Summary

The overturning circulation of the ocean plays a governing role in the earth's climate because of the enormous capacity of the ocean to hold heat and carbon dioxide. The Southern Ocean, which surrounds Antarctica, plays a disproportionate role in this overturning circulation because this is one of the main areas where deep waters rise to the surface to exchange heat and carbon dioxide with the atmosphere. Although the Antarctic Circumpolar Current (ACC) system brings deep water to the surface, dynamical constraints inhibit meridional exchanges. Ocean eddies are believed to play a dominant role in transporting water south across the ACC above deep ridges, feeding water driven northward by the intense winds. The extent to which this isopycnal circulation is "short-circuited" by mixing across density layers is important to climate models but is unknown.

Intellectual Merit: Conceptual models of global meridional overturning and numerical predictions for future climate are strongly sensitive to the methods used to represent mixing along and across the Antarctic Circumpolar Current (ACC), where isopycnals are steeply tilted. Neither diapycnal nor isopycnal mixing has been measured in the Southern Ocean in a systematic way. The goals of the Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean (DIMES) are to measure eddy mixing along density surfaces in the subsurface ocean (isopycnal mixing), and across those density layers (diapycnal mixing), and to determine how those processes depend on the larger scale dynamics of the ocean, so that they can be properly represented in numerical models of ocean circulation and of climate.

To reveal these processes at work in the ACC, a chemical tracer and 75 floats that follow the water along isopycnal surfaces will be released in the ACC near 1300 m depth, 60 S, and 110 W, early in 2008. Floats that measure fine-structure T, S, and velocity within and above the tracer cloud will be released at the same time. The floats and tracer will be carried by the ACC over the relatively smooth bottom of the SE Pacific, spreading both across and along the current as they travel. After a year, the leading edge of the tracer will just start to pass over the ridges of Drake Passage into the Scotia Sea. Another 75 isopycnal floats will be released near the center of the tracer patch at this time. Trajectories of the floats, measured acoustically with an array of sound sources, will be used to study and to measure isopycnal dispersion. Spreading of the tracer will give integrated measures of both isopycnal and diapycnal dispersion. The eddy field, and its vertical structure, will be studied with sea surface height measured by satellite altimeters, and with hydrographic profiles taken from research vessels and from autonomous instruments drifting with the tracer. Turbulent dissipation, from which diapycnal mixing can be estimated, will be measured with ship-based free-falling profilers to study the spatial and temporal scales of the mixing and to examine suspected hot spots of mixing. Shear driving this mixing will be measured with the free-falling profilers and with special floats drifting with the tracer and floats that profile between the surface and the tracer layer.

Broader Impact: DIMES will deploy a variety of instruments including microstrucutre and fine-structure profilers and and isopycnal-following autonomous floats, some for the first time in Southern Ocean. Ultimately DIMES mixing results will be made available to aid in improving representations of mixing in climate models. In addition, profiling DIMES floats will augment the Argo database for the Southern Ocean. The project will involve a postdoctoral investigator, graduate students at FSU and SIO and will offer research opportunities to one to two undergraduates per year.

C.1 Results from Prior NSF Support

OCE-0350743, $702,711, 5/15/04-4/30/06, A Salt Finger Tracer Release Experiment – Analysis, J. Ledwell, R. Schmitt, J. Toole. The diapycnal diffusivity of a tracer was compared with the diffusivities of heat and salt estimated from dissipation rates and salt finger phenomenology in the salt finger staircase east of Barbados. The diffusivity of the tracer, and presumably salt, were twice as great as that of heat, and both were an order of magnitude larger than would be driven by the turbulence generated by the ambient shear levels [Schmitt et al., 2005]. Analysis of the full experiment continues, with additional publications in the works.

OCE-9985203/OCE-0049066, $472,046, 4/1/00-3/31/06 CAREER: Linking Southern Ocean Dynamics to Global Climate, S. Gille. Southern Ocean autonomous float data have been analyzed and compared to historic hydrography. Major findings have shown that float temperatures from 1000 m to the surface are systematically warmer than older hydrographic temperatures, implying that the Southern Ocean has warmed by at least 0.01$\circ$C/year since the 1950s [Gille, 2002]. Eddy heat fluxes and topographic steering have also been explored [Gille, 2003a,b].

OCE-9986700, $226,485, 3/1/00-2/28/04, Diffusion Studies in Guiana Abyssal Water Masses using Velocity Finestructure Measurements and Float Trajectories, T. F. Duda. Shearmeter-type RAFOS floats were deployed in Feb. 2001 east of Barbados in conjunction with the Guiana Abyssal Gyre Experiment (GAGE) [Duda 2006]. Time-series of hourly shear yielded estimates of the diapycnal eddy diffusivity at heights of 3200 to 1500 m above bottom, based on the parameterization proposed by Gregg [1989] and Polzin et al. [1995].

OCE-0516870, $170,241, 2/01/2005-1/31/2007, Finestructure Profiling Floats in Support of Summer 2005 EDDIES Tracer Release Experiment, J. Girton and T. Sanford. Four EM-APEX floats measuring velocity and CTD finestructure were deployed along with a patch of SF_6 tracer in a Sargasso Sea mode water eddy to investigate mixing at the base of the euphotic zone. In total, 812 round trip profiles were made to 200 m over the course of 49 days. Enhanced shear from inertial motions generated by the passage of 3 tropical storms was a significant feature of the record. Initial results, including the comparison of shear parameterization-based dissipation estimates with the tracer spreading will be presented at the 2006 AGU Ocean Sciences meeting (Girton and Sanford 2006).

OCE0117618; $414,234; 10/1/01-8/31/05, Southern Ocean Transport, K. Speer and R. Lumpkin. This grant has supported the development of a global box inverse model, including all major oceans and marginal seas. It is designed to resolve circulation in coarse sectors of the Antarctic Zone, distinguishing convection regions near the Antarctic continent, especially to address the connections between the upper and deep cells of meridional circulation around Antarctica. The role of the Ekman transport and eddy fluxes in the meridional exchanges are considered [Lumpkin and Speer (in revision); Sallee et al., 2005].

OCE-0137122; $828,583, 4/1/2002-3/31/06, Collaborative Research for WOCE-AIMS: Global Velocity Estimation Project,W. Brechner Owens and Steven Jayne. An extended version of Optimal Estimation has been developed [Cornuelle, et al., (in prep.)] and applied to the North Atlantic Ocean [Jayne, et al., (in prep.)] and the Equatorial Pacific to estimate the mean geostrophic and ageostrophic velocity and dynamic pressure fields.

C.2 Introduction

The goal of the Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean (DIMES), a joint project between the United States and the United Kingdom, is to develop better understanding of mixing in the Antarctic Circumpolar Current (ACC). Mixing appears critical to the dynamics of the global meridional overturning circulation (MOC). In the Southern Ocean, deep and intermediate waters are hypothesized to move south and upwell in two cells, an upper cell and a lower cell, as shown schematically in Fig. 1. At the surface in the upper cell, water masses are carried by the wind to the north and transformed into Subantarctic Mode Waters, which in turn downwell, and spread to temperate latitudes. In the lower cell, water upwells near the continent and mixes into the dense plumes that eventually produce Antarctic Bottom Water. Since the primary current of the Southern Ocean, the ACC, is zonally connected above mid-depth bathymetric obstructions, the zonally integrated meridional geostrophic current must vanish above those obstacles. The dominant mechanism for the meridional transport of mass, heat, and potential vorticity above the bounding topography and below the wind-driven Ekman layer at the latitude band of Drake Passage is thus believed to be quasi-geostrophic, mesoscale eddy motions and standing waves [Johnson and Bryden, 1989; Marshall et al., 1993; Speer et al., 2000; Bryden and Cunningham, 2003; Marshall and Radko, 2003]. At the same time, theoretical studies indicate that isopycnal and diapycnal processes are closely linked through the buoyancy budget [Garrett et al., 1995; Tandon and Garrett, 1997; Speer et al., 2000]. We propose to measure the turbulent diffusion component of transport along and across isopycnal surfaces in the ACC in the southeast Pacific, where the bottom is relatively smooth and the eddy energy relatively low, and in the Drake Passage and Scotia Sea, where the bottom is very rough and the eddy energy high. With this information we will infer the regional strength and nature of the MOC, calibrate models of the whole ACC, and improve the representation of climate anomaly transport in coarse-resolution models of ocean circulation.

Much recent effort has gone into quantifying mesoscale subduction and upwelling near Southern Ocean fronts, but these have been focused on the near surface waters [e.g., Boyd et al., 2000; Naveira Garabato et al., 2001; Barth et al., 2001]. A new field program, led by L. Talley, is taking place at present to observe the processes forming deep mixed layers directly north of the Sub Antarctic Front in the southeast Pacific, an area that is included in DIMES. This study complements DIMES in that it is focused on the upper and northern part of the upper cell (Fig. 1), while DIMES is focused on the deeper part. Winter and summer hydrographic, XBT, and ADCP surveys obtained during this program will aid the planning and interpretation of our experiment.

The Southern Ocean component of the MOC is particularly relevant for climate, because the Southern Ocean has been identified as a likely region of rapid climate change both in observations [Gille, 2002] and in model predictions of anthropogenic climate change [Banks and Wood, 2002]. In addition, the Southern Ocean has been implicated as the major region for global ocean uptake of excess CO_2 generated by the burning of fossil fuels and by net global deforestation [Caldeira and Duffy, 2000], and has been shown to play a pivotal role in driving glacial – interglacial atmospheric CO_2 change [Watson and Naveira Garabato, 2005]. In climate-scale ocean models, the structure and size of the Southern Ocean limb of the MOC depend crucially on the representation of subgrid-scale mixing processes [e.g., Danabasoglu et al., 1994], but no dedicated field program has attempted to measure interior isopycnal or diapycnal mixing in the Southern Ocean in order to identify physically realistic parameterizations for these mixing processes.

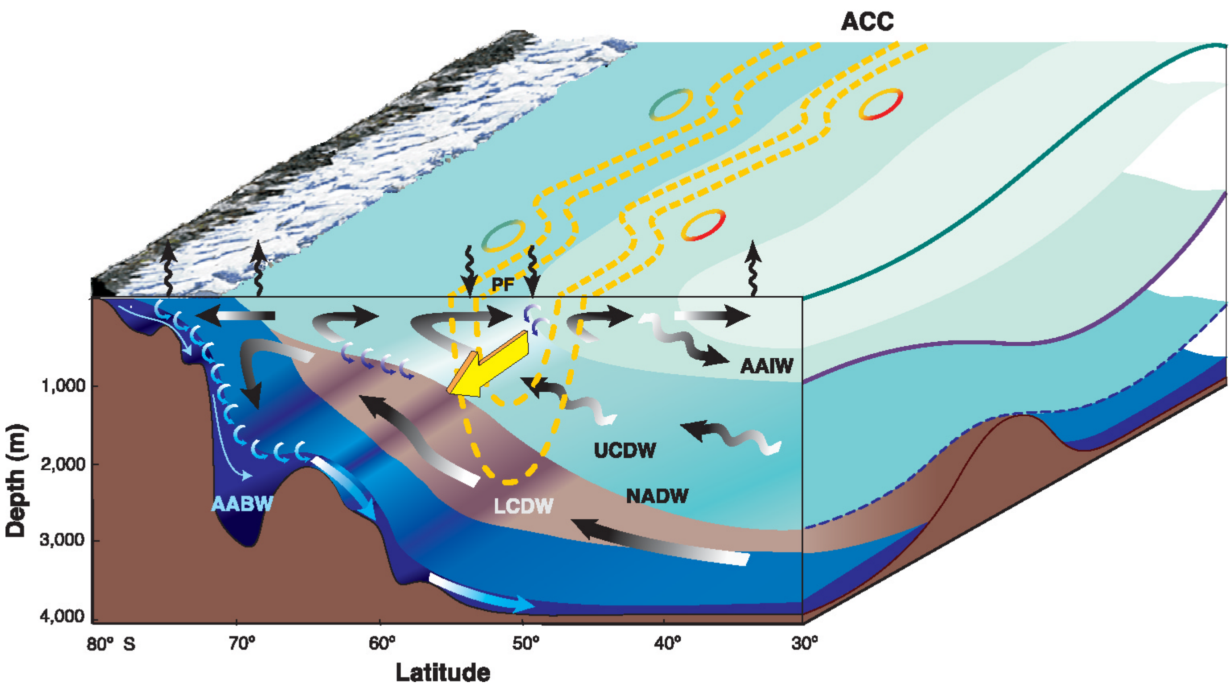


Figure 1: Schematic of the Southern Ocean MOC including the wind-driven Ekman transport, deep and bottom water flow supported by topography, and eddy-driven mass fluxes at mid-depth, adapted from Speer et al., [2000].

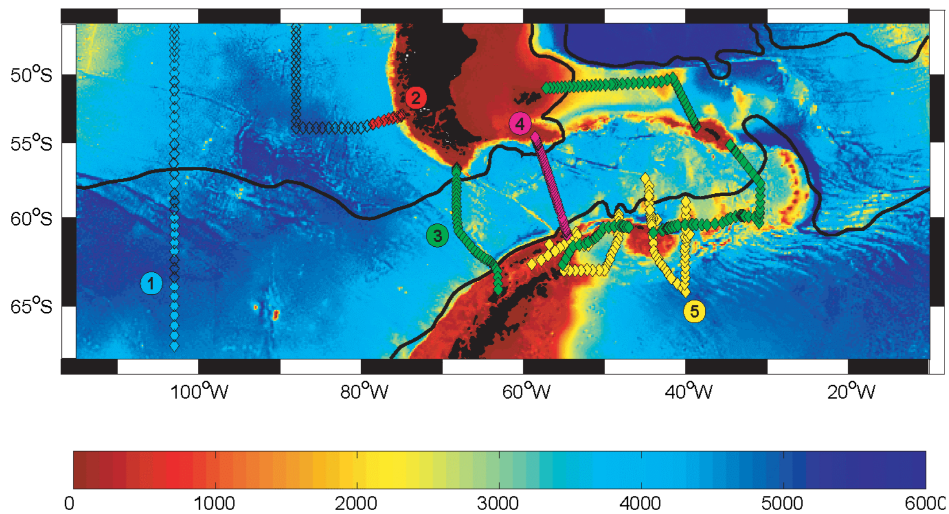
C.3 Scientific Background

C.3.1 Diapycnal Mixing

One extreme hypothesis for diapycnal mixing in the interior of the ocean is that it is insignificant so that virtually all diabatic processes occur in the surface layer, driven directly by air sea fluxes of heat, fresh water and momentum, and during entrainment into the plumes of deep water during their journey from the surface to the bottom past various density levels. Plausible models of the ocean circulation have been constructed with this scenario [Toggweiler and Samuels1998; Webb and Suginohara, 2001]. In support of this extreme are estimates that the diapycnal diffusivity at mid depth in much of the open ocean is on the order of 5 x 10^{-6} m^2/s, from the measurements of turbulent dissipation rates [Gregg, 1989; Toole et al., 1994; Polzin et al., 1995; Polzin et al., 1997; Ledwell et al., 2000]. It is possible that mixing is enhanced sufficiently near the boundaries of the ocean, especially for the abyssal water [e.g., Pozin et al., 1997; Ledwell et al., 2000], but existing evidence from most of the ocean that this is an important effect for mid-depth waters is unconvincing. At the other extreme, it has often been posited that diapycnal mixing below the surface layer of the ocean governs the MOC [Stommel and Arons, 1960;

Munk, 1966; Stern, 1975; Munk and Wunsch, 1998]. In support of this extreme, inverse models incorporating much of the currently available observations infer diapycnal diffusivities of 10^{-4} to 10^{-3} m^2/s, which indeed are large enough to impact the MOC [Ganachaud and Wunsch, 2000; Sloyan and Rintoul, 2000]. One goal of DIMES is to test the null hypothesis: that there is insufficient mixing at mid depth in the Southern Ocean, where mixing ought to be enhanced over most places in the ocean, to affect the global MOC significantly.

