A STRATEGY FOR OPEN OCEAN MIXING EXPERIMENTS

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ABSTRACT

Tracer release experiments to study diapycnal mixing in the open ocean on 500 km x 12 month scales are in prospect. These should be combined with small scale physics measurements to interpret the experiments and to develop relatively inexpensive robotic techniques for diapycnal mixing studies over the coming decades. The robotic techniques may eventually supplant tracer releases as a means of exploring the parameter space in which diapycnal mixing is controlled. Armed with these tools we may be able to develop a nearly complete parameterization for diapycnal mixing throughout the ocean over the next 30 years.

INTRODUCTION

Why do we care about diapycnal mixing in the ocean? One model may show that the value of the diapycnal mixing coefficient is important to the meridional heat flux (e.g., Bryan, 1987), another may suggest that it isn't (e.g., Gargett, this volume). Classical models such as Stommel and Arons (1960) imply a dominant role for diapycnal mixing in determining the interior abyssal circulation. Yet, for some reasonable depth dependencies of the diffusivity it can be shown that the interior circulation driven by diapycnal mixing through the absolute vorticity balance is virtually nil, or is equatorward rather than poleward.

Are the diapycnal processes at the air-sea interface, together with lateral transport at the surface, sufficient to explain what is known about the circulation and hydrographic structure of the ocean? I suspect not, otherwise there would be no tritium on those density surfaces in the North Pacific which don't outcrop (see, e.g., Gargett et al., 1986). If we were to add diapycnal processes at the topographic boundaries at the bottom and around the rim of the ocean, would it then be sufficient? Maybe, but if so, we need to show that it is so. That is, we at least need to demonstrate that interior diapycnal processes aren't important, and that boundary processes are large enough to account for the observations.

The flow of mass, heat, salt and trace constituents through the density strata of the ocean is one of the most intrinsically fascinating processes for study in the ocean. The storage of these properties under the transient conditions accompanying climatic change on time scales of decades to millenia are important to the prosperity of civilization. I would like to sketch some new field techniques for the study of diapycnal mixing in the ocean on much larger lateral and temporal scales than have been attempted up until now. I would also like to suggest a strategy for combining these techniques in a way that within the next 30 years could reveal the magnitude and spatial distribution of diapycnal mixing in the ocean.

TRACER RELEASE EXPERIMENTS

One technique under development involves the release of a tracer on an isopycnal surface and the measurement of its subsequent diapycnal and lateral dispersion. Floats released with the tracer to enable tracking will also yield the lateral mixing. Prospective experiments have been described in some detail elsewhere (e.g., Ledwell and Watson, 1988). The tracers being used at present are fluorinated compounds detected by gas chromatography with an electron capture detector. The tracer to be proposed for the first open ocean experiments is sulfur hexafluoride (SF_6). The sensitivity is such that a 12 month x 500 km scale experiment could be performed in the open ocean with just 100 kg of this tracer.

The injection will be performed by towing an injection device as near to an isopycnal surface as possible. The injection pump is shut down when the ambient density is more than a preset distance away from the target density. It is also shut down when any one of a number of transducers indicate malfunction of the injection. The tow speed for injection will be 20 to 40 cm/s. This slow speed enables the initial streak to be spread laterally without creating a large initial dispersion due to the wake. A week or so will be required for injection of a patch with an initial length scale of 30 km or so. The scientific advantage of spreading the initial patch out is that there is less chance of the tracer being in an anomalous spot early on. Technical advantages are that the density anomaly associated with the tracer is diluted by the wake of the injector, and that sections of the initial plume may be readily encountered by cutting across the injection streaks with a sampling ship. A small spot of tracer would be difficult to find, and once found, the danger would be that sampling it would induce artificial mixing of some consequence.

Because the tracer distribution is expected to be streaky, the tracer must be sampled by towing a vertical array of integrating samplers through the patch. The center of the array is kept on the target isopycnal surface in the same way as the injector. A multichamber sampler could be placed at the center of the array, with the chambers filled sequentially to give a lateral resolution of better than 1 km for locating the tracer streaks. The samples can be analyzed on board the ship at a rate of about 10/hour for a single instrument manned by an analyst and an assistant.

