A BRIEF OVERVIEW OF

TIDES IN THE INDONESIAN SEAS

BY RICHARD D. RAY, GARY D. EGBERT, AND SVETLANA Y. EROFEEVA

Tidal phenomena in the Indonesian seas are among the most complex in the world. Complicated coastal geometries with narrow straits and myriad small islands, rugged bottom topography next to wide shelves of shallow water, and large quantities of tidal power input from the adjoining Indian and Pacific Oceans—all combine to form a complex system of interfering three-dimensional waves. The seas feature multiple amphidromes (points in the sea where there is zero tidal amplitude due to canceling of tidal waves), strong tidal currents, residual circulations, internal waves, and solitons. Diurnal tides are unusually strong and are dominant along some coastlines. The tides are known to affect local mixing and circulation, but the tidal energy available for these processes is not yet reliably determined. And while mapping of the Indonesian tides has benefited markedly by assimilating satellite altimeter measurements into numerical models, improvements to the energy budget will likely require higher-resolution analyses and a densified network of satellite tidal measurements.

Gross characteristics of the Indonesian tides were worked out during the colonial period in the early twentieth century. Summary descriptions of coastal tides were published by both Krümmel and Van der Stok in 1911, and tidal phase charts were published by Dietrich during the war in 1944. Given the difficulties of collecting *in situ* data, it is worth noting that those early measurements still form the bulk of the available station data in the International Hydrographic Bureau's tidal archives. Much of that early work was subsequently recompiled and synthesized by Wyrtki (1961), who constructed diurnal and semidiurnal cotidal charts based on all available coastal and island information. Owing to lack of data, Wyrtki could draw no contours in the adjoining Indian and Pacific waters, but his (subjective) interpolations over the region of enclosed seas were—and still are—eminently reasonable.

More recently, Hatayama et al. (1996) computed two major diurnal and semidiurnal tides with a numerical barotropic model; they emphasize the importance of tidally generated residual circulation, especially east of Sulawesi, for horizontal mixing.

Ffield and Gordon (1996) and Hatayama (2004) noted the important role of tides in vertical mixing, a fact that calls for development of high-resolution, three-dimensional tidal models in order to investigate the sources and variability of internal tides. Some initial steps in that direction are presented in this issue by Robertson and Ffield. See also related work by Schiller (2004).

The charts we show here are based on the data-assimilation work of Egbert and Erofeeva (2002). Data assimilation is especially attractive in regions such as the Indonesian Archipelago where numeri-

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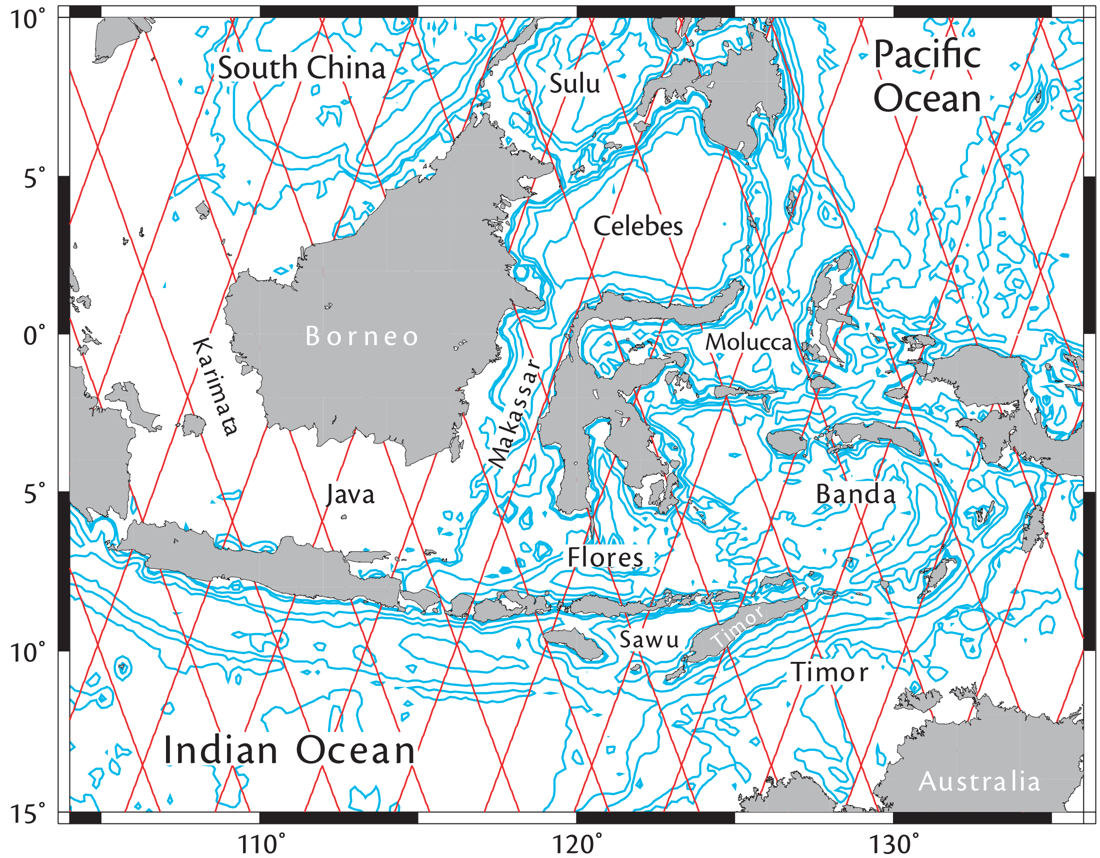