A "no mixing" hypothesis also prevails more locally for the ACC, in that some workers have speculated that sub-surface diapycnal mixing in the upper cell of the Southern Ocean MOC is negligible, and that diabatic transformations are confined to the surface layer [e.g. Treguier et al., 1997; Karsten and Marshall, 2002; Bryden and Cunningham, 2003]. Some doubt about this view is cast by shear measurements with Lowered Acoustic Doppler Current Profilers (LADCP) that suggest that diapycnal mixing is large in topographically rough areas, such as the Kerguelan Plateau [Polzin and Firing, 1997], and Drake Passage and the Scotia Sea [Naveira Garabato et al., 2004]. The latter authors measured shear in austral summer from measurements over an



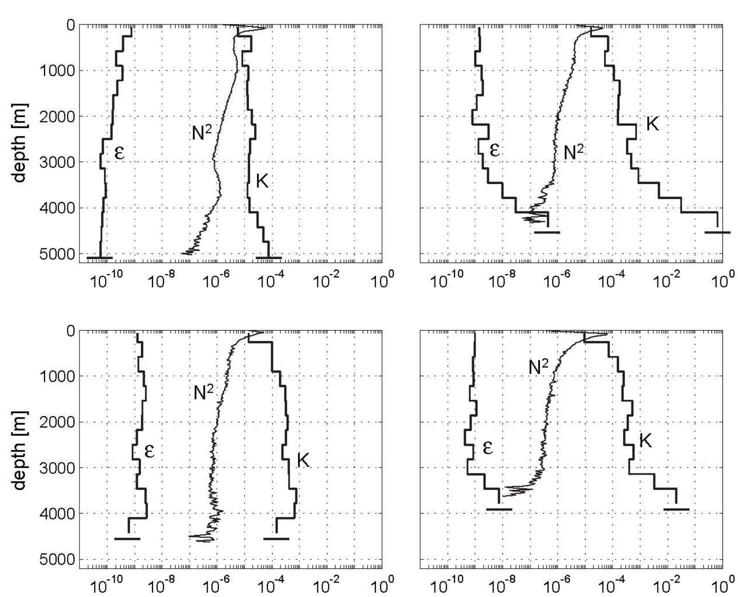


Fig 2. Top panel: Bathymetry of the Southern Ocean with the station positions of CTD/LADCP casts used by Naveira Garabato et al. [2004]. The black lines mark the meridional boundaries of the ACC from Orsi et al., [1995]. Lower panels: Profiles of mean buoyancy frequency (N^2) and inferred turbulent dissipation rate (ε) and diapycnal diffusivity (K) from Naveira Garabato et al. [2004]: Upper left: from stations in regions 1 and 2; upper right: from section 3; lower left: from section 4; lower right: from the section south of South Georgia Island.

extensive cruise track (Fig. 2). Diffusivities inferred from the shear were relatively small in the SE South Pacific, where the bathymetry is relatively smooth (Fig 2, middle left panel), while they were greater than 10^{-4} m^2s^{-1} at mid-depth, and increased by more than 2 orders of magnitude near the bottom in Drake Passage and the Scotia Sea (Fig. 2, panels on right), particularly towards the south. Regions of very intense finescale shears and strains were also observed near the ridge systems forming the boundary of the Scotia Sea.

Given the limited data base available to these investigators, use of a finescale parameterization scheme for the turbulent dissipation not yet validated in the ACC, and LADCP shear estimates possibly contaminated by noise at higher vertical wavenumbers (E. Kunze, personal communication), one may question the accuracy of these estimates, as well as how representative they are of the spatial or temporal mean for the areas in question. Note, for example, that only a handful of profiles from the ACC in the SE Pacific were available from just one synoptic section. It is possible that intense winter wind forcing greatly enhances internal wave energies and, in turn, the frequency of wave breaking and intensity of turbulent mixing. Hints of seasonal modulation of diapycnal mixing were reported by Thompson et al. [2006] in northern Drake Passage based on overturn statistics, in spite of the only modest input of wind energy to mixed layer inertial motions in the Southern Ocean estimated by Alford [2003].

Barotropic tidal and low-frequency flows over rough bathymetry are another potential energy source for finescale motions and diapycnal mixing in the Southern Ocean, which vary strongly in space and time. Han et al. [2005], analyzing satellite gravity data, report locally-enhanced semidiurnal tidal energy in the SE Pacific and Drake Passage, though the most extreme energies were observed within the Weddell Sea. Simmons et al.'s [2004] modeling study found significant scattering of semidiurnal tidal energy into baroclinic modes within Drake Passage and the Scotia Sea. Polzin [2004a,b] and MacKinnon and Winters (submitted) have explored how bottom-generated high-mode waves might propagate up into the overlying water column, interact with themselves and the background mesoscale flow field, break and support interior mixing.

In summary, there are a few rather indirect, but tantalizing, estimates of diapycnal diffusivities based on observations, and a number of reasons to expect high diffusivities over rough topography and during the stormier seasons in the ACC. DIMES aims to provide much more direct estimates of diapycnal diffusivity in the ACC with a set of measurements which together cover all seasons, all depths, and about 80 degrees of longitude.

C.3.2 Isopycnal Mixing

Temperature (heat), salinity, potential vorticity, and chemical anomalies (e.g. carbon dioxide perturbations) are exchanged between the ocean and the atmosphere in the upper cell as deep water upwells mainly along isopycnals to the surface layer, is modified, and then subducts. These flows are predominantly driven by Ekman transport and quasi-geostrophic eddies and are especially strong and important in the Southern Ocean, because of its large area, strong winds, and low temperatures. The response and feedback of the ocean to atmospheric forcing, and in particular, *which* water mass upwells, and where, depends on eddy processes [e.g. Hallberg and

Gnanadesikan, 2005]. Eddy fluxes are particularly important in the region of the Antarctic Circumpolar Current (ACC) because they represent the only mechanism that can transport properties meridionally above the topography and below the wind driven Ekman layer within the latitude band of Drake Passage.

Numerical models of the coupled ocean-atmosphere system are still either too coarse or too expensive to run long enough or for enough different cases to understand the effect of isopycnal eddy transport and diapycnal diffusion on climate, although progress is being made. However, recent modeling [Hallberg and Gnanadesikan, 2005; Lee and Coward, 2002] and theory [e.g. Karsten et al., 2003; Olbers, 2004] both indicate that these processes are of first order importance. For example, with no eddy fluxes and no diapycnal mixing the Ekman flow of over 20 Sv (1 Sv = 10^6 m^3/s) in the ACC must be returned to the south as very dense deep water below the topography across the latitude of Drake Passage [Warren et al., 1996; Gnanadesikan and Hallberg, 2000]. Isopycnal eddy transport changes substantially the circulation pattern in the upper ocean from that dictated by the Ekman transport and geostrophic return flow alone, by driving an upper circulation cell (Fig. 1; also Karsten and Marshall, [2002]).

Climate models are sensitive to the way in which eddy fluxes are parameterized. Different choices will lead to different circulation cells, meridional exchange, and stratification [e.g. Speer, et al., 2000]. Using large scale observations to test these parameterizations is problematic since sampling requirements are extreme. Grid-based tracer inversions [McKeague et al., 2005] are promising but require numerous assumptions. Eulerian measurements from moorings give valuable insight into the eddy fluxes and their vertical structure; however, these fluxes are in principal nonlocal and Lagrangian measures are required to understand their net effect on tracer transport. Several approaches have been used to estimate eddy fluxes or their net effect in the Southern Ocean, using altimetry, numerical tracer studies, and surface drifters. Keffer and Holloway [1988] used geostrophic streamfunction amplitudes to scale eddy diffusion, and made estimates from altimetry. Marshall et al. [2006] inferred eddy mixing using temporally varying circumpolar geostrophic flow estimates from sea-surface altimetry to advect a tracer in numerical simulations. They found cross-stream eddy mixing values of order 1000 m^2/s, with enhanced mixing to the north of the ACC. Surface drifters have also been used to estimate eddy mixing [Sallee et al., 2005] in the Southern Ocean, producing similar values but emphasizing regional zonal variations. These estimates of horizontal eddy diffusion are only appropriate for the upper few hundred meters of the water column.

Since there are no comparable estimates at deeper levels in the Southern Ocean and there is no tested theory to extrapolate the surface values downward, deeper observations of eddy mixing are needed to understand the dynamics of the upper cell and to accurately parameterize its effect in coarse models. The upper cell is driven by vertical gradients in the eddy fluxes, so combining the near-surface observations with deeper isopycnal observations is necessary to understand this problem.

C.3.3 The Integrated Diapycnal and Isopycnal Mixing Experiment

To recapitulate, isopycnal mixing is the basis for the idealized upper cell of the Southern Ocean, in which all diapycnal mixing is near the ocean surface. Subsurface diapycnal mixing can "short-circuit" advection in the upper cell, and reduce the meridional exchange of climate anomalies with the rest of the World Ocean. Therefore, measurements of both components are essential to an understanding of the dynamics of the upper cell and by extension its role in the general circulation of the ocean and climate. The rate at which the Southern Ocean overturns depends on atmospheric forcing, the ACC, eddy motions, and diapycnal processes, though the ways in which these processes interact remain unclear. DIMES seeks to investigate these connections with observations that span the water column from the surface to the abyss.

While DIMES does achieve logistical cost savings by simultaneously investigating diapycnal and isopycnal processes, great scientific synergy is also developed by this joint approach. The hub of the study is the tracer program that will yield estimates of both diapycnal and isopycnal dispersion. The other program elements will shed light on the physical processes responsible for the mixing. Importantly, mesoscale flow, finestructure and microstructure measurements will be obtained together in DIMES and the interrelationships between these scales of motion will be documented. Thus, in addition to looking for geographic variability, the properties of the finescale fields relative to the mesoscale strain field will be quantified. DIMES will also facilitate investigation of the role of mesoscale straining in generating intrusive finestructure and of turbulent diapycnal processes in its destruction. Finally, surface and near-surface observations from shipboard and autonomous instruments will provide additional ground truth to satellite and model-based air-sea fluxes and upper-ocean mixing. The result of the DIMES measurements will be improved constraints and parameterizations of diapycnal and isopycnal diffusivity in terms of such quantities as mean and eddy flow, topographic roughness parameters, and wind and tidal energy input.

C.4 Proposed Field Program

C.4.1 Overview

The U.S. contribution to DIMES includes a tracer release in the Upper Circumpolar Deep Water (UCDW), float releases in the same layer, and measurements of finestructure and microstructure from various platforms. The floats will be tracked with a network of sound sources. Most of the floats will remain on an isopycnal surface until the end of their mission, but some will periodically come to the surface to obtain a vertical profile of the hydrography. The float program will be augmented with conventional Argo floats. Extensive surveys of fine- and microstructure will be done over the full ocean depth with free-falling profilers during austral summer. Finestructure measurements will be extended over all seasons with specialized floats measuring shear and stratification in the layer occupied by the tracer, and others profiling the upper 1500 m. The tracer and floats will be released in the Southeast Pacific, with much of the tracer and many of the floats passing through the Scotia Sea during the 3-year duration of the experiment. The POP model at LANL [Maltrud and McClean, 2005] has been used to plan the experiment and will be used to further guide it and to interpret the results (see letter from Julie McClean in the supplemental information section). The U.K. contribution to DIMES is outlined in the supplemental information section. It includes: a study of the transfer of energy between mesoscale eddies, internal waves and turbulence in the northern Scotia Sea; the deployment of US sound source moorings; sampling of the tracer we release; sampling of the terrigenic He-3 plume for a study of mixing in the Scotia Sea at a level below that of the tracer; and incorporation of results in high-resolution and inverse models of the Southern Ocean. Both nations will contribute ship time to the experiment, and there will be participants from both nations on most major cruises (Table 1).

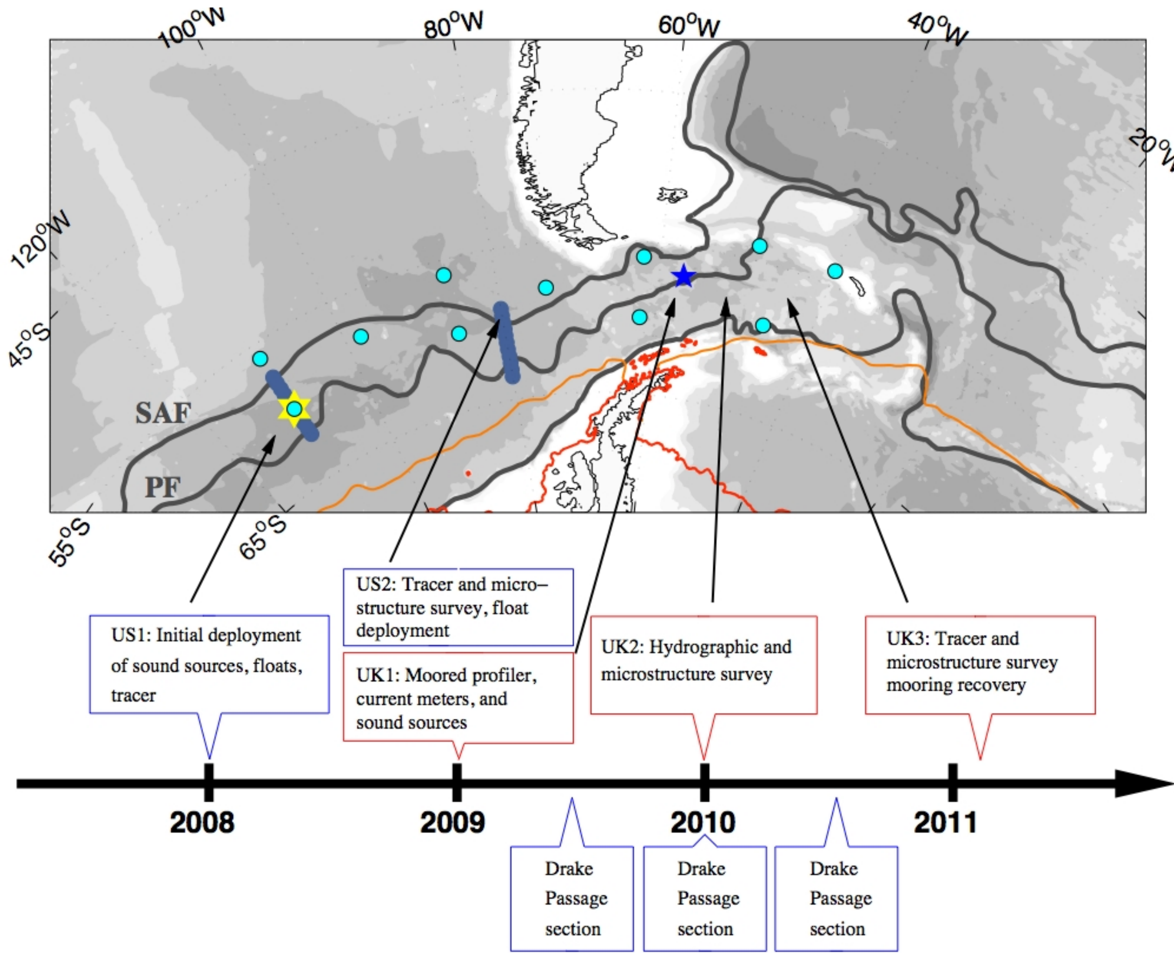


Figure 3. Time line for DIMES field activities. Text boxes at the bottom give the timing of the field activities. The yellow star with cyan dot indicates the tracer deployment location, blue circles show tentative float deployment sites, and cyan dots indicate locations of sound sources. The blue star in the Scotia Sea marks the site of the U.K. mooring array. The gray shading indicates the bathymetry, with 1000-m contour interval; the climatological locations of the Subantarctic Front (SAF) and Polar Front (PF) (both from Orsi, [1995]) are labeled; the remaining lines mark the maximum (orange) and minimum (red) seasonal sea-ice extent.