Three sampling cruises are planned for the first open ocean tracer release experiment. The first will be carried out shortly after the injection operation from a second ship. This ship will tow the samplers through the patch of recently injected streaks, guided by floats released with the tracer. The patch at this point might be about 50 km across. A second sampling cruise will be performed about six months after injection, or when the anticipated patch is about 250 km across. The samplers will be towable at 5 km/hr, with four 15-km tracks performed per day. Thus, in a month an overall track length of 1500 km could be traced out; i.e., the patch could be crossed approximately five times with virtually unbroken track. Again, the float positions would be used to plan the sampling tracks. A final survey would be performed about a year after the injection, or when the patch size is anticipated to be about 500 km. The sampling track could cross the patch five times again in a month, but this time the tracks would not be continuous, having gaps of 15 km length between the individual tow tracks. An experiment starting in the spring would yield two measures of the diapycnal diffusion, one for the "summer" season and one for the "winter" season.

I should note that it would be better if the tracer could be measured with an in situ instrument at a high sampling rate to examine the details of the tracer patch and to more accurately determine the distribution of the tracer in density space. Although an in situ gas chromatograph for sulfur hexafluoride could be conceived, the expense would be great and the sampling rate would still be relatively low, say 2 min/sample at best. A more promising approach might be to push the sensitivity of in situ fluorometric techniques for the sensing of fluorescent dye, with sampling rates of 1 Hz or better. Either approach would take at least a few years of development, but would be worth pursuing.

The first open ocean tracer release experiment will be proposed for the upper pycnocline of the eastern subtropical North Atlantic. This first experiment may be viewed as a pilot to get the technique into open water. It should also serve as a pilot for float-based and mooring-based small scale measurements. The site has been chosen to take advantage of available resources, both ships and scientific manpower. In particular, the experiment will coincide with the Subduction Experiment presently planned by the U.S. Office of Naval Research, and the site enables heavy participation by the United Kingdom and Canada, as well as the U.S., as part of the World Ocean Circulation Experiment.

An idea of the diapycnal spreading to be expected can be had from Table 1, where I list the square root of the second moment of the vertical distribution, σ, for various values of the diffusivity and for an initial value of $\sigma_0 = 5$ m. The values in the table are simply calculated from the formula:

$$\sigma^2 = \sigma_0{}^2 + 2\,Kt \tag{1}$$

where K is the diapycnal diffusivity for the tracer and t is the time since injection. It is important to design the experiment to minimize the initial dispersion; based on our experience so far, 5 m is a conservative estimate for the stratifications to be encountered in the main pycnocline. For $K = 0.01$ cm^2/s, σ does not quite double over the course of a year. This value should probably be viewed as the minimum detectable level of K for the experiment. The experiment would certainly be valuable, however, even if it only succeeded in setting this upper limit on K, as 0.01 cm^2/s is a very low value in the context of the general circulation and water mass transformation.

Two pilot experiments in the basins off the coast of Southern California have been performed to develop the technique. Ledwell et al. (1986) reported the first experiment in Santa Monica Basin (sill depth of 737 m; bottom depth of about 914 m; and area of about 1800 km^2). The injection was performed on the 5.085°C potential temperature surface, at about 800 m depth. The subsequent spreading of the patch (Fig. 1) yields an estimate of the diapycnal diffusivity of approximately 0.3 cm^2/s at a buoyancy frequency of about 1.0 cph. Most of the uncertainty in the result is due to changes in the horizontally averaged hydrographic structure from one cruise to another.

The second experiment was started in 1988 in Santa Cruz Basin (sill depth of 1084 m; bottom depth of around 1950 m; area of around 1800 km^2) on the 4.0681°C potential temperature surface at about 1500 m depth. The buoyancy frequency at the injection depth was about 0.2 cph, i.e., about five times less than for the Santa Monica experiment. Preliminary analysis suggests that the diapycnal diffusivity is greater than 1 cm^2/s, while lateral processes are much slower than in Santa Monica Basin. One of the primary accomplishments in this experiment was the use of a protoype injector for sulfur hexafluoride which has the capacity required for open ocean experiments.