Figure 1. Topographic chart, with isobaths drawn at 100, 200, 1000, 2000, 4000, 6000 m. Red lines denote the groundtracks of the *Topex/Poseidon* satellite. Although these tracks are too widely spaced to support a purely empirical mapping of the tides in this region, the satellite data provide critically valuable data for assimilation.

cal modeling efforts are hindered by inadequate knowledge of bathymetry and stratification and by uncertainties concerning dissipation. Data assimilation can compensate for some of these modeling difficulties. Our charts are based on ten years of sea-level measurements from the *Topex/Poseidon* satellite altimeter. The altimeter data are used to compute linearized inverse adjustments to a prior, multi-constituent, nonlinear, barotropic, time-stepping model (for details, see Egbert and Erofeeva, 2002). The satellite track pattern is shown in Figure 1.

Cotidal charts of the largest semidiurnal tide M_2 and diurnal tide K_1 are shown in Figures 2 and 3, respectively. The semidiurnal response is clearly dominated by the large tide from the Indian Ocean, where amplitudes are well over a meter off northwest Australia. This wave is delayed slightly (about 2 hours) as it passes into the Banda and Flores Seas. Those seas are sufficiently deep that high tide occurs almost simultaneously throughout both basins. From the Banda Sea, the semidiurnal tide passes slowly northwards through the Molucca Sea region. From the Flores, it propagates slowly northwards into Makassar Strait and also westwards, but more weakly, across the Java Sea.

The diurnal tide, in contrast to the semidiurnal, passes southwards through Makassar Strait and Molucca Sea. In the Banda and Flores Seas this wave meets the tide from the Indian Ocean, with increased amplitudes in the Flores Sea and with markedly increased amplitudes westward in the Java Sea. The diurnal tide propagates westward around both the northern and southern coasts of Borneo, intersecting to form a complicated system of large-amplitude, nearly amphidromic systems west of Borneo.

From Figures 2 and 3 it is evident that the tides throughout the eastern archipelago, as well as in the adjoining Pacific, are predominantly semidiurnal but with significant diurnal inequality, whereas the tides west of about 118°E are mixed diurnal, and west of Borneo almost wholly diurnal. The large M_2 amplitude on the coast of west-northwest Borneo is a localized shelf resonance, but not well determined because it falls almost perfectly between two satellite tracks.