The progression of the tracer and the floats across the study region will set the pace and the evolution of the experiment (Fig. 3). As already noted, the bathymetry beneath the Pacific ACC immediately to the east of 110˚W, where the tracer will be released, is relatively smooth and the eddy energy is relatively weak. In contrast, Drake Passage and the Scotia Sea are rough, and the eddy field there and north of the Falkland Ridge is intense. Hence, in the first stage of the experiment we expect to sample and quantify a region of relatively weak isopycnal and diapycnal mixing in the ACC. Once the tracer and floats pass into and through Drake Passage, we expect to sample waters characterized by high mixing and transport parameters. With these data bounding the extremes of diapycnal and isopycnal mixing, DIMES will enable improved Southern Ocean mixing estimates ranging from circumpolar extrapolation guided by the bathymetry to analysis of models that employ regionally validated sub-grid-scale parameterizations.

Table 1. Cruise Summary and Activities

Nation	US	US	UK	US	US	UK	US	UK
Ship	Large	Large	Large	Gould	Gould	Large	Gould	Large
Time	Jan 2008	Jan 2009	2008/09	Jul 2009	Jan 2009	2009/10	Jul 2010	2010/11
Days	46	50	~28	+4	+4	~35	+4	~45
Area	SE Pac.	SE Pac.	Scotia S.	Drake P.	Drake P.	Scotia S.	Drake P.	Scotia S.
UK			Mooring Array EM floats			Tracer Micro		Tracer Micro
FSU	Floats SoSos	Floats Micro	SoSos EM floats			Micro		Micro
UW	EM floats	EM floats						
WHOI	Tracer Inj. Moorings Floats ShearM	Tracer Micro Floats ShearM		Tracer	Tracer	Tracer	Tracer	Tracer Micro

Abbreviations: +4: four days added to a crossing; Micro: Fine- and microstructure profiler; SoSos: Sound source deployment; ShearM: Shearmeter floats.

C.4.2 The Tracer Program

The tracer will be released early in 2008 on neutral surface $\gamma = 27.9$ ($\sigma_\theta = 27.68$), between the SubAntarctic Front (SAF) and the Polar Front (PF) near 110˚W. The $\gamma = 27.9$ surface lies in the lower part of the UCDW, i.e., in the lower part of the upper cell of the MOC. The oxygen minimum core of the CDW is near this surface (Fig. 4), and the mean cross-streamline flow here is presumably poleward. The depth of this surface is about 1300 meters between the SAF and PF in the SE Pacific (Fig. 4). The deployment longitude is chosen to be about 2 years upstream of Drake Passage, at 70˚W, given a mean current of about 0.03 m/s in the ACC band, estimated from Argo and ALACE float displacements near 900 meters, combined with hydrographic and mooring data to adjust to 1300 m.

A new tracer, trifluoromethyl sulfur pentafluoride (CF_3SF_5) will be used for this experiment in place of SF_6, to reserve the latter for use in combination with chlorofluorocarbons (CFC-11, CFC-12, and CFC-113) as a transient tracer invading the Southern Ocean from the atmosphere to study ocean circulation. CF_3SF_5 behaved identically to SF_6 over 12 months in a pilot experiment in Santa Monica Basin in 2005. A big advantage of CF_3SF_5 is that the background concentration in the ocean is below the minimum detectable value of 0.03 fmol/kg in 300 ml of water, while the background concentration of SF_6 is expected to be detectable on the 27.9 surface poleward of the PF.

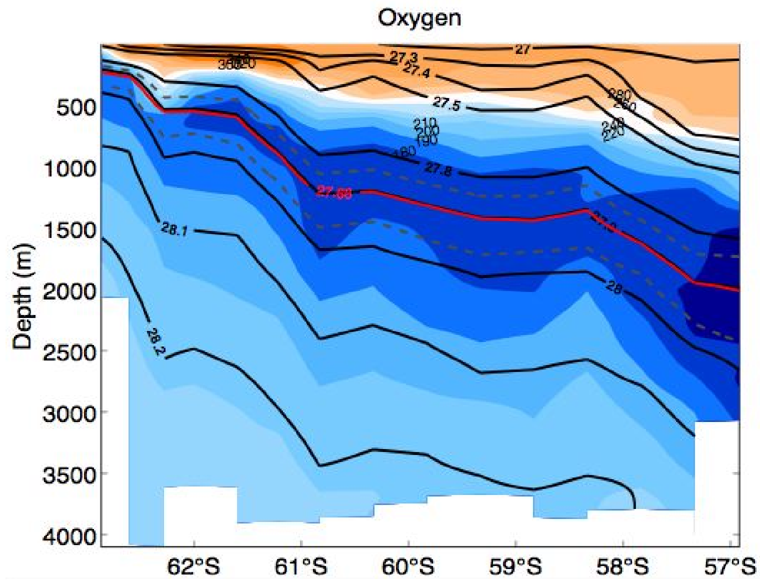


Fig. 4. Section from Drake Passage showing oxygen, in color, σ_θ (black lines) and the target surface for tracer and float releases at $\gamma = 27.9$ (red line).

The tracer injection system will be similar to that described by Ledwell et al [1998], except that a gang of 25-micron orifices will be used in place of two 50-micron orifices because CF_3SF_5 is about 7 times less soluble than SF6 at the conditions of the release. We plan to release 480 kg of tracer at a rate of 40 kg per day in a series of 12 streaks, each 30 km long, spaced about 5 km apart. The lines will likely be approximately zonal, due to constraints of the tow direction relative to the wind, and will end up filling a rectangle approximately 40 km east-west by 60 km north-south. Shipboard ADCP data, satellite data, and a current meter on the injection sled will be used to follow the general flow of the water to keep the initial tracer patch relatively compact.

After release of the tracer and an excursion to deploy floats to the north we will return to the patch, guided by 6 pop-up floats released with the tracer, and samples of the initial distribution of the tracer will be taken with the towed array of integrating samplers described by Ledwell et al. [1998]. The goal of this sampling is to confirm that the tracer has dissolved in the desired density window, rather than to map the patch completely at this stage. At the center of the array of samplers will be a 50-chamber sampler that will provide a resolution of the tracer distribution of about 600 m along the tow tracks.

The initial root mean square (rms) vertical spread of the tracer relative to the target isopycnal surface will be approximately 5 meters, estimated from previous injections with similar tow speeds and sled geometries at various buoyancy frequencies. The tracer will spread over the SE Pacific sector of the ACC as it is carried toward Drake Passage and stirred and dispersed by the mesoscale eddy field and the mean shear in the ACC. We will sample its distribution one year after release, early in 2009, along the cruise track shown schematically in Fig. 5. The lateral distribution of the tracer at one year shown in the figure was estimated using the 0.1 degree-resolution POP model at LANL [Maltrud and McClean, 2005]. The tracer at that point will have sampled mixing over all seasons and over an area on the order of 10^6 km^2. Even if the diffusivity is as low as 0.1×10^{-4} m^2/s in the SE Pacific, the rms spread will have grown to 25 meters, and the second moment, which essentially determines the diapycnal diffusivity, will have grown from around 25 m^2 to 625 m^2.

The leading edge of the tracer patch will reach Drake Passage after about one year. True, there are jets at 1300 meters that would carry tracer there more quickly, and so small quantities of tracer may arrive earlier. However, we believe, and the POP model confirms, that the vigorous stirring by eddies in the ACC will insure that the tracer patch as a whole will feel the mean current much more than the extremes, as the tracer samples progressively larger regions of the mean.

We will begin to sample the tracer at Drake Passage during the survey one year after the release, and we will continue to occupy a section across Drake Passage every 6 months thereafter until the end of the field experiment, three years after release, either from crossings on *R/V Gould* or on DIMES cruises (Table 1). The distribution of the times of transit through the Scotia Sea will be estimated from DIMES float trajectories, augmented with high resolution numerical models and with the displacements of ALACE and Argo floats. The mean transit time through the Scotia Sea of floats released in the POP model at 1500 meters depth was 266 days, and the standard deviation was 205 days.

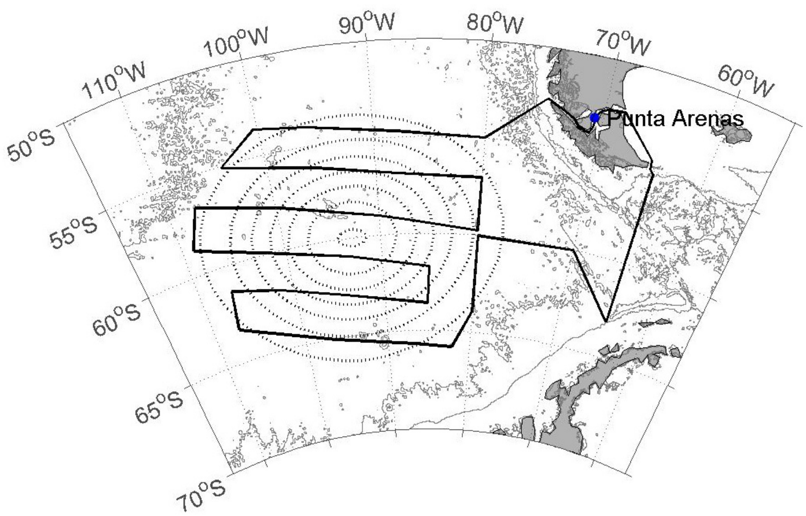


Fig. 5. Track (heavy solid line) for the cruise one year after deployment. The ellipses show the expected distribution of the tracer. Floats will be released along 80˚W between 57˚S and 6˚S during this cruise.

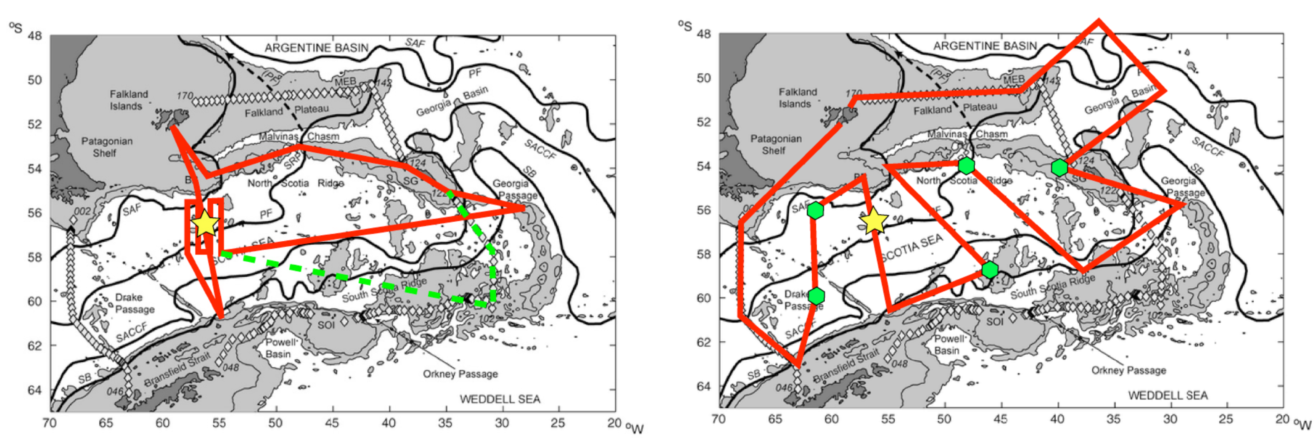


Figure 6. Left panel: Prospective cruise track on the UK cruise in 2009/10 (red). The green dashed line shows an alternate track. The UK mooring array will be at the yellow star. Right panel: Prospective cruise track for the UK cruise in 2010/11. DIMES sound sources in the Scotia Sea will be recovered on this cruise (green dots).

The center of mass of the tracer patch is expected to be near 90˚W one year after release, near Drake Passage two years after release, and near the exits of the Scotia Sea three years after release. We have scheduled sampling accordingly. Two years after release, in austral summer 2009/10 sections will be occupied across the Scotia Sea at about 50˚W along WOCE line SR1b, and along the north rim of the Scotia Sea (Fig. 6). These two sections will be occupied by a UK ship with both US and UK participants. The difference between the tracer distribution in these sections, together with models for the time of transit and the vertical shear in the mean ACC, will be used to estimate the diapycnal diffusivity in the western and eastern sectors of the Scotia Sea.

A final survey of the tracer will be done three years after release in 2010/11, again from a UK ship with UK and US participants (Fig. 6, right panel). This survey will be more thorough than the year-2 sections, so that more spatial resolution on variations in the mixing intensity may be obtained, but the principle of the method will be the same. An integrated measure for all of the Scotia Sea, from the Drake Passage to the north rim, will be obtained.

A scenario for the difference between the profiles at Drake Passage and the north rim is shown in Fig. 7 for parameters listed in Table 2. Values were chosen for the shear of the mean flow and for along-current diffusivity following the model floats. The along-current diffusivity was made to fall smoothly to 1000 m^2/s at the entrance and exit of the Scotia Sea to simulate resistance to back diffusion at these choke points. The diapycnal diffusivity is taken to be 10 times greater in the "Scotia Sea" than outside of it, $3x10^{-4}$ m^2/s versus $0.3x10^{-4}$ m^2/s. The difference between the profiles at the entrance and exit of the region of enhanced diffusivity, in the right panel of Fig. 7, illustrates the sensitivity of the experiment to enhanced mixing in the Scotia Sea. A more elaborate model, and one more suited to the data will be used to guide and analyze the actual observations.

