Abyssal Recipes-II—An Informal Reprise or Abyssal Recipes 2′, or Abyssal Snacks, or...

Preliminary Draft

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Abstract

1 Introduction

In an earlier paper (Munk and Wunsch, 1998; hereafter MW98) we suggested that much of the abyssal flow in the ocean was controlled by turbulent diffusion driven in large-part by mechanical energy input by the tides. The suggestion that an important element of the oceanic general circulation depends upon the presence of the moon seemed to be a somewhat outrageous hypothesis, and we were thus surprised by the vigor by which the idea was embraced by much of the oceanographic community. In the intervening years a great deal has been learned about oceanic mixing mechanisms, and although there are still many issues, it is useful to briefly provide some perspective on the subject from the point of view of the 1998 paper. This note is emphatically *not a review article*—it is highly, and arbitrarily selective of some results that appear to bear most closely on the arguments in MW98, or that we simply found interesting.

The MW98 paper attempted to semi-quantitatively synthesize the ability to estimate tidal dissipation estimates newly available from TOPEX/POSEIDON data (e.g., Egbert and Ray,) with the growing indication from microstructure profiler (Polzin et al., 199x) and tracer experiments (Ledwell, et al.,) that abyssal mixing was spatially extremely inhomogeneous.

It is very important to recall that MW98, like its predecessor (Munk, 1966), addressed only the *abyssal* circulation. No discussion nor inferences were intended concerning mixing in the ocean in the thermocline and above. Thus several criticisms of MW98 (e.g., Webb and Suginahara, xxxx) were really saying that the MW98 picture did not necessarily apply in the upper ocean—including the thermocline—an assertion with which we fully agree. Many energy sources act on the upper ocean (e.g., hurricanes (Emanuel,2001), or even biology (Munk, 1966)) that have no direct influence on isopycnals that do not outcrop. More specifically, much of the theoretical literature produces abyssal stratifications that are vanishingly small. Although the observed stratification below about 1000m is much less than that across the thermocline, it almost nowhere actually vanishes and parameters such as $N/f > 1$ everywhere. That this vast volume of ocean is stably stratified is one of the zero-order dynamical features of the real ocean. There is a strong temptation to oversimplify the ocean. For present purposes, an intermediate course between treating the ocean as a large number of layers with differing dynamics and the wish to reduce it to a single physics is perhaps most sensible. We can refer to the upper ocean (above, very crudely 1000m), and a true abyssal ocean (below about 2500m), separated by a "mid-depth" ocean lying between. The physics of the mid-depth ocean may well prove to be the most subtle of all.

2 Energy Inputs

A central point of MW98 is an obvious one—that oceanic mixing requires an energy source, and that any claim to complete understanding of the ocean circulation requires accounting for that energy. Traditionally, oceanographers have ignored the oceanic energy budget, and one seeks in vain in most oceanographic textbooks to find even its mention.

The turbulent energy required to mix the ocean is most commonly parameterized in numerical models in terms of eddy coefficients. One typically writes turbulent mixing as an analogue (Reynolds analogy) of molecular diffusion. The energy source providing for the consequences of molecular-scale mixing is clear—it is the internal energy of the fluid ultimately resting with the quantum level fluctuations of the fluid molecules. (Consider that if one takes a stably stratified insulated container of fluid, and waits long enough, the fluid properties will homogenize. At the end, the center of mass of the fluid is higher than at the beginning, and work has been done—energy extracted from the internal energy of the fluid.) In a model, no such internal energy source is available, and consequently models, analytical or numerical, that invoke "eddy-coefficients" to represent turbulent mixing are energetically open. Whether the analysis of systems lacking an energy principal can be regarded as scientifically useful could be debated.

In the intervening years, there have been a number of attempts to close the complete energy budget of the ocean, with the tidal component being only one of several contributors. Sorting out the energetics of the ocean is, on the basis of the history of science, a critical element of any understanding of the importance of any element. R. X. Huang and his collaborators (Huang,....)

has made the most determined effort to calculate all of the elements of the transfer of energy from external sources into the ocean. As discussed by Wunsch and Ferrari (2004; hereafter WF04), two separate problems exist: the total transfer, particularly across the air-sea interface, and the distinguishable problem of transferring this energy into the thermocline and below into the range of isopycnals with no surface outcrops.

