Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean (DIMES)

Case for Support: Part 2

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I. Executive Summary

Climate-scale ocean models unanimously stress the key regulatory function played by the oceanic overturning circulation in the Earth's climate and biogeochemical cycles over decadal and longer time scales. Yet in their quest to resolve many topical climate problems, the models' credibility is challenged by their extreme sensitivity to the representation of mixing processes in the Southern Ocean. This peculiarity of model behaviour reflects the unique role of mixing in mediating the vertical and horizontal transports of water masses in the Antarctic Circumpolar Current (ACC), which shape the overturning circulation through their respective impacts on the overturning rate and inter-ocean exchange. Despite the acknowledged climatic significance of Southern Ocean mixing, direct observations of mixing in the region are lacking, and state-of-the-art theories and models of the Southern Ocean limb of the overturning circulation have to date been based on several defining assumptions (such as that of adiabatic flow in the ocean interior) that are now beginning to be disputed by indirect evidence.

In order to assess how Southern Ocean mixing processes should be represented in climate-scale ocean models, we propose to test and, if necessary, redefine the present paradigm of Southern Ocean mixing by obtaining the first systematic measurements of mixing processes in two contrasting regimes (the SE Pacific and the SW Atlantic) of the ACC. We propose to do this with a multi-cruise experiment conducted in collaboration with a group of U.S. scientists. Our international partnership stems from the recognition that obtaining the observations needed to challenge present views of the Southern Ocean circulation is beyond the logistic capabilities of any single nation. To achieve our overarching goal, we will obtain multiple, concurrent measures of the rates of isopycnal and diapycnal mixing and upwelling, and their underpinning physical processes, throughout the study region. The focal element of the experiment will be the spreading of a chemical tracer released in the SE Pacific zone of the ACC, with which we will directly measure the spatially and temporally averaged rates of mid-depth mixing and upwelling throughout the experimental domain. In order to measure diapycnal mixing at other depths and investigate the physical processes driving it, we will collect full-depth profiles of oceanic microstructure with novel free-falling profilers during three austral summer cruises, and finestructure profiles obtained year-round with specialized floats within and above the tracer cloud. In combination with innovative analyses of satellite altimetric data and the trajectories of isopycnal floats released by our American partners, these measurements will also enable us to study the distribution and mechanisms of isopycnal mixing. We will seek to challenge one of the essential principles of the present paradigm of Southern Ocean mixing by measuring the physical processes regulating the coupling between isopycnal and diapycnal mixing in the ACC with a moored instrument cluster deployed in Drake Passage for two years. Finally, we will use inverse techniques to integrate the experimental data set into an optimal diagnosis of the large-scale overturning circulation in the study region, with which we will investigate its sensitivity to mixing processes occurring at the small- and mesoscale. In conclusion, this collection of unprecedented measurements and analyses will allow us to appraise the validity of our current conceptualization of a key component of the global ocean circulation and, if necessary, put forward a fresh, alternative paradigm. This will lead to significant developments in the representation of mixing processes in climate-scale ocean models, and is thus set to foster the advancement of Earth system and climate science.

II. Introduction

The Meridional Overturning Circulation (MOC) of the ocean is a critical regulator of the Earth's climate and biogeochemical cycles over time scales of decades to millennia (*1,2*). Through its action, heat, carbon and other climatically important tracers are distributed around the globe and stored in the deep ocean. Yet in the quest to understand the changing climate system, climate-scale ocean models are confronted by a seemingly insurmountable hurdle: their acute sensitivity to the representation of mixing processes in the Southern Ocean (*3-6*). This peculiarity of model behaviour reflects a key physical fact, that the MOC is, to a large degree, powered by the strong westerly winds blowing on the Southern Ocean (*7*). This power manifests itself in intense mixing of water masses along and possibly across isopycnals, which ultimately lifts water from great depth to the upper ocean and exposes it to the atmosphere (Fig. 1). In so doing, mixing processes act to shape the baroclinic structure and transport of the ACC and thus contribute decisively to regulating inter-ocean exchange (*8*). It is this unique role of mixing in mediating the vertical and horizontal transport of water masses in the ACC that underlies the Southern Ocean's disproportionate importance in the global MOC.

The large uncertainty in the representation of Southern Ocean mixing processes in climate-scale ocean models casts great doubt on their reliability for the study of climate problems to which the region is pivotal. According to current observational and modelling evidence, these encompass many of the most topical and pressing issues of contemporary climate research. Thus, the Southern Ocean has been identified as a region of particularly pronounced rapid climate change (*9*) of possibly anthropogenic origin (*10,11*). It has also been singled out as the primary oceanic sink of the excess CO_2 generated by the burning of fossil fuels and net global deforestation (*12*). Further, the supply of nutrients to global marine ecosystems has been shown to exhibit great sensitivity to the vertical transport of water masses in the Southern Ocean (*2*), as has the long-term effectiveness of a widely considered climate engineering strategy consisting of the fertilization of the ACC with iron to boost carbon sequestration by the ocean (*13*). Finally, changes in the Southern Ocean mixing environment have been repeatedly put forward as a likely driver of glacial – interglacial atmospheric CO_2 variability, although the nature of the changes remains controversial (*14,15*).

The present paradigm of Southern Ocean mixing

In the almost complete absence of direct observations of mixing in the region, theories and models of the Southern Ocean circulation have to date been built on the premise of *adiabatic* flow in the ocean interior, with *diabatic* processes confined to the upper-ocean mixed layer. Much of our appreciation of what sets the structure of the Southern Ocean limb of the MOC, the ACC transport, their dynamical coupling to the global ocean and the range of biogeochemical and palaeoclimatic problems listed above has been nurtured under this extreme assumption, which stems from the direct observation of weak diapycnal mixing in the upper pycnocline of the North Atlantic (*16*). This classical paradigm of Southern Ocean mixing is reflected in many plausible global ocean general circulation models (*17,18*) incorporating adiabatic parameterizations of mesoscale eddies (*19*), but it is most elegantly expressed by a family of conceptual models relying on similar mesoscale eddy closures and grounded in residual mean theory (*20-25*). These models portray the zonal-average Southern Ocean overturning as a residual circulation arising from an approximate balance between a wind-driven Ekman contribution, which tends to steepen isopycnals, and an opposing eddy-driven contribution acting to flatten isopycnals. The cancellation is not perfect because a non-zero, predominantly eddy-driven residual flow is warranted to satisfy the buoyancy and momentum balances of the ACC. The resulting overturning circulation expressed by the models is one in which mesoscale eddies drive upwelling along the mid-depth ACC isopycnals with an average vertical velocity of $O(10^{-1}\ \mathrm{m\ d^{-1}})$, while compensatory sinking at a similar rate occurs in the Southern Ocean both north and south of the ACC.

Whilst this paradigm of Southern Ocean mixing combines powerful simplicity with an impressive qualitative consistency with the overturning circulation pattern inferred from observations (Fig. 1), it also has some potentially fatal weaknesses. These relate primarily to the uncertain nature, magnitude and distribution of eddy-driven mixing in the ACC. The currently favoured parameterizations (*19*) represent eddy-driven mixing as a downgradient transfer along isopycnals at a rate proportional to a diffusivity coefficient. Based on a range of indirect observational estimates in the upper few hundred metres of the water column (*26-28*), this diffusivity is believed to be of $O(100 – 1000\ \mathrm{m^2\ s^{-1}})$ and to exhibit marked but inconclusive spatial variability. In the present paradigm, the Southern Ocean limb of the MOC is driven by vertical gradients in the isopycnal mixing rate, so knowing the detailed distribution of the diffusivity is critical. Existing theories relating the magnitude of the eddy diffusivity to the properties of the large-scale circulation (*24*) remain untested in an oceanic context, yet they lead to widely different predictions on the properties of the ACC and its residual circulation. Perhaps most fundamentally, the validity of conceptualizing eddy-driven mixing as a diffusive, isopycnal process is beginning to be questioned on both observational and theoretical grounds. Thus, altimetric estimates of the eddy-driven mixing rate in the surface Southern Ocean (*28*) suggest that mixing may be forced strongly by the breaking of Rossby waves along highly localized critical layers, a mechanism that can display striking non-diffusive behaviour (*29*). Further, the adiabatic parameterizations of mesoscale eddies endorsing the present paradigm of Southern Ocean mixing have been shown to require purely viscous dissipation of the eddy energy most likely in thin surface and bottom boundary layers, a scenario that Tandon and Garrett (*30*) judge to be physically implausible. If, as conjectured by those authors, a substantial fraction of the eddy energy is instead dissipated in the ocean interior through internal wave breaking, intense turbulent diapycnal mixing is implied. Hence, it becomes apparent that the present paradigm of Southern Ocean mixing, built on the premise of interior adiabatic flow, may carry the seeds of its own demise.

