Collaborative Research: Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean (DIMES)—Float Component

Project Summary

This component of the Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean (DIMES) will use autonomous floats to measure mixing along isopycnals.

**Intellectual Merit:** DIMES focuses on diapycnal and isopycnal mixing in the Southern Ocean, because understanding mixing in this region is crucial for understanding of the global meridional overturning circulation. 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. Isopycnal mixing rates obtained in DIMES will be used to advance both the physical understanding of processes governing meridional overturning of the ocean and the numerical simulation of these processes.

The float component of DIMES will deploy a total of 200 acoustically-tracked isopycnal-following floats split between two different isopycnal surfaces. These floats will be tracked from the relatively quiescent southeastern Pacific through Drake Passage, and into the Scotia Sea, where topography is expected to play a role in controlling their behavior.

Analysis of the float data will focus on using dispersion statistics to quantify isopycnal mixing and to estimate eddy fluxes across the ACC. The estimates will be compared with fluxes derived from repeat measurements in Drake Passage and with results from isopycnal and level models.

**Broader Impact:** DIMES will deploy sound sources and isopycnal-following autonomous floats for the first time in Southern Ocean, and carry out pathbreaking research using the floats. 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 graduate students at FSU and SIO and will offer research opportunities to approximately one undergraduate per year.
Results from Prior NSF Support

Southern Ocean Transport OCE-0117618 (K. Speer) 10/01/01-09/30/04. $414,000. Climate Process Team: Eddy-mixed layer interactions OCE 0336697 (K. Speer) 09/01/03-08/31/05, $201,100.

Recent support also involves in-situ field testing and modeling of acoustic propagation in the Southern Ocean environment. See http://dscholarship.lib.fsu.edu/oceanography/. Publications supported by these NSF projects:


CAREER: Linking Southern Ocean Dynamics to Global Climate OCE-9985203/OCE-0049066 (S. Gille); 4/1/00 - 3/31/06, $472,046.

This project has focused on analysis of Southern Ocean autonomous float and drifter data, with comparisons to historic hydrography and wind data. Major findings have shown that float temperatures at depths between 700 and 1100 m are systematically warmer than older hydrographic temperatures, implying that the Southern Ocean has warmed approximately 0.01˚C/year since the 1950s. Eddy heat fluxes and topographic steering have also been explored.


A Mediterranean Undercurrent Seeding Experiment – Analysis and Modeling OCE 96-16952 (A. Bower and A. Rogerson (Effective August 1, 1999 LaCasce replaced Rogerson as Co-PI); 2/1/97-7/31/00, $346,000.

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LaCasce replaced Audrey Rogerson for the final four months of this project. The other P.I., Amy Bower, had deployed RAFOS floats in the Mediterranean sea outflow in pairs, so LaCasce and Bower took that data, as well as other data from earlier experiments, and calculated particle pair statistics for the North Atlantic.


**PROJECT DESCRIPTION**

1 **Introduction**

The Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean (DIMES) is a three-component field program. The project will use microstructure measurements, tracer release, and floats to study mixing within the climatically important region of the Antarctic Circumpolar Current (ACC). The three components of DIMES are synergistic, not only logistically, but also scientifically. At the request of NSF program management, separate proposals have been written for each component. Section 1 of this proposal represents an introduction to DIMES that is common to all three proposals. Subsequent sections of this proposal describe the specific details of the DIMES isopycnal float program.

1.1 **Motivation**

DIMES is focused on mixing in the Southern Ocean because the process is critical for explaining the global meridional overturning circulation (MOC). As shown schematically in Fig. 1, in the Southern Ocean, deep and intermediate waters are hypothesized to upwell along isopycnals. At the surface, these water masses are advected meridionally and transformed to create bottom water and SubAntarctic Mode Water, which in turn downwell along isopycnals. Since the primary current of the Southern Ocean, the ACC, is zonally connected, no mean geostrophic current exists that can carry water meridionally along these isopycnal surfaces. The dominant mechanism for the meridional transport of mass, heat, and potential vorticity above the topography and below the wind driven Ekman layer at the latitude band of Drake Passage is thought to be quasi-geostrophic, mesoscale eddy motions (Johnson and Bryden, 1989; Marshall et al., 1993; Bryden and Cunningham, 2003; Marshall and Radko, 2003; Speer et al., 2000). Standing waves (as opposed to transient eddies) or internal lee waves are also mechanisms for eddy fluxes whose role may be important, at least locally.

