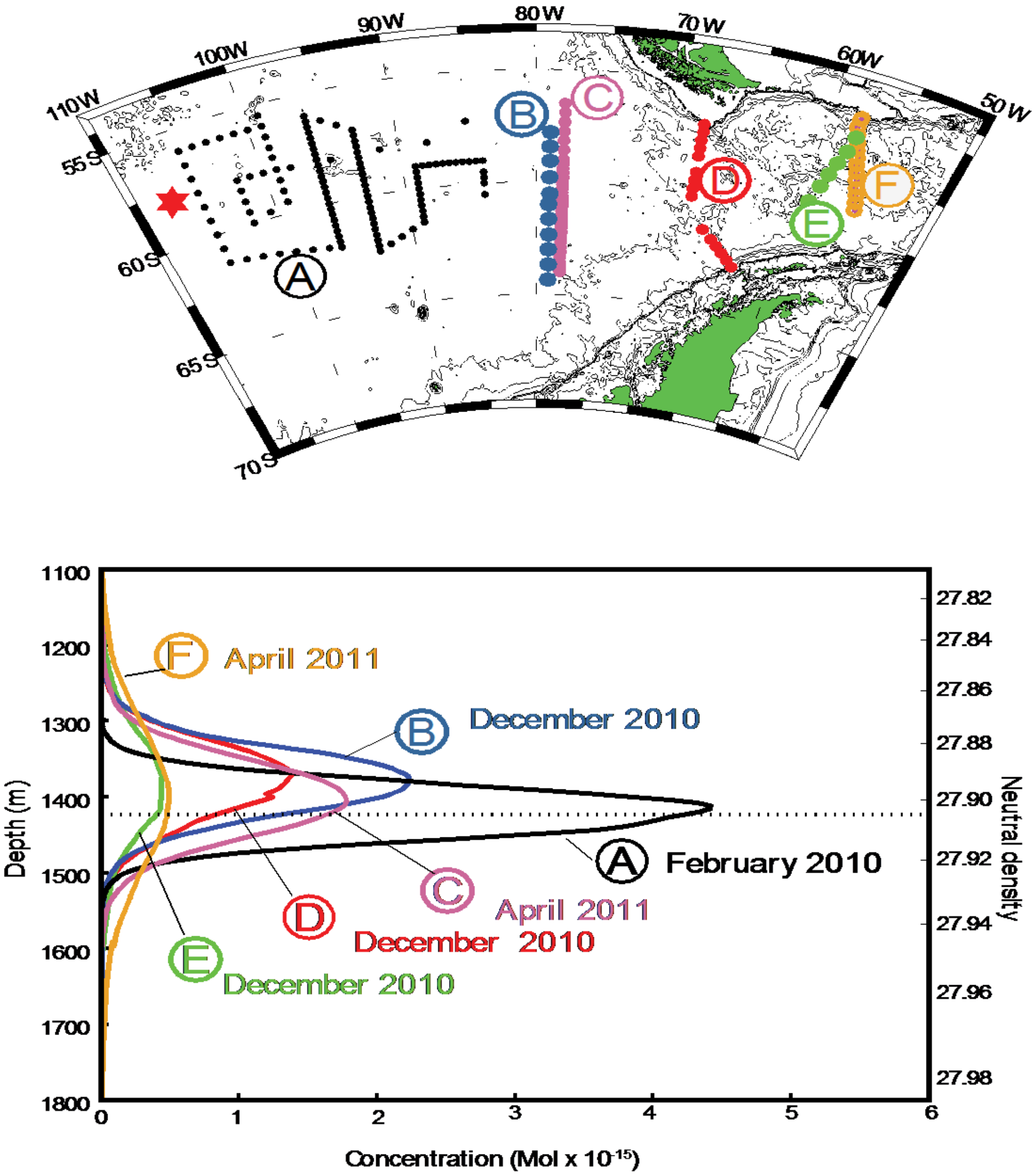

Figure 1: Upper panel: location of the tracer release in February 2009 (red star) and of subsequent measurements and surveys: A: East Pacific survey, 1 year after release, B and C: Sections near 78W, at 1.9 years and 2.2 years after release, D: Section at western entrance to Drake Passage, 1.9 years after release, E and F: Sections at eastern exit of Drake Passage, 1.9 and 2.2 years after release.