The M_2 tidal current velocities, shown in Figure 4, reflect bathymetry for the most part, with shallow water giving rise to rapid currents. A few exceptions where relatively strong currents appear in deeper water are along the southern and northern coasts of the island of Timor and in the Molucca Sea and its boundaries. These are regions of intense barotropic energy fluxes, as can be seen explicitly in Figure 5. Figure 6 shows similar fluxes for K_1. These diagrams re-

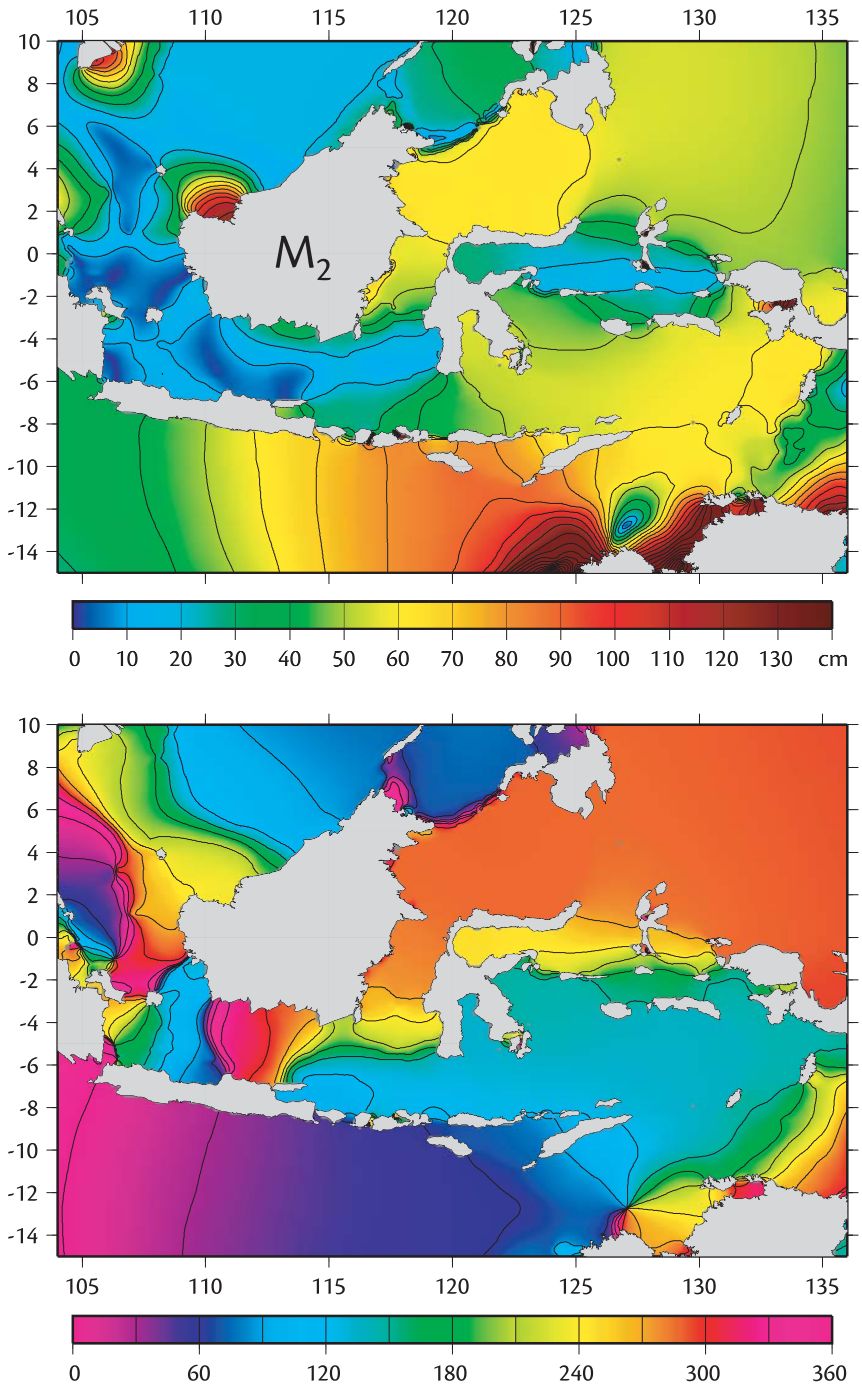

Figure 2. Amplitude (top) and Greenwich phase lags (bottom) of the M_2 tide, based on assimilation of ten years of *Topex/Poseidon* satellite altimetry into a nonlinear hydrodynamic model (Egbert and Erofeeva, 2002). Phase-lag contour interval is 30°, equivalent to 1 lunar hour. Inverse theoretic error estimates suggest that these charts are accurate to a few centimeters, except in a few high-amplitude locations that fall between satellite tracks (e.g., the large tides on the west coast of Borneo and off Australia).

inforce the notion that the Indian Ocean tide governs the regional energetics of M_2, and the Pacific governs K_1. The barotropic M_2 fluxes either side of Timor are very large, exceeding 500 kW m^{-1}.