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 (e.g. 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). In climate-scale ocean models, the structure and size of the Southern Ocean limb of the MOC change substantially, depending on the representation of subgrid-scale
Figure 1: Schematic meridional overturning, including the wind-driven Ekman transport, deep and bottom water flow against topography, and eddy-driven mass fluxes at mid-depth (from Olbers et al. (2004), adapted from Speer et al. (2000).) Diapycnal mixing can “short-circuit” these paths.

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 forms for these mixing processes. 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 Garaboto et al., 2001; Barth et al., 2001).

Existing estimates of diapycnal mixing in the ocean interior are based on internal wave models validated at mid-latitude (e.g. Naveira Garabato et al., 2004), and existing measures of mixing due to mesoscale eddies are based on isolated current meter measurements (e.g. Phillips and Rintoul, 2000) and isobaric (ALACE) floats that were not tracked continuously (Gille, 2003).

An important aspect of DIMES is that the project seeks to measure both diapycnal and isopycnal mixing at the same time. The two processes are closely linked through the buoyancy budget (Garrett et al., 1995; Tandon and Garrett, 1997; Speer et al., 2000). Some studies have speculated that all sub-surface mixing in the Southern Ocean occurs on isopycnals and that diapycnal mixing depends entirely on buoyancy fluxes at the ocean surface (e.g. Treguier et al., 1997; Karsten and Marshall, 2002; Bryden and Cunningham, 2003). However, observations suggest that diapycnal mixing varies spatially and is significant in locations such as the Drake Passage and the Scotia Sea, where topography is rough and tidal and mesoscale eddy amplitudes are large (Heywood et al., 2002; Naveira Garabato et al., 2004). This subsurface diapycnal mixing can “short-circuit” the meridional fluxes associated with the Southern Ocean MOC. For example, a CO₂ anomaly subducted with Antarctic Bottom Water could reemerge relatively quickly if the anomaly were diffused vertically into the overlying deep waters within the ACC and carried back south. Moreover, in addition to the possibility noted above that diapycnal mixing processes might support residual ageostrophic circulations, Naveira Garabato et al. (2004) also note that turbulent dissipation within
the ACC may be a significant sink for the energy put into the ocean by winds acting on the Southern Ocean.

1.2 DIMES Goals

DIMES aims to obtain multiple measures of both diapycnal diffusivity and mesoscale isopycnal diffusivity at several levels and in several environments within the ACC. The project will focus on the southeast Pacific, the Drake Passage and Scotia Sea, and the southwest South Atlantic. We have chosen this particular sector of the Southern Ocean for DIMES primarily because of the expected contrast in mixing intensity west versus east of the Drake Passage.

Diapycnal diffusivity will be estimated from the dispersion of a passive tracer initially released near 1500 meters depth and from full-depth finestructure and microstructure measurements in all three of these regions, with special attention on flow and topographic features likely to support strong mixing. The tracer experiment will yield a time-space-integrated estimate of the diapycnal diffusivity in the Southeast Pacific at one level over a patch whose area will grow from 1000 km$^2$ initially to more than 1 million km$^2$ after one year. The time and space averaging scales for the diffusivity estimate to be derived for the Scotia Sea region will be similar. The proposed finestructure and microstructure profiling will return data over the full water column. When weather permits, profiles will be collected at each tracer sampling station. Our cruise schedule also includes additional time for focused profiling in regions of observed or anticipated intense turbulent mixing. Importantly, the High Resolution Profiler we will use provides not only measurements of dissipation rate, from which diapycnal diffusivity can be estimated, but also the finescale shear and stratification, from which the flow of energy from large vertical scales to dissipation scales can be characterized, and from which the nature of the processes that force the mixing may be determined. Complementing the austral summer survey work, a Moored Profiler mooring will provide full depth velocity and density profiles at one point for a period of a year. In addition, an array of Shearmeter floats will measure shear and stratification (strain) at one depth and at 7.5-meter separation only, but over the full time of the tracer dispersion and along representative paths within the tracer cloud. These measurements all serve to complement one another in the estimates of diapycnal mixing and the physical processes that force it. Given the large area to be sampled in DIMES and the expected large dynamic range in turbulent dissipation rates over this region, the combination of measurements will be key to quantifying the average diapycnal diffusivity characterizing each region and documenting the physical processes responsible for the mixing.