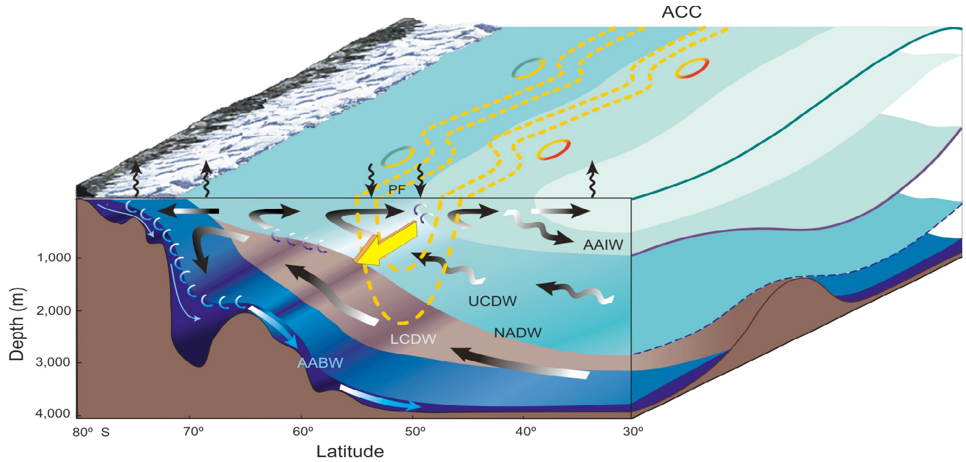

Figure 1. Schematic of the present paradigm of the Southern Ocean limb of the MOC. The isopycnal upwelling of Upper and Lower Circumpolar Deep Water (UCDW and LCDW, with sources in the North Atlantic) is supported by mean geostrophic mass fluxes below the level of topographic obstacles to the ACC and by mesoscale eddy-driven mass fluxes at mid-depth. The upwelled water changes density through air-sea-ice interaction. It then returns northward in the wind-driven Ekman layer to form Antarctic Intermediate Water (AAIW), and as Antarctic Bottom Water (AABW) in mean geostrophic flows.

An emergent new paradigm of Southern Ocean mixing?

We have, in fact, several observational clues suggesting a shift away from the present paradigm of Southern Ocean mixing. Some of these originate from a series of hydrographic inverse models (*31-33*) and abyssal buoyancy and tracer budgets (*15,34*), all of which diagnose large basin-average diapycnal diffusivities of $10^{-4} - 10^{-3}$ m^2 s^{-1} (i.e. one to two orders of magnitude above background values) in the deepest layers of the Southern Ocean. These diagnostics emphasize the first-order importance of turbulent diapycnal mixing in the dynamics of the lower cell of the Southern Ocean overturning (Fig. 1), and draw attention to the region's high-ranking status in 'short-circuiting' the deep global MOC's predominantly isopycnal pathways. However, the most tantalizing evidence hinting at an emergent new paradigm of Southern Ocean mixing is provided by recent *in situ* estimates of the diapycnal diffusivity associated with breaking internal waves, as inferred from the application of internal wave-wave interaction models to observations of density and velocity finestructure (*35-37*). These suggest that the ACC's circumpolar path may be seeded with diapycnal mixing 'hot spots', or regions in which diapycnal diffusivities exceeding background values by at least an order of magnitude are common below depths of a few hundred metres and over horizontal distances of O(1000 km). The collocation between these 'hot spots' and areas of rough seabed leads those authors to contend that the enhanced levels of turbulence may be primarily sustained by internal wave generation as mesoscale flows impinge upon bottom topography, although other evidence (*38, 39*) indicates that the contributions of internal tides and wind-generated near-inertial waves are likely non-trivial. According to the same studies, the rate of turbulent kinetic energy dissipation by the breaking waves may be of a similar magnitude to the wind work on the ACC and the rate at which mesoscale eddies extract available potential energy from the mean flow (*7,40,41*). This raises the fascinating possibility that, in the spirit of Tandon and Garrett's conjecture, internal wave breaking (and the associated diapycnal mixing) in the ACC may provide a significant sink of mesoscale eddy energy.

Although the patchy indirect evidence available to date points to topographic generation as a key agent in the transfer of eddy energy to the internal wave field, other mechanisms are likely to enhance this transfer. In particular, theory predicts that the elevated eddy and internal wave energy levels in the ACC provide an optimum setting for the interaction between internal waves and the mesoscale flow [see (*42*) and references therein] and the generation of internal waves by loss of balance in the mesoscale [see (*43*) and references therein] to prosper in the ocean interior. The occurrence of these processes is suggested by altimetric evidence of a significant forward eddy kinetic energy cascade at sub-deformation scales in the Pacific sector of the ACC (*44*). Whichever combination of transfer processes prevails, the likely existence of a significant physical link between mesoscale eddies and internal waves in the Southern Ocean suggests that it may no longer be appropriate to consider (or parameterize) isopycnal and diapycnal mixing in isolation (*45*).

Far from being a minor dynamical side issue, these budding ideas defy our current conceptualization of the ocean mixing problem as a competition between isopycnal and diapycnal deep ocean pathways (*46*), and pose a formidable challenge to the credibility of state-of-the-art climate-scale ocean models that are reliant on adiabatic eddy closures. In an ocean where isopycnal and diapycnal mixing are physically intertwined, understanding the nature of the link stands as a prerequisite to predicting how the rate and structure of the Southern Ocean overturning may be moulded by mixing processes under changing climatic forcing. Thus, with the use of indirect techniques approaching a point of diminishing returns, it is now timely for a dedicated, high-impact experiment in Southern Ocean mixing to seek the decisive breakthrough in the field.

III. Specific Objectives, Relationship to the U.S. DIMES Programme and the Need for a Consortium Approach

The overall aim of DIMES (Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean) is to test and, if necessary, redefine the present paradigm of Southern Ocean mixing. This proposal represents the U.K. contribution to a joint U.K.-U.S. programme to obtain the first systematic measurements of mixing, upwelling and their underlying driving processes in two contrasting regimes (the SE Pacific and the SW Atlantic, Fig. 2) of the ACC. Our international collaboration stems from the recognition that obtaining the observations needed to challenge the present paradigm of Southern Ocean mixing is beyond the logistic capabilities of any single nation. The specific objectives of the joint programme are to:

1. Quantify the (spatially and temporally) integrated rates of isopycnal mixing, diapycnal mixing and upwelling in the two regions.
2. Determine the (spatial and temporal) distribution, intensity and energy sources of turbulent kinetic energy dissipation and (isopycnal and diapycnal) mixing in the two regions.
3. Identify and quantitatively assess the physical processes responsible for driving isopycnal and diapycnal mixing.
4. Identify and quantitatively assess the physical processes regulating the coupling between eddies and internal waves in an area of intense isopycnal and diapycnal mixing.
5. Assess the validity of current parameterizations of isopycnal and diapycnal mixing in the ACC and make recommendations on how to improve them.
6. Provide a one-of-a-kind testbed for assessing existing indirect techniques to estimate isopycnal and diapycnal mixing rates, and for developing new ones.

We will meet these objectives by obtaining multiple, concurrent measures of the rates of isopycnal and diapycnal mixing and upwelling, and their underlying driving processes, in the two distinct regions of the ACC. The logistic effort of the experiment will be shared approximately evenly with our U.S. collaborators, with U.S. and U.K. ships conducting the bulk of operations west and east of Drake Passage, respectively. The combined research programme will be completed on an equal partnership with our American colleagues, many components of the experiment being jointly led by U.K. and U.S. scientists. The major exceptions to this partnered leadership will be a U.K.-led mooring cluster element to study the physical processes regulating the coupling between eddies and internal waves in Drake Passage, and a U.S.-led isopycnal float programme to investigate the character and distribution of isopycnal mixing at mid-depth in the DIMES sector. All data will be shared freely amongst all investigators both to maximize their usage and to facilitate collaborative analysis at national and international levels.

