

The Diapycnal and Isopycnal Mixing Experiment: A First Assessment

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The Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean (DIMES) was designed as a multi-pronged US and UK CLIVAR effort to measure and to better understand diapycnal mixing and along-isopycnal eddy transport in the Antarctic Circumpolar Current (ACC), because these processes together appear to play a key role in the Meridional Overturning Circulation (MOC) (Gille et al., 2007). The project represents an unusual effort to evaluate simultaneously the roles of diapycnal and isopycnal mixing, and the program has benefited from close collaboration between observationalists, theoreticians and modelers. Fieldwork for DIMES began in early 2009, and the initial phase of the field observations is now

wrapping up. This article provides a brief preliminary summary of early DIMES findings.

The DIMES field program was centered around the 2009 release of 76 kg of trifluoromethyl sulfur pentafluoride, CF₃SF₅, in the ACC near 105°W (yellow star in Figure 1) between the Subantarctic Front (SAF) and the Polar Front (PF). Starting in 2010, the tracer concentration has been measured at regular intervals in order to evaluate the displacement and vertical diffusion of the tracer throughout the southeastern Pacific and the Scotia Sea. Microstructure measurements have been collected at the same time to provide a direct measurement of the small-scale turbulence that controls tracer diffusion. Over 200 RAFOS floats were also released, starting with 75 floats near 105°W in 2009 and 105 floats at about the same location in 2010 (blue dots). Sound sources (cyan dots) were deployed throughout the southeastern Pacific and the Scotia Sea to track the floats. In late 2009 a mooring array was deployed east of Drake Passage to study energy transfer from the mesoscale through the internal wave field to mixing (blue star).

The experiment was planned so that the tracer and floats would first pass through the region of relatively smooth topography and low eddy energy of the eastern Pacific, and then through the region of relatively rough topography and high eddy energy in Drake Passage. Results available now include tracer survey data and microstructure measurements from the initial 2010 and 2011 surveys and trajectories from 44 of the RAFOS floats, along with independent ancillary data, including numerical simulations, Argo floats, surface drifters, and altimetry.

The tracer was released approximately 1500m deep on the $\gamma_n = 27.9 \text{ kg m}^{-3}$ neutral density surface, near the transition between Lower Circumpolar Deep Water and Upper Circumpolar Deep Water. These waters rise to the south to feed Antarctic Bottom Water that descends and spreads over the abyss in the “Lower Limb” of the MOC as well as Antarctic Intermediate Water and Subantarctic Mode Water that are driven north near the surface by the winds in the “Upper Limb”. Eddy fluxes play a dominant role in cross-ACC transport of mass and properties in the waters above topography, i.e. above ~1500m. Diapycnal mixing is needed to transform abyssal water to deep water, closing the “Lower Limb”. The degree to which diapycnal mixing modifies density in the upper waters, and thereby short-circuits the “Upper Limb” is an outstanding question. Observing diapycnal mixing throughout the water column, over both rough and smooth topography underlying the ACC, is one of the main objectives of DIMES.

Ledwell et al. (2011) reported on the initial assessment of vertical diffusivity obtained from the first year’s tracer survey and microstructure measurements. Their measurements indicated weak mixing in the ocean interior upstream of Drake Passage, with the tracer indicating averaged diffusivities of $(1.3 \pm 0.2) \times 10^{-5} \text{ m}^2 \text{ s}^{-2}$, and microstructure profiles implying a diffusivity about half that size at $(0.75 \pm 0.2) \times 10^{-5} \text{ m}^2 \text{ s}^{-2}$. Measurements with profiling velocity-shear Argo floats – the Electromagnetic-Autonomous Profiling Explorer (EM-APEX) floats – indicate a peak in shear variance in June which may explain the difference between the tracer diffusivity, which

integrates over a year of mixing, and diffusivities K_p estimated from energy dissipation rates, which were measured in February/March 2010. From these results Ledwell et al. (2011) inferred that despite strong wind conditions that are common in the Southern Ocean, wind does not generate elevated internal wave activity to drive extra turbulent mixing in the mid-depth ocean. Levels of diapycnal mixing in the Southern Ocean, in the absence of strong bathymetry, appear to be similar to background levels in other areas of the ocean.