Isopycnal diffusivity will be estimated from the trajectories of acoustically-tracked isopycnal floats released on two isopycnal surfaces in the ACC and from the lateral dispersion of the tracer patch. The floats and tracer will both give estimates of isopycnal dispersion, although the floats have the advantage that they can all be located acoustically and their trajectories documented and used for the study of dispersion mechanisms. Two different float designs are planned. Three-quarters of the floats will be isopycnal-following RAFOS floats, designed to have a compressibility that matches that of sea water. The remaining floats will be modified Argo floats, which will be acoustically tracked and will follow density by actively pumping to remain on an isopycnal surface. Both of these float designs are likely to stray a little from their designated density. The tracer cloud will also suffer steady diapycnal spreading, but which will be well known from the measurement program. None of the approaches is perfectly isopycnal, but they are diapycnal in different ways, and a comparison of the isopycnal dispersion will be of interest. The tracer will probably be well
spread across the full width of the Drake Passage when it arrives there, and so information about isopycnal dispersion from the tracer in the Scotia Sea and beyond will be minimal, while the floats will continue to provide the statistics necessary to estimate isopycnal diffusivity.

The progression of the tracer and the floats across the study region will set the pace and the evolution of the experiment. 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, the 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 mixing in the ACC. Once the tracer and floats pass into and through the 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 simple circumpolar...
extrapolation guided by the bathymetry to analysis of models that employ regionally-validated sub-grid-scale parameterizations.

1.3 DIMES Field Program

A time line for the major components of the experiment is illustrated in Fig. 2. In austral summer 2007-08, a cruise will be mounted to deploy sound sources in the southeast Pacific, install one Moored Profiler mooring in Drake Passage, inject the tracer and deploy floats. Survey cruises to sample the evolution of the tracer will be carried out annually thereafter. In austral summer 2008-09 the tracer will be surveyed in the Pacific, accompanied by finesture and microstructure profiling at each tracer station. The more western sound sources and the Moored Profiler mooring will also be recovered on this cruise. To continue to track the floats as they transit the Scotia Sea and enter the southwest South Atlantic, the recovered sound sources will be redeployed east of Drake Passage on a second cruise in 08-09. The tracer will be sampled in the Scotia Sea in 2009-10 from a UK ship. Then in austral summer 2010-11, again from a UK ship, the tracer distribution in the Scotia Sea and southeast Atlantic will be measured together with a second program of finesture and microstructure profiling.

In addition to these annual survey cruises, tracer will be sampled in Drake Passage every six months during the experiment to provide the boundary condition for the Atlantic part of the tracer experiment. Sampling at Drake Passage in the summer will be performed as part of the annual survey cruises listed above. Sampling in the austral winters of 2008, 09 and 10, will be performed from US science support ships, probably R/V Gould, as they cross to Antarctica.

1.4 DIMES in a Broader Context: US and International Components

DIMES was conceived as a contribution to the international CLIVAR program, and it has received endorsements from the US CLIVAR Southern Ocean Working Group and the US CLIVAR Scientific Steering Committee. DIMES has also been proposed as a component to the International Polar Year (IPY; March 2007-March 2009), and analysis of DIMES data will benefit from the rich array of coincident observations planned as part of the IPY.

The DIMES field program involves three US groups. Microstructure and finesture measurements are proposed by Toole, Schmitt and Montgomery (WHOI). A neutrally-buoyant float program is proposed by Speer (FSU), Gille (SIO), and Owens/LaCasce (WHOI). The tracer release experiment is proposed by Ledwell and Duda (WHOI). DIMES planning takes advantage of Parallel Ocean Program (POP) model runs provided by M. Maltrud at the Los Alamos National Laboratory and J. McClean at the Naval Postgraduate School under separate funding. Although the DIMES field program does not include an explicit model development component, DIMES will encourage complementary modeling efforts, and results will be available to aid in improving coarser resolution climate models.

DIMES has also been planned with a substantial contribution from the United Kingdom. The UK proposal, to be submitted in June 2005, will involve a group of almost 20 investigators, including A. Watson and K. Heywood at the University of East Anglia, and A. Naveira Garabato and B. King at the Southampton Oceanography Center. The UK investigators will seek support to participate in the tracer release experiment, as well as to conduct microstructure and finesture sampling to augment the measurements proposed by the US group. The DIMES field plan has been
constructed in the anticipation that a significant fraction of the experiment will be performed from
UK ships.

Contacts will be made with oceanographers in Chile and in Argentina for their cooperation and
possible collaboration in the DIMES survey cruises and participation in the data analysis activities.