The net transfer of energy from wind to ocean is very large (TW from Lueck and Reid, 1984, and xx in Huang's (200x) synthesis (see also Fig. xx of WF04). The tidal input of energy is bounded above by the astronomy at about 3.2TW (MW98). Bottom heating (TW) is significant but weak. Consistent with Faller (196x) , Huang (200x) finds the work done by buoyancy forces to be essentially negligible. In the case of the wind, most of the energy input is thought to go into surface waves and near-surface turbulence and the main issue is the fraction of the energy which somehow manages to penetrate into the abyss. The parallel statement for the tides is the extent to which the total dissipation is partitioned between the shallow seas with no circulation consequences, and baroclinic conversion in deep water. Once energy appears in the internal wave field it can, in principle, propagate for long distances vertically and horizontally. Internal wave generation by the wind can take place through several mechanisms. Watanabe and Hibiya (2002), Alford (2003) among others have estimated the contribution through inertial motion generation. The latter's estimate is approximately 0.5TW, a significant fraction of the required total energy. The importance of the remaining mechanisms is less clear.

Wind input into the ocean appears to be dominated by the Southern Ocean, both in the geostrophic (Wunsch, 1998) and ageostrophic components (Huang, 200x). Assuming that much of this energy is dissipated locally, rather than being exported meridionally to the rest of the world ocean, the overall dissipation rates there must be considerably higher than elsewhere. Possible support for this inference is lent by the result of Garabato et al. (200x) who inferred very strong abyssal mixing in a region without exceptional tidal forcing. In any event, the energy balance of the Southern Ocean would appear to warrant a special effort to understand it.

2.1 Tidal Component

The tidal component of energy input differs in kind from that by the wind in that the main conversion from the large scale into scales that can mix the ocean directly occurs in the abyss through the topographic coupling. A comparatively large number of papers has been published (e.g.,) attempting to calculate the rate of conversion of barotropic into baroclinic tidal energy (primarily as a scattering process). What is the evidence that mixing is tidally dominated? We will not attempt to review this subject, but raise as a question the extent to which, on a global basis, abyssal mixing is dominated by the tides?

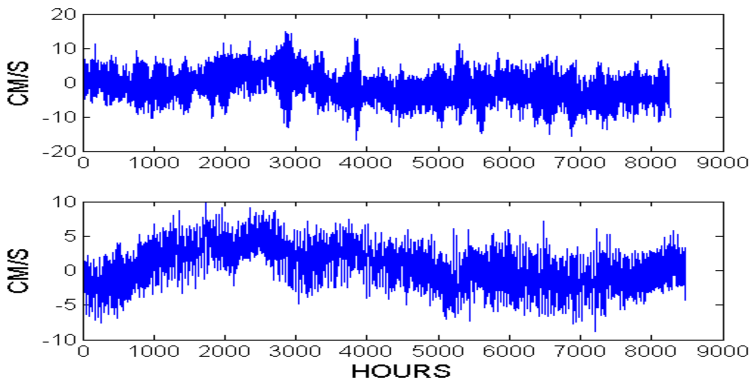

Figure 1: East component of currents from two deep records in the North Atlantic. Upper is for an instrument in proximity to the Mid-Atlantic Ridge with its complex terrain. Lower is for an instrument over the abyssal plane.

Apart from the Hawaii Ocean Mixing Experiment (HOME) results (Rudnick et al., 200x), unfortunately there is not a great deal of evidence. [?Walter, can anything specific be said briefly?] Should one expect the tides to dominate? There does not yet seem to be a very clear consensus. If one takes two arbitrarily chosen abyssal current meter records (Fig. 1) and computes their spectra (2, 3), one sees that the abyssal kinetic energy over a one year period is about 70% in the band at periods longer than $2\pi/f$, with about 10% in the tidal band, and with the remainder in internal waves and “other”. To the degree that abyssal mixing is the result of interaction of these motions with topography, there is no particular reason to single out the tides for special discussion.

This last statement is too simple in a number of ways. The conversion of barotropic to baroclinic motions may, in the near-field, mix the ocean locally, and significantly. The internal wave band itself may be maintained by tidal inputs. (Although the Mediterranean results of van Haren and Millot, 2004, and H. Van Haren, private communication, 2004) show an essentially normal level of internal wave activity without any significant tidal component.) The main observation is that much of the abyssal kinetic energy lies outside the tidal band and any complete theory of the oceanic energetics and mixing has to account for all of it, not just the tides.