More detailed tracer surveys of the topographically rough Drake Passage region in 2011 indicate that the diapycnal spreading of the tracer was much greater to the east of Drake Passage than to the west (St. Laurent et al., 2012). Figure 2 shows mean vertical profiles of the tracer along two different meridional lines. S3 is located to the west of Drake Passage around 78°W, and SR1 is to the east of Drake Passage between 55°W and 60°W. The difference in the width gives a diapycnal diffusivity for the tracer of $\sim 6 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$, based on a preliminary estimate of the mean velocity of the tracer between the sections. With account taken of the weaker stratification in the east than in the west, the diffusivity is around 30 times larger in Drake Passage than in the eastern Pacific.

Microstructure measurements are consistent with the tracer findings and provide evidence of the vertical variations in diapycnal diffusivity. In Drake Passage, measurements were collected in early 2010 along the rough topography of Phoenix Ridge (approximately 65°W). At the tracer level, on the $\gamma_n = 27.9 \text{ kg m}^{-3}$ neutral density surface the mean diffusivity K_p was found to be more than an order of magnitude greater than that found from dissipation rates in the eastern Pacific. Microstructure measurements have typically shown diffusivities of order $10^{-3} \text{ m}^2 \text{ s}^{-1}$ within 1000 m of the bottom. To the west of Phoenix Ridge, microstructure stations occupied in December 2010 over smoother topography indicated an intermediate diffusivity, with a mean value of K_p at the surface $\gamma_n = 27.9 \text{ kg m}^{-3}$ about 3 times greater than in the eastern Pacific (St. Laurent et al., 2012).

The preliminary float data (Figure 3) indicate that the large scale Lagrangian flow on the $\gamma_n = 27.9 \text{ kg m}^{-3}$ surface closely mirrors geostrophic contours implied by satellite altimetry measurements (not shown). Similarly, Argo temperature and salinity profiles also indicate that subsurface anomalies correlate well with eddy variability at the surface from altimetry. Argo-based TS correlations are strongest at mid-depth, since the upper ocean temperature structure is strongly influenced by transient air-sea exchanges. These findings suggest that eddy variability measured by altimetry can serve as a proxy for subsurface eddy variability, thus providing a means to enhance the analysis of the float observations. Independent observations are also critical for identifying the background mean state, in order to evaluate the dispersion.

At the same time, assessments of artificial “floats” deployed in numerical models have indicated that traditional particle dispersion methods used to infer Lagrangian diffusivities agree with Eulerian diffusivities. Isopycnal diffusivities derived from numerical model output typically range between 200 and 1500

$\text{m}^2 \text{ s}^{-1}$. However, statistics based on Lagrangian methods are slow to converge, requiring many hundreds or thousands of particles to reduce error bars (Griesel et al., 2009; Klocker et al., 2012a; Sallée et al., 2012), and they can be biased. This has introduced a new challenge to identify the most robust measures of diffusivities. Both Lyapunov-exponent based methods and Nakamura (1996) diffusivities are being explored using model output and the new observations.

Theory predicts low diffusivities near the surface and high diffusivities at a subsurface critical depth below the core of the ACC, where the eastward ACC velocity approximately balances the westward Rossby wave phase speed. This works well for an equivalent barotropic system, with sufficient information (Klocker et al., 2012b). However, results may prove more difficult to interpret in systems with realistic bathymetry and additional forcing mechanisms (Griesel et al., 2009; Sallée et al., 2012). The DIMES float program, in combination with a variety of ocean models, will provide data to help assess these processes.

In summary, the first DIMES data to emerge indicate low diapycnal diffusivities in the eastern Pacific and elevated diapycnal diffusivities in Drake Passage. Efforts to understand the mechanisms driving the diapycnal mixing, to extrapolate the results to the whole ACC, and to assess implications for the overturning circulation are underway. Float data are providing constraints on along-isopycnal diffusivities in the region; formal uncertainties are expected to be large, given the slow convergence of dispersion statistics. Thus, satellite remote sensing and model output, together with other ancillary data will be critical for evaluating the strength and impact of along-isopycnal diffusion.