2 Lagrangian Measures of Isopycnal Stirring in the ACC

2.1 Objectives

Acoustically-tracked floats have been used for years to study the ocean. Their autonomous nature
means they can sample much broader regions than could reasonably be surveyed from a ship.
Because they are swept along by the current, their motions reflect directly on oceanic mixing. Fluid
parcels tend to mix along isopycnals, so the ideal Lagrangian float similarly 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.

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

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

2.2 Observational Plan

Floats. The DIMES float program will deploy a total of 200 acoustically-tracked isopycnal-
following floats. Half of the floats will be placed on the isopycnal surface $\sigma_\theta = 27.21$ at depths
between about 200 and 800 m, (left panel of Fig. 3) in order to track Antarctic Intermediate Water
(AAIW) (see left panel of Fig. 4). The remaining floats will be placed on the same isopycnal sur-
face as the tracer, $\sigma_\theta = 27.68$, at depths between 1500 and 800 m (right panel of Fig. 3), to track
Upper Circumpolar Deep Water (UCDW) (see right panel of Fig. 4).

The objective in placing floats on two separate isopycnal layers is to evaluate differences in
eddy processes within the AAIW and UCDW and to obtain an estimate of the vertical variations
in isopycnal eddy mixing. DIMES uses floats rather than current meters, because our analyses
of historical current meter data and gridded fields from POP model output suggest that roughly
10 years of data would be required to estimate Eulerian heat fluxes that are reliably statistically
different from zero.

Two different float designs are planned. A total of 150 isopycnal following RAFOS floats will
be deployed, 75 on each surface. 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, 1994; Rossby, 1996; Barth et al.,
They will be ballasted by the University of Rhode Island and they are expected to follow their designated isopycnal surface with an error of \( \pm 0.05\sigma_\theta \).

On each surface we will also deploy 25 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 roughly every four months, allowing us to retrieve their subsurface trajectories as the experiment progresses. Retrieving data in this way permits a continuous monitoring of the experiment, as was done advantageously for example in the EUROFLOAT experiment in the northeast Atlantic (Speer et al., 1999). Four months represents a time that is long compared to the estimated (Lagrangian) integral time, so that four month duration should provide several statistically independent segments (e.g. Davis, 1998). Second, because the floats actively track density surfaces using their onboard CTDs, they are in principle able to track averaged isopycnal surfaces where the averaging can be controlled. This provides independent trajectories for comparison with the isopycnal RAFOS design and a way to reduce unwanted high-frequency diapycnal excursions. Furthermore, each time the floats rise to the ocean surface, they will profile temperature and salinity. These data will provide a record of the background stratification in the experiment region. Lastly, the floats’ Iridium antennas allow high bandwidth data transmission and two-way communication, meaning that they can be reprogrammed as the experiment progresses. Thus, floats with failing sensors can be redirected to follow constant depth or constant potential temperature surfaces, floats that are on outcropping isopycnals will be reset for a denser isobaric or isopycnal surface. Floats leaving the ensonified region will be reprogrammed to rise to the surface every 10 days, following a standard Argo sampling pattern. Such flexibility in float performance is highly desirable in the difficult environment of the Southern Ocean. Profiling floats are targeted for both the shallow and deep surfaces, because the deep floats will provide deep profiles, while shallow floats will more likely benefit from the reprogramming capability, since they are more likely to advect out of the ensonified region or outcrop.

WHOI will build 25 profiling floats, based on the Sounding Oceanographic Lagrangian Ob-
server (SOLO) float design (Davis et al., 2001). These floats use a single-stroke hydraulic pump, which means that they can accurately adjust their buoyancy to seek the desired isopycnal surface. The isopycnal-following SOLO floats are being evaluated in the North Atlantic during winter 2005 as part of a DIMES preparatory study. Steve Riser at the University of Washington will supply 25 of the profiling Argo floats, built using the Autonomous Profiling Explorer (APEX) float design (Webb Research Co.). Isopycnal-following versions of these floats were used in the Kuroshio, where they had an accuracy of $0.1\sigma_\theta$ (Shimizu et al., 2004).

All floats will be deployed along meridional lines spanning the ACC. Floats will be released in pairs and 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.

Half of the floats are planned for release concurrently with the tracer, in 2007-08 in the southeastern Pacific. As indicated in Fig. 3, on both the shallow and deep surfaces we will release 30 floats in triplets (consisting of two RAFOS floats and one profiling float) along 110°W and 20 floats in pairs (consisting of two RAFOS floats) at 90°W, for a total of 50 floats on each surface. Each triplet release of floats will yield three pairs. We will program some of the RAFOS floats to surface after one year, in order to evaluate their overall performance, and will allow others to continue for two years in order to achieve longer time series.

