THE MOON, OF COURSE . . .

By Walter Munk and Carl Wunsch

THIS IS AN ESSAY* on tidal friction and ocean mixing. Tides are not a subject at the forefront of current interest. Many oceanographers believe the subject died with Victorian mathematicians. But TOPEX/POSEIDON (T/P) altimetry measurements have suggested an enhanced lunar role in ocean processes and put a new face on an ancient subject. In contrast, oceanic mixing is alive (even fashionable); we wish to convince the reader that the connection between these ancient subjects is deep, important, and not obviously lunatic.

The reader should hold in mind that we are dealing with two quite distinct manifestations of ocean mixing: 1) *pelagic* turbulence (away from topography) is associated with a diapycnal diffusivity of order $\kappa_{PE} = 10^{-5}$ m²/s and a global dissipation of 200 GW (1 gigawatt = 10^9 W); 2) the maintenance of *abyssal stratification* requires order (2,000 GW) and is associated with concentrated turbulence at the ocean boundaries and over submarine ridges and other topographic features, often (improperly) represented by a global mean diffusivity of $\kappa_{AS} = 10^{-4}$ m²/s (1 cgs).

The subject has the aspect of a zero-sum game: we know the global tidal dissipation quite accurately, 2,500 ± 100 GW for M_2, ~3,700 total, but we do not know where and by what processes dissipation takes place. The magnitude is comparable with the present global electric generating capacity, and tiny as compared with 2 × 10^6 GW associated with equator-to-pole heat-flux.

Astronomy

The subject of tidal friction has a long and labored history of errors and misconceptions. Fundamental questions remain about the interpretation given in this essay. A brief sketch will provide some perspective.

In 1695 Halley found that data on ancient eclipses could not be reconciled with his "modern" measurements of the Moon's orbit, and concluded that the Moon was being accelerated by 10 arcsec/century². This was confirmed by subsequent observations. Euler and Lagrange tried in vain to account for the acceleration in terms of Newtonian mechanics. The role of tidal friction was proposed in 1754 by Emanuel Kant in an essay "Untersuchung der Frage, ob die Erde in ihrer Umdrehung um die Achse, wodurch sie die Abwechslung des Tages und der Nacht hervorbringt, eine Veraenderung seit der ersten Zeiten ihres Ursprunges erlitten habe, und woraus man sich ihrer versichern koennen" (title, not abstract). Finally in 1787 Laplace announced that he had discovered the explanation: planetary perturbations gave 10.18 arcsec/century². This explanation was considered a major triumph of 18th century science.

In 1853 Adams found that Laplace had made an error, and that the correct answer was but one-half of Laplace's result, requiring some additional phenomenon (such as tidal friction) to account for the astronomical measurements. This was rejected because it destroyed a widely acclaimed theory. Not until G.I. Taylor's 1919 estimates of tidal dissipation in the Irish Sea, followed by Jeffreys' and Heiskanen's global extrapolation, was tidal dissipation accepted as an important factor in orbital dynamics.

We now have independent estimates of global dissipation from ancient eclipses, from modern measurements of the length of day and month, and from the tidal perturbation of artificial satellite orbits. They all agree within expected error limits. The most precise information comes from lunar laser ranging using the retroflectors places on the Moon in 1969 during the Apollo mission. The semimajor axis of the Moon's orbit is increasing at a rate 3.82 ± 0.07 cm/y, from which the above dissipation estimate of 2,500 ± 100 GW has been derived. About 100 GW is dissipated in bodily tides leaving

$$2400 \pm 100 \text{ GW } M_2.$$

$$3500 \text{ GW all tides} \quad (1)$$

The Moon dominates (and is emphasized in this essay), but the solar tides are by no means negligible. The extension to all semidiurnal and diurnal tides is complex on account of the nonlinear interactions (LeProvost and Lyard, 1997).

Dissipation in Marginal Seas

G.I. Taylor estimated tidal dissipation of 41 GW in the Irish Sea, using the boundary layer formula $C_D\, \rho\, \langle u^3_{tidal} \rangle$ W/m² with a drag coefficient C_D = 0.0025. This was in fair agreement with his independent estimate of 60 GW of net horizontal flux $\langle p\, u \rangle_{tidal}$ W/m² into and out of the boundaries. Jeffreys extended Taylor's estimates to a global value of 2,200 GW. Since 1920, it has been taken for granted that nearly all of the dissipation takes place in the turbulent bottom boundary layer (BBL) of marginal seas. Typical tidal currents are of the order of 1 cm/s in the deep sea, and of 1 knot = 50 cm/s in shallow seas. The cubic dependence on tidal current velocity leads to the conclusion that 99% of the ocean accounts for less than 1% of the dissipation.