As will become apparent in §IV, the different components of our research programme are of limited individual value for testing and possibly redefining the present paradigm of Southern Ocean mixing. Whilst, at a minimum, this task calls for objectives 1-4 to be met, each individual programme component can at most fulfil one objective. Attaining the central aim of DIMES necessarily entails the study of oceanic phenomena at length scales spanning up to nine orders of magnitude [from the O(10^{-2} - 10^{-1} m) mixing scale to the O(10^{6} - 10^{7} m) MOC scale]. This requires expertise in an unusually wide range of areas of physical oceanography (hydrographic analysis, inverse modelling, tracer oceanography, oceanic fine- and microstructure measurements, long-term moored observation of small- and mesoscale motions, satellite remote sensing, and numerical modelling), as well as a high level of staff effort across several U.K. Higher Education Institutions and NERC centres. The consortium framework provides a natural mechanism to bring together the different disciplines and groups into a focussed, coherent project that can tackle the breadth of scales involved in the Southern Ocean mixing problem.

IV. Approach and Methodology

Overview of research and field programmes

We propose to address the objectives in §III with a collection of five interdependent work packages, designed to investigate both the physics of mixing processes occurring at the small- and mesoscale and their impact on the large-scale circulation. The focal element of the experiment will be the spreading of a chemical tracer released at mid-depth in the SE Pacific zone of the ACC [§IV(*a*)], with which we will directly measure the spatially and temporally averaged rates of mid-depth isopycnal mixing, diapycnal mixing and upwelling in the major sectors of the DIMES region (objective 1). We will complement the integrated tracer measurement at one level with a set of full-depth fine- and microstructure profiles collected with free-falling profilers in austral summer, and a large number of finestructure profiles obtained year-round with EM-APEX (Electromagnetic Autonomous Profiling Explorer) floats within and above the tracer cloud [§IV(*b*)]. These measurements will go a long way towards meeting objectives 2 and 3. On one hand, they will enable us to assess the distribution of turbulent kinetic energy dissipation and diapycnal mixing in the DIMES area, and to investigate their underlying driving physical processes. On the other, when combined with novel analyses of satellite altimetric data and the U.S. isopycnal float programme, they will allow us to study the distribution and mechanisms of isopycnal mixing in the experimental domain. In order to characterize the physical processes regulating the coupling between isopycnal and diapycnal mixing in the ACC (objective 4), we will make further use of the fine- and microstructure data to complement the analysis of observations of eddy – internal wave interaction made in Drake Passage with a cluster of moored instrumentation [§IV(*c*)]. The three preceding work packages will enable us to appraise the validity of current parameterizations of isopycnal and diapycnal mixing in the ACC, which are grounded in the assumption of mutual independence, and advocate future developments (objective 5). The collection of hydrographic, velocity, fine- / microstructure and float data gathered by the joint U.K. – U.S. DIMES programme will be integrated into an optimal estimate of the three-dimensional circulation in the study region using inverse techniques [§IV(*d*)]. The goals of this exercise will be to provide a large-scale spatial context for analyzing fine- / microstructure and tracer measurements (the temporal context will in turn be based on satellite, EM-APEX float and mooring cluster measurements), and to evaluate the net impact of small- and mesoscale mixing processes on the overturning circulation of the DIMES sector of the Southern Ocean (a further contribution to objective 1). Finally, we will conduct a series of experiments with a state-of-the-art, eddy-resolving ocean model [§IV(*e*)] to guide both our interpretation of the tracer measurements and our use of indirect techniques to derive isopycnal mixing and upwelling rates from altimetric and *in situ* observations. An assessment of these and other indirect techniques in the extreme dynamical environments of the ACC (objective 6) is implicit in work packages *b*, *c* and *e*.

In order to gather the measurements needed to fulfil the objectives of the joint U.K. – U.S. DIMES experiment, we collectively propose a field programme of eight cruises (three of them U.K.-led) over a period of 3 to 3.5 years. The time line and primary purpose of each of these cruises are synthesized in Figure 2. The first cruise (USD-1) will be led by our American collaborators and take place in the SE Pacific in the austral summer of 2007 / 08. Its goal will be to deploy the tracer, a range of different floats and the array of sound sources required to track the isopycnal floats. Approximately one year later, a second U.S.-led cruise (USD-2) will conduct a hydrographic, microstructure and tracer survey in the SE

Pacific to characterize the regional mixing environment, and will deploy more floats. The first U.K.-led cruise (UKD-1) will take place shortly after, in the same summer season of 2008 / 09, with the mission of deploying the U.K. mooring cluster in Drake Passage and five U.S. sound sources in the Scotia Sea. In winter of 2009, summer of 2009 / 10 and winter of 2010, our American colleagues will monitor the arrival of the tracer in Drake Passage by conducting hydrographic and tracer surveys during routine transects by U.S. Antarctic supply vessels. The second U.K.-led cruise (UKD-2) will occur in the summer of 2009 / 10 and carry out a hydrographic, microstructure and tracer survey of Drake Passage and the northern boundary of the Scotia Sea, as well as servicing the mooring cluster. The concluding DIMES cruise (UKD-3), taking place in the summer of 2010 / 11, will also be led by U.K. scientists. The cruise's goals will be to conduct an extensive hydrographic, microstructure and tracer survey of the Scotia Sea and its environs, and recover the mooring cluster and sound sources. The tracks and scientific rationale of each of the U.K.-led cruises will be described in detail in §IV(*a*-*c*).

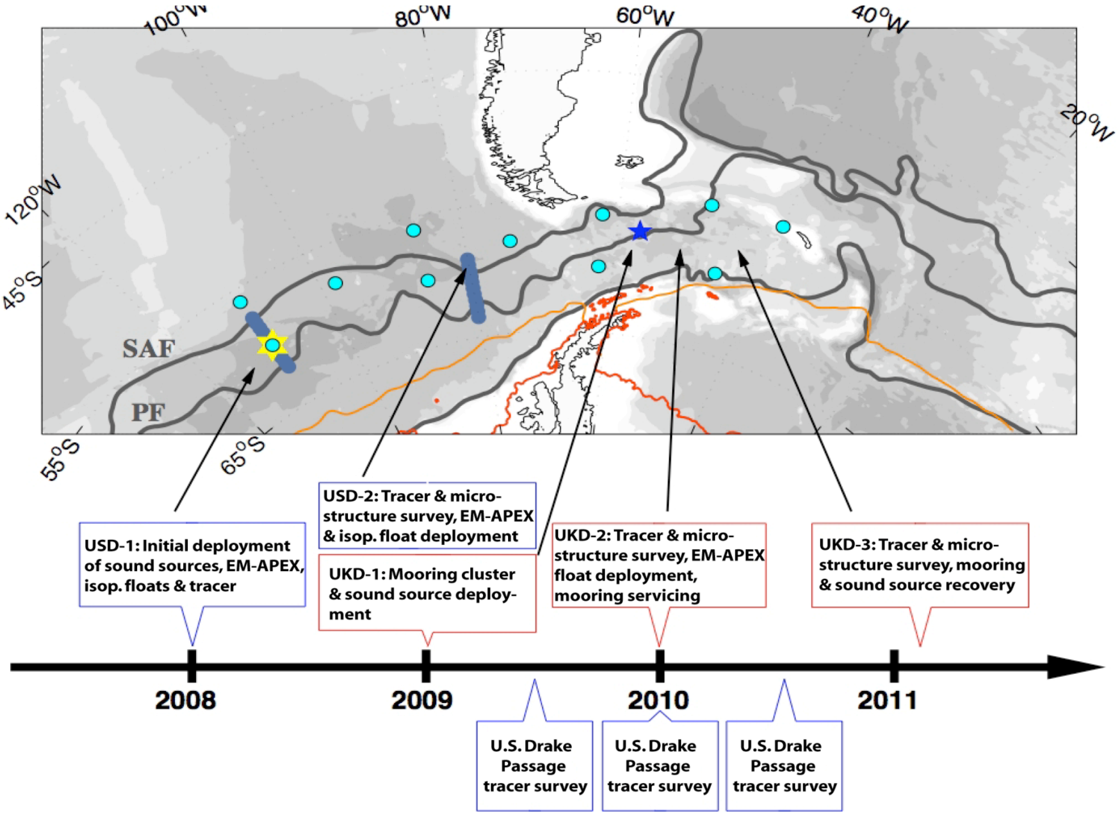

Figure 2. Time line for the U.K. – U.S. DIMES field activities. Text boxes at the bottom show their approximate timing. The yellow star indicates the tracer deployment location, blue circles show U.S. isopycnal float deployment sites, and cyan dots mark the positions of U.S. sound sources. The blue star indicates the U.K. mooring cluster site. The grey shading displays the bathymetry, with 1000-m contour interval; the climatological locations of the Subantarctic Front (SAF) and Polar Front (PF) are labelled; the remaining lines mark the maximum (orange) and minimum (red) seasonal sea ice extent.