Lower Panel, mean profiles obtained from each of these locations. These are plotted in neutral density space (right hand axis) which is also translated into a depth scale (left hand axis) using a mean density versus depth profile appropriate to Drake Passage (the mean of sections C and F).

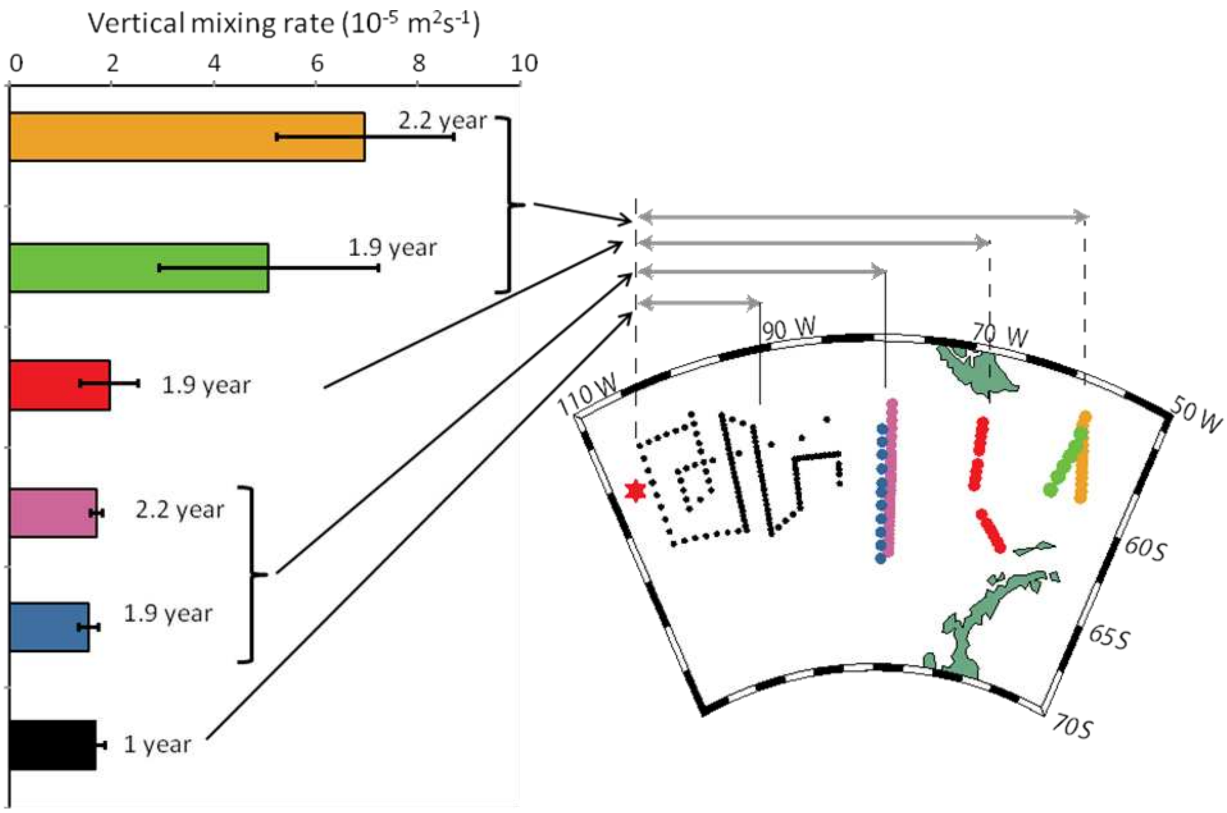

Figure 2: Mean diapycnal diffusivitiess from the point of release calculated from the second moments of the mean profiles in Figure 1. These are averages over the times since release, and spatial extents indicated by the grey arrows above the inset. The approximately threefold increase in the mean when averaged over a path including Drake Passage indicates diffusivities increase by at least an order of magnitude east of 70°W compared to west of it. Note that the water column in Drake Passage is less stratified than in the Eastern Pacific, so the tracer distribution on survey A in figure 1 occupies a wider depth span when mapped Drake Passage depth-vs –density profile, than used in the calculations of Ledwell et al[5]. Correspondingly the diffusivity shown here for the Pacific sector after 1 year is ~25% larger than that quoted by them. Error bars show 95% confidence limits, calculated from the statistics of individual profiles (see supplementary information for details).

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