Table 1. Vertical dispersion, σ, in m, of a tracer patch at various times for different values of K, assuming $\sigma_0 = 5$ m.

	Time (days)		
K (cm_2/s)	10	180	330
0.01	5.2	7.5	9.1
0.03	5.5	11	14
0.1	6.5	18	24
0.3	8.8	31	42
1	14	56	76
3	23	97	131
10	42	176	239

LIMITATIONS OF THE TRACER RELEASE TECHNIQUE

A single open ocean tracer release experiment, as presently envisioned, requires several months of a full crew on at least a 50-m research vessel. It also requires deployment and tracking of a dozen or so neutrally buoyant floats. The minimum cost is on the order of 3 million 1989 US dollars. Obviously a large number of such experiments cannot be done quickly. Yet the number of independent variables that govern diapycnal mixing is potentially large, among them might be:

depth
latitude
buoyancy frequency
density ratio
wind forcing of the internal wave field
mesoscale eddy forcing of the internal wave field
mean shear
along-isopycnal T/S variations
topographic parameters.

Clearly we cannot expect, even in several generations of scientists, to be able to explore this parameter space with tracer release experiments alone. Instead, we must develop relatively inexpensive means of reliably estimating diapycnal mixing averaged over at least as large temporal and spatial scales as achievable with tracer release experiments.

Furthermore, even if tracer release experiments were inexpensive, they would not answer all of the questions on diapycnal mixing. The most important reason is that a dynamically passive tracer may not behave the same as heat or salt, which of course are both dynamically active. It is true that the molecular diffusivity of a tracer of moderate molecular weight is of the same order of magnitude as that of salt, and on this ground the tracer is expected to mimic salt. However, I believe that one must be cautious about even this expectation, especially where the salinity gradient contributes to the stratification, and even more so where salt fingering is occurring.