IV(*a*) *Tracer release experiment*

The tracer release experiment at the heart of DIMES will be initiated early in 2008 during the USD-1 cruise. The tracer will be released on the neutral surface γ^n= 27.9 kg m^{-3}, at a depth of ~1300 m, in the region between the two main frontal jets of the ACC (the Subantarctic Front and Polar Front) near 110°W (Fig. 2). The selected neutral surface lies in the lower part of the Upper Circumpolar Deep Water (Fig. 1), close to the oxygen minimum surface that characterizes this water mass. This layer is ideal to study the role of mesoscale eddies in driving the Southern Ocean overturning because it very rarely intersects topography around the ACC's path, thereby precluding the existence of a mean cross-stream geostrophic transport within the layer (*8*). The deployment longitude is chosen to be about 2 years upstream of Drake Passage, given a mean current of ~0.03 m s^{-1} that we have estimated from historical Argo and ALACE float displacements in the ACC band. Concurrent to the tracer release, our U.S. colleagues will deploy 75 isopycnal floats and 11 floats of other types, with a further 75 and 7 units being respectively released one year later (during USD-2) near the core of the tracer patch.

Although the tracer release and sampling techniques will be identical to those originally developed and successfully used by a co-I (Watson) and the U.S. DIMES PI (Ledwell) in previous experiments (*16,47*), the tracer itself will be different. We will use trifluoromethyl sulphur pentafluoride (CF_3SF_5) rather than the previously used sulphur hexafluoride (SF_6) in order to avoid contaminating the increasingly valuable oceanic transient tracer signal derived from atmospheric SF_6. CF_3SF_5 has recently been the subject of a successful test release in the Santa Monica Basin off the California coast (*48*). This tracer can be readily analysed on a system designed for measuring chlorofluorocarbons and SF_6 after some modification (Smethie, pers. comm.). Such a system has been built at UEA with NERC funding (Joint Infrastructure Fund, 2001). It was first used on a NERC-funded (NER/O/S/2003/00627) North Atlantic cruise in 2005 and shown to work well. Thus, the major capital costs for the tracer analysis at UEA have already been met and only consumable costs will be required for DIMES.

Jointly with our U.S. colleagues, we will monitor the spreading of the tracer over a period of 3 - 3.5 years as part of the three major summer cruises (USD-2, UKD-2 and UKD-3), during which we will respectively conduct ~100, ~90 and ~120 CTD / LADCP / tracer stations within the tracer patch and its vicinity with variable horizontal resolution and maximum depth (typically 2500 m to full ocean depth, to expedite the collection of samples in the tracer-containing layer). Our American collaborators will augment the resulting time series of the tracer's entry into the Scotia Sea with measurements from U.S. Antarctic supply vessels (Fig. 2). We will use the information on the spreading of the tracer obtained during all these surveys to estimate isopycnal and diapycnal mixing and upwelling rates integrated over large regions of the experimental domain (principally the SE Pacific, Drake Passage and the remainder of the Scotia Sea). Based on particle-tracking experiments by our American colleagues using the 1/10° resolution Parallel Ocean Program (POP) model, we expect that the significant horizontal and vertical shear of the ACC will cause the tracer to form a progressively larger and more elongated patch over the DIMES period. The tentative tracks of USD-2, UKD-2 and UKD-3 are schematically displayed in Figure 3. These tracks are broadly based on the POP simulation and may be modified in response to the actual trajectories of the floats deployed with the tracer. Cruise USD-2 will measure the tracer field in the SE Pacific one year after the release and enable us to estimate mixing and upwelling rates in that region. In turn, cruise UKD-2 will survey the tracer distribution in eastern Drake Passage and the northern boundary of the Scotia Sea two years after the release. When combined with the contemporary U.S. tracer survey across western Drake Passage and three estimates of the transit time distribution of tracer particles crossing the Scotia basin (from isopycnal floats, a streamfunction field derived from hydrographic and float observations [§IV(*d*)], and a numerical model [§IV(*e*)]), UKD-2 measurements will allow us to obtain initial estimates of mixing and upwelling rates in Drake Passage and possibly in the remainder of the Scotia Sea. Finally, cruise UKD-3 will gather a snapshot of the bulk of the tracer patch three years after the release, which in combination with the Drake Passage tracer time series and the information on transit times will enable a second, more accurate set of estimates of mixing and upwelling rates to be made within the Scotia basin.

Despite the simplicity of their underlying principle, the above calculations of mixing and upwelling rates are complicated (and their accuracy challenged) by horizontal and vertical differential advection effects and the lateral reorganization and meandering of the ACC flow. In order to overcome these complications, a team of UEA, BAS and NOC co-Is will jointly direct a hydrographic analysis programme to characterize the large-scale circulation in the DIMES domain. This largely qualitative study will feed into a quantitative Bernoulli inverse analysis of the horizontal circulation in the region [§IV(*d*)], yielding a streamfunction field that can support the interpretation of the observed tracer spreading. Additional, more extensive guidance on how to optimally analyze our tracer measurements will be provided by a simulation of the tracer evolution in an eddy-resolving numerical model [§IV(*e*)]. Finally, we plan to seek supplementary funding to collect samples of the isotopic fraction of helium ($^3He/^4He$) and the concentrations of ^3He and ^{20}Ne during the three major DIMES summer cruises, to be measured in the re-commisioned (NE/D003245/1) Manchester automated ^3He-tritium laboratory. If we are successful, we will analyze these measurements in conjunction with sparser historical data to map the penetration into the ACC in the vicinity of Drake Passage of a quasi-steady terrigenic helium plume with sources in the tropical Pacific. A pilot study (*41*) suggests that the signal-to-noise ratio of this 'natural tracer release', although low, is high enough to provide useful estimates of mixing and upwelling rates ~1000 m below the DIMES CF_3SF_5 plume, within the Lower Circumpolar Deep Water. We expect that the combination of two tracers with different source regions and contrasting injection histories will aid us to unravel the effects of spatial and temporal variability in the measured CF_3SF_5 fields. Most importantly, it may provide us with insight into the vertical distribution of the isopycnal mixing rate, which current theories predict to be key in determining the rate of deep water upwelling in the Southern Ocean [§II].

IV(*b*) *Measurements of oceanic fine- and microstructure*

In order to elucidate the (spatial and temporal) representativeness of the integrated mid-depth diffusivity estimates yielded by the tracer and investigate the physical processes driving the mixing, we will obtain profiles of oceanic fine- and microstructure across the DIMES region in a number of ways. First and foremost, we will collectively measure full-depth fine- and microstructure during the three major summer cruises (USD-2, UKD-2 and UKD-3) with a suite of three free-falling profilers (the WHOI-owned High Resolution Profiler [HRP-II], and two different versions of the Deep Microstructure Profiler [DMP], one owned by FSU and another by the U.K.'s National Marine Equipment Pool). HRP-II is a well-proven instrument, whereas at the time of submitting this proposal the FSU-owned DMP has been successfully trialled and the U.K.'s DMP is under construction by Rockland Scientific International Inc. (http://www.rocklandscientific.com/products_vmp5500.php). By the time of DIMES, both DMPs will be operational instruments: FSU will utilize their profiler during fieldwork in the North Atlantic in mid-2006, whereas the British instrument will be trialled in early 2007 and operated in the southern Indian Ocean in late 2007 (as part of the NERC standard grant NE/B503717/1). As the profilers are sensitive instruments, our strategy will be to build in some redundancy in each of the cruises to ensure data acquisition is successful: HRP-II and the FSU-owned DMP will be operated in USD-2 and the two DMPs in UKD-2, with HRP-II and the British DMP being used in UKD-3. This multiplicity of instruments may enable us to conduct more frequent sampling at time series stations than is possible with a single profiler.

One of the microstructure profilers will be deployed at each of the ~300 stations encompassed by the three major summer cruises, following a tracer-driven sampling strategy (Fig. 3). There will be a few exceptions to this sampling mode. In the USD-2 and UKD-3 cruises, we will conduct short (~2 days) exploratory time series of multiple profiles at a few selected sites with an enhanced fine- and microstructure signal, so as to characterize the dominant time scale of the finestructure and study the physical processes at its origin. In the UKD-2 cruise, our sampling will target two archetypal cases of ACC flow – topography interaction, which previous CTD / LADCP finestructure measurements (*35*) suggest obey distinct dynamics. The instance of an ACC jet interacting with steeply sloping topography will be investigated with a focussed microstructure survey of the Shag Rocks Passage, where the Polar Front jet overflows the North Scotia Ridge (Fig. 3). This is a physical setting where the topographically driven sharpening and baroclinic instability of a frontal jet appears to enhance geostrophic shear to a point where it may be susceptible to loss of balance (as evidenced by the occurrence of near-unity geostrophic Froude numbers). In turn, the scenario of the ACC flow interacting with small-scale topographic roughness (in the form of small ridges and abyssal hills) will be studied with three nested grid surveys with different horizontal resolution (~2 km, ~8 km and ~30 km, respectively) and centred around the Drake Passage mooring cluster [§IV(*c*)]. The grid surveys will span an area where intense mesoscale eddy activity and topographically enhanced finestructure levels hint at an active generation of internal waves and oscillations by the geostrophic flow and possible subsequent eddy – internal wave interactions away from the bottom boundary. The rationale behind the nested grid sampling will be outlined below.

