ALTIMETRIC STUDIES OF OCEAN TIDAL DYNAMICS

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The accurate measurements of the global ocean tides by TOPEX/POSEIDON provide powerful constraints that allow a number of outstanding problems in tidal dynamics to be addressed. Foremost among these is the problem of energy dissipation: How does the ocean dissipate the nearly 4 terawatts imparted to it by the 1 and moon? And what role do internal tides play? These and other questions can now be addressed in a serious way. Inverse methods will play a key role, since establishing realistic error bounds is a crucial step.

Introduction

Anyone familiar with satellite altimetry is aware of the burst of activity in tide-modeling brought about by the TOPEX/POSEIDON mission: at least a dozen new global charts of the tides have been produced by international groups of investigators. We intend to continue to use the ongoing T/P measurements to improve our knowledge of global tides. But, in addition, we believe that it is now time to move further, to find out what these new measurements can tell us about the behavior of the ocean and to address in detail questionsósome old, some newóabout the dynamics of the ocean tide.

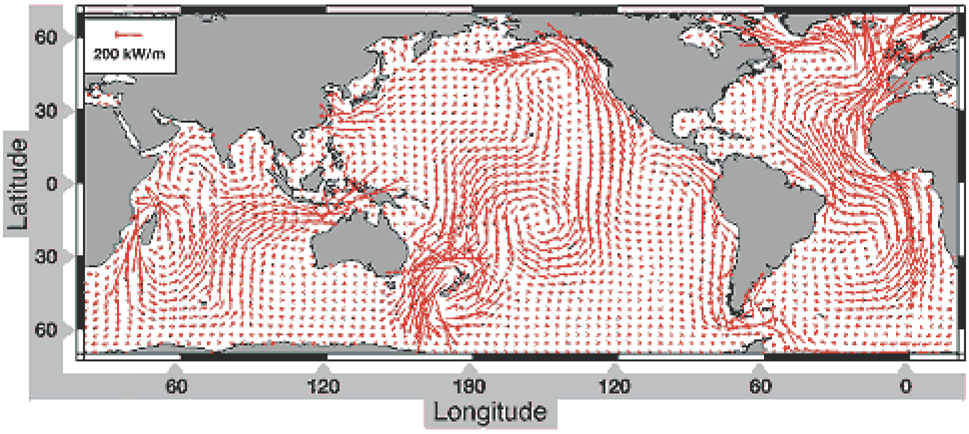
What follows is a brief synopsis of our ongoing work to determine tidal energy balances. We also touch on some related topics.

Energetics

Estimates of the total rate of energy dissipation by the ocean tide are tightly constrained by global measurements of tidal elevations and their phases. For the M2 tide this dissipation rate is approximately 2.5 TeraWatts (TW) [Cartwright and Ray, 1991]. Estimating further terms in the energy budget, such as fluxes or local dissipation rates, requires knowledge of tidal currents as well as elevations; this generally requires a numerical model, which in turn requires invoking dynamical assumptions, including assumptions about dissipation. The problem is therefore somewhat circular. Inverse methods give us the ability to explore the severity of this sensitivity to dynamical assumptions; at the very least, we can establish energy balances such that the data, the dynamics, and the error bars are mutually consistent.

We have made some preliminary energy calculations for several global tidal solutions, derived by both empirical and assimilation methods. Here we focus on the recent T/P solution TPXO.3, an update to the solutions discussed by Egbert et al. [1994]. This is a global inverse solution, using linear bottom friction and scalar approximations for ocean loading and self-attraction [Egbert, 1997].

Figure 1 shows the energy fluxes (averaged over a tidal cycle) for the TPXO.3 solution. These fluxes immediately suggest that certain shallow seas are important energy sinks. Note the large fluxes into the northwest European shelf, the Norwegian, Greenland, and Labrador Seas, the East China Sea, and the Timor Sea. Most remarkable is the large energy flux across the equatorial Atlantic, from south to north, which integrates to about 700 GW, nearly a third of the entire M2 energy input [Lyard and Le Provost, 1997]. Figure 1 also allows us to rule out a sink that was once thought potentially important: tidal flexing of Antarctic ice shelves; because most energy enters the ocean at lower latitudes and because Figure 1 displays relatively little integrated flux toward Antarctica, the Antarctic coastline cannot be an important sink for the global tide [Ray and Egbert, 1997].



(93 kb)

Figure 1

Mean tidal energy fluxes for the M2 barotropic tide, as determined from measurements by TOPEX/POSEIDON.

More quantitative analyses may be had by differencing the flux divergence div P obtained from Figure 1 with the mean rate of working per unit area generated by the astronomical forcing (including various secondary forcings such as ocean self-attraction). This difference:

$$N = W - \text{div } P$$

is shown in Figure 2. Were the dynamics of our model exactly correct, then N would be an estimate of the local dissipation rates, and indeed N is large in many of the shallow seas known to account for much of the tidal dissipation. Owing to dynamical errors, however, N also includes additional unmodeled dissipation, which, in some sense, represents work done (either positive or negative) by the dynamical residuals in our inversion. Some dipolar features, usually located near small-scale topography and islands, appear to result from overly coarse spatial resolution in the model [Egbert, 1997]. In a few areas of the open ocean, N is again large and positive, suggesting the need for additional model dissipation in areas where bottom friction cannot possibly be important. Intriguingly, most of these areas are located near trench or ridge systems. This association is certainly suggestive of additional dissipation by conversion to open-ocean internal tides [Sjoberg and Stigebrandt, 1992].