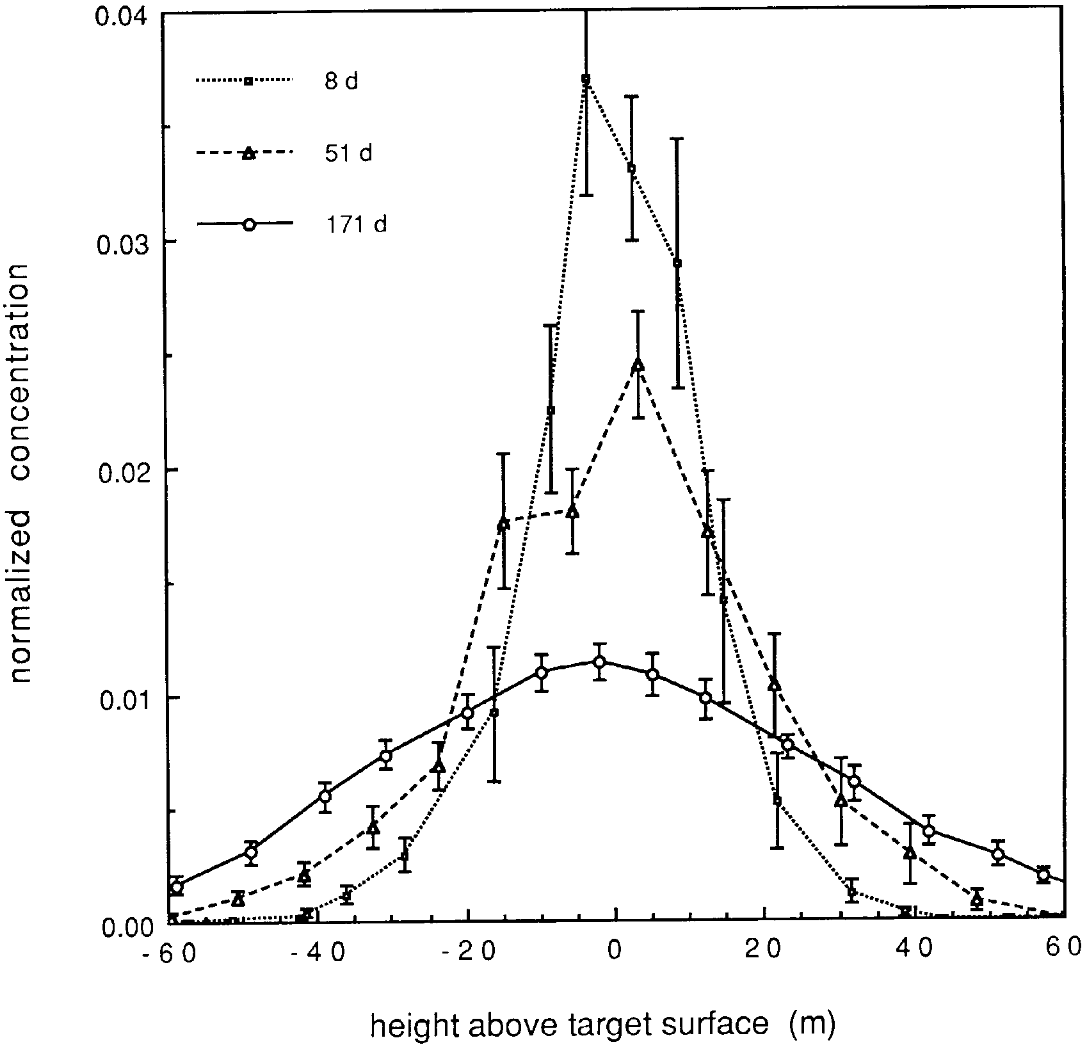

Fig. 1. Vertical spreading of the tracer during the Santa Monica Basin Experiment. Each profile is an average of ten or so individual profiles, with the error bars indicating the variance in shape of the individual profiles. The target surface of the injection was the 5.085°C potential temperature surface. The height is really a transformed coordinate based on the potential temperature profiles and the mean height versus temperature profile for the middle (51 d) survey. The concentration shown is normalized so that the area under each curve is unity. The days after injection given in the key are nominal; in reality each survey cruise was about 10 days long. The diapycnal diffusivity inferred from the spreading is about 0.3 cm^2/s.

Differences between the diffusivity of heat and the tracer are even more likely. Clearly such differences will arise in double diffusive regimes where order of magnitude differences between the diffusivity of heat and salt are expected. Even in diffusively stable regimes the eddy diffusivity may depend on the molecular diffusivity, as recently pointed out by Gargett (1988). Conditions of relatively weak turbulence can arise in which the smallest eddies are large enough that, while temperature variance is effectively dissipated by molecular diffusion on a time scale short compared with the time scale of a mixing event, salinity or tracer variance is not. This effect will lead to a larger eddy diffusivity for heat than for salt or tracer.

ROBOTIC TECHNIQUES

Hypotheses exist, of course, for the relation of diapycnal mixing to characteristics of the fine structure and microstructure (see, e.g., Gregg, 1987, for a review). Examples of relevant parameters are the kinetic energy dissipation rate, the temperature variance dissipation rate, the fine-scale Richardson number or simply the fine-scale shear (see, Gregg, this volume, for a study of the last). Most of these quantities up to now have been measured using sophisticated profilers which require special cruises for deployment. Measurements are thus very expensive and yield averages for a week or so at one site, or else cover a long section with little temporal averaging.

Nevertheless, it seems likely to me that some of these quantities will soon be accessible to autonomous devices deployed for months at a time. Already a float exists to measure temperature and velocity gradients to estimate Richardson number on 1 to 5 m scale (Williams et al., 1987). There seems little in the way of deploying such floats for six months, especially in view of the success of long term moored deployments. Another technique which may be developed in the next few years is the measurement of temperature variance dissipation from floats which bob up and down through a layer of interest as they roughly follow the lateral flow. Perhaps it will prove feasible to do the same with shear probes to measure the kinetic energy dissipation rate. It is even feasible with presently available battery packs to power neutrally buoyant drones to cruise at speeds of 30 km/day for several months while sampling small scale features. Moored instruments which measure small scale features as they are advected past the sensors by the ambient flow might also prove useful in some situations.