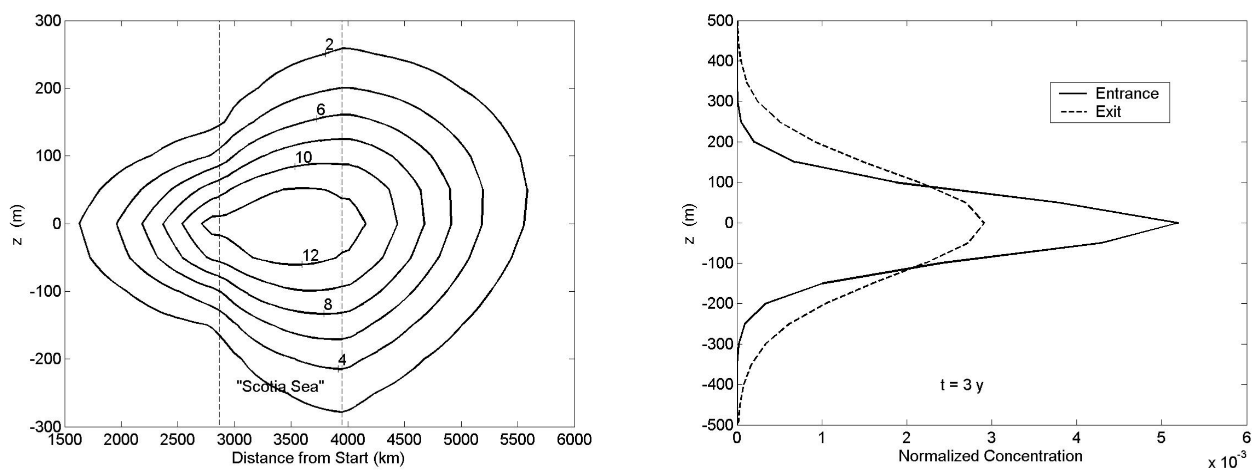


Figure 7. Distribution of tracer after 3 years from a simple 2-D advection-diffusion model. The left panel shows a transect of tracer along the path of the current, with the "Scotia Sea" indicated between the dashed lines, i.e., where diapycnal mixing is taken to be enhanced. The right panel shows normalized vertical profiles at the entrance and exit of this region at 3 years. *z* is height above the target density surface.

Table 2. Parameters Used in the 2-D Advection-Diffusion Model Run for Fig. 7.

Diapycnal diffusivity in the Pacific and north of the North Scotia Ridge:	0.3×10^{-4} m^2/s
Diapycnal diffusivity in the Drake Passage and Scotia Sea:	3×10^{-4} m^2/s
Along-ACC velocity at 1500 meters:	0.04 m/s
Vertical shear in the along-ACC velocity:	2×10^{-5} s^{-1}
Zonal diffusivity at 1500 meters depth:	5000 m^2/s
Exponential scale height for the zonal diffusivity:	1000 m

C.4.3 Finestructure and Microstructure Program

The tracer will give a robust estimate of the diapycnal diffusivity at one level in the SE Pacific and a second estimate for the Scotia Sea. These will represent averages over many months and over large areas. While valuable, the usefulness of the tracer results is greatly enhanced if in addition, the physical processes forcing of the mixing are measured. With such added information, existing parameterizations of the diffusivity can be tested or new ones developed. The diapycnal mixing component of DIMES seeks to answer the following questions:

> What are the spatial and/or temporal patterns of diapycnal mixing in the Southern Ocean?
> What physical processes are responsible for the mixing?
> Are the currently available parameterization schemes for diapycnal mixing applicable to the Southern Ocean?

Several techniques will be used to study diapycnal mixing in DIMES. Diapycnal diffusivities will be estimated from the dissipation rates of turbulent kinetic energy (ε) and temperature variance (χ) following Osborn [1980] and Osborn and Cox [1972], respectively. Gregg [1989] and Polzin et al. [1995] have additionally shown that at mid-latitudes, a reasonable predictor for ε is the spectral level of finescale shear at vertical wavelengths of 10 meters and greater. However, a number of discrepancies from this relation have been documented: in the upper ocean; in submarine canyons [Kunze et al, 2002; Gregg et al, 2005]; and on continental shelves [MacKinnon and Gregg, 2003]. One might also expect exceptions in the ACC, where the source of internal wave energy is likely to be flow over nearby bottom topography and the dissipation of local mesoscale eddies, as well as wind and tidal forcing that predominate for the mid latitude data.

We propose to measure dissipation rates with free falling profilers during the DIMES cruises. These profilers also measure the shear and stratification at all scales and so can test the relations of Gregg [1989] and Polzin et al. [1995]. However, the profiler measurements will be confined to three austral summer cruises and thus be limited in space and time. We therefore propose to deploy two sets of floats to measure shear and stratification at fine scales over all seasons. One type, the shearmeter, will drift in the layer of the tracer and return continuous records of shear and stratification for more than a year. The other, EM-APEX, will repeatedly profile from approximately 1500 meters depth to the surface on missions also of more than a year. Both types of floats will quantify finescale shear and stratification variability, allowing assessment of seasonal bias in the ship-based profiler measurements. Furthermore, using the finescale relations for ε either confirmed or newly developed from the profiler measurements, the float data will facilitate comparisons between the tracer dispersion rate and the diffusivity estimates from the microstructure profilers.

C.4.3.1 Shearmeters

Eight shearmeter floats will measure shear and stratification continuously about the isopycnal layer of the tracer for a period of a year or more. Five of these will be deployed concurrently with the tracer in the Pacific. At the one-year point, three additional floats will be deployed near 90˚W for eighteen-month missions to sample conditions in Drake Passage and the Scotia Sea. Data from the floats will be transmitted by the Iridium system upon mission completion.

The shearmeters have vanes rigidly mounted at each end that are similar to those of a cup anemometer. Torques imposed by the response of the vanes to the apparent lateral currents, which are close to being equal and opposite at each end of the freely-drifting floats, cause the floats to rotate in response to vertical shear. Logging the rotation using a compass completes the measurement. Absence of bearings makes possible measurement of very small shear. To this shear measurement, we will add a temperature sensor at each end to measure variations in stratification. The floats will be an updated 7.5-m version of the 10-m-tall shearmeter floats that were used during BBTRE and GAGE [Duda, 2004; Duda, 2006]. The shorter floats will not have sectional hulls and will consequently be more robust. They will have an APEX-type buoyancy control that will enable them to remain near the target isopycnal surface via feedback from the temperature sensors. However, the floats need not remain rigorously confined to this surface since conditions should be similar immediately above and below the patch. One shearmeter will be configured to have a very small righting moment. This unit will tilt in response to the shear, with these tilts sampled with a three-axis flux-gate type attitude sensor. Combination of the velocity difference and tilt data will provide the required information to deduce the direction of the shear, and thus the shear vector.

The floats will provide time series of the magnitude of the horizontal velocity difference and the temperature difference over 7.5 meters every 10 minutes. From these data the shear magnitude, S, and the square of the buoyancy frequency, N^2, will be inferred. Together these gradients provide an estimate of gradient Richardson number $Ri = N^2/S^2$, which gives a qualitative idea of the intensity of the forcing available to drive mixing. The shearmeters therefore promise to give a continuous record of the forcing of diapycnal mixing along several trajectories within the tracer patch. The shearmeters will be tracked with the DIMES sound sources so, from existing bathymetric charts, we will know the topography over which the measurements are made. Furthermore, the mesoscale environment of the measurements will be provided by satellite altimeter data and other DIMES floats in their neighborhood. Near the start of the deployment, and possibly at other times as luck allows, hydrographic profiles will be available near the shearmeters from DIMES and Argo profiling floats that will be deployed in the vicinity of the shearmeters.

C.4.3.2 EM-APEX Floats

While the shearmeters will focus on the tracer layer, a set of profiling floats will measure shear and stratification over the upper 1500 meters of the water column. The recently-developed EM-APEX is an enhancement to the standard Webb Research Corporation APEX float incorporating sensors to derive horizontal currents in addition to temperature, pressure and conductivity

[Sanford et al., 2005]. One-year missions designed to resolve inertial motions in the upper water column will be accomplished though burst sampling of multiple profiles every 2 days (Fig. 8). This profiling schedule allows the separation of inertial and sub-inertial components of velocity in the upper 1200 m by making pairs of profiles separated by half an inertial period (6.9 h at 60˚S; see Fig. 8). In addition, GPS positions at the two surfacing locations will allow an accurate measurement of the absolute velocity profile. Resulting statistics of shear, strain and Richardson number over the duration of the experiment will be compared to diapycnal diffusivities inferred from the tracer and microstructure data, allowing testing and improvement of internal wave mixing parameterizations in the Southern Ocean. In addition, finestructure data from the floats will be compared with finestructure data gathered in austral summer by the free-falling profilers to assess seasonal variability.

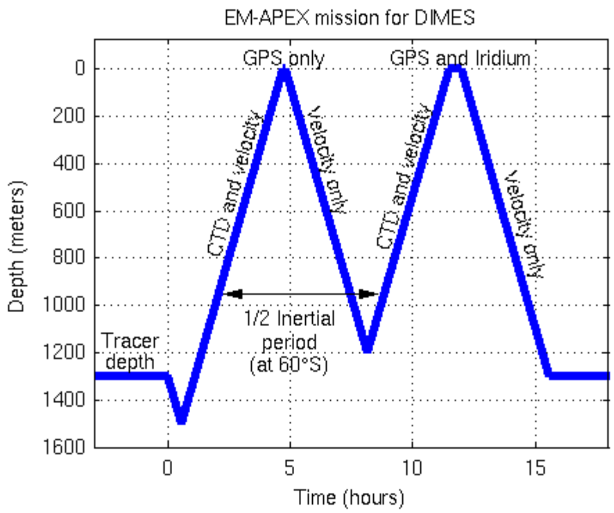


Fig 8. Profile pattern for 1 "burst" for the EM-APEX floats. At the start of the pattern, the float will dip to 200 meters below the $\gamma = 27.9$ surface, or to 2000 meters, whichever is shallower. The depth range spanned by the second up-profile will be tuned to make the two up-profiles separated in time by half an inertial period. The vertical speed of the EM-APEX is approximately 0.1 m/s. Because of the positioning of the CTD at the top of the instrument, CTD profiles will only be obtained on the up-profile. Between bursts the float will stay at the 27.9 surface to move laterally with the tracer as closely as possible.

The EM-APEX is a standard (Argo-type) APEX profiling float with the addition of an APL-UW subsystem for measuring motionally-induced electric fields generated by the ocean currents moving through the vertical component of the Earth's magnetic field [Sanford et al., 1978]. The temperature and salinity observations are obtained from a Sea Bird Electronics SBE-41 CTD. External fins cause the EM-APEX to rotate while profiling, allowing the removal of electrode offset voltage. Float position is determined by the GPS system when the float surfaces. The temperature, salinity, velocity, and position observations are processed within the float and transmitted over the Iridium global phone system. The overall accuracy of the velocity measurement technique is estimated at 0.005 m/s for the relative velocity profile and 0.01 to 0.02 m/s for the GPS-referenced absolute velocity. A detailed assessment of the specific noise level of the EM-APEX system is ongoing.

The slow rise/fall rate of the EM-APEX gives a high-resolution profile of the horizontal water velocity and allows the separation of the near-surface profile into surface wave and mean shear components. The amplitude, period, and direction of the dominant surface waves can be determined and have compared favorably with wider-area wave spectra under Hurricane Frances. In dynamic environments such as the surface mixed layer, it is also possible to make estimates of vertical velocity using variations in the floats' rise/fall rate from the CTD pressure and the float rotation rate. The resulting $\langle u'w' \rangle$ Reynolds flux can be used in vertical momentum budgets.

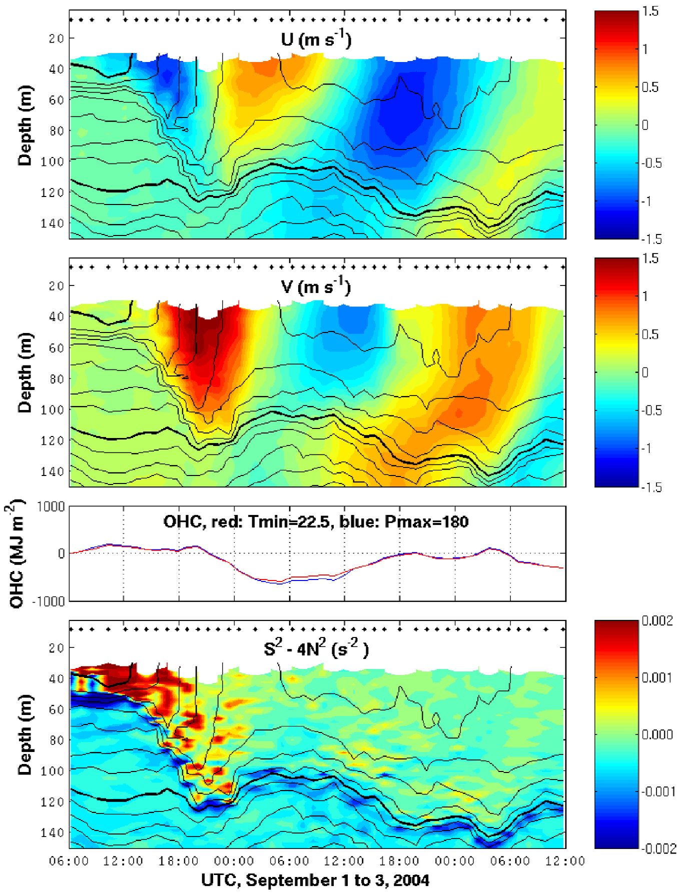


Fig. 9. EM-APEX view of the upper-ocean response to the passage of Hurricane Frances [Sanford et al., 2005]. The storm arrived at the site shown (50 km to the right of the eye) around 1200 UTC on 1 September 2004. Acceleration of the upper layer by winds up to 60 m/s resulted in a rapid increase in shear accompanied by mixed layer deepening and cooling. The east (U) and north (V) components indicate clockwise-rotating inertial motions, and both components exhibit the upward phase propagation indicative of downward energy propagation. During the initial deepening, ocean heat content (OHC) remained nearly constant, indicating one-dimensional mixing. Subsequent lateral divergence across the storm casued heat content to drop. Note that the OHC change due to surface heat loss was 40-60 MJ/m^2, much smaller than the upwelling-induced changes. The bottom panel presents calculations of "reduced shear", S^2 - 4N^2. This quantity is zero for Richardson number (*Ri*) equal to ¼. Regions of $Ri < ¼$ are red and tend to be unstable to shear, while the blue regions are stable.

EM-APEX floats have been used in two field programs to date. The first was the ONR CBLAST Hurricane experiment, in which 3 floats were air-dropped in front of Hurricane Frances in September 2004. Hourly velocity and stratification profiles provided a direct window into the intense shears and rapid mixed layer deepening produced as the hurricane passed overhead (Fig. 9). The second was the NSF EDDIES experiment in the Sargasso Sea, July-September 2005 [Girton and Sanford, 2006]. Here, the floats were used to characterize internal wave finestructure at the base of the euphotic zone (80-100 m depth) for comparison with diapycnal diffusivities inferred from the spreading of a patch of SF_6. In this latter experiment, the application was very similar to the planned DIMES strategy. We anticipate three significant differences between the first set of EM-APEX floats used in the hurricane and EDDIES experiments and the ones to be used in DIMES. The first is the pressure capability, which will be increased to 2000 m as is standard for Argo floats. The second is the addition of a continuously-pumped CTD, which will allow for a finer sampling resolution in the vertical than is currently possible. This will come with some tradeoff in terms of power usage and data volume, and so additional testing and modeling will have to be done before the final decision is made. The third difference will be the replacement of the float's alkaline batteries with lithium batteries to increase the mission length and data return.

We plan to deploy 6 EM-APEX along with the tracer in 2008 and another 4 on the Pacific survey cruise in 2009 near 90˚W. Five more EM-APEX will be deployed in 2009 as part of the UK eddy/internal wave/turbulence study near 55˚W (partly with UK funding). Our goal is to achieve an even coverage of the southeast Pacific, Drake Passage and the Scotia Sea. This mission strategy will be tested prior to deployment by tracking floats in the POP model velocity field. In addition, two-way communications will allow mission adjustments to be made during the experiment. With lithium batteries, each EM-APEX will be capable of making 200 profile pairs over the mission duration, with the intervening time spent drifting at the depth of the tracer isopycnal. For a 400-day mission, this drift time would be 32 hours, leading to a profile pair (burst) every 2 days. Although the floats will not measure the local velocity while drifting because they will not rotate fast enough, the displacements at the tracer depth will add to statistics obtained by DIMES isopycnal floats on the flow variability at timescales from around a day to many months.