Mesoscale kinetic energy dominates these records both locally and globally (WF04). Theory strongly suggests that the origin of the mesoscale kinetic energy is the windfield, primarily through instability of the large-scale general circulation. As WF04 note, however, the mechanisms by which the mesoscale kinetic energy is dissipated seems essentially unknown. With an

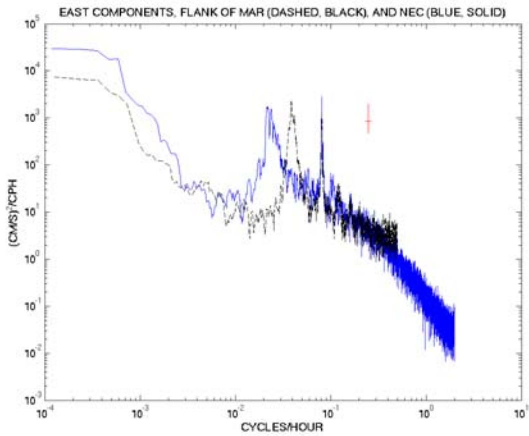

Figure 2: Power density spectral estimates for the two records in 1.

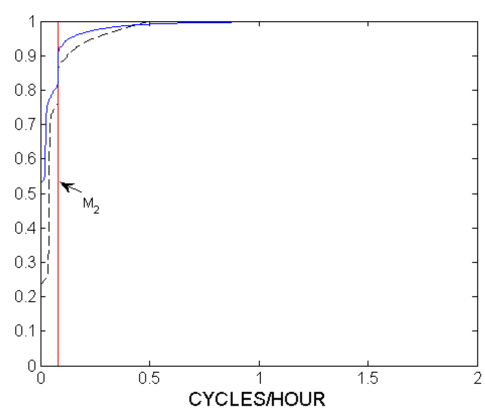

Figure 3: Sums of the power densities in Fig. 2 normalized to unity so that power fractions are easily inferred.

unknown physics, the extent to which this very large kinetic energy source can produce turbulent mixing is also obscure. Interaction with interior topography and continental slopes seems likely to provide a strong, but undemonstrated, sink.

Within the internal wave band, inertial motions dominate the kinetic energy spectrum, whether from direct wind generation (e.g., Alford, 2003) , or through non-linear interactions (Ref.?), or as the caustic generated by the background Garrett-Munk spectrum (see Fu, 1981), or other possible mechanisms (large-scale ageostrophic instability) is unclear and perhaps not directly relevant. How these strong motions interact with topographic slopes and whether they are significant sources of oceanic mixing remains nearly unexplored. The question would be complicated by the probable need (Fu, 1981) to account for strong β-effects in their dynamics.

3 The Sandström Theorem

The "theorem" discussed by Sandström (190x) is not a rigorous one—rather it is a plausibility argument that vigorous circulations cannot be set up in a fluid driven by buoyancy sources in which the heating lies at or above the pressure level of cooling, as appears to be true for the ocean. His result, which was based upon invocation of a Carnot cycle for a perfect fluid, appears to be qualitatively correct. It is not correct to infer that it implies either no circulation exists, nor that buoyancy forcing is unimportant in the ocean circulation. It does imply that in energy terms, buoyancy forces cannot be "driving" the ocean circulation in the sense of transferring significant amounts of energy to the ocean circulation ("driving" implies work being done in a force-times-distance sense). The main conceptual conclusion is that the ocean is not a heat engine the way the atmosphere is—in the latter, the powerful heating from below dominates the input of energy, and no mechanical driving is required (or available) to set up the observed circulation. In the ocean, to the contrary, the inference is that if there is no mechanical input of energy (tides, winds) the observed circulation would be radically different from what is actually present. That the actual circulation is different from what it would be if there were no buoyancy forces is also true.

The argument that mechanical energy sources were required to drive the deep circulation led to a renewed interest in so-called horizontal, or type 3, convection, a configuration epitomized by the discussion in Sandström (19xx) and in the experiment of Rossby (1965). Paparella and Young () and Mullarney et al. (2004) ; Siggers et al. (2004) have all attempted, using very simplified models, to understand the extent to which a purely buoyancy-driven circulation can simultaneously produce a circulation with a vigorous deep flow and a stable stratification over much of the domain. We emphasize the latter requirement: it is possible to produce circulations that are quite vigorous, but which give rise to nearly isothermal interiors. Sandström's theorem (slightly reinterpreted) says nothing about the vigor of a circulation in a deep nearly homogeneous fluid layer, only that if a stable stratification exists that it cannot be driven purely by buoyancy forcing at the surface. The analytical argument of Siggers et al. (2004) gives an upper bound on a heat flux which is large enough to accomodate the entirety of the estimated oceanic total of about 2PW. But whether this bound is a tight one or not is unclear (at the present time, a lower bound would likely be more informative). None of these results has been connected to fluids in rotating spherical shells.