The remaining floats will be released in Drake Passage and the southwestern Atlantic in 2008-09, when the sound source array is redeployed from the Pacific into the Atlantic. These floats
Figure 5: (left) The sound source network deployed in 2007-08. (right) The source source network from 2008-09 onwards. The four westernmost Pacific sources will be moved to the Atlantic after the 2008-09 tracer survey, while the Drake Passage sources will remain in place.

will also be deployed in pairs to quantify relative dispersion, and the pairs will be positioned to compensate for gaps in coverage obtained by the floats deployed to the west. We note that our deployment strategy will be informed further by an analysis of trajectories generated in POP model output from the Southern Ocean.

**Sound sources.** The array of sound sources used to track the floats will be deployed initially to the west of Drake Passage. After the first year of measurements, the western-most sound sources will be moved into the Scotia Sea and south Atlantic to follow the progression of floats into the south Atlantic Ocean as shown in Fig. 5.

Sound sources have not previously been deployed for a large-scale experiment in the Southern Ocean. (Sound sources were placed in the Agulhas Retroflection region as part of KAPEX (Richardson et al., 2003), but these were used to track floats that were north of the ACC.) 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 there is no real sound channel, sound waves are expected to reflect off the ocean surface and the acoustic range is hypothesized to be 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 800 km in the Antarctic Zone even south of the Polar Front are generally attainable with a 195 db source (Lazarevich, 2003).

To help place the in situ results in a broader context, FSU contracted with SAIC to develop a model of acoustic propagation in the ACC, addressing the range limits of sound sources that might be used in the Southern Ocean environment. Figure 6 shows an example model result for propagation in the South Pacific sector, using a full 3d representation (Kraken) with sound speed and bathymetry, and parameterized bottom and surface characteristics. A ray trajectory model was also used for comparison. Model results appear to be consistent with field observations of acoustic range, and we used the combined results to design the sound source array. The planned array uses a mix of regular and higher-power sources in the proposed network as appropriate to ensonify the region with a minimal number of instruments and limited redundancy.
Figure 6: Coupled-mode model radials from a source at 60°S, 130°E (260 Hz source at 950 m depth). Map for float receiver at 950 m depth, 116 dB transmission loss contour shown (rough elliptical shape), with volume attenuation and 1 m surface roughness effect. Results show the lopsided propagation, with larger ranges to the north. Ranges were checked with an in situ sound source and RAFOS float experiment south of Tasmania (Lazarevich, 2003; Lazarevich and Speer, 2005).

3 Analysis plan

The float trajectories will be analyzed statistically to assess the flow structure and the mixing characteristics of the ACC both upstream and downstream of Drake Passage. The analysis can be subdivided roughly as follows: single particle measures, two particle correlations, and flux estimates from velocity-scalar correlations. Analyses like these have been used previously in relation to turbulent diffusion in geophysical and idealized settings (see for example Bennett, 1987; Davis, 1991).

Single particle statistics. Single-particle statistics can be used to quantify the means and variances of Lagrangian velocities. If one thinks of an initial cloud of particles, the single particle statistics quantify the displacement and the spread of that cloud. The mean velocity is the most commonly sought statistic in Lagrangian studies in the ocean. Mean fields are important not only to define the basic circulation but also to provide the background fields needed for further statistical calculations, particularly given the meridionally-varying structure of the ACC which will result in mean shear dispersion (e.g. Young et al., 1982). Because the ocean exhibits strong inhomogeneity (e.g. the active Gulf Stream region vs. the quiescent eastern Atlantic), Lagrangian means are usually calculated by dividing individual particle velocities into geographical bins. As such, the Lagrangian mean is a proxy for the Eulerian mean (e.g. Owens, 1984; Davis, 1991; Swenson and Niiler, 1996). Refinements to binning include objective analysis (e.g. Gille, 2003) and spline fitting techniques (Bauer et al., 2002). Float only means have some shortcomings, however, such as being adversely affected by non-uniform float deployment (Davis, 1991). Therefore in addition to com-
puting means from the float data, we will also derive independent estimates of the background field and its uncertainties based on formal objective mapping (Bretherton et al., 1976) of hydrographic data (e.g. Gouretski and Jancke, 1998; Conkright et al., 2002), Argo float profiles, and background CTD measurements collected as part of the DIMES surveys of fine/microstructure and tracer.