C.4.3.3. Finestructure and Microstructure Profiling

Profiles of finestructure and microstructure taken with free-falling profilers during the survey cruises will provide estimates of diapyncal diffusivity based on dissipation rates of turbulent kinetic energy and temperature variance over the full ocean depth. Furthermore, they will provide the finestructure environment of these dissipation rates, which will aid the interpretation and parameterization of the diffusivities. During the survey in 2009 in the SE Pacific, profiles will be taken at every tracer-sampling station, sea state permitting, yielding a broad scale survey of that region. On the cruises in the Drake Passage and Scotia Sea, profiling will be focused on places of interest, such as near ridges or rough abyssal hills, in the region of the UK mooring array near 55˚W, and at the exit passages along the north rim. On all of the cruises, short time series consisting of multiple profiles at particular sites will be occupied to quantify the dominant time scale of the finestructure.

Two profiling systems will be employed in DIMES. The recently upgraded WHOI High Resolution Profiler (HRP-II, see http://hrp.whoi.edu/hrpgrp/new/newhrp.html.) will be used on the survey cruises during the first and third years after the tracer deployment. Deep Microstructure Profilers (DMP, see http://rocklandocean.e-newsletter.com.au/)), developed recently at the University of Victoria by R. Lueck (RGL Consultants, Ltd.), will supplement the HRP on those cruises, and a pair of DMPs will be used on the year-2 cruise: one provided by FSU and one by the UK. (Prior to DIMES, FSU will operate a DMP at the Mid-Atlantic Ridge during a field program in summer of 2006, while the UK group will operate their own system during Southern Ocean work in 2007.) It is critical to have this redundancy of profilers on these extended cruises to insure data acquisition. Also, multiple profilers will allow more frequent sampling at time-series stations than is possible with a single device. Personnel from WHOI, FSU, and the UK will jointly operate the suite of profilers.

The HRP and DMP systems have many common characteristics. Both systems are full-depth capable profilers with fine- and microstructure sensing for temperature, conductivity, and shear. Diapycnal diffusivity is inferred from the turbulent dissipation rate estimates, while the finestructure observations yield estimates of Richardson number, vertical wavenumber shear spectra, and the characteristics of the mesoscale and large-scale flow and stratification. Both systems are free-falling, autonomous, internally-recording profilers with body dimensions (length and diameter exceeding 3 and 0.3 meters respectively) and shape (cylindrical with rounded ends) optimized to create a stiff, low-vibration platform for the sensitive shear probes, while allowing undisturbed flow to reach all the sensors. As such, the HRP and DMP are not subject to ship or cable-induced vibrations, and allow for dissipation measurements with lower noise levels than tethered systems. Both systems are designed to profile on the down-going trajectory with a fall-rate of ~0.6 m/s. Profiler descent is terminated through weight release, triggered by pressure, elapsed time, or proximity to the bottom. Rise rates are ~2 m/s. After recovery, data from the profilers are offloaded in seconds via a digital connection, allowing quick, preliminary assessment of the data so that faulty sensors, such as shear probes or fast thermistors, can be identified and replaced prior to the next deployment.

The microstructure sensors on each system are essentially identical in design. Both systems employ up to 6 probes for measuring temperature, conductivity, and velocity microstructure and deriving thermal and kinetic energy dissipation rates (ε and χ) [e.g., Lueck et al. 2002]. For the expected ocean environments, resolution of the shear-dissipation wavenumber spectrum will be easily achieved by the 0.6 m/s descent rate and the 1 kHz sample rate of the profilers. Both systems are capable of resolving turbulent kinetic energy dissipation to $\sim 5\times10^{-11}$ W/kg (see below). Finestructure sensing is achieved on each profiler with CTD and velocimeter hardware. Both employ GPS position data and sensors analogous to those on the EM-APEX float detecting the motionally-induced electric field to derive absolute ocean velocity profiles. Resultant velocity profile accuracies are comparable to the EM-APEX (see above) with shear resolvable down to 10-m vertical scale. The HRP-II adds an onboard acoustic current meter (a customized variant of the Nobska, Instruments Inc. MAVS) to resolve flow structures to scales smaller than the instrument's length. For temperature and salinity, the DMPs employ SBE3/4 conductivity and temperature sensors and a Keller pressure sensor while HRP-II supports a newly-designed CTD by Neil Brown.

Each profile operation of the HRP or DMP will consist of a deployment, autonomous dive, and recovery. Deployment is accomplished using customized lifting rigs positioned along the ship's rail or stern. This is easily accomplished by a 3-person team. The dive component of the operation will take 2-4 hours depending on depth. After ballast release, both instruments rise to the surface tail-up, with the fragile sensors lying below the water line by roughly 2 m. A strobe light and radio transmitter are activated once the profilers reach the surface. For recovery, the research vessel must approach the instrument slowly and carefully, closing to within a few meters from the ship's beam. Personnel first attach a tag line using a shepherd's pole with a snaphook. The instrument is then handled by loosely tethering the tag line to a cleat, with adjustments made to bring the instrument within range of a second pole-deployed snaphook tethered to the recovery winch integral to the lifting rig. A recovery operation of this type can be done by 3 to 4 people in 15 minutes, assuming competent ship handling. The WHOI and FSU PI's are very experienced with this type of operation from their prior work with the HRP. By dividing the science team into two or three watches, around-the-clock profile operations will be possible.

Profiler dives in conjunction with tracer sampling will be initiated during the tracer cast so that the CTD package will be back on deck and the ship free to maneuver for the recovery by the time the profiler returns to the surface. Experience with HRP has demonstrated that profiler operations can continue through nearly the range of conditions in which CTD casts can be made. In addition to joint stations with tracer casts, short time series will be occupied in regions of enhanced finestructure or microstructure to better quantify the dissipation rates and characterize the dominant time scale of the internal wave field. We anticipate that 5000-meter profiles can be completed within 4 hours, allowing up to six deep profiles per day with a single profiler, if no transit time is required. Faster sampling will be possible by alternating profilers.

Past experience from joint tracer release and microstructure profiling experiments in the North Atlantic, Brazil Basin and western tropical Atlantic suggests that diapycnal diffusivities from the two approaches can be reconciled within standard-error uncertainty (the 1-sigma confidence interval). The Osborn [1980] diffusivity relation $\kappa_\rho=\Gamma\cdot\langle\varepsilon\rangle / \langle N^2\rangle$ involves an *a priori* specification of the mixing efficiency parameter (Γ). Conventional application uses Γ=0.2, which has been shown to be appropriate for mixing in most geophysical shear flows [Peltier and Caulfield, 2003]. Uncertainty in this parameter has been estimated at $\delta\Gamma$=0.04 [St. Laurent and Schmitt, 1999]. Beyond uncertainty in Γ, the other significant source of uncertainty in microstructure-based diffusivity estimates derives from the statistical variation of the turbulent dissipation estimates. In practice, estimation of diffusivity is done for large ensembles of profile segments. Statistics for log-normally distributed dissipation rate data have been shown to be stable using arithmetic averaging for sample sizes with O(100) degrees of freedom [Davis, 1996]. Typical scatter in the sampled distribution results in a 50% uncertainty on the mean; i.e., $\delta\langle\varepsilon\rangle/\langle\varepsilon\rangle$=0.5. Assuming uncorrelated errors and small uncertainty in $\langle N^2\rangle$, the resulting microstructure-derived diffusivities will be typically resolved to within 55% of the mean values. We therefore expect DIMES microstructure-based diffusivity confidence intervals at the 95% level will typically extend over a factor of two for a given estimate.

C.4.4 The Isopycnal Mixing Program

Because acoustically tracked floats are Lagrangian devices, their motions directly reflect oceanic mixing [Freeland, et al., 1975]. Fluid parcels tend to mix along isopycnals, so the ideal Lagrangian float tracks isopycnals in much the same way that tracer tracks isopycnals. This is particularly important for DIMES, since isopycnals tilt strongly in the ACC and therefore are distinctly different from isobars. Isopycnal-following floats have been used previously, primarily in the North Atlantic [Zhang et al., 2001; Rossby and Hebert, 2002]. DIMES will be the first time that acoustically-tracked floats have been deployed in the ACC, and it will provide the first observations of isopycnal mixing in the Southern Ocean. DIMES floats will be used to estimate dispersion statistics that can only be obtained from Lagrangian measurements; these floats will sweep by the moored current meter array placed in the ACC by the UK, so that the Eulerian and Lagrangian estimates of eddy fluxes can be compared.

The isopycnal component of DIMES aims to answer the following questions:

How do we characterize the mixing process (dispersion and strain) in the ACC?
Does that mixing vary significantly spatially?
Can the mixing be represented as a diffusive process, and if so, with what diffusivities?

C.4.4.1 Floats.

DIMES will deploy a total of 150 acoustically-tracked isopycnal-following floats. (The EM-APEX floats are not isopycnal in that they spend about a third of their time profiling; the shearmeters are approximately isopycnal but because of their different mission objectives are not counted in the 150-float total). The floats will be ballasted for the same isopycnal surface,

σ_θ =27.68 (γ = 27.9), as the tracer, at depths between about 1000 and 2000 m (Fig. 3). The objective in placing floats on this isopycnal surface is to evaluate eddy isopycnal mixing in the Upper Circumpolar Deep Water. Vertical variations in isopycnal eddy mixing will be obtained by analyzing profile data from both our APEX floats and Argo float data [e.g. Gille, 2003b], and surface data (altimetry, drifters) analyses. Data-based results will be compared to tracer-based inversions and assimilation products.

Two different float designs are planned. A total of 135 isopycnal following RAFOS floats will be deployed. These floats are the same type that have been used in North Atlantic experiments and have been selected because they are comparatively inexpensive, and their performance has been well-documented [e.g. Rossby et al., 1985; Rossby et al., 1994; Rossby, 1996; Barth et al., 2004]. They will be ballasted in the WHOI and University of Rhode Island facilities and they are expected to follow their designated isopycnal surface with an error of $\pm$0.05 σ_θ.

We will also deploy 15 profiling Argo-like floats that have been modified to follow isopycnals and to be tracked acoustically when in range of sound sources. These floats differ from conventional RAFOS floats in several specific ways. First, they will be programmed to report to the surface after 3-4 months. Second, because the floats actively track density surfaces using their CTDs, they can follow an isopycnal surface to within $\pm$0.03 σ_θ and fully compensate for salinity variations. This provides independent trajectories for comparison with the isopycnal RAFOS design and a way to reduce unwanted high-frequency diapycnal excursions. Third, after the initial 3-4 month trajectories have been obtained, the floats will begin profiling temperature and salinity regularly to the surface to provide background stratification in the region as well as real-time data return. Profiles will also be obtained from the EM-APEX floats and Argo floats deployed during DIMES (as well as any other nearby Argo floats). By using Iridium communications systems, the floats will need to spend only minimal time at the ocean surface where wind-driven currents might deflect them from the tracer and subsurface floats [Gille and Romero, 2003]. Iridium communications provide two-way communications capabilities, additionally allowing us the possibility of reprogramming individual floats if their mission requirements changed. Isopycnal-following versions of these floats were used in the Kuroshio, where they achieved their programmed accuracy of $\pm$0.1 σ_θ. [Iwao et al. 2003]; this range could have been programmed to be significantly narrower.

Floats will be deployed along meridional lines spanning the ACC. Half will be released initially with the tracer, and half during the first tracer survey, one year after the tracer release. The floats will be released in triplets to facilitate computation of two-particle dispersion [e.g. LaCasce and Bower, 2000] and hence of the isopycnal stirring (see below). The deployment plan will allow us to quantify isopycnal mixing across the width of the current, while providing dense enough float clustering to generate robust statistics for the portions of the ACC, such as the Subantarctic Front, the Polar Front, and the Polar Frontal Zone that separates the two fronts.

C.4.4.2 Sound sources

The first part of the array of sound sources used to track the floats will be deployed to the west of Drake Passage when the tracer and first floats are released. Sounds sources in the Scotia Sea will be deployed from a UK ship about the time of the second float release. The Pacific sources will not be recovered because of their remoteness, while the Scotia Sea sound sources will be picked up after the second group of floats completes its two-year mission.

RAFOS have only recently been deployed in the Southern Ocean, for a large-scale experiment in the Weddell Sea [Klatt et al., 2005] and in the Agulhas Retroflection region, north of the ACC [Richardson et al., 2003]. At mid-latitudes, where there is usually a prominent mid-depth sound channel, RAFOS floats have been able to receive transmissions from moored sources at ranges sometimes in excess of 2000 km. At high latitudes, where the sound channel rises to the surface, sound waves are expected to reflect off the ocean surface and the acoustic range is smaller than at mid-latitudes. As a preparatory study for DIMES, an in situ test of acoustic propagation was carried out by FSU. In order to make a useful estimate of the low-frequency acoustic propagation characteristics at 260 hz, a 195 db acoustic source was moored south of Australia late in 2003. The results of this study indicated that acoustic ranges in excess of 600 km in the Antarctic Zone even south of the Polar Front are generally attainable with a 188 db source. Ranges were checked with an in situ sound source and RAFOS float experiment south of Tasmania [Lazarevich, 2003].

To help place the in situ propagation results in a broader context, FSU contracted with SAIC to simulate acoustic propagation in the ACC, addressing the range limits of sound sources that might be used in the Southern Ocean environment. Maps of the results for the South Pacific sector, based on a full 3d representation (Kraken model) with sound speed and bathymetry, and parameterized bottom and surface characteristics were prepared. A ray trajectory model was also used for comparison. These results are consistent with field observations of acoustic range, and we used the combined results to design the sound source array. The planned array will ensonify the region with a minimal number of instruments and limited redundancy.

C.4.4.3 Sampling requirements

To facilitate particle pair statistics calculations (described below), the DIMES floats will be deployed in triplets. A group of three floats yields three pairs, as opposed to a group of two which yields only a single pair. Groups of four or more yield six or more pairs, but this is not desirable because the pairs are not strictly independent.

How many floats are required to obtain significant Lagrangian statistics? In general, single particle statistics converge more rapidly than pair statistics and inhomogeneous flows require more sampling than homogeneous ones. The standard deviation for the single particle diffusivity (defined below, sec. C.6.2.2), decreases as $n^{-1/2}$, if n is the number of floats [Davis, 1991]. It also increases as $t^{1/2}$, which effectively limits the length of the calculation. Both particle diffusivity errors exhibit a similar scaling at long times, when the pairs become decorrelated (see below). But the errors are larger, and more sensitive to the sample size, when the velocities are correlated. It is of course during this period when pair statistics are most valuable for measuring the strain.

To estimate the number of floats required for statistical convergence, we used different numbers of POP model floats (from the model's DIMES region) to calculate single particle and pair diffusivities. Because the mean flow is nearly zonally-oriented here, we focused on the meridional diffusivities. The single particle diffusivity initially increases rapidly, reflecting vigorous advection by eddies, but settles down after several months to a values near 1000 m^2/sec. With 162 floats, the 95% confidence limits are approximately ±200 m^2/s, or 20% of the diffusivity. With 81 floats, the errors increase to about 300 m^2/s, in line with the aforementioned

$n^{-1/2}$ dependence. The relative errors for the pair diffusivities are approximately the same at the later times, because the pairs have become decorrelated. The initial growth in pair separations is not well resolved in the model, but the results suggest that halving the sample size greatly increases the uncertainty in the dispersion.