4 Global Mixing Rates

The inference that intense abyssal mixing is largely confined to regions of special topography now seems reasonably well established both from local measurements (e.g., Kunze and Sanford, 1996; Polzin et al., 199x) and large-scale integrated boxes (e.g., Hogg et al., 1982; Ganachaud and Wunsch, 200x). True global averages are, however, difficult to make, and most of the direct evidence applies to the lowest parts of the water column. In the mid-depth range of the ocean (perhaps 1000-2500m), almost nothing is known.

Mixing inferred from profiles of properties as in Munk (1966) and MW98 have to be done with some care. If one takes the original "abyssal recipes" property balance,

$$w\frac{\partial C}{\partial z}-\kappa\frac{\partial^2 C}{\partial z^2}=0,$$

for any sourceless property, C, the full solution is

$$C=A\exp\left(zw/\kappa\right)+B.$$

Determining A,B separately for known w/κ requires specifying the boundary conditions. If $C\left(z_1\right)=C_1$, $C\left(z_2\right)=C_2$, then

$$C=-\frac{C_2-C_1}{e^{\left(z_1\frac{w}{\kappa}\right)}-e^{\left(z_2\frac{w}{\kappa}\right)}}e^{(zw/\kappa)}+\frac{-e^{\left(z_2\frac{w}{\kappa}\right)}C_1+C_2e^{\left(z_1\frac{w}{\kappa}\right)}}{e^{\left(z_1\frac{w}{\kappa}\right)}-e^{\left(z_2\frac{w}{\kappa}\right)}}$$

For $\kappa\rightarrow 0$, there will be boundary layers near $z_{1,}z_2$ of vertical scale κ/w with a nearly homogeneous interior. For large κ, the solution is linear between z_1 and z_2. On the other hand, if the lower boundary condition is an insulating one,

$$\left.\frac{\partial C}{\partial z}\right|_{z_1}=0$$

then $A=0$, and the solution is again a constant, independent of κ. This dependency is discussed by Wunsch, 200x. The one-dimensional balance ultimately becomes too simplistic.

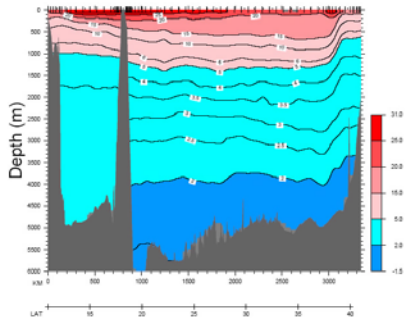

Figure 4: Potential tempeature section along 66°W in the North Atlantic from Joyce et al. (200x). The near-homogeneous temperatures in the deep Caribbean at the southern end is typical of all properties (salinity, density, oxygen, nutrients) and contrasts markedly with the open North Atlantic Ocean. Possible explanations of this behavior include the possibility that it is an example of a "filling-basin" mode with little vertical mixing, to a basin with very high mixing but boundary conditions permitting a near uniform interior.

In this context, it is interesting to note the behavior of the Caribbean as seen, e.g., in Fig. 4 from the data of Joyce et al. (200x), The Caribbean is conceivably an example of a "filling" (or "filled") basin as discussed by MW98, where water spills over the sills near 1000m to fill from basin from below in the presence of small interior mixing. Alternatively, it could be an example of a basin in which the upper and lower boundary conditions on temperature are conducive to a uniform interior independent of the mixing. (We prefer the former explanation, as the near-homogeneity is seen in all the tracers measured by Joyce et al. (200x) and it seems unlikely that all would have the same boundary conditions.

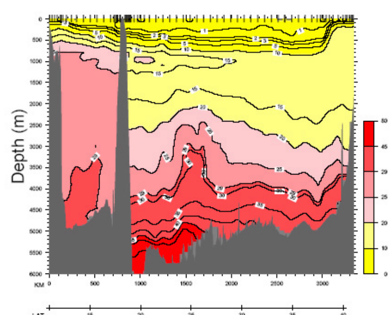

Figure 5: Same as Fig. 4 except for the silica distribution. Evidence of bottom sediment as a local source for silicate in the Caribbean might be inferred.