The spread of the cloud of particles relative to the mean is dictated by the single particle variance. This is calculated from the residual velocities (the in situ velocity minus the local mean). Of particular interest is the single particle or “absolute” diffusivity, which is the integral of the autocorrelation of the residual velocity (Taylor, 1921), for example in the zonal direction:

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

where \( x \) refers to the residual displacement. If the integral converges, the mixing is statistically equivalent to a diffusive process and can be represented thus.*

The absolute diffusivity can be defined in zonal and meridional coordinates or with respect to other coordinates, such as the topography (e.g. LaCasce and Speer, 1999; LaCasce, 2000), the mean potential vorticity (O’Dwyer et al., 2000), or the mean streamlines. Combined with information about scalar fields, such as temperature or isopycnal layer thickness, the absolute diffusivity can be used to infer scalar eddy fluxes (Taylor, 1921; Davis, 1987, 1991); we consider this further below. For analysis of the MOC, the cross-stream eddy fluxes of heat and potential vorticity are particularly relevant.

**Multiple particle statistics.** A key feature of DIMES is that floats will be deployed in pairs and triplets to allow calculation of two-particle relative dispersion. Relative dispersion has been described only rarely in the ocean (Davis, 1985; LaCasce and Bower, 2000; LaCasce and Ohlmann, 2003), and never in the ACC. While single particle statistics tell us about mean flow (drift) and diffusivity (or spreading), multiple particle statistics measure the cross correlation between velocities of different particles to quantify the strain. When the particles are far apart, their velocities are uncorrelated and the relative diffusivity is twice the absolute diffusivity. When particles are closer together, their velocities are correlated, and the diffusivity varies depending on the type of spreading.

To illustrate the possibilities, consider two examples, each concerning a cloud of tracer. In the first example, particle motions are uncorrelated, and the cloud retains its shape while its border is diffused away. In the second example, the cloud is stirred by eddies of a similar scale; the tracer is drawn into filaments that are eventually diffused away at smaller scales. The absolute diffusivities in these two examples can in some circumstances be the same, but the scenarios are easily distinguished using pair dispersion. The tracer deployed in the North Atlantic Tracer Release Experiment (NATRE) (Ledwell et al., 1998) was drawn into filaments as described in the second scenario (Sundermeyer and Price, 1998; Polzin and Ferrari, 2004). In a subset of the second case (termed “nonlocal dispersion” by Bennett (1984)), the length of the filaments grows exponentially in time. This implies that the mean separation between particle pairs also grows exponentially in time, and this is a signature of Lagrangian chaos. Exponential pair growth has been observed among balloons in the atmosphere (Morel and Larcheveque, 1974; Er-el and Peskin, 1981) and among surface drifters in the Gulf of Mexico by LaCasce and Ohlmann (2003).

*Davis (1991) discusses several ways to calculate the diffusivity. Results from the surface North Atlantic suggest that the best results are obtained from the correlation between the residual velocity and the residual displacement (e.g. Zhurbas and Oh, 2004).
Just as a mean flow can disrupt single particle estimates, a mean shear can alter pair behavior. For example, two particles in a linear shear will separate at a constant velocity and the relative dispersion will increase quadratically in time. If lateral mixing is superimposed on the shear, the relative dispersion can grow even faster than quadratically (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 shear dispersion occurs at larger scales and that small scale stirring is generally isotropic. 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 growth will need to take shear dispersion into account.

How many floats are required to obtain significant Lagrangian statistics? Single particle statistics generally converge more rapidly than multiple particle statistics (e.g. Babiano et al., 1990), and inhomogeneous flows require more sampling than homogeneous ones. Using varying numbers of POP model “floats”, we tested the robustness of absolute and relative diffusivity statistics. Since the POP model flow is less energetic and possibly more homogeneous than the actual Southern Ocean, POP statistics are likely to converge with fewer floats than will be required in the ocean. We adjusted POP estimates accordingly to arrive at our request of 50 floats per layer both to the west and east of Drake Passage, which we believe represents a plausible minimum for convergence. Grouped in pairs and triplets, these floats will yield a total of 65 pairs per layer.

Taken together, the single and two particle results can be synthesized to form a statistical description of Southern Ocean mixing. The single particle results will provide the means and diffusivities, while the multiple particle results will illustrate the local straining and will complement the tracer release. These results will be available to tune diffusive parameterizations in ocean circulation models, to develop better scale-dependent representations of mixing, and for use in Lagrangian-based stochastic models of tracer evolution.

