Tidal Friction in the Earth and Ocean

Richard D. Ray

Space Geodesy Branch, NASA Goddard Space Flight Center
Greenbelt, Maryland, USA

"Tidal Friction" is a classic subject in geophysics, with ties to some of the great scientists of the Victorian era (or even earlier). The subject has been reinvigorated over the past decade by space geodesy, and particularly by the Topex/Poseidon satellite altimeter mission. In fact, the subject is beginning to appear downright modern, with possibly important implications for the oceano-graphic problems of mixing, thermocline maintenance, and thermohaline circulation.

The recent space geodetic work has considerably clarified what is meant by the term tidal friction—that is, what physical mechanisms are at work and how much tidal power is consumed in which sinks. The traditional dissipative mechanism, since the work by Harold Jeffreys and G.I. Taylor around 1920, was thought to have been bottom boundary layer turbulence in shallow seas. The recent work confirms that most friction does indeed occur in the shallow seas, but a significant fraction, perhaps 25-30%, occurs in the deeper waters of the open ocean. Only about 5% or so occurs in the solid earth. These numbers are summarized more carefully in the figure below, and the paper reviews the arguments and evidence for this energy budget. Relevant citations to the recent literature are also given below.

Several approaches can be taken to place constraints on the amount of tidal energy being dissipated by the solid earth, including estimating the mantle's effective tidal *Q* by interpolating between the *Q* of the gravest seismic free oscillation (period 54 minutes) and the *Q* of the Chand-ler wobble (14 months). Another elegant approach is to compare estimates of the degree-2, order-2 spherical harmonic component of the ocean tide as deduced from satellite tracking measurements and from satellite altimetry. Any small lag in the earth's body tide would affect these estimates differently (i.e., gravitationally vs. geometrically), and in fact a small discrepancy in the estimates is found and can be used to determine the body-tide lag, and hence the solid-earth tidal dissipation. The semidiurnal tidal lag is 0.204°±0.047°, implying a *Q* of 280 (1-σ error bounds between 230 and 360), and energy dissipation of 110±25 gigawatts (M_2 only).

The ocean's dissipation is considerably larger, about 2.4 terawatts. While this total has been well determined for some time, the location of the dissipation has not been well determined. (Jeffreys reckoned that a very large fraction occurred in the Bering Sea, but later tidal measurements in the region refuted that.) The very accurate tidal elevation estimates provided by the Topex/Poseidon satellite altimeter afford a unique way of mapping the dissipation. This is explained more fully in the two papers by Egbert and Ray (2000, 2001). Briefly, the dissipation at any point in the ocean is determined as a balance between the rate of working by all tidal forces and the diver-gence of horizontal energy flux. This balance is a very small difference between two relatively large numbers, and the result is understandably somewhat noisy. Nonetheless, it shows a signif-icant fraction of energy being dissipated in the open ocean, always in regions of rugged bottom topography. The physical mechanism is apparently conversion of energy into internal tides and other baroclinic motions. These internal waves, in turn, can provide a potentially important source of mechanical power for