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* We cannot give adequate references in this essay and will have to refer to a forthcoming paper by the authors: "The Moon and Mixing: Abyssal Recipes II."

Most modern tidal models *a priori* impose a 0.0025 $\rho <u^3_{tidal}>$ dissipation, with the conclusion that substantially all the dissipation takes place in the BBL. This has some of the earmarks of a self-fulfilling prophecy. The most recent estimate by G. Egbert (1997) using T/P altimetry has led to a somewhat reduced BBL dissipation: 1,800 GW for M_2 (out of 2,400), but he regards the result as very preliminary (see also LeProvost and Lyard, 1997).

Surface to Internal Tide Conversion

Most of oceanography deals with baroclinic processes, and therefore the possibility of surface tidal dissipation by scattering into internal modes is very attractive. The authors have independently strived in this direction for most of their career, but were discouraged by the low numerical estimates of mode conversion. Extensive calculation by P.G. Baines yielded only 15 GW of mode conversion along 155,000 km of global coastline. But there are reasons why such estimates might be severely low (as recognized by Baines). Mode conversion is proportional to Q^2 where Q is the volume flux *across* the shelf edge. But most of the flux is *parallel* to the ocean boundaries, as a glance at global tidal charts will show. Off-shore ridges do not so constrain the flux and are more favorably situated with regard to mode conversion. A second reason emphasized by Thorpe and Wunsch is associated with the transverse canyons, rills, and gullies in the shelf edge that are neglected in a two-dimensional treatment.

Interest in the subject was revived by some unexpected observational results. Dushaw *et al.* (1995) in an Acoustic Tomography triangle deployed 2,000 km northwest of Hawaii detected internal tides radiating from the islands, and this was convincingly confirmed by Ray and Mitchum (1996) with T/P altimetry. Surface manifestations of internal waves have an amplitude of order $\Delta\rho/\rho$ times the internal amplitude, or $10^{-3} \times 50$ m = 5 cm, as measured. Ray and Mitchum extracted the semidiurnal tidal components from the three years T/P measurements at 10-day intervals (hardly in accord with conventional sampling practice) and found coherent waves propagating from the island chain with wave lengths of order 100 km, consistent with low-order internal tides. The detection of internal tides from satellite altimetry came as a surprise to some in the oceanographic community, who had been accustomed to applying a "rigid-lid" surface boundary condition on internal waves.

With the use of the appropriate group velocities, the total internal tide flux from Hawaii was estimated at 15 GW. Kantha and Tierney (1997) have extended this to a global estimate of 360 GW of M_2 mode conversion, uncertain by a factor of two.

Pelagic Turbulence

Measurements of turbulent dissipation are difficult because of the small scales (down to 1 cm) at which the turbulent fluctuations are irreversibly converted into heat. Shear microstructure measurements were pioneered by Cox, Osborn, Gregg, Gargett, and Garrett (for recent discussions see Kunze and Sanford 1996, Lueck and Mudge 1997) . Dissipation is proportional to $N^2(z)$ over a wide range of open-sea conditions, with a proportionality constant κ_{PE} of ~10^{-5} m²/s. This value is in agreement with remarkable tracer release experiments by Ledwell and his associates. The inferred energy dissipation is

$$\varepsilon(z) = \gamma^{-1}\kappa_{PE}N^2 \text{ W/kg} \qquad (2)$$

where $\gamma \approx 0.2$ is the mixing efficiency. Integration of ρ $\varepsilon(z)$ over the global oceans gives 200 GW, a value similar to the surface to internal tide conversion. This suggests that tidal mode conversion is a factor in maintaining pelagic turbulence. A possible mechanism is that the discrete line spectrum of internal tides is converted into the internal wave continuum, which in turn feeds the pelagic turbulence. The remarkable universality (within a factor of 2) of both the fields of internal waves and of pelagic diffusivity has been ascribed to the low fractional dissipation rate of internal waves; Munk (1997) argues for a more reliable source than just wind energy.

Abyssal Stratification

We now turn to our second subject: mixing implications of the abyssal ocean. Bottom water formation of 25 Sverdrups (an uncertain estimate) would fill the ocean basins with dense, cold water in 3,000 years. How is the abyssal stratification maintained in the presence of deep convection?