Direct estimates of eddy fluxes. In addition to deriving eddy fluxes from dispersion statistics, we will also be able to compute them directly by correlating residual velocities (measured float velocities minus local means) with residual temperatures (e.g. measured potential temperatures minus local means). This method for deriving heat fluxes is distinctly different from methods using dispersion statistics and results will provide an independent test of the assumptions used to interpret absolute diffusivities. Direct velocity-temperature correlations been used for drifters in the California Current (Swenson and Niiler, 1996) and for Southern Ocean ALACE floats (Gille, 2003). Like absolute dispersion statistics, velocity-temperature correlations are also sensitive to the choice of mean field, and we will test a number of options.

Our analysis will project velocities into cross-stream and along-stream components in order to identify the cross-stream fluxes. Using approximately 10,000 ALACE float observations spanning the entire Southern Ocean, Gille (2003) found cross-stream eddy heat flux estimates that were statistically different from zero. Thus we expect to derive statistically meaningful fluxes from the 200 to 300 float years of daily data expected from the DIMES region. We will also carry out similar calculations using model data to help identify biases or sampling errors in our eddy flux estimates.†

†Marshall and Shutts (1981) demonstrated that eddy heat fluxes can be represented as a sum of a rotational and a divergent component, and that only the divergent component is responsible for a net eddy heat flux. In the framework developed by Marshall and Shutts (1981), the divergent and rotational components can be distinguished if mean streamlines and mean temperature are well known. It is straightforward to show that the meridional component of the rotational flux is small when the fluxes are integrated zonally (or along streamlines) over a lengthscale \( L \) that is long
With isopycnal floats we are able to compute fluxes of several quantities in addition to heat. Isopycnal layer depth fluxes are \( \langle v'z' \rangle \), where \( z \) is the depth of an isopycnal, smoothed over eddy length scales to account for inhomogenous sampling. This is a direct measure of isopycnal slumping, or eddy volume transport between the surface of the ocean and the isopycnal surface. Isopycnal thickness fluxes can be estimated from heat or layer depth fluxes using a leading order approximation (e.g. Karsten and Marshall, 2002), so that for example \( \langle v'h' \rangle \approx \langle v'z' \rangle \frac{\partial h}{\partial z} \), where \( h \) is layer thickness and \( \frac{\partial h}{\partial z} \) is a measure of the background change in layer thickness with depth. (More refined estimates may be possible by taking advantage of the fact that floats do not follow isopycnals instantaneously and therefore provide some information about local instantaneous stratification.) Eddy thickness fluxes are commonly used in numerical models to represent along-isopycnal mixing (Gent and McWilliams, 1990), but they have never been measured in the ocean. By using our flux estimates from two different isopycnal levels along with surface flux estimates from altimetry (e.g. Karsten and Marshall, 2002), we will also be able to estimate crudely the vertical gradients in fluxes, which are the eddy-induced transport (or “bolus”) velocities (e.g. Andrews et al., 1987; Gent and McWilliams, 1996; Tandon and Garrett, 1996) that are responsible for explaining how eddies influence mean tracer balances.

4 National and international links and partners

Other field programs. AWI (Bremerhaven) has a program to measure flow with RAFOS floats within the Weddell Sea and under sea-ice. We are collaborating with AWI (see attached letter from Fahrbach) to take advantage of cruise deployment opportunities and to optimize the location of sound sources.

The interpretation of DIMES data will be enhanced by the availability of extensive other data sets from the Drake Passage region. Underway ADCP measurements of velocities in the upper 1000 m of the ocean are collected by the US icebreakers R/V Laurence M. Gould and R/V Nathaniel B. Palmer (T. Chereskin, SIO, and E. Firing, U. Hawaii). In addition, the Gould completes high-resolution XBT lines on six to eight Drake Passage crossings per year (J. Sprintall, SIO). These data have been used to estimate upper ocean heat fluxes (Lenn et al., 2003) and will serve as a point of comparison for the float observations.

In situ eddy flux estimates will also be available from the Drake Passage current meter line scheduled to be deployed from January 2006 through January 2008 by C. Provost (LODYC–LOCEAN, Paris), which is targeted for partial redeployment during the IPY period.