A second source of finestructure data will be provided by a set of 15 profiling EM-APEX floats (*49*) measuring shear and stratification year-round over the uppermost ~1500 m of the water column with an effective vertical resolution of 2 m. Three of these floats will be purchased by the U.K. DIMES consortium. Each EM-APEX float will be capable of conducting ~300 profiles over its mission duration, which will typically exceed one year. Thus, the floats used in DIMES will collectively gather an order of magnitude more finestructure profiles than it will be feasible to obtain with shipboard instrumentation. Float position is routinely determined by GPS on surfacing, after which the preceding two profile data streams (temperature, salinity, velocity and position) are transmitted via the Iridium satellite network. EM-APEX floats can be programmed to profile in complex sequences and adjustments to their mission can be made in real-time via Iridium. Our default float profiling strategy will consist of bursts of multiple profiles taking place every other day. Each burst will comprise two pairs of (upward and downward sets of) profiles separated by half an inertial period (i.e. 7-8 h), so as to allow us to discriminate between subinertial and near-inertial finestructure. The 15 EM-APEX floats will be deployed in three clusters to achieve an even coverage of the experimental domain (Fig. 3): 10 U.S. floats will be released in two groups in the SE Pacific, whereas the remaining 2 U.S. units will be deployed with the 3 U.K. floats immediately upstream of the Drake Passage mooring cluster. The profiling mode of the latter 5 floats will initially deviate from the default strategy. These floats will be programmed to profile continuously whilst they remain within ~100 km of the mooring cluster, subsequently reverting to the default profiling mode. The purpose of this intensive survey is to gather a quasi-synoptic snapshot of the finestructure environment that will provide added value to the mooring cluster observations [§IV(*c*)].

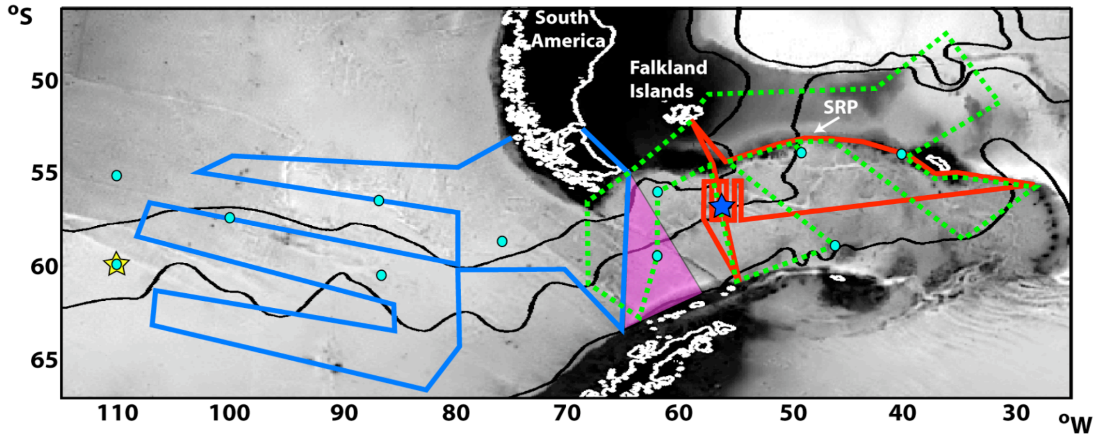

Figure 3. Schematic tracks of the USD-2 (blue, solid), UKD-2 (red, solid) and UKD-3 (green, dashed) cruises. The envelop of tracks of the 3 U.S. Drake Passage transects is shaded in magenta. The yellow star indicates the tracer deployment location and cyan dots show positions of U.S. sound sources. The blue star marks the location of the U.K. mooring cluster. The grey shading indicates the bathymetry; the climatological locations of the Subantarctic Front, Polar Front and southern boundary of the ACC are indicated by the black lines from north to south; SRP = Shag Rocks Passage.

The basis of our analysis of the microstructure profiler data will be the estimation of the dissipation rates of turbulent kinetic energy (ε) and temperature variance (χ) over the full ocean depth from the measured temperature, conductivity and velocity microstructure. Estimates of the diapycnal diffusivity (K_ρ) will be obtained from ε using the classical Osborn relation (*50*). Subsequently, we will gauge the extent to which finescale shear and strain spectral characteristics deviate from the predictions of existing theoretical models of internal waves (*50*), and test current parameterizations of ε in terms of shear and strain at wavelengths in excess of 10 m against our measurements in the ACC. These relations (*50,51*) have been developed using fine- and microstructure data from low- and mid-latitude regions where near-inertial winds and tides represent the dominant sources of internal wave energy, and so may be expected to falter in the ACC if the internal wave field is primarily sustained by the interaction of mesoscale geostrophic flows with topography. The outcome of these evaluations will provide the first elements of evidence on the energy sources and physical processes underpinning diapycnal mixing in the ACC, and guide our estimation of ε and K_ρ profiles from the EM-APEX float finestructure data set. Upon completion of this exercise, we will have a large ε and K_ρ data set of ~4500 finestructure-derived profiles in the upper ~1500 m and ~300 microstructure-derived full-depth profiles. This extended data set will enable us to characterize the (spatial and temporal) distribution and intensity of turbulent kinetic energy dissipation and diapycnal mixing across the experimental domain, and to assess the degree of localization of diapycnal mixing in the ACC by reference to the integrated tracer-derived K_ρ values. In order to further our investigation of the energy sources and physical mechanisms underlying the observed distribution of ε and K_ρ, we will then analyze the profiles in groups defined according to their signal intensity, direction of the vertical flux of internal wave energy (estimated with finescale rotary spectra), and combinations of environmental parameters. The latter will include the spectral characteristics of the topography as measured with a multibeam swath system, mesoscale eddy energy quantified from altimetry, ACC mean flow properties estimated with a Bernoulli inverse [§IV(*d*)], model predictions of barotropic tides, and near-inertial wind stress and work from atmospheric reanalyses and scatterometry. As part of this study, we will seek to interpret the characteristics of finescale spectra and ε profiles in regions of intense diapycnal mixing in the light of theoretical predictions for internal lee waves and tides (*52-55*), given the observed topographic and bottom flow settings. This analysis will allow us to both expose the dominant energy sources and physical processes supporting the occurrence of intense diapycnal mixing in the ACC, and to assess the extent to which ε and K_ρ can be parameterized in terms of environmental variables.