5 Energy Required

One of the MW98 estimates of the energy required to maintain the deep stratification was based upon the assumption that about 30Sv of abyssal water had to be returned from the ocean abyss to about 1000m. The 30Sv value can be an over-estimate if it represents in part fluid entrained in the sinking regions, perhaps at great depth. If, for example, only 10Sv must be returned to 1000m, there would be a reduction in the estimated 2TW (but with a value dependent upon the vertical profile of entrainment, which is likely to be both cause and consequence of the overall interior stratification). We will not, at the present time, guess at entrainment rates as a function of depth in the world ocean.

The energy required to mix the upper ocean does not seem to have been quantified, and remains as an important future chore.

6 Consequences

An exploratory literature of various consequences of the focus on mixing and energetics has been growing rapidly. It includes the first attempts to understand in models the consequences of a strongly spatially varying mixing because of the topographic control (e.g., Marotzke, 199x; xx; Simmons et al., Scott and Marotzke), The climate consequences of an energy dependence of mixing rates are interesting. Huang (xxxx) explored the implications of assuming that the energy expended in mixing remained constant through time in a numerical model, rather than the mixing coefficients. It is not so easy to understand why constancy of energy for mixing should be maintained, but it is at least as logical as constancy of mixing coefficients. Wunsch (2005) used a simplistic model to understand how changing sealevels during a deglaciation could produce major changes in ocean circulation by shifting open ocean mixing rates. A closely related calculation. focussing on a more realistic tidal model, is Egbert and Ray (2004). In related work, Nilsson and Walin (200x) showed that the widely shared inference that fresh water suppression of convection would reduce the oceanic heat transport was likely incorrect, or at least not an obvious conclusion.

The extent to which an increase or decrease in mixing rates, whether wind or tidal derived would shift the oceanic mass fluxes and related but different heat fluxes, remains obscure. It has been argued (e.g., Boccaletti et al., 2005) that the upper ocean must dominate the oceanic heat flux simply because the temperature drop across the top 1000m is considerably larger (O(10°)) than that across the remaining 4000m (O(4°); that is, the thermocline is an upper ocean phenomenon). In a kinematic sense, this argument is surely correct, as unacceptably large abyssal mass fluxes would be required to have an abyssal flow compete with the net temperature differences available to flows taking place across the thermocline. It might then be argued that changes in abyssal mixing coefficients would thereby have little effect on the net oceanic heat flux, which would depend more directly upon the directly wind-driven circulation. This deduction is compelling, assuming that a change in the abyssal mass flux owing to a change in mixing, would leave the thermocline structure and circulation largely unchanged. Such an inference does not appear to be straightforward, as in many theories the thermocline structure depends upon the upwelling velocity, w, which as we have seen, is sensitively dependent upon the mixing distribution. The question would appear to be open. A quite separate issue concerns the magnitude of a shift in heat flux, perhaps quite minor, that would have noticeable climate consequences, even if small compared to the total.

In any case, even should the net heat flux not ultimately be sensitive to abyssal mixing, the inference is almost surely false for other climatologically important properties such as the nutrients and carbon whose movement into and within the abyss is probably determined at first order by the abyssal circulation. (See for example Fig. 5.)

On longer time-scales, those lying between about 20,000 and 100,000 years, one is within the realm of the so-called Milankovitch theory, in which variations in the earth's orbital configuration relative to the sun is believed to exert a major control over climate. Because orbital variations relative to the sun are also responsible for the solar tides, it is unsurprising that if tidal theory is extended out to 100,000 years, tidal energy modulations appear within the traditional Milankovitch bands. Munk and Bills (2005) ...[??]

7 Summary

This is a time of ferment in the general subject of oceanic mixing and energetics. We reiterate that this paper is not intended as a review—too much is happening too quickly for us to be remotely complete. Quantification of global average mixing rates as functions of depth remains a major challenge as does closing the energy budget of the ocean circulation. The relative roles of tides and winds in mixing, both in the modern ocean and in past climate states looms ever larger in importance. A host of unresolved sub-elements of the problem remains.

References

Alford, M. H., 2003. Redistribution of energy available for ocean mixing by long-range propagation of internal waves. *Nature*, 423, 159-162.

Boccaletti, G., R. Ferrari, A. Adcroft, J. Marshall, 2005. . .

Egbert, G. D. and R. D. Ray, 2000. Significant dissipation of tidal energy in the deep ocean inferred from satellite altimeter data. *Nature*, 405, 775-778.

Egbert, G. and R. D. Ray, 2004. . .