What becomes of all this tidal energy in the Indonesian seas is a topic of some importance, but dissipation estimates are not well determined. In fact, in the global compilation by Egbert and Ray (2001), the estimated tidal dissipation in the Indonesian region was the most poorly determined of any region in the world oceans, with estimates for M_2 ranging from 20 GW to 250 GW. A somewhat de-

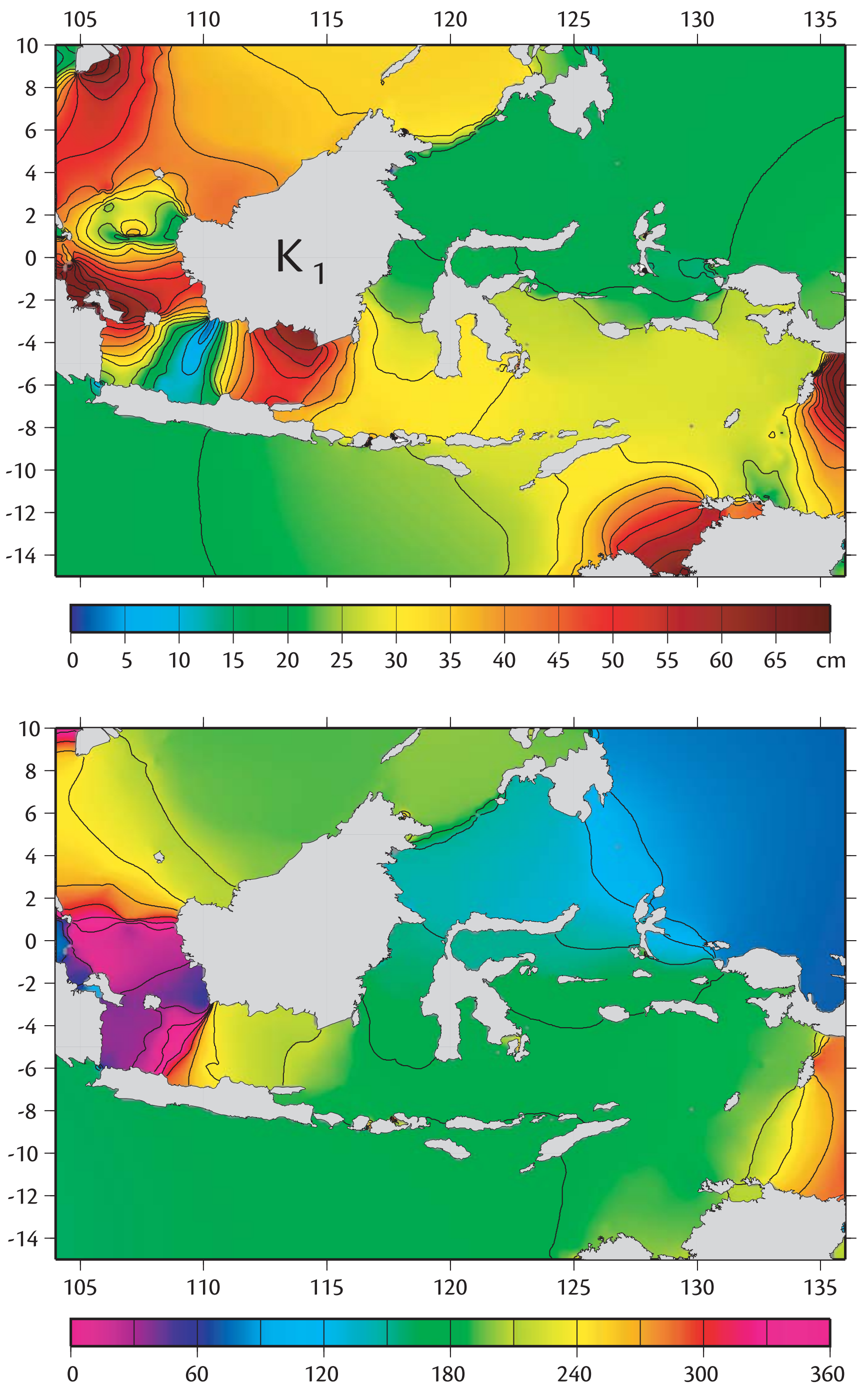

Figure 3. Amplitude (top) and Greenwich phase lags (bottom) of the diurnal K_1 tide. Phase-lag contour interval is 30°, equivalent to 2 sidereal hours. These diurnal tides are unusually large, and they dominate the semidiurnal tides in some regions, such as the Java Sea and much of the South China Sea (extending also into the Gulf of Thailand, just off the chart).