Although the most immediate purpose of collecting fine- and microstructure data is to study the physics of diapycnal mixing, these measurements will also serve as the hub of an investigation of the distribution, intensity and mechanisms of isopycnal mixing in the ACC. We will commence the investigation by examining how the magnitude of thermohaline variability on isopycnal surfaces — the signature of stirring by mesoscale eddies — varies as a function of horizontal scale in Drake Passage, the region that we will survey with three nested grids of microstructure profiles and a large number of EM-APEX float finestructure profiles. The goals of this exercise will be to assess the extent to which the vertical thermohaline variability present in fine- and microstructure data is created by mesoscale eddy stirring within different density classes, and to explore the nature of the stirring process by contrasting the observed spectral characteristics of horizontal thermohaline variability with the predictions of theoretical models (*56*). We will then estimate the rate of isopycnal mixing by mesoscale eddies as a function of density in Drake Passage by invoking mixing length theory (*57*). In this theoretical framework, the rate of isopycnal mixing (described in principle by a downgradient diffusivity K_e) can be expressed as $K_e \approx c_e U_e L_e$, where U_e is a root-mean-squared eddy velocity along isopycnals derived from altimetry and the observed baroclinic geostrophic shear; L_e is a characteristic lateral filamentation scale that can be quantified from the observed thermohaline variability on isopycnals; and c_e is an efficiency factor whose magnitude will be gauged with an analysis of temperature and velocity correlations in mooring cluster [§IV(*c*)] and float records. We will then extend the calculation to the rest of the DIMES region by studying the distribution of thermohaline variability on isopycnals in the context of the ACC mean flow properties, and altimetric estimates of mesoscale eddy activity, eddy – mean flow interaction and flow – topography interaction (*58*). This exercise will lead to a characterization of the different isopycnal mixing regimes present in the DIMES domain, and yield a broad understanding of the family of mechanisms driving the downscale cascade of horizontal thermohaline variance in the ACC. We will use this knowledge to guide our grouping of fine- and microstructure profiles (augmented with historical CTD or Argo profiles) according to geographical and data density criteria. Within each of these groups, we will replicate the Drake Passage analysis to obtain an estimate of the three-dimensional distribution of K_e in the DIMES sector that can be contrasted with five other sets of diagnostics: the integrated tracer-based measurements of K_e at the target isopycnal [§IV(*a*)]; single-particle and two-particle diffusivity diagnostics from isopycnal floats at the same density level in the SE Pacific; scaled estimates of eddy heat fluxes at and around the target isopycnal throughout the study region from isopycnal and profiling floats; scaled estimates of eddy heat fluxes at a wide range of vertical levels in Drake Passage from the mooring cluster [§IV(*c*)]; and an estimate of the three-dimensional distribution of K_e across the experimental domain derived from altimetric measurements using a novel technique (*59*) [§IV(*e*)]. The comparative analysis of this range of diagnostics, which have different strengths, will enable us to build a robust picture of the distribution and nature of isopycnal mixing in the ACC sector under study. We will particularly endeavour to resolve the vertical distribution of K_e and identify the mesoscale mechanisms that shape it, as this is a key first step toward understanding how the rate and structure of the Southern Ocean overturning are established [§II]. The entire investigation of isopycnal mixing will be guided, and the interpretation of its results enriched, by a parallel analysis of an eddy-resolving model [§IV(*e*)].

To conclude our analysis of fine- and microstructure data, we will combine our diagnostics of isopycnal and diapycnal mixing using the triple decomposition formalism (*60*) with the aim of exposing how the two processes conspire to shape the water mass configuration of the ACC. In this framework, the fact that eddy-induced thermohaline variability is density-compensated can be used to distinguish between the turbulence-driven and eddy-driven components of the production of buoyancy and temperature variance (*57*). Since we will effectively measure the rate of dissipation of both variances ($\Gamma\varepsilon$ and χ, respectively, where Γ is a characteristic mixing efficiency) with our microstructure profilers, we will be able to construct variance budgets and assess the relative importance of eddies and internal waves in determining the θ-S relation across the range of density classes and hydrographic zones. We will conduct this analysis on a regional basis, following the profile grouping strategies in our prior investigations. The end product will be a comprehensive view of the controls directly exerted by eddies and internal waves on the physical structure of the modern ACC.

IV(c) Observations of eddy – internal wave interaction in Drake Passage

The research outlined in §IV(*b*) will provide a rich account of the *direct* constraints imposed independently by mesoscale eddies and internal waves on the anatomy of the modern Southern Ocean overturning. Nonetheless, developing the capability to predict how the overturning's rate and vertical structure will change under shifting climatic forcing requires that the *indirect* controls arising from any existing interdependence between the two types of motions be also identified and understood. This is so because many conceivable changes in forcing are expected to have an immediate influence on both the eddy and internal wave fields. If the transfer of energy, potential vorticity and other dynamical quantities between the two is significant as current evidence suggests [§II], then it stands to reason that the ultimate impact of the change in forcing on the rates of isopycnal and diapycnal mixing in the ACC must depend crucially on the nature of the eddy – internal wave link [see (*60*) for a detailed discussion]. It is with the goal of characterizing the key rate-limiting process(es) that we will deploy a cluster of moored instruments in central Drake Passage that is designed to investigate the candidate eddy – internal wave interaction mechanisms outlined in §II (namely, the generation of internal lee waves and oscillations by mesoscale flow – topography interaction; dissipation of eddies in a bottom boundary layer; eddy – internal wave coupling away from the boundary; and loss of balance in the mesoscale). The need for the mooring cluster arises from the fact that, at best, these mechanisms are amenable to be surveyed in a cursory and serendipitous manner with short shipboard microstructure time series or EM-APEX float finestructure profiles. Our choice of the mooring cluster's location (Fig. 4) is based on both scientific and logistical reasons. Thus, the site has been shown to host a pronounced finestructure signal (*35*), high mesoscale eddy variability and complex topography, suggesting that it offers optimal conditions for the various interaction mechanisms to be active. Further, the local hydrographic and flow fields are regularly transformed by long-period (a few months and longer), internally driven excursions of the Polar Front (*61*), which will make it possible to study a variety of eddy and internal wave regimes with localized instrumentation. Finally, the site is centred on an altimetry crossover point and lies just off the WOCE SR1b hydrographic section, which has been repeated annually by U.K. scientists since 1993 and provides both an ideal opportunity to service the cluster half way through its 2-year deployment and a large historical data set that will serve to enhance the mooring data analysis.

The design of the cluster is outlined in Fig. 4. It will consist of 5 moorings arranged in a cross with one of its arms oriented along the SW – NE direction, following the local mean orientation of the Polar Front and the neighbouring West Scotia Ridge. The separation between the central mooring and each of the other moorings will be approximately 7 km, which is close to one half of the Rossby radius of deformation in the region. The central mooring (C) will be the most complex. Owing to mooring design requirements, it will consist of two units spaced horizontally by ~1 km along the through-passage axis of the cluster. The westernmost unit (C-1) will include a low-frequency (75 kHz) ADCP and 10 RCM-11 vector-averaging current meters with a 15-min sampling rate (which resolves the Nyquist frequency of the entire internal wave band) distributed in the vertical between the sea floor (at ~3500 m) and ~500 m. The second unit (C-2) will incorporate 3 McLane Moored Profilers (MMPs), each profiling over ~1000 m in the vertical and, mounted on the ocean floor, an inverted echo sounder with a bottom pressure sensor (PIES) and (for the first year of the deployment) a Rising Microstructure Profiler (RMP). The latter is a novel bottom-moored microstructure profiling system that has been developed at SAMS (funded by the NERC Small Business Research Initiative MIDAS programme) and comprises a seabed resident winch system (*62*), a light-weight, partially elastic non-conducting tether, and a temperature microstructure profiler that we will modify under DIMES for deep-ocean rising measurements. The 4000-m rated RMP can perform a total of ~450 profiles from 2 to 200 m above the seabed on a pre-programmed sampling regime, measuring 2-m binned χ as well as conventional conductivity, temperature and pressure. Each of the other four moorings (N, E, S and W) will include 5 current meters at depths coincident with some of those in mooring C.

The rationale for the cluster's five-mooring structure is dictated by the calculation of the intensity of eddy – internal wave interaction (commonly expressed in terms of horizontal and vertical viscosities), which hinges on the estimation of temporal correlations between the (horizontal and vertical components of) strain associated with mesoscale eddies and internal wave stresses [see (*63*) or (*42*) for a detailed description of analysis techniques]. The former quantity will be calculated by differencing the low-passed horizontal velocity components on the horizontal plane (for the horizontal strain terms) or in the vertical (for one of the vertical strain terms; the other will be computed by differencing low-passed density on the horizontal plane). In turn, internal wave stresses will be estimated at individual current meter positions as products of the high-passed velocity components (including the vertical velocity, calculated from high-passed density by invoking knowledge of the low-passed vertical density gradient) and density.

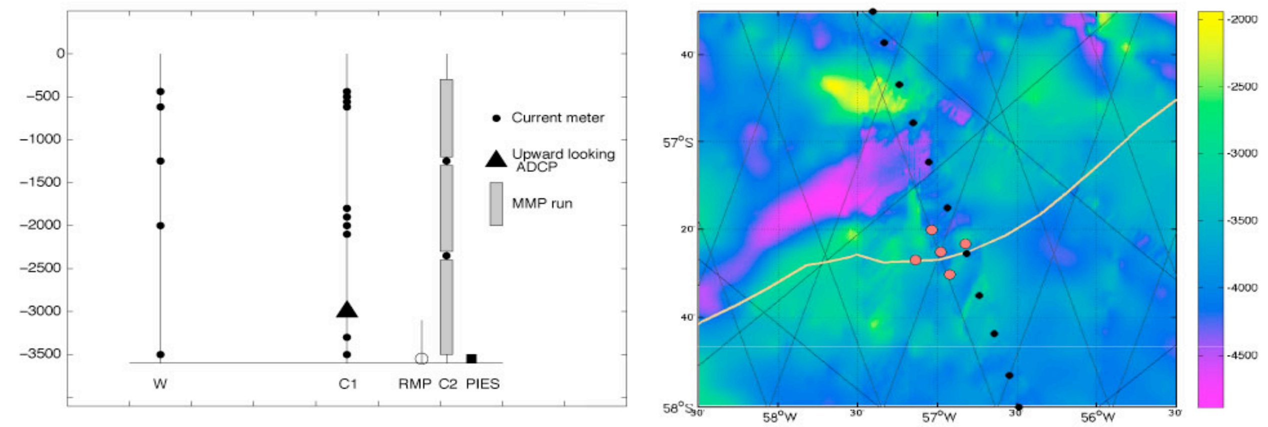

Figure 4. *Left*: Outline of each mooring type configuration in the DIMES cluster. *Right*: Proposed location of each of the DIMES moorings (red circles), superimposed on a map of the bathymetry (colour shades). The black circles indicate the annually repeated WOCE SR1b hydrographic stations. The climatological position of the Polar Front is shown by the white line, with black lines marking altimeter tracks.