Interactions with numerical modeling studies. In the DIMES planning stages we have worked closely with M. Maltrud (Los Alamos Nat’l Lab) and J. McClean (Naval Postgraduate School) to evaluate Eulerian fields and float trajectories from the POP Model. This analysis will continue as we prepare for the first DIMES cruises and as we analyze our field program results (see attached letter). DIMES is designed to provide measurements that will ultimately allow improvements in model parameterizations of isopycnal and diapycnal mixing in the ocean interior, and for this reason the DIMES field program is supportive of complementary modeling studies.

compared with the scale of eddies. Our fluxes will be determined as zonal integrals over the study region in order to minimize spurious effects due to the rotational component.
5 Summary: Significance of proposed work

5.1 Intellectual Merit

This component of DIMES focuses on measuring along-isopycnal eddy fluxes in the Southern Ocean using floats.

- Isopycnal-following floats will be deployed in the Southern Ocean in order to assess the along-isopycnal eddy dispersion and fluxes across the ACC. Understanding these processes is essential if we are to evaluate Southern Ocean overturning, and quantify the ocean component of meridional heat transport.

- As part of the float analysis, historic hydrographic data, Argo float profiles, and DIMES hydrography will be interpreted to provide a best estimate of the background mean temperature, density, and velocity fields in the DIMES region.

- Fluxes obtained through DIMES will provide the first observation-based statistical estimates of mixing in the Southern Ocean and the also the first estimates of heat and thickness fluxes along the steeply tilting isopycnals of the ACC. The results will provide a valuable picture of the dynamical processes that carry water upwards along isopycnals in the Southern Ocean. They will also provide quantitative estimates of along-isopycnal fluxes to help evaluate and constrain ocean general circulation models.

- DIMES float measurements will also complement DIMES tracer and microstructure measurements collected to provide a comprehensive view of mixing and its role in the MOC within the Southern Ocean.

5.2 Broader Impacts

- DIMES will pioneer the use of isopycnal-following Argo floats to study oceanic mixing processes and will make innovate use of two-way communication to ensure that the float data quality is maintained.

- Float data collected by DIMES profiling floats will also add to the archive of temperature profiles and mid-depth velocities collected through the Argo program and available for assimilation and climate studies.

- The float component of DIMES will involve graduate students at SIO and FSU and will also support postdoctoral investigators. We also anticipate provide research opportunities for undergraduates as part of DIMES.
References cited


BUDGET JUSTIFICATION (SIO)

Salary: Partial salary support is requested for the SIO PI Sarah Gille. Gille will be responsible for establishing a final float deployment strategy (year 1), mapping and analyzing the float data (years 2-6), and supervision of the postdoctoral scholar and graduate students.

Funds are requested for a graduate student (years 1-6) with a thesis topic related to the DIMES float project, to be supervised by Gille.

Salaries for the Research Project Assistant are for tasks that will specifically benefit this project, will be assigned by the PIs and charged on a time reported basis. These tasks should normally include technical typing and editing, copying project literature, making travel arrangements, and co-ordination of efforts between project participants.

Computer Costs: Funds are requested for computer support at $XX per month, which covers cost of software maintenance, network support and facilities, storage devices, internet connections etc. Funds are also requested for desktop computers for the graduate student ad postdoc (year 1) for analysis related to the DIMES float data, and for a computer for data processing and quality control (year 2).

Supplies and Materials: Supply and expense items categorized as project specific are for expenses that specifically benefit this project, are reasonable and necessary for the performance of this project, and can be readily allocable to this project.

Travel: Travel and per diem is requested for 1 SIO participant in the DIMES cruises during years 2 and 3, that we anticipate to be Punta Arenas, Chile.

Travel and per diem are also requested for two PIs to present results from the DIMES cruises and float deployments at the AMS Southern Oceanography and Meteorological Conference in Wellington, NZ in year 3. Funds are also requested in year 4, for one PI and the student to attend and present DIMES results at the AGU Ocean Sciences meeting in Hawaii, February 2006, and for 2 PIs to attend and present results at the AGU Fall Meeting in San Francisco, December 2006.

Other: Funds are requested for publication costs associated with a scientific journal in years 2 through 6.

Funds are also requested for project specific costs such as communication charges, xeroxing, mailing etc. that specifically benefit and are necessary for the performance of this project.
BUDGET JUSTIFICATION (WHOI)

**Salary:** Partial salary support is requested for WHOI PI LaCasce, to conduct model and in situ data analyses, and to aid in deployment strategies.

**Computer Costs:**

**Supplies and Materials:**

**Travel:**

**Other:**