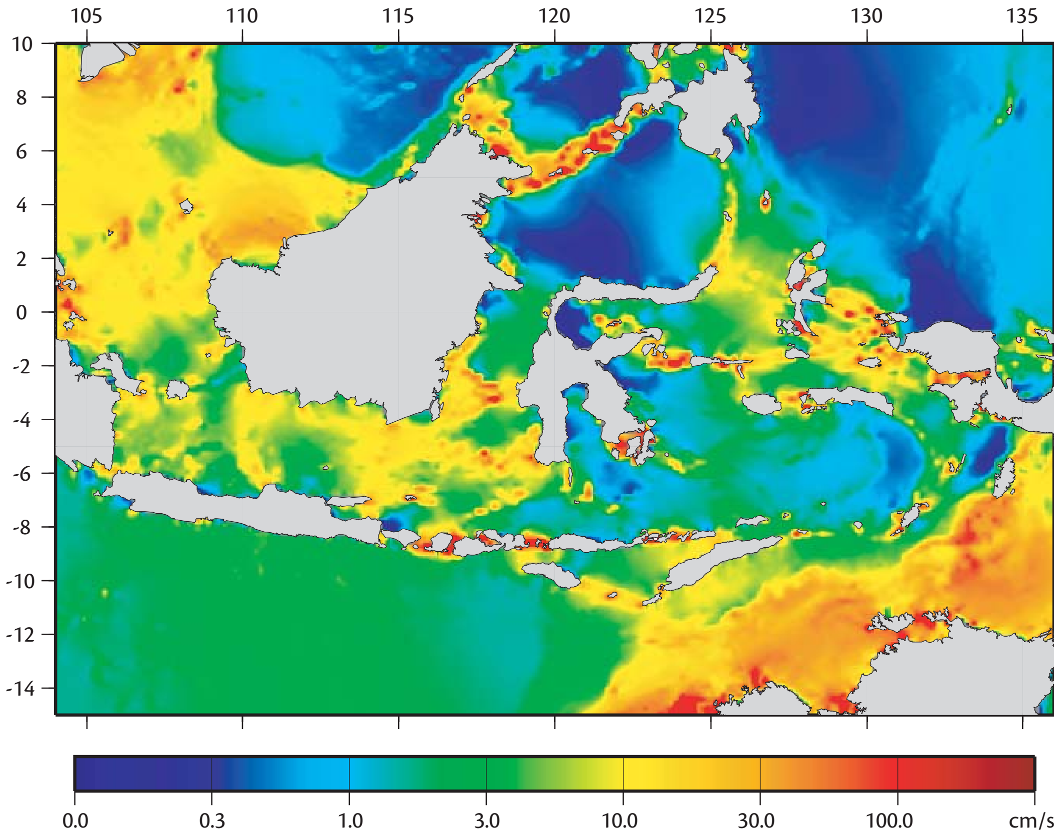

Figure 4. Maximum barotropic current velocity of M_2 tide (equivalent to length of semi-major axes of tidal current ellipses). Note nonlinear color bar. Units are cm s^{-1}. In general, these velocities reflect bathymetry, with shallow water giving rise to rapid currents. Currents in the Banda, Timor, and part of the Flores Seas tend to rotate anticlockwise; currents elsewhere are generally close to rectilinear, although the deep Pacific currents rotate clockwise.

fendable upper bound is 150 GW, which is about 6 percent of the global total. The uncertainty is a reflection of several complications: the large energy fluxes entering the region through some very narrow channels, limited data constraints from relatively widely spaced satellite tracks, and uncertainties in bathymetry and implied currents; the latter must be well determined to compute the balance between energy flux divergence and the direct rates of working by the astronomical tidal forces and self-attraction forces.