The POP model flow is less energetic than the actual Southern Ocean flow, so it is likely the actual errors will be larger. The requested number of floats (and hence pairs), 150, represents a plausible minimum for statistical convergence, given the budget constraints. This estimate derives not only from the POP analysis, but from previous pair dispersion studies. LaCasce and Bower [2000], who examined sets with 30-70 pairs of floats from the North Atlantic, found relatively poor convergence; LaCasce and Ohlmann [2003], with 140 pairs of surface drifters in the Gulf of Mexico, obtained much better convergence. Like those authors, we will also use "chance" groupings (of pairs which randomly come close to one another) to augment the total numbers, if possible.

We gleaned additional information from the POP analysis. For one, the initial pair separation was insufficient (due to the grid resolution) to resolve sub-deformation scale straining. In order to resolve this behavior in the ACC, we must deploy the triplets essentially together. Initial separations will thus be 1-2 kilometers, similar to the float positioning error. Second, the POP floats, like those in DIMES, were deployed in two groups (of 81) in successive years. The statistics from the separate sets were not significantly different, meaning the model eddy field, at least for those years, was stationary. This permits us to combine the two sets, making a larger sample size.

C.5 Data Management Plan

There are several institutions and investigators directly involved in this proposal and in the UK DIMES proposal. Furthermore, there are many investigators and projects already closely connected to DIMES, such as M. Maltrud, J. McClean, T. Chereskin, and J. MacKinnon, and there will be many more as the project evolves. Hence it is important for us to plan from the beginning an accessible data base with timely submission of data. A DIMES web site already exists and will be made public when the project starts. A password-protected system has already been established to allow DIMES investigators to post data to the web site and to access all available data efficiently. These data will be made public and will be submitted to the required data centers by the date required by NSF at the latest. The data we anticipate posting are:

Cruise reports	CTD/O2 profiles from standard CTD/rosette systems
Deployment Information	CTD/O2 calibration data
Sound source moorings	CTD/O2 profiles
Float types and launch sites	Tracer concentrations
Tracer injection tracks	LADCP and shipboard ADCP data
Profiler deployments	CTD and velocity profiles from free-fall profilers
Float surfacing coordinates	EM/APEX velocity and CTD profile data
Float subsurface trajectories,	Shearmeter velocity shear and temperature time series data
pressures and temperatures	Turbulent dissipation estimates from free-fall profilers

The PI responsible for each type of data will post them via the DIMES web site within 3 months of acquisition for sharing within the group for most of these data. One year may be required for processing of the float trajectories, finestructure data, and microstructure data.

C.6 Analysis Plan.

C.6.1 Isopycnal processes

The tracer dispersion and float trajectories will be analyzed statistically to assess the flow structure of the ACC and along-isopycnal dispersion, both upstream and downstream of Drake Passage. The tracer will provide an integrated measure of dispersion, while the floats will yield a detailed estimate of the spatial and temporal variations of lateral dispersion. This analysis will encompass three activities: characterizing the background flow, computing dispersion from floats and tracer, and estimating fluxes from velocity-scalar correlations. Analyses like those described below have been used previously for turbulent diffusion in geophysical and idealized settings [e.g. Bennett, 1987; Davis, 1991; Sawford, 2001].

C.6.1.1 Characterizing the background flow. DIMES will provide an extensive survey of the flow field both west and east of Drake Passage through the combination of isopycnal following floats, CTD measurements collected as part of the DIMES surveys of finestructure, microstructure and tracer, DIMES profiling floats, as well as Argo floats in the region. These observations will be used to identify the position of the ACC frontal features during DIMES, to map isopycnal surface depths, and to characterize evolving quasi-geostrophic flow on and above the targeted isopycnal. One of the most straightforward methods for mapping quantities measured by floats (i.e. isopycnal depth and velocity on an isopycnal surface) is to bin average the observations geographically [Davis, 1991]. This is a widely-used procedure [e.g. Owens, 1984; Swenson and Niiler, 1996; Davis, 1998; Bauer et al. 2002] and one which has been modified and improved over recent years. Improvements include correcting for non-uniform float distributions [Davis, 1991], using objective analysis [Davis, 1998; Gille 2003a] and using spline-fitting techniques [Bauer, et al., 2002]. An important step is to take advantage of the statistical formalism of objective mapping [Bretherton et al., 1976] to merge multi-instrument observations that have different error bars [e.g. Wunsch, 1996].

The resulting mean fields will provide a reference framework, identifying the location of the ACC frontal features during the DIMES field program, permitting us to distinguish between processes occurring north and south of the primary frontal features, and allowing us to carry out analyses following the stream coordinates of the flow (see below).

C.6.1.2 Isopycnal diffusivity estimates. A major goal in DIMES is to estimate how material is dispersed along isopycnal surfaces. Isopycnal dispersion can be estimated from the spread of the tracer, and from the statistics of float displacements.

The tracer will be released over a period of 14 days as a patch about 40 km x 60 km in coordinates moving with the water, as described earlier. The tracer will be resampled within 2 weeks of the end of the injection, to confirm the initial distribution of tracer in density space. While this will be insufficient to completely map the patch laterally, a 50-chamber sampler deployed at the center of the towed sampling array will give a lateral resolution of the tracer streaks at this time of 600 meters along the sampling tows, and so will give estimates of streak width at times between 4 and 26 days since injection (with this “age” determined crudely from the trajectories of the isopycnal floats and shearmeters released with the tracer). These widths, coupled with strain estimates from the triplets will give a crude estimate of cross-streak diffusivity at scales of 1 to 10 km [Ledwell et al., 1998; Sundermeyer and Price, 1998; Polzin and Ferrari, 2005].

The tracer will then be resampled 12 months after the injection. While this is too long a period to provide information about the evolution of the isopycnal distribution, it will provide an integrated picture of the eddy stirring across and along the ACC. We will see, for example, whether the tracer becomes homogenized [Ledwell et al., 1998, Ledwell et al., 2000]. We will also be able to fit our measurements of the patch to predictions based on the float statistics to check consistency with the latter. The tracer may be spread all across Drake Passage as it enters Scotia Sea. Hence, information from the tracer on isopycnal dispersion past this point may be limited, although we may obtain useful estimates of exchange across the Polar Front beyond Drake Passage.

Floats are expected to provide a more accurate characterization of the time-evolving isopycnal dispersion. This analysis will be done both by using the trajectories of single floats and by using float pair separations. Single float trajectories yield the single particle diffusivity, the time derivative of the dispersion (the mean square separation of a particle from its starting position). Following Taylor [1921], the diffusivity can be expressed in terms of the integral of the autocorrelation of the "residual velocity", or the difference between the float velocity and the average regional velocity. For example, the diffusivity in the zonal direction can be written:

$$\kappa_x \equiv \frac{1}{2}\frac{d}{dt}\left\langle (x-x_0)^2 \right\rangle \approx \left\langle xu \right\rangle = \int_0^t \left\langle u(t')u(t) \right\rangle dt'$$

where x and u refer to the residual displacement and velocity. If the integral converges, the mixing is statistically equivalent to a diffusive process.

Derived in this quasi-Eulerian way [Davis, 1991], the diffusivity approximates the Eulerian isopycnal diffusivity (i.e. that which is used in models). We are currently working to evaluate the validity of this assumption in the DIMES region and the alternate ways of calculating the diffusivity [e.g. Zhurbas and Oh, 2004] by comparing Eulerian and Lagrangian diffusivity estimates obtained from the POP model. Mixing is not guaranteed *a priori* to be a diffusive process, but the results of previous studies suggest that if the mean is captured with sufficient detail, the diffusivities converge to well-defined values [e.g. Bauer et al., 2002].

Besides calculating diffusivities with respect to zonal and meridional coordinates, one can employ other coordinates, such as those defined by the topography [e.g. LaCasce and Speer, 1999; LaCasce, 2000]. The POP results suggest this may prove useful, given the extent to which topography affects float spreading. Combined with information about scalar fields, like temperature or isopycnal layer thickness, the absolute diffusivity can be also used to estimate scalar eddy fluxes [Taylor, 1921; Davis, 1987; Davis, 1991]; we consider this further below.

Pair statistics are a key feature of the DIMES float program and are central to Lagrangian dispersion. The dispersion of a cloud of tracer about its center of mass is proportional to the mean square separation (or "relative dispersion") of particles in the cloud, so tracking the pair separations provides a direct estimate of how the tracer is sheared out by eddies. Relative dispersion has been described only rarely in the ocean [Okubo, 1971; Kirwan et al., 1978; Davis, 1985; LaCasce and Bower, 2000; LaCasce and Ohlmann, 2003], and never in the ACC.

"Relative" diffusivity can be defined much like single particle diffusivity, but using the cross correlation between the pair's velocities. If the particles' motions are uncorrelated, the relative diffusivity can be shown to equal (twice) the single particle diffusivity. But if the particles are correlated, the dispersion (and hence the diffusivity) can exhibit a range of behavior, depending on the character of the strain field. Thus pair dispersion has been an important diagnostic tool for turbulence researchers. Coherent vortices, for example, can cause pair separations to grow exponentially in time, a signature of Lagrangian chaos. This produces filamentation in continuous tracers, as observed for example in the North Atlantic Tracer Release Experiment (NATRE) [Ledwell et al., 1998; Sundermeyer and Price, 1998; Polzin and Ferrari, 2004]. Exponential pair growth has been observed among balloons in the atmosphere [Morel and Larcheveque, 1974; Er-el and Peskin, 1981] and surface drifters in the Gulf of Mexico [LaCasce and Ohlmann, 2003].

Just as a mean flow affects single particle estimates, a mean shear impacts pair behavior. Two particles in a linear shear will separate at a constant velocity, causing their mean square separation to increase quadratically in time. If lateral mixing is superimposed on the shear, the relative dispersion can grow even faster [Young et al., 1982; Bennett, 1987]. The ACC represents a significant shear flow and these issues are relevant. However previous observations [Morel and Larcheveque, 1974; Er-el and Peskin, 1981; LaCasce and Bower, 2000; LaCasce and Ohlmann, 2003] and our analysis of POP model floats suggest that mean shear dispersion occurs at larger scales and that the small-scale stirring is generally isotropic. If this is the case, our analysis of DIMES pair dispersion will focus on phenomena such as filamentation that occur during the initial growth, when isotropic behavior is expected. Analysis of later behavior will necessarily take shear dispersion into account.

C.6.1.3 Direct estimates of eddy fluxes. In addition to computing diffusivities from float trajectories, we will also use the float data to compute Eulerian eddy fluxes $\langle v'z' \rangle$, where z is the depth of an isopycnal, smoothed over eddy length scales to account for inhomogeneous sampling. This is analogous to computing velocity-temperature correlations on an isobaric surface, as has been done for drifters in the California Current [Swenson and Niiler, 1996] and for Southern Ocean ALACE floats [Gille, 2003b]. This method for deriving eddy fluxes is distinctly different from methods using dispersion statistics. As Swenson and Niiler [1996] demonstrated, comparisons between these flux estimates and those inferred from the absolute diffusivity can be used to test the applicability of diffusive parameterizations of mixing.

Our analysis will project velocities into cross-stream and along-stream components in order to identify the cross-stream fluxes computed relative to best estimates of the mean field. Chinn and Gille [2005] estimated that a minimum of approximately 100 independent observations, corresponding to approximately 1000 float days of data, are required to determine eddy heat fluxes that are statistically different from zero. By this standard, the 150 floats deployed in DIMES will provide as many as 100 distinct geographic estimates, allowing us to evaluate spatial variations in eddy fluxes. As part of our analysis, we will carry out analogous calculations using model data to help identify biases or sampling errors in our eddy flux estimates.[1]

C.6.2 Diapycnal processes

C.6.2.1 Tracer estimates of diapycnal diffusivity The strategy for determining the diapycnal diffusivity in the SE Pacific is simple and familiar; one averages the tracer concentration on isopycnal surfaces over the whole patch and models the evolution from initial condition to final condition. The strategy for determining the diapycnal diffusivity in the Scotia Sea from the tracer is different because of the heterogeneity of the system. We will compare the diapycnal distribution along the north rim of the Scotia Sea with the inflow history at Drake Passage, taking into account the probability distribution function of the time of transit across the sea, as already discussed in Section C.4.2.

C.6.2.2 Turbulent dissipation estimates Data from the free-fall profilers will be calibrated and processed to uniformly incrementing pressure series of temperature, salinity, absolute horizontal velocity and the dissipation rates of turbulent kinetic energy and temperature variance. The former will be used to quantify the intensity and characteristics of the finescale flow field with geographic position and local flow conditions while the latter will be used to estimate diapycnal diffusivity following Osborn and Cox [1972] and Osborn [1980]. In regions characterized by thermohaline intrusions, the scalar microstructure data will be interpreted in terms of 2-D production-dissipation balances [Joyce, 1978; Davis, 1994; Ferrari and Polzin, 2005]. As we have done in previous Tracer Release Experiments, regional estimates of average diapycnal diffusivity will be constructed, with those estimates about the tracer isopycnal compared to the estimates of diapycnal tracer dispersion.

C.6.2.3 Finescale time series Data from the shearmeter floats will be acquired via Iridium phone link in early 2008 and in early 2009. The temperature, pressure and rotation (shear) data will be in processed form. It will be analyzed very rapidly at WHOI and made available to the community. The arrival-time data for the RAFOS tracking signals will be passed to float tracking groups and be made available to the community. The primary shearmeter product will be time-series of shear and strain, and gradient Richardson number at the location and depth of (*i.e.* within) the dispersing tracer cloud. Shear and strain data will be analyzed for seasonal and geographical variation. The shear intensity will be compared to prior estimates obtained during two experiments at the Mid-Atlantic Ridge [Duda 2004, Duda 2006]. Means and variations of shear (dominated by low-frequency waves), strain (dominated by high-frequency waves, and Richardson number will be analyzed for consistency with the Garrett-Munk spectral model. As noted earlier, one float will measure the horizontal vector of shear, allowing decomposition in rotary components, and providing information as to the role of near-inertial and internal tidal waves to the shear field.

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[1] Marshall and Shutts (1981) demonstrated that eddy fluxes can be represented as a sum of a rotational and a divergent component, where only the divergent component is responsible for a net eddy flux. The divergent and rotational components can be distinguished if mean streamlines and mean temperature are well known. In addition, the meridional component of the rotational flux is small when the fluxes are integrated zonally (or along streamlines) over a lengthscale that is long compared with the scale of eddies. Our fluxes will also be estimated as zonal integrals in order to evaluate and minimize spurious effects due to the rotational component.