The DIMES program continues. Additional DIMES floats are now arriving at the surface, and these will allow a more complete effort to analyze dispersion on isopycnal surfaces. The in situ measurement program for tracer and microstructure will continue into 2014 with additional ship time scheduled primarily aboard the British Antarctic Survey research vessel RRS James Clark Ross, in order to track the tracer all the way through the topographically-complex Scotia Sea and into the Atlantic Ocean. Further information about DIMES is available from <http://dimes.ucsd.edu>.

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Fig 1: Schematic diagram showing location and timeline for the DIMES field program. Tracer and floats were initially released in early 2009 at 105°W. Subsequent float releases were also concentrated at 105°W, and tracer and microstructure surveys have progressively moved downstream as the tracer has been advected by the Antarctic Circumpolar Current.

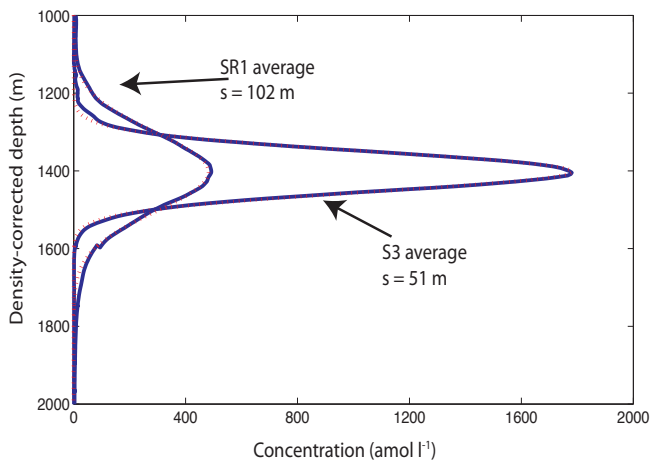
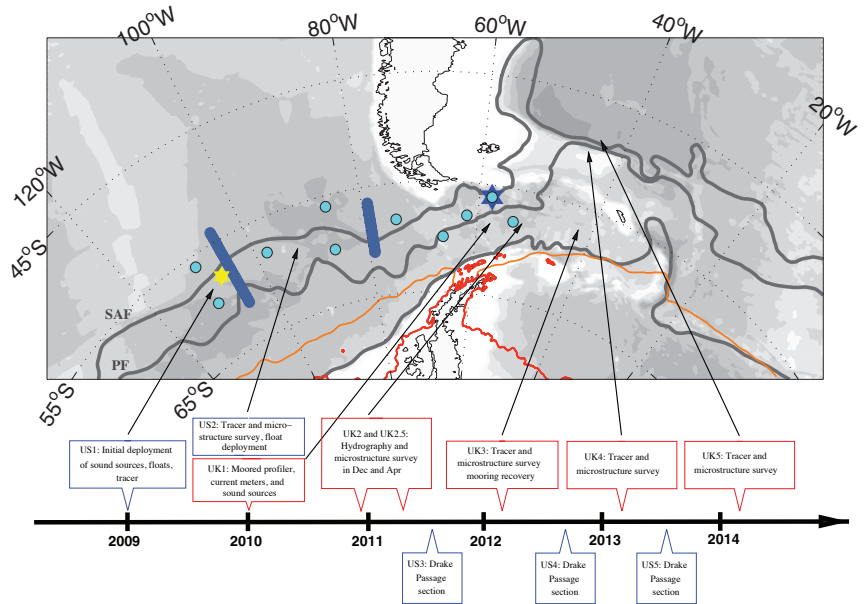


Fig 2. Mean vertical profiles of tracer (blue lines) from west of Drake Passage (S3) and east of Drake Passage (SR1), with Gaussian fits to the curves (red dotted lines). Both profiles were obtained in April 2011, 26 months after tracer release. The depth is from the mean depth/density relation for April 2011.

Fig 3. Preliminary two-year float trajectories from the first 44 DIMES RAFOS floats show that a few floats were advected rapidly downstream by the ACC, while many of the floats circulated around the basin upstream of Drake Passage.