Using experience with the POLYMODE Local Dynamics Experiment data set (*63*) as guidance, our proposed deployment of current meters at 5 different sites and 5 depth levels common to all moorings represents a strategy to both mitigate the impact of instrument failure on the calculation and allow investigation of the horizontal and vertical structure of the interaction. The latter will enable us to broadly characterize the length and time scales of the eddies that interact most efficiently with the internal wave field, with eddy length scales in excess of the Rossby radius being studied with along-track altimetric data. In turn, the primary purpose of instrumenting mooring C-1 more heavily than the other current meter moorings is to resolve the vertical scales of the internal wave field with a lag-correlation analysis, so that the characteristics and origin of the internal waves coupling most strongly with the eddy field can be explored. Our investigation of the submesoscale dynamics of the ACC will be advanced with an enquiry into the prominence of vortical modes in this energetic region and their role in mediating the transfer of dynamical quantities between the mesoscale and the internal wave field. To this end, we will follow the general approach of (*64,65*) to isolate the signatures of small-scale, low-aspect-ratio subinertial motions in the many fine- and microstructure profiles collected around the cluster site [§IV(*b*)] and in the current meters and MMPs in the cluster, interpreting the spectral characteristics of those motions in the light of theoretical predictions for different generation and decay processes (*65*).

Complementing the above observations of eddy – internal wave coupling, mooring C-2 will target the interaction mechanisms involving the bottom boundary and loss of balance. The rate and processes of eddy dissipation in the bottom boundary layer will be measured by two different instruments. First,the RMP will obtain 2-day-long bursts of 8 profiles of temperature microstructure and finescale stratification in the deepest 200 m of the water column every 7 days, from which time series of χ and K_ρ will be estimated. Based on Ekman theory, we expect the frictional boundary layer to have a thickness of several tens of metres and thereby elude sampling by the shipboard microstructure profilers, which are programmed to keep a cautionary ~50 m away from the ocean floor. Second, the deepest of the 3 MMPs will acquire 2-day-long bursts of 8 temperature, salinity and velocity finestructure profiles in the deepest ~1000 m of the water column every 7 days. From these measurements, a second set of estimates of ε and K_ρ across the bottom boundary layer will be obtained with a Thorpe scale analysis and a Richardson number scheme. The other two MMPs will be operated in an identical mode and in synchrony with the deepest instrument, so that ~2-day finestructure time series are retrieved over nearly the full ocean depth with a weekly periodicity during the 2-year deployment. As well as facilitating the estimation of ε and K_ρ

profiles, the chain of MMPs will provide a periodic view of the vertical and temporal evolution of the large-scale flow and the internal wave field with which theoretical models of internal lee wave and tide generation will be rigorously tested [following the analysis in (*66*)] and the conditions for the onset of loss of balance (should it occur) explored. The temporal representativeness of the patchy MMP observations will be assessed by reference to the continuous PIES-derived record of barotropic and baroclinic variability in the density field. Since loss of balance commonly manifests itself in the form of a critical layer instability (*43*), its identification will be greatly aided by the evaluation of the intrinsic, non-Doppler shifted frequency of wave disturbances propagating past the mooring cluster. This exercise will rely heavily on the estimation of the horizontal wavenumber of the disturbances with a lag-correlation analysis of the measurements of different moorings, particularly C-1 and C-2 as they are most closely spaced and aligned along the expected dominant direction of wave propagation (i.e. through-passage).

In order to fully assess the significance of eddy – internal wave interaction in the dynamics of the Southern Ocean overturning, we will construct energy and potential vorticity budgets of the circulation in Drake Passage including forcing, mean – eddy – internal wave transfer and dissipation terms [see (*67*) and (*7*) for two examples in the Gulf Stream recirculation and the global ocean]. The design of the proposed mooring cluster, which permits estimation of horizontal and vertical derivatives of momentum and density fluxes at the key information-containing scales, is ideally suited for estimating the transfer terms. Since the energy and potential vorticity budgets are widely used as metrics of numerical model dynamics, examining these budgets in the ACC will enable us to identify the important deficiencies in the way state-of-art-models represent the overturning circulation and its sensitivity to change.

IV(d) Inverse estimation of the three-dimensional circulation

Building on our initial, hydrography-based qualitative study of the large-scale circulation [§IV(*a*)], we will use inverse techniques to integrate the collection of hydrographic, velocity, fine- / microstructure and float data gathered by the DIMES programme into an optimal estimate of the three-dimensional circulation in the SE Pacific and SW Atlantic sectors of the ACC. Our inverse estimation of the ocean circulation in the DIMES region will proceed along two distinct, yet complementary lines of research. In the first, we will obtain a dynamically consistent estimate of the horizontal circulation at all depths and throughout the experimental domain by combining direct velocity measurements (from ADCPs and microstructure profilers) and float displacement mapping (*68*) with the Bernoulli inverse method (*69,70*) applied to hydrographic data. The ultimate aim of this investigation will be to gain sufficient insight into the time-mean lateral structure of the ACC flow in the DIMES region to be able to determine isopycnal mixing and upwelling rates from the observed tracer evolution, as well as to examine the link between mean flow forcing and the measured ε and K_ρ fields. In the second exercise, we will optimally diagnose the horizontal and vertical circulation across several coarse areas of the DIMES domain (namely, the SE Pacific, Drake Passage and the remainder of the Scotia Sea) by combining hydrographic sections forming closed volumes into a box inverse model (*71*). This inverse framework will enable us to assess the significance of the small- and mesoscale mixing processes measured during DIMES in driving the overturning circulation of the surveyed Southern Ocean sector. Further, the information provided by both inverse analyses will be central to testing current parameterizations of isopycnal and diapycnal mixing rates in terms of the properties of the large-scale flow.

The primary goal of our proposed Bernoulli inverse study will be to derive a dynamically consistent estimate of the time-mean streamfunction in the DIMES region that can serve as the spatial coordinate system in the determination of isopycnal mixing and upwelling rates from the observed tracer evolution, as well as in the investigation of the physics underlying the measured ε and K_ρ fields. The Bernoulli inverse method is ideally suited to the inversion of a set of widely spaced, randomly distributed hydrographic profiles, such as the one we expect to collect with EM-APEX floats and with shipboard instrumentation during several of the DIMES cruises (this data set will be supplemented with historical CTD and Argo float data). The method's essential principle is that in steady, geostrophic, hydrostatic flow, potential temperature, salinity, linear potential vorticity and a compressible Bernoulli function (whose horizontal gradient is related to the unknown sea surface height, SSH, that the method aims to determine) be conserved along streamlines. Following this premise, the Bernoulli approach initially identifies intersections between hydrographic profiles in potential temperature – salinity space, and assumes that the profiles with intersecting thermohaline characteristics are connected by a streamline.

The requirement that the linear potential vorticity and Bernoulli function also match at these intersections then leads to a heavily overdetermined problem for SSH that can be solved using inverse techniques. Finally, a depth-independent reference velocity can be derived from the Bernoulli estimate of SSH and combined with geostrophic shear to calculate the absolute geostrophic velocity. While the application of the Bernoulli inverse method requires no *a priori* velocity information, we will explore the extent to which adding such information (from ADCP and microstructure profiler measurements, and isopycnal and EM-APEX float displacements) to the problem improves the solution by taking advantage of the common mathematical formalism shared by the inverse and objective mapping algorithms (*71*). We will also investigate the value of augmenting the inverse problem with altimetric measurements of SSH and state-of-the-art estimates of the geoid, which will be central to our analysis of the temporal representativeness of the regional circulation and mesoscale eddy variability during DIMES. The proposed Bernoulli inverse study will reap the benefits of an ongoing research project within BAS (the NERC centre leading this element of the DIMES programme), as part of which the Bernoulli approach is being applied to hydrographic data collected in the southern rim of the Scotia Sea (south of the DIMES domain) during the late 1990s.