C.6.2.4 Finescale profile data The finescale velocity and CTD profiles from the EM-APEX and ship-based profilers will be analyzed individually and in groups to generate several distinct products: (1) Absolute velocity profiles will be obtained by combining the adjacent surfacing locations with the integrated electric field velocity measurements over each round-trip profile. (2) Pairs of profiles separated by close to half an inertial period will be fitted to an inertial plus mean current to estimate the magnitude and direction of propagation of the inertial signal as well as the low-frequency shear (with an additional check provided for the EM-APEX data by using the velocity profile pairs in both the up and down directions). (3) Shear and stratification data will give indications of the overall scales of variability and internal wave energy encountered. Individual profiles will be used to form vertical shear wavenumber spectra for comparison with the Garrett and Munk [1975] internal wave model, upon which many finestructure mixing parameterizations are based. (4) Statistics of shear and strain will be converted into dissipation and diffusivity estimates using the Gregg [1989] and Polzin et al [1995] parameterizations. The comparison between these finestructure diffusivities averaged over the float deployments and the tracer-based diffusivity will be an important facet of the parameterization validation. (5) In addition, Richardson number statistics at various first-difference intervals will be used to connect other mixing parameterizations, such as those commonly used in models [Hallberg, 2000; Large et al., 1994; Pacanowski and Philander, 1981] with the finestructure-estimated diffusivities. (6) Density inversions will be analyzed for CTD noise and evidence of salinity spiking [Galbraith and Kelly, 1996] and the remaining Thorpe scales will be used to provide an additional estimate of dissipation rate and diffusivity, though (due to power and data considerations) the CTD sampling rate of the EM-APEX may not be fast enough to resolve overturns smaller than 1 m so this measure will only be useful during relatively intense mixing events. An important goal of the EM-APEX program will be to characterize the temporal variability of mixing by analyzing the multiple float releases for a seasonal cycle in inertial energy and inferred dissipation. In addition, hotspots indicated in the EM-APEX data will be compared with bathymetric and satellite maps and previous finestructure surveys for evidence of correlation with rough topography or enhanced eddy energy. These in turn will provide guidance for the subsequent DIMES microstructure surveys.

C.6.2.5 Diapycnal synthesis We anticipate documenting multiple sources of mixing in the ACC. First and perhaps most importantly in the deep ocean, we expect to observe significant upward propagation of internal waves, both from lee waves and from tidal generation. Based on modeling work now underway by Jennifer MacKinnon that is tightly related to DIMES, the bottom generated internal tide is believed to have an upward energy flux about an order of magnitude smaller than the lee waves when averaged globally, but locally they might be dominant. In the upper ocean, near-inertial waves generated by the wind are likely to have significant impact. Rotary vertical wavenumber spectra and time series of finescale velocity will be used to develop regional characterizations of the internal wave field and the associated diapycnal mixing.

We also plan to characterize the internal wave field relative to the mesoscale flow. One hypothesis we will explore, raised by St. Laurent and Garrett [2002], is that the ACC might be a sink for low-mode internal waves generated remotely. In support of that idea, Luc Rainville has been looking at the inertial and semidiurnal velocity and isopycnal displacement fields in the Kuroshio (from the KESS moorings) and finding that the mesoscale activity significantly affects the energy, flux, phase, and amplitude of the baroclinic waves, apparently scattering low modes to higher modes. Also, as noted previously, the relationships between mesoscale straining, intrusive finestructure and turbulent dissipation will be examined in the many frontal regions of the DIMES area.

This research will be carried out collaboratively by Toole, Duda, St. Laurent, Girton, Rainville and Naveira Garabato, with guidance provided by MacKinnon's modeling work. Toole and Rainville will have initial responsibility for the HRP-II data, while St. Laurent and Naveira Garabato will have comparable roles for the DMP data. Duda will be initially responsible for the shearmeter data and Girton will direct the EM-APEX effort. Once the various data are in processed form, the observations will be shared within the DIMES group and analyzed jointly. Close interaction with Ledwell is anticipated when we reach the stage of comparing microstructure and tracer estimates of diapycnal diffusivity, and with the isopycnal float team when investigating relationships between the mesoscale and internal wave fields. Ultimately, the DIMES synthesis will provide tests of model results and parameterizations against direct estimates of mixing in areas where turbulence processes may have order-one importance.

C.7 Summary

The various components of DIMES are interlinked, scientifically as well as logistically. The goal is to measure isopycnal and diapycnal mixing in the ACC region in a way that will help to understand the meridional overturning circulation, and that will lead to better parameterizations of mixing in numerical models. The tracer release will give integrated measurements of diapycnal diffusivity and isopycnal dispersion along and across the ACC. The isopycnal float program will study and quantify the mechanisms of isopycnal stirring and will obtain better estimates of isopycnal dispersion parameters. These floats will also provide part of the forcing information for diapycnal mixing, and the float trajectories and time of transit through the Scotia Sea will help interpret the tracer diapycnal dispersion there. Ship-based fine- and microstructure profilers will measure diapycnal mixing from top to bottom in austral summer and will evaluate existing parameterizations of diffusivity in terms of shear and stratification, and perhaps suggest new ones in this region of exceptionally strong mean and eddy currents and rough topography. The shearmeters in the tracer layer, and the EM-APEX floats in the upper 1500 meters will obtain year-round measurements of finestructure from which diapycnal diffusivities may be estimated using these parameterizations. The experiment will study the relatively smooth and low energy area west of Drake Passage first, and then the rough area of intense eddies in Drake Passage and Scotia Sea, two extremes which encompass conditions encountered around the whole ACC belt.

C.8 Work Plan (by project year)

Period 1: 9/1/06 – 8/31/07
Prepare tracer injection/sampling equipment, moorings, floats (EM/APEX/RAFOS/Shearmeter), profilers; begin construction of mean fields from historical ship hydrography and ALACE/PALACE/Argo datasets. PI planning workshop (WHOI).

Period 2: 9/1/07 – 8/31/08
Cruise US1: Tracer, SE Pacific moorings, RAFOS/EM/APEX/Shearmeter deployments; profiling floats return data; processing, tracking, analysis begins; mean field construction plus altimetry, vertical structure of eddy fluxes.

Period 3: 9/1/08 – 8/31/09
Cruises US2, UK1, USDP1: Tracer sampling; fine/microstructure profiling; RAFOS/EM-APEX float deployments; Scotia Sea moorings; simulation of dispersion and eddy flux studies from our own analyses; reanalysis and models; comparison of mean field with models; first results of diapycnal studies. PI workshop (NOCS).

Period 4: 9/1/09 – 8/31/10
Cruises USDP2, 3, UK2: Tracer sampling; hydrographic sections, fine/microstructure profiling; returns from 2-year-long RAFOS deployment; begin float tracking; implementation of statistical model of ACC tracer advection-diffusion; first results on float dispersion and internal wave propagation and breaking in the ACC. PI workshop (FSU).

Period 5: 9/1/10 – 8/31/11
Cruise UK3: Tracer survey, fine/microstructure profiling, mooring recovery.
Return of data from all EM and RAFOS floats; tracking; preliminary results on distribution and strength of eddy fluxes; begin assessing relationships between diapycnal and isopycnal mixing. PI workshop (WHOI).

C.9 Broader Impacts

DIMES is motivated by the need to understand the ocean circulation and the role it plays in moderating climate change, through both the heat budget and the carbon budget of the atmosphere-ocean system. Understanding climate change is of great importance to the well being of human society, and is the motivation of the entire CLIVAR program. Within CLIVAR and related programs, a number of process studies have been developed to understand important components of the climate system (http://www.clivar.org). One of these is SAMFLOC, for "SubAntarctic Mixed layers, FLuxes and Overturning Circulation". This project consists of hydrographic surveys of dense winter mixed layer formation in the southeast Pacific, and complements DIMES by providing additional northern boundary conditions on the near-surface descending branch of the upper cell. Also, EM-APEX float deployments planned near 140˚E by H. Phillips will complement our finestructure measurements in the western hemisphere.

Upper ocean processes including wind-driven mixing, Ekman transport and near-inertial energy input are important facets of the Southern Ocean mixing problem, not addressed above. Validation of satellite measurements is particularly valuable in such a remote region. To this end, meteorological and ADCP data from the DIMES cruises will augment the database of Southern Ocean surface observations and aid in calibrating air-sea fluxes in the outcropping and subduction regions of isopycnal layers. Furthermore, the various profiling measurements, including ship-deployed profilers and drifting EM-APEX floats, will serve to connect upper ocean properties with deeper levels through characterization of eddy and front structure and timeseries observations of near-inertial wave generation and propagation.

Much of the benefit of DIMES to climate change research will be realized through numerical models of the ocean circulation and of climate. DIMES observations will measure sub-grid-scale mixing parameters that are uncertain in current ocean models, and will study how they depend on variables that are accessible to models, such as topography, baroclinicity, and large scale flows. We will open our final science team meeting to the broader modeling community, and we will sponsor one or more special sessions at AGU or EGU meetings to foster the dialog necessary to lead to model improvement. More elaborate plans for working with the modeling community, perhaps in the form of a Climate Process Team, will evolve as the experiment unfolds.

DIMES will be a truly collaborative effort between U.S. and U.K. scientists, and so is intrinsically international. We have also initiated participation of scientists and students from Chile, and we plan to do the same with Argentina. In the U.S., DIMES will educate graduate students at SIO and FSU, will support one or more post-docs, will provide early-career support for Rainville, Girton, and St. Laurent, and will afford undergraduate research opportunities at all four institutions.

A web site will be maintained to transmit scientific results to the community of scientific colleagues. Funds have been budgeted at SIO for a system manager to develop the planning site http://dimes.ucsd.edu.

References

Alford, M.H., Improved global maps and 54-year history of wind-work on ocean inertial motions. *Geophys. Res. Lett.*, **30**(8), 1424–1427, 2003.

Banks, H. and R. Wood, Where to look for anthropogenic climate change in the ocean. *Journal of Climate*, **15**, 879–891, 2002.

Barth, J. A., T. J. Cowles, and S. D. Pierce, Mesoscale physical and bio-optical structure of the Antarctic Polar Front near 170°W during austral spring. *J. Geophys., Res*., **106**, 13,879-13,902, 2001.

Barth, J.A., D-Hebert, A.C-Dale, and D. S-Ullman, Direct observations of along-isopycnal upwelling and diapycnal velocity at a shelfbreak front. *J. Phys. Oceanogr*., **34**, 543-565, 2004.

Bauer, S., M, S. Swenson, and A. Griffa, Eddy-mean flow decomposition and eddy diffusivity estimates in the tropical Pacific Ocean. 2: Results. *J. Geophys. Res*., **107**(010), 2000JC000613, 2002.

Bennett, A. F., A Lagrangian analysis of turbulent diffusion. *Rev. Geophys,* **25**, 799-822, 1987.

Boyd, P.W., A. J. Watson, C. S. Law, E. R. Abraham, T. Trull, R. Murdock, D. C. E. Bakker, A. R. Bowie, K. O. Buesseler, H. Chang, M. Charette, P. Croot, K. Downing, R. Frew, M. Gall, M. Hadfield, J. Hall, M. Harvey, G. Jameson, J. Laroche, M. Liddicoat, R. Ling, M. T. Maldonado, R. M. Mckay, S. Nodder, S. Pickmere, R. Pridmore, S. Rintoul, K. Safi, P. Sutton, R. Strzepek, K. Tanneberger, S. Turner, A. Waite, and J. Zeldis, A mesoscale phytoplankton bloom in the polar Southern Ocean stimulated by iron fertilization. *Nature,* **407**, 695–702; doi:10.1038/35037500, 2000.

Bretherton, F. P., R. E, Davis, and C. B Fandry, A technique for objective analysis and design of oceanographic experiments applied to MODE-73. *Deep-Sea Res*., **23**, 559 582, 1976.

Bryden, H. L. and S. A. Cunningham, How wind-forcing and air–sea heat exchange determine the meridional temperature gradient and stratification for the Antarctic Circumpolar Current. *J. Geophys. Res*., **108**(C8), Art. No. 3275, 2003.

Caldeira, K. and P. B. Duffy, The role of the Southern Ocean in uptake and storage of anthropogenic carbon dioxide. *Science*, **287**, 620–622, 2000.

Chinn, B. S. and S. T. Gille, Estimating Eddy Heat Flux from Float Data in the North Atlantic: The Impact of Temporal Sampling Interval. submitted to *J. Atmos. Ocean. Tech*, 2005.

Danabasoglu, G., J. C. McWilliams, and P. R. Gent, The role of mesoscale tracer transports in the global ocean circulation. *Science*, **264**, 1123–1126, 1994.

Davis, R. E., Drifter observations of coastal surface currents during CODE: The statistical and dynamical view. *J. Geophys. Res*., **90**, 4756, 1-772, 1985.

Davis, R. E., Modeling eddy transport of passive tracers. *J. Mar. Res*., **45**, 635-666, 1987.

Davis, R. E., Observing the general circulation with floats. *Deep-Sea Res*., **38**, S531-S571, 1991.

Davis, R.E., Diapycnal mixing in the ocean: The Osborn-Cox model. *J. Phys. Oceanogr*., **24**, 2560-2576, 1994.

Davis, R. E., Sampling turbulent dissipation. *J. Phys. Oceanogr*., **26**, 341-358, 1996.

Davis, R. E., Preliminary results from directly measuring mid depth circulation in the tropical and South Pacific. *J. Geophys. Res*., **103**, 24, 619-24,639, 1998.

Duda, T. F., Finescale shear at 1660 and 2850 dbar over the Mid-Atlantic Ridge in the eastern Brazil Basin. *J. Phys. Oceanogr*., **34**, 1281-1292, 2004.

Duda, T. F., Comparison of deep-ocean finescale shear at two sites along the Mid-Atlantic Ridge. *Deep-Sea Research II*, in press, 2006.

Er-el, J. and R. Peskin, Relative diffusion of constant-level balloons in the Southern Hemisphere. *J. Atmos. Sci.*, **38**, 2264-2274, 1981.

Ferrari, R., and K. L. Polzin, Finescale structure of the T-S relation in the eastern North Atlantic. *J. Phys. Oceanogr.*, **35**, 1437-1454, 2005.

Freeland, H.J., P.B. Rhines, and H.T. Rossby, Statistical observations of the trajectories of neutrally buoyant floats in the North Atlantic. *J. Marine Res.*, **33**, 383-404, 1975.

Galbraith, P.S., and D.E. Kelley, Identifying overturns in CTD profiles. *J. Atmos. Ocean. Tech.*, **13**, 688–702, 1996.

Ganachaud, A., and C. Wunsch, Improved estimates of global ocean circulation, heat transport and mixing from hydrographic data. *Nature*, **406**, 453-457, 2000.

Garrett, C. J. R., and W. H. Munk, Space–time scales of internal waves: A progress report. *J. Geophys. Res.*, **80**, 291–297, 1975.

Garrett, C., K. Speer, and E. Tragou, The relationship between water mass formation and the surface buoyancy flux, with application to Phillips Red Sea model. *J. Phys. Oceanogr.*, **25**, 1696–1705, 1995.

Gille, S. T., Warming of the Southern Ocean since the 1950s. *Science*, **295**, 1275–1277, 2002.

Gille, S. T., Float observations of the southern ocean: Part 1, Estimating mean fields, bottom velocities, and topographic steering. *J. Phys. Oceanogr*, **33**, 1167-1181, 2003.

Gille, S. T., Float observations of the Southern Ocean: Part 2, Eddy fluxes. *J. Phys. Oceanogr.*, **33**, 1182–1196, 2003.

Gille, S. T., and L. Romero, Statistical behavior of ALACE floats at the surface of the Southern Ocean. *J. Atmos. Ocean. Tech.,* **20**, 1633-1640, 2003.