Thus, the coming decade may bring measuring systems that do not require the continual presence of a research vessel, and are therefore considerably less expensive than present techniques. The development of such systems should be encouraged, and mixing experiments involving tracer releases should be coordinated with small scale physics measurements with a view toward exploiting robotic techniques in the future.

LONG TERM STRATEGY

Neither tracer release experiments, nor the robotic techniques I have alluded to, have been tried in the open ocean in anything close to 12 month x 500 km experiments. While we are still very much in the development stage on all fronts, it is wise to ask where we ought to be headed. I believe our goals should be to construct a climatology of diapycnal mixing in the present ocean, and to be able to predict how diapycnal mixing will vary with hydrographic and dynamic variables. Predictive schemes will be especially useful if they are posed in variables likely to be the products of coupled atmosphere-ocean numerical models to be developed in the next several decades.

It seems to me that the best way to achieve these goals is with a combination of tracer release experiments and the development of robotic techniques to measure small scale physics. The tracer technique promises direct measurements of diapycnal mixing of a passive tracer, albeit in a relatively modest number of situations. If simultaneous studies of small scale physics are performed on the same spatial and temporal scale as the tracer release experiments, then we can hope to confirm existing hypotheses or to discover new relationships which will ultimately enable the use of the small scale measurements alone for accurate estimates of the diapycnal diffusivities. Then, if these measurements can be made without great expense using robotic techniques, we can explore the parameter space more thouroughly than would be possible with the tracer release technique.

Ultimately we would perform fewer and fewer tracer release experiments, using them only for qualitatively new situations, or where they are uniquely suited to a special situation. Of course, the success of this plan depends on the development of small scale measurements from floats, drones or moorings, and on advances in the interpretation of the small scale measurements. It is important, then, to develop the various techniques together in a series of experiments for which interpretation promises to be straightforward.

I can envision performing three to six mixing experiments during the 1990's, depending on how many nations and scientists become involved. We can hope that by the end of the decade inexpensive robotic techniques will be proven, and their products interpretable. During the first two decades of the next century, the robotic techniques could be deployed in increasingly ambitious programs, with tracer releases used as needed, until at the end of the period we have largely achieved a basic parameterization and understanding of diapycnal mixing in the ocean. I believe that we stand at the threshold of a very exciting time: we can solve within the coming generation a problem which has long been a central enigma of oceanography.

REFERENCES

Bryan, F., 1987: Parameter sensitivity of primitive equation ocean general circulation models. *J. Phys. Oceanogr.*, 17, 970-985.

Gargett, A.E., G. Ostlund, and C.S. Wong, 1986: Tritium time series from Ocean Station P. *J. Phys. Oceanogr.*, 16, 1720-1726.

Gargett, A.E., 1988, Reynolds number effects on turbulence in the presence of stable stratification. In: *Small Scale Turbulence and Mixing in the Ocean*, J.C.J. Nihoul and B.M. Jamart, eds., pp. 517-528, Elsevier, Amsterdam.

Gregg, M. C., 1987: Diapycnal mixing in the thermocline: a review. *J. Geophys. Res.*, 92, 5249-5286.

Ledwell, J.R., A.J. Watson., and W.S. Broecker, 1986: A deliberate tracer experiment in Santa Monica Basin. *Nature*, 323, 322-324.

Ledwell, J.R., and A.J. Watson, 1988: The use of deliberately injected tracers for the study of diapycnal mixing in the ocean. In: *Small Scale Turbulence and Mixing in the Ocean*, J.C.J. Nihoul and B.M. Jamart, eds., pp. 11-20, Elsevier, Amsterdam.

Stommel, H., and A.B. Arons, 1960: On the abyssal circulation of the world ocean - I. Stationary planetary flow patterns on a sphere. *Deep-Sea Res.*, 6, 140-154.

Williams, A.J. 3rd, C.H. Converse, and J.W. Nicholson, 1987: Richardson number float. In: *Current Practices and New Technology in Ocean Engineering - 1987 - OED - Vol 12*, G.K. Wolfe, (Ed.), pp. 25-29, Am. Soc. Mech. Eng., New York.