Since the Bernoulli inverse method provides no direct information on features of the circulation other than the time-mean geostrophic flow, we will use a box inverse model to investigate the relative roles of the small- and mesoscale mixing processes measured during DIMES in driving the overturning circulation of the surveyed ACC sector. The model will be constructed using hydrographic sections collected in the DIMES region (including all relevant CLIVAR section repeats such as the meridional P18 transect along 110°W, which is to be occupied in 2008, and the S4A section along the boundary between the Weddell and Scotia seas, which is planned for 2010) forming closed volumes, resulting in several 'boxes' in the SE Pacific, Drake Passage and the eastern Scotia Sea. Box inversions rely on the assumption that the large-scale thermal wind transports observed at the times of the cruises are representative of the time-mean values to a good approximation. With this premise, full-depth and isopycnal layer-specific conservation of mass, heat and salt is enforced within specified uncertainties to determine a depth-independent reference velocity at each station pair, a profile of the diapycnal mixing rate in the ocean interior (commonly expressed as a set of diapycnal vertical velocities), and a collection of terms quantifying the impact of air-sea interaction on the circulation [see (*33*) or (*72*)]. The inverse framework can also accommodate additional conservation statements describing reasonably well-known features of the circulation, such as the mass transports through certain passages. In the DIMES application, we will use the unprecedented year-round time series of upper ocean properties collected by EM-APEX floats and a suitably modified version of Walin's framework [see (*33*) and references therein] to investigate how the box inverse model may solve for mixing processes in the upper ocean mixed layer separately from those at greater depth for isopycnal layers outcropping within the model domain (as opposed to the merging of the two in classical inversions). The model's solution will be guided by initial estimates of the reference velocities (from ADCPs), air-sea interaction terms (from climatological and atmospheric reanalysis data) and upper-ocean and interior mixing rates (from EM-APEX float, microstructure and tracer data). This will be the first time that a box inverse model, commonly unable to determine mixing rates with statistical significance, is initialized with dedicated mixing measurements. This novel addition will bring about a large and decisive reduction in the *a posteriori* uncertainties of the mixing terms diagnosed by the model, which will enable us to readily determine the relative importance of isopycnal and diapycnal closures at different levels of the Southern Ocean overturning and to investigate the overall energy budget of the circulation. We will seek to use this analysis of the overturning in the DIMES region to test the predictions of residual mean descriptions of the overturning [§II]. We will do this by obtaining streamwise-average hydrographic fields (averaging along Bernoulli streamlines) and applying the range of parameterizations used in residual mean models to those fields so as to estimate the rates of mixing and upwelling within each inverse model box. Lastly, we will use the posterior covariance matrix of the inversion to explore the sensitivity of the overturning and other climatologically important variables [such as the meridional heat flux (*27*)] to the range of mixing processes embedded in the model.

IV(e) Numerical modelling

To push the boundaries of observations, we will conduct a series of experiments with an eddy-resolving global ocean general circulation model (OCCAM; http://www.soc.soton.ac.uk/JRD/OCCAM/ OC12/) to guide both our interpretation of the relatively sparse tracer measurements and our use of indirect techniques to derive isopycnal mixing and upwelling rates over the full ocean depth from altimetric and *in situ* data. OCCAM is a state-of-the-art model with a horizontal resolution of 1/12° and 66 vertical levels; layer thickness varies between 5 m at the surface to 200 m in the abyssal ocean. Partial bottom grid cells enable the depth of the ocean to be accurately represented, an important feature for the strongly bottom-steered ACC. Surface forcing is based on NCEP reanalysis products for the period 1985 – present day.

Our analysis of OCCAM will follow three distinct lines of research. In the first, we will use 5-day mean velocity and density fields to simulate the DIMES tracer release experiment offline (the cost of an online simulation at 1/12° resolution is prohibitive). This simulation will take the form of an ensemble with each member initialised at a different time. In addition to this ‘standard run’ reproducing the circumstances of the actual tracer release as closely as possible, we will conduct a number of simulations of tracer releases in other ACC zones and density surfaces. Using the standard run, we will assess the sensitivity of tracer-based estimates of mixing and upwelling rates to the sampling strategy, provide an informed view on the fate of the unsampled part of the tracer patch, and devise an algorithm to optimally estimate mixing and upwelling parameters from the sparse measurements collected. We will also obtain estimates of transit time distributions between key tracer sampling locations, such as the flanks of Drake Passage and the northern boundary of the Scotia Sea. We will study the other runs comparatively to evaluate how representative the DIMES tracer release may be of the upwelling limb of the Southern Ocean overturning, and to investigate the density dependence of isopycnal mixing and upwelling rates. A further goal of our analysis will be to gain insight into the mesoscale mechanisms leading to cross-stream tracer transport (such as the breaking of Rossby waves along localized critical layers), which we will explore in the context of eddy – mean flow interaction and flow – topography interaction diagnostics (*58*). This study will provide an interesting backdrop to our tracer-, float- and altimetry-based investigations of isopycnal mixing and upwelling during DIMES, enabling us to interpret imperfect observational diagnostics and learn about the deficiencies of state-of-the-art numerical models.

The second strand of our OCCAM-based investigation will aim to develop a strategy to diagnose the three-dimensional distribution of the isopycnal diffusivity in the surveyed ACC sector and beyond from a novel technique formulated on a tracer-based coordinate system (*59*). This ‘effective diffusivity’ technique involves the numerical driving of an advection-diffusion equation for an idealized tracer using a two-dimensional, non-divergent flow while monitoring the lengthening of tracer contours as they are stretched and folded by the flow. A pilot application to altimetry-derived velocities to explore the meridional distribution of the zonally averaged surface eddy diffusivity in the Southern Ocean (*28*) has demonstrated the technique’s great potential for investigating isopycnal mixing and upwelling in the ACC. This is so because, owing to dynamical reasons, the ACC is equivalent barotropic (*73*). The self-similarity of the flow in the vertical translates into a high degree of predictability of the deep thermohaline characteristics of the current in terms of its surface streamfunction (*74*). This leads us to hypothesize that, using thermal wind, the straining properties of the deep circulation (and thereby the rate of eddy-driven mixing) may be feasibly related to those of the surface flow, given adequate knowledge of SSH and the hydrography. We will test this hypothesis by applying the effective diffusivity technique to 5-day mean OCCAM velocity fields at a number of vertical levels and examining how the diagnosed diffusivity scales with depth and a collection of bulk properties of the velocity field (such as root-mean-square magnitude and horizontal strain) that are inferable from the surface flow and deep hydrography. In this context, we will assess the accuracy with which the rate of eddy-driven isopycnal upwelling may be derived from the diagnosed effective diffusivity profile. Upon identification of simple relationships between the effective diffusivity and the bulk properties of the velocity field, we will apply the same strategy to altimetric measurements of the surface eddy flow in the DIMES region and the large (CTD-, EM-APEX- and microstructure-derived) hydrographic data set gathered during the experiment. A second aim of this investigation will be to gauge the size of the smallest region to which the effective diffusivity technique may be successfully applied, so that we can maximize the amount of information on regional variability in isopycnal mixing and upwelling rates extracted from observations.

Building on the preceding modelling work, the third line of research that we will pursue with OCCAM will endeavour to test and, if necessary, refine, the ‘mixing length’ technique that may allow us to map the isopycnal mixing rate from knowledge of the eddy velocity field and thermohaline variability on density surfaces [§IV(*b*)]. OCCAM is ideally suited to assessing this technique's skill, as lateral mixing in the model is almost exclusively driven by resolved physical motions (the only exception is a slight velocity-dependent implicit biharmonic mixing associated with the advection scheme). Thus, the fundamental assumption of the technique, that the production of density-compensated thermohaline variability on isopycnals is the result of mesoscale eddy stirring, should be well represented by the model. With this basis, we will investigate whether the isopycnal diffusivity (as calculated from the simulated tracer release experiments and the effective diffusivity calculations above) obeys the 'mixing length' theoretical scaling and, if so, with what efficiency factor c_e and with what definitions of the root-mean-squared eddy velocity U_e and lateral filamentations scale L_e. In this way, we will establish the optimal strategy that we must follow in applying this isopycnal diffusivity estimation technique to our fine- and microstructure measurements [§IV(*b*)], and gain insight into its limitations and promise for diagnosing isopycnal upwelling rates.

V. References

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