Girton, J. B., and T. B. Sanford, EM-APEX observations in a mode-water eddy: Internal waves, mean velocity structure, and upper-ocean mixing. *Eos Trans. AGU*, **87**(36), Ocean Sci. Meet. Suppl., Abstract OS13H-05, 2006.

Gnanadesikan, A., and R. Hallberg, On the relationship of the circumpolar current to Southern Hemisphere winds in coarse resolution ocean models. *J. Phys. Oceanogr.,* **30**, 2013-2034, 2000.

Gregg, M. C., Scaling turbulent dissipation in the thermocline. *J. Geophys. Res.*, **94**, 9686–9698, 1989.

Gregg, M. C., G. S. Carter, and E. Kunze, Corrigendum. *J. Phys. Oceanogr.*, **35**, 1712-1715, 2005.

Hallberg, R., Time integration of diapycnal diffusion and Richardson number dependent mixing in isopycnal coordinate ocean models. *Monthly Weather Review*, **10**, 1402–1419, 1970–1980, 2000.

Hallberg, R., and A. Gnanadesikan, The role of eddies in determining the structure and response of the wind-driven Southern Hemisphere overturning: Initial results from the modeling of eddies in the Southern Ocean project. *J. Phys. Oceanogr.,* in press 2005. available at: http://www.gfdl.noaa.gov/~rwh/papers/MESO_revised.pdf

Han, S.-C., C.K. Shum and K. Matsumoto, GRACE observations of M2 and S2 ocean tides underneath the Filchner-Ronne and Larsen ice shelves, Antarctica. *Geophys. Res. Lett.*, **32**, doi: 10.1029/2005GL024296, 2005.

Iwao, T., M.Endoh, N.Shikama, and T.Nakano, Intermediate circulation in the northwestern North Pacific derived from subsurface floats. *J. Phys. Oceanogr.*, **59**, 893-904, 2003.

Johnson, G. C. and H. L. Bryden, On the size of the Antarctic Circumpolar Current. *Deep- Sea Res.*, **36,** 39–53, 1989.

Joyce, T.M., A note on the lateral mixing of water masses. *J. Phys. Oceanogr.*, **7**, 626-629, 1977.

Karsten, R. H. and J. Marshall, Constructing the residual circulation of the ACC from observations. *J. Phys. Oceanogr*., **32**, 3315–3327, 2002.

Karsten, R. Jones, H., and J Marshall, The role of eddy transfer in setting the stratification and transport of a Circumpolar Current. *J. Phys. Oceanogr.,* **32**, 39-54, 2002.

Karsten, R. and J.Marshall, Constructing the residual circulation of the ACC from observations. *J. Phys. Oceanogr.,* 2002

Keffer, T and G. Holloway, Estimating Southern Ocean eddy flux of heat and salt from satellite altimetry. *Nature*, **332**, 624-626, 1988.

Kirwan, A.D., G.J. McNally, E. Reyna and W.J. Merrell, The near-surface circulation of the eastern North Pacific. *J. Phys. Oceanogr*., **8**, 937-945, 1978.

Klatt, O., O. Boebel, I. Nunez-Riboni, and E. Fahrbach, Float observations within the Weddell Sea, CLIVAR Exchanges, **35**, 43-46, 2005. http://www.clivar.org/publications/exchanges/ex35/pdf/Exchanges35_web.pdf.

Kunze, E., L. K. Rosenfield, G. S. Carter, and M. C. Gregg, Internal waves in Monterey submarine canyon, *J. Phys. Oceanogr*., **32**, 1890-1913, 2002.

LaCasce, J. H., and K. G. Speer, Lagrangian statistics in unforced barotropic flows. *J. Mar. Res*., **57**, 245-274, 1999.

LaCasce, J. H., Floats and f/H. *J. Mar. Res*., **58**, 61-95, 2000.

LaCasce, J. H. and A. Bower, Relative dispersion in the subsurface north Atlantic. *J. Mar. Res*., **58**, 863-894, 2000.

LaCasce, J. H. and C. Ohlmann, Relative dispersion at the surface of the Gulf of Mexico. *J. Mar. Res*., **61**, 285-312, 2003.

Large, W. G., J. C. McWilliams, and S. Doney, Oceanic vertical mixing: A review and a model with a nonlocal boundary layer parameterization. *Rev. Geophys*., **32**, 363–403, 1994.

Lazarevich, P., Cruise report: Southern Ocean acoustics. D-Scholarship Repository Article #2, Florida State University, http://dscholarship.lib.fsu.edu/oceanography/2, 2003.

Ledwell, J. R., A. J. Watson, and C. S. Law, Mixing of a tracer in the pycnocline. *J. Geophys. Res*., **103** (C10), 21,499–21,529, 1998.

Ledwell, J. R., K. L. Polzin, L. C. St. Laurent, R. W. Schmitt, and J. M. Toole, Evidence for enhanced mixing over rough topography in the abyssal ocean. *Nature*, **403** (6766), 179–182, 2000.

Lee, M-M. and A Coward, Eddy mass transport for the Southern Ocean in an eddy-permitting global ocean model. *Ocean Modelling*, **5**, (3), 249-266, 2003.

Lueck, R. G., F. Wolk, and H. Yamazaki, Oceanic velocity microstructure measurements in the 20th Century. *J. Phys. Oceanogr.*, **58**, 153—174, 2002.

MacKinnon, J.A. and M.C. Gregg, Mixing on the late-summer New England shelf – Solibores, shear and stratification. *J. Phys. Oceanogr*., **33**, 1476-1492, 2003.

Maltrud, M. E., and J. L. McClean, An eddy resolving global 1/10-degree ocean simulation. *Ocean Modelling*, **8**, (Issues 1-2), 31-34, 2005. http://authors.elsevier.com/sd/article/S146350030300684.

Marshall, J., D. Olbers, H. Ross, and D. Wolf-Gladrow, Potential vorticity constraints on the dynamics and hydrography of the Southern Ocean. *J. Phys. Oceanogr*., **23**, 465–487, 1993.

Marshall, J. and T. Radko, Residual-mean solutions for the ACC and its associated overturning circulation. *J. Phys. Oceanogr*., **33**, 2341–2354, 2003.

McKeague, I., G. Nicholls, and K. Speer, Statistical inversion of tracer data in the South Atlantic Ocean. *J. Mar. Res.*, **63**, 683-704, 2005.

Morel, P. and M, Larcheveque, Relative dispersion of constant-level balloons in the 200 mb general circulation. *J. Atmos. Sci*., **31**, 2189-2196, 1974.

Munk, W.H., Abyssal recipes. *Deep-Sea Res*., **13**, 707-730, 1966.

Munk, W., and C. Wunsch, Abyssal Recipes II: Energetics of tidal and wind mixing. *Deep- Sea Res*., *I*, **45,** 1977-2010, 1998.

Naveira Garaboto, A. C., J. T. Allen, H. Leach, V. H. Strass, and R. T. Pollard, Mesoscale subduction at the Antarctic Polar Front driven by baroclinic instability. *J. Phys. Oceanogr*., **31**, 2087–2107, 2001.

Naveira Garabato, A. C., K. L. Polzin, B. A. King, K. J. Heywood, and M. Visbeck, Widespread intense turbulent mixing in the Southern Ocean. *Science*, **303**, 210–213, 2004.

Okubo, A., Oceanic diffusion diagrams. *Deep-Sea Res*., **18**, 789-802, 1971.

Orsi, A. H., T. Whitworth III, and W. D. Nowlin, Jr., On the meridional extent and fronts of the Antarctic Circumpolar Current. *Deep-Sea Res. I*, **42**, 641-673, 1995.

Osborn, T.R. and C. S. Cox, Oceanic fine structure. *Geophys. Fluid Dyn.*, **3**, 321–345, 1972.

Osborn, T. R., Estimates of the local rate of vertical diffusion from dissipation measurements. *J. Phys. Oceanogr*., **10**, 83–89, 1980.

Owens, W. B., A statistical description of the vertical and horizontal structure of eddy variability on the edge of the Gulf Stream recirculation. *J. Phys. Oceanogr*., **14**, 195-205, 1984.

Pacanowski, R. C., and S. G. H. Philander, Parameterization of vertical mixing in numerical models of tropical oceans. *J. Phys. Oceanogr*., **11**, 1443–1451, 1981.

Peltier, W. R., and C. P. Caulfield, Mixing efficiency in stratified shear flows. *Ann. Rev. Fluid Mech*., **35**, 135-167, 2003.

Polzin, K. L., J. M. Toole, and R. W. Schmitt, Finescale parameterizations of turbulent dissipation. *J. Phys. Oceanogr*., **25**, 306–328, 1995.

Polzin, K., and E. Firing, Estimates of diapycnal mixing using LADCP and CTD data from 18^{o}S. *Internat. WOCE Newslett.*, **29**, 39-42, 1997.

Polzin, K. and R. Ferrari, Isopycnal dispersion in NATRE. *J. Phys. Oceanogr*., **34**, 247-257, 2004.

Polzin, K. L., J. M. Toole, J. R. Ledwell, and R. W. Schmitt, Spatial variability of turbulent mixing in the abyssal ocean. *Science*, **276**, 93-96, 1997.

Polzin, K., A heuristic description of internal wave dynamics. *J. Phys. Oceanogr*., **34**, 214–230, 2004a.

Polzin, K., Idealized solutions for the energy balance of the finescale internal wave field. *J. Phys. Oceanogr*., **34**, 231–246, 2004b.

Richardson, P. L., J. R. E. Lutjeharms, and O. Boebel, Introduction to the 'Inter-ocean exchange around southern Africa. *Deep-Sea Res. II*, **50**, 1-12, 2003.

Rossby, H. T, E. R, Levine, and D. N. Conners, The isopycnal Swallow float - a simple device for tracking water parcels in the ocean. *J. Phys. Oceanogr.,* **14,** 511-525, 1985.

Rossby, T., J. Fontaine, and E. C. Carter, The f/h float - measuring stretching vorticity directly. *Deep-Sea Res*., **41**, 975-992, 1994.

Rossby, T., The North Atlantic Current and surrounding waters: At the crossroads. *Rev. Geophys*., **34**, 463-81, 1996.

Rossby, T., and D. Hebert, LIDEX-Lagrangian isopycnal dispersion experiment. In Lagrangian analysis and prediction of coastal and ocean dynamics, Key Largo. http://www.rsmas.miami.edu/LAPCOD/2002-KeyLargo/abstracts/absA205.html., 2002.

Sallee, J.-B., N. Wienders, K. Speer, and R. Morrow, Formation of subantarctic mode water in the southeastern Indian Ocean, *Ocean Dynamics*, Feb 2006, 1-18, DOI: 10.1007/s10236-005-0054-x, 2006.

Sanford, T. B., R. G. Drever, and J. H. Dunlap, A velocity profiler based on principals of geomagnetic induction. *Deep-Sea Res*., **25**, 183-210, 1978.

Sanford, T. B., J. H. Dunlap, J. A. Carlson, D. C. Webb, and J. B. Girton, Autonomous velocity and density profiler: EM-APEX, Proceedings of the IEEE/OES Eighth Working Conference on Current Measurement Technology, pp. 152-156, 28-29 June2005.

Sawford, B., Turbulent relative dispersion. *Ann. Rev. Fluid Mech*., **33**, 289-317, 2001.

Schmitt, R. W., J. R. Ledwell, E. T. Montgomery, K. L. Polzin, and J. M. Tool, Enhanced diapycnal mixing by salt fingers in the main thermocline of the tropical Atlantic. *Science*, **308**, 685-688, 2005.

Simmons, H.L., R.W. Hallberg and B.K. Arbic, Internal wave generation in a global baroclinic tide model. *Deep-Sea Res. II*, **51**, 3043-3068, 2004.

Sloyan, B. M., and S. R. Rintoul, Estimates of area-averaged diapycnal fluxes from basin-scale budgets. *J. Phys. Oceanogr*., **30**, 2320-2341, 2000.

Speer, K., E. Guilyardi, and G. Madec, Southern Ocean transformation in a coupled model with and without eddy mass fluxes. *Tellus*, **52A**, 554-565, 2000.

Speer, K., S. R. Rintoul, and B. Sloyan, The diabatic Deacon cell. *J. Phys. Oceanogr*, **30**, 3212–3222, 2000.

Stern, M. E., *Ocean Circulation Physics*, Academic Press, New York, 246 pp., 1975.

St. Laurent, L., and R. W. Schmitt, The Contribution of Salt Fingers to Vertical Mixing in the North Atlantic Tracer Release Experiment. *J. Phys. Oceanogr.,* **29**, 1404–1424, 1999.

St. Laurent, L., and C. Garrett, The role of internal tides in mixing the deep ocean. *J. Phys. Oceanogr*., **32**, 2882-2889, 2002.

Stommel, H., and A. B. Arons, On the abyssal circulation of the world ocean – II, An idealized model of the circulation pattern and amplitude in oceanic basins. *Deep-Sea Res*., **6**, 217-233, 1960.

Sundermeyer, M. A., and J. F. Price, Lateral mixing and the North Atlantic Tracer Release Experiment: Observations and numerical simulations of Lagrangian particles and a passive tracer. *J. Geophys. Res.*, **103**, 21481-21498, 1998.

Swenson, M. S., and P. Niiler, Statistical analysis of the surface circulation of the California Current. *J. Geophys. Res.*, **101**, 22631-22646, 1996.

Tandon, A., and C. Garrett, Water mass formation from thermodynamics: A framework for examining compatibility with dynamics. *Internat. WOCE Newslett.*, **28**, 34–36, 1997.

Taylor, G. I., Diffusion by continuous movements. *Proc. London Math. Soc*., **20**, 196-212, 1921.

Thompson, A. F., S. T. Gille, J. A. MacKinnon, and J. Sprintall, Spatial and temporal patterns of small-scale mixing in Drake Passage. *J. Phys. Oceanogr*., accepted, 2006.

Toggweiler, J. R., and B. Samuels, On the ocean's large-scale circulation in the limit of no vertical mixing. *J. Phys. Oceanogr*., **28**, 1832-1852, 1998.

Toole, J. M., K. L. Polzin, and R. W. Schmitt, Estimates of diapycnal mixing in the abyssal ocean. *Science*, **264**, 1120-1123, 1994.

Warren, B., J. LaCasce, and P. Robbins, On the obscurantist physics of "form drag" in theorizing about the Circumpolar Current. *J. Phys. Oceanogr.,* **26**, 2297-2301, 1996.

Watson, A. J., and A. C. Naveira Garabato, The role of Southern Ocean mixing and upwelling in glacial-interglacial atmospheric CO_2 change. *Tellus B*, **58**, 73-87, 2006.

Webb, D., and N. Suginohara, Vertical mixing in the ocean. *Nature*, **409**, 37, 2001.

Wunsch, C., *The Ocean Circulation Inverse Problem*. Cambridge Univ. Press, New York, 1996.

Young, W. R., P. B, Rhines, and C. J. R. Garrett, Shear-flow dispersion, internal waves, and horizontal mixing in the ocean. *J. Phys. Oceanogr*., **12**, 515-527, 1982.

Zhang, H.-M-, M. D. Prater, and T. Rossby, Isopycnal Lagrangian statistics from the North Atlantic Current RAFOS float observations. *J. Geophys. Res*., **106**, 13,817-13,836, 2001.

Zhurbas, V. M. and I. S. Oh, Drifter-derived maps of lateral diffusivity in the Pacific and Atlantic Oceans in relation to surface circulation patterns. *J. Geophys. Res*., **109**, c05015.5, 2004.