Perhaps the simplest model is one where vertical upwelling of cold water is balanced by downward diffusion from the warm surface, as represented by the linear differential equation

$$\kappa d^2\rho/dz^2 = (w - \kappa\kappa')d\rho/dz, \qquad (3)$$

with $\kappa' = d\kappa/dz$. The authors have estimated the energy required to maintain the turbulent diffusion as follows: starting with a global mean $\rho(z)$ and its first and second derivatives, as compiled from Levitus atlases, a solution to equation (3) yields an expression for

$$\alpha(z) = [w(z) - \kappa'(z)]/\kappa(z) \qquad (4)$$

Then using very rough guesses about the upwelling w(z) from circulation models, equation (4) is solved for $\kappa(z)$. The global power required to maintain the abyssal stratification is obtained from equation (2) using $\kappa(z)$. The result is ~2,000 GW, with very large error limits.

Egbert's estimate of 2,600 GW for BBL dissipation leaves only 900 GW for other losses (Eq. 1). All numbers are extremely uncertain, and the very assumption of the one-dimensional balance (Eq. 3) may not provide a useful basis for discussion.

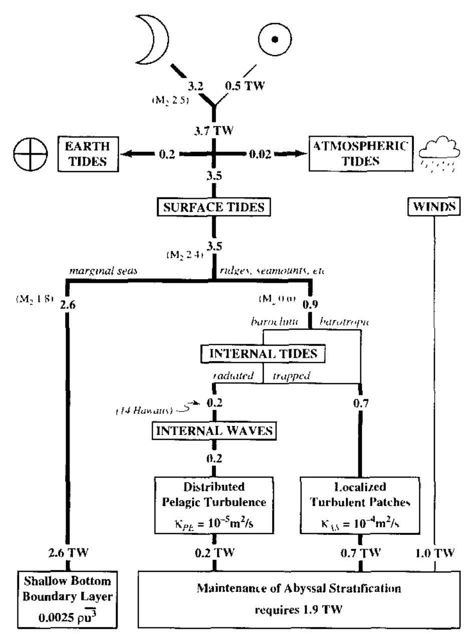

Fig. 1: Sketch of the proposed flux of tidal energy. The traditional sink is in the bottom boundary layer (BBL) of marginal seas. Preliminary results from Egbert (1997) based on TOPEX/POSEIDON altimetry suggest that 0.9 TW (including 0.6 TW for M_2) are scattered along open ocean ridges and at seamounts. "Winds" is to include surface generation of internal waves that radiate into the abyss and contribute to mixing. Light lines represent speculation with no observational support.

Fig. 2: The Moon, of course; a pronouncement by Kozma Prutkov.

We attach a sketch of the proposed energy flux (Fig. 1), without much hope for future survival. The notation κ_{AS} for the diffusivity derived from the abyssal stratification is to distinguish it from κ_{PE} associated with pelagic turbulence. Typical values are $\kappa_{AS} = 10^{-4}$ m^2/s and $\kappa_{PE} = 10^{-5}$ m^2/s, and this has led to a discussion of a *dichotomy* of diffusivities. This may not be a useful viewpoint. The pelagic value is a measure of the *distributed* turbulent mixing. We regard κ_{AS} as a surrogate for a small number of *concentrated* (almost point) sources of buoyancy flux (region of extreme mixing) from which the water masses (but not the turbulence) are exported into the ocean interior.

Discussion

Our very tentative conclusions are that 1) tidal dissipation plays a dominant role in pelagic mixing processes and 2) a significant role in maintaining the abyssal stratification.

The labored history of the subject has taught us that progress comes from new and decisive measurements. We are pleased to hear of a number of plans for direct *measurements* of tidal dissipation on ocean ridges, in canyons, and on the continental margins. Off Hawaii, 15 GW of internal tide energy is radiated into the far zone. Could it be that a much larger dissipation is associated with energy trapped in the near zone?

In all events, the Moon plays a respectable role in the dissipation drama. This has severe implications for past climates when the continental configuration was very different from what it is today; it also raises interesting questions concerning the energetics of the modern so-called thermohaline circulation.

Twentieth century oceanographers have largely ignored the Moon. Kozma Prutkov is featured in Russian literature as a dumb private in the Czar's army who usually has the right answers (Fig. 2). When asked which is more important, the Moon or the Sun, Kozma replies: ". . . The Moon, of course, because the Sun shines only in daytime when it is bright anyhow. . . ."

Acknowledgement

W. Munk holds the Secretary of the Navy Chair in Oceanography. Mike Dormer drew Figure 2.

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