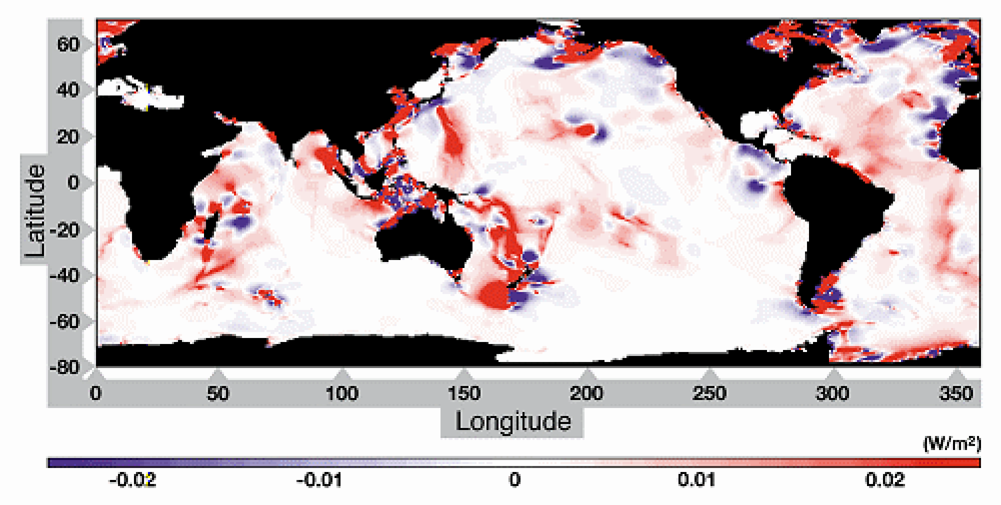


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Figure 2
The net energy flux convergence, based on Figure 1, plus the rate of working of astronomical tidal forces (plus secondary forces). Large red patches in shallow seas are areas of known dissipation by bottom friction. Large red patches in deep water are areas where the model may have inadequate dissipation (perhaps from neglecting conversion to internal motions).

A key to understanding and interpreting these data will be a careful analysis of errors and uncertainties in estimated tidal fields, including all energy terms. This calls for a rigorous use of inverse methods along with sensitivity studies on prior error covariances.

Internal Tides

The tie to internal tides is further strengthened by the recent discovery that T/P is capable of detecting the mean surface manifestation of phase-locked internal tides ("phase-locked" meaning coherent with the astronomical potential). These are observed as high-wavenumber modulations of the tide as estimated along T/P tracks. The surface amplitudes range from 3 to 5 cm near some ridge systems to well under 1 cm in other, quieter regions (Ray and Mitchum, 1996). Figure 3 shows an example, for nine T/P tracks crossing the Tuamotu Archipelago.

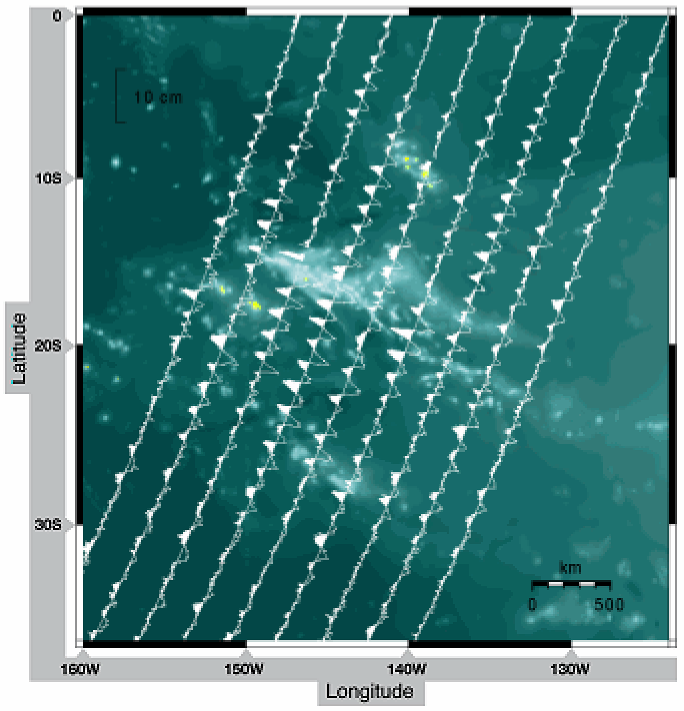

Figure 3
High-pass filtered M2 amplitudes, estimated along nine T/P tracks across the Tuamotu Archipelago. (Tahiti is the small yellow dot near 17°40'S, 149°30'W.) The clear waves are the surface manifestation of phase-locked internal tides [Ray and Mitchum, 1997].

These T/P data open up a new avenue in the investigation of internal tides. They already are helping to identify sources and sinks of internal tides and should eventually help to determine local fluxes and flux directions and to estimate conversion and dissipation rates. For example, the data (combined with in situ information) imply about 15 GW of tidal power is converted from barotropic to baroclinic motion at the Hawaiian Ridge [Ray and Mitchum, 1997].

Other Applications

The above discussion only touches on some of the problems that can now be addressed with the T/P data. The study of long-period tides, radiational tides, temporal variations in tides are all ripe for investigation. As the T/P time series grows longer, its utility for tidal studies only grows more valuable.

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