Emanuel, K., 2001. Contribution of tropical cyclones to meridional heat transport by the oceans. *J. Geophys. Res.-Atmospheres*, 106, 14771-14781.

Faller, A. J., 1968. Sources of energy for the ocean circulaton and a theory of the mixed layer. *Proc. Fifth U. S. Congress of Applied Mechs., ASME, U. of Minn., Minneapolis, June 14-17, 1966*, 651-672.

Fu, L.-L., 1981. Observations and models of inertial waves in the deep ocean. *Revs. Geophys. and Space Phys.*, 19, 141-170.

Ganachaud, A. and C. Wunsch, 2002. Large-scale ocean heat and freshwater transports during the World Ocean Circulation Experiment. *J. Clim.*, 16, 696-705.

Garabato, A. C. N., K. L. Polzin, B. A. King, et al., 2004. Widespread intense turbulent mixing in the Southern Ocean. *Science*, 303, 210-233.

Hogg, N. G. P. Biscaye, W. Gardner, and W. J. Schmitz, 1982. On the transport and modification of Antatrctic Bottom water in the Vema Channel. *J. Mar. Res.*, 40(supplement), 231-263.

Kunze, E. and T. B. Sanford, 1996. Abyssal mixing: where it is not. *J. Phys. Oc.*, 26, 2286-2296.

Ledwell, J. R., E. T. Montgomery, K. L. Polzin, L. C. St. Laurent, R. W. Schmitt and J. M. Toole, 2000. Evidence for enhanced mixing over rough topogrpahy in the abyssal ocean. *Nature*,403, 79-182.

Lueck, R. and R. Reid, 1984. On the production and dissipation of mechanical energy in the ocean. *J. Geophys. Res.*,, 89, 3439-3445.

Marotzke, J., 1997. Boundary mixing and the dynamics of three-dimensional thermohaline circulation. *J. Phys. Oc.*, 27, 1713-1728.

Mullarney, J. C., R. W. Griffiths, G. O. Hughes, 2004. Convection driven by differential heating at a horizontal boundary. *J. Fluid Mech.*, 516, 181-209.

Munk, W. and C. Wunsch, 1998. Abyssal recipes II: energetics of tidal and wind mixing. *Deep-Sea Res.,* 45, 1976-2009.

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

Nilsson, J. and G. Walin, 2001. Freshwater forcing as a booster of thermohaline circulation. *Tellus*, 53A, 629-641.

Paparella, F. and W. R. Young, 2002. Horizontal convection is non-turbulent. *J. Fluid Mech.*, 466, 205-214.

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

Rossby, H. T., 1965. On thermal convection driven by non-uniform heating from below: an experimental study. *Deep-Sea Res.*, 12, 9-16.

Rudnick, D. L. and 18 others, 2003. From tides to mixing along the Hawaiian Ridge. *Science*, 301, 355-357.

Sandström, J. W., 1908. Dynamicsche Versuche mit Meerwasser. *Annalen der Hydrographie under Martimen Meteorologie*, 36, 6-23.

Siggers, J. H., R. R. Kerswell and N. J. Balmforth, 2004. Bounds on horizontal convection. *J. Fluid Mech.*, 517, 55-70.

Simmons, H. L., S. R. Jayne, L. C. St. Laurent, A. J. Weaver, 2004. Tidally driven mixing in a numerical model of the ocean circulation. *Ocean Mod.*, 3-4, 245-263.

van Haren, H. and C. Millot, 2004. Rectilinear and circular inertial motions in the Western Mediterranean Sea. *Deep-Sea Res.*, 51, 1441-1455.

Wataname, M. and T. Hibiya, 2002. Global estimates of

the wind-induced energy flux to inertial motions in the surface mixed layer. *Geophys. Res. Letts.*, 29, Art. No. 1239.

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

Wunsch, C. and R. Ferrari, 2004. Vertical Mixing, Energy, and the General Circulation of the Oceans. *Ann. Revs. Fl. Mech.*, 36, doi:10.1146/annurev.fluid.36.050802.122121.

Wunsch, C., 1998. The work done by the wind on the oceanic general circulation. *J. Phys. Oc.*, 28, 2332-2340.

Wunsch, C., 2002. Oceanic age and transient tracers. Analytical and numerical solutions. *J. Geophys. Res.*, 107(C6), DOI:10.1029/2001JC000797, 1-1 to 1-16.

Wunsch, C., 2005. Speculations on a theory of the Younger Dryas. 2005, *J. Mar. Res.*, (Fofonoff Volume), in press.