How much of the barotropic dissipation is attributable to frictional stresses in bottom boundary layers and how much to conversion of energy into internal waves and turbulence is even more of a mystery. Yet, developing a reliable budget for the energetics is of considerable importance to understanding the effects of tides on circulation and mixing in the region. To our minds, the most fruitful approach to such problems will likely be through development of generalized-inverse, three-dimensional tidal models, which can provide a framework for exploring errors in dynamical assumptions and in individual terms of an energy balance. Such work is in its infancy. These problems also call for additional high-quality tidal measurements over a much denser network. The recent shift of the *Topex/Poseidon* satellite to fly tracks interleaving those shown in Figure 1 is a valuable step toward improved data coverage.

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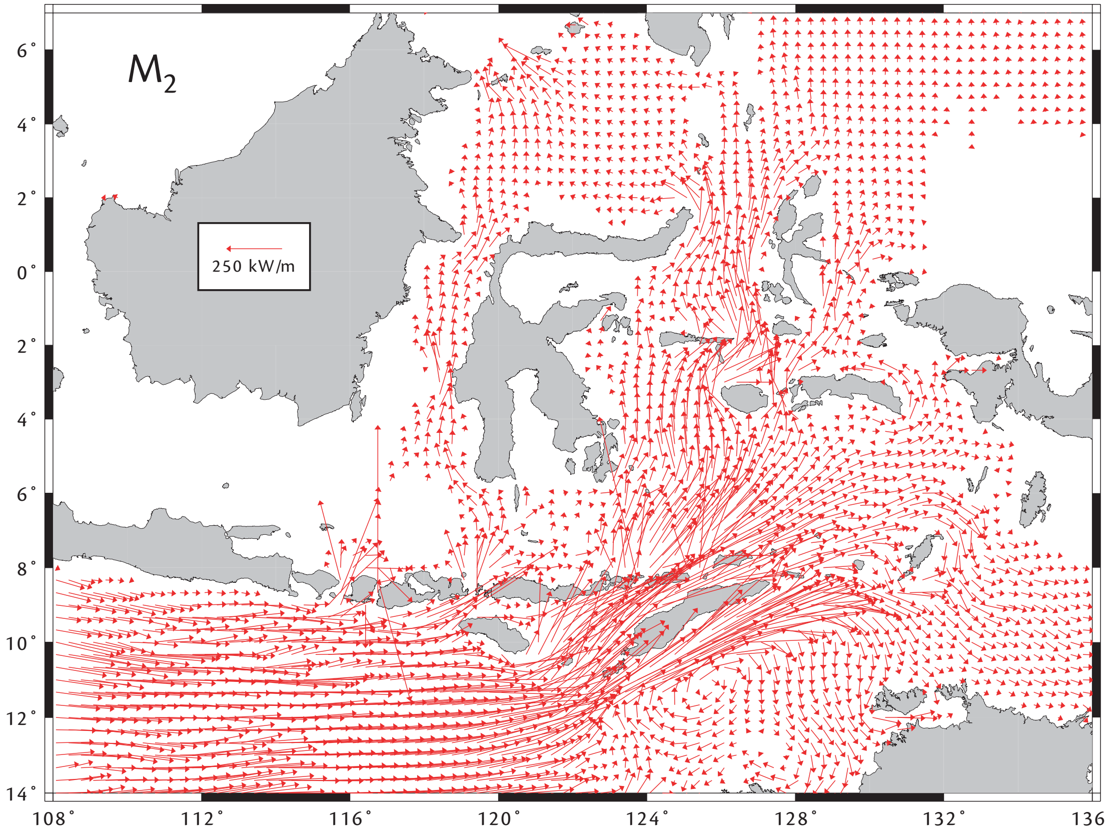

Figure 5. Mean barotropic energy flux vectors for the M_2 tide. Fluxes smaller than 20 kW m^{-1} are not drawn. The very large integrated flux from the Indian Ocean and the relatively small flux into the Pacific suggests, at first glance, large tidal dissipation throughout the region, but part of the incoming energy works against Earth's body tide (Egbert and Ray, 2001, Plate 1). An accurate accounting of the local tidal energy budget remains an outstanding issue, with published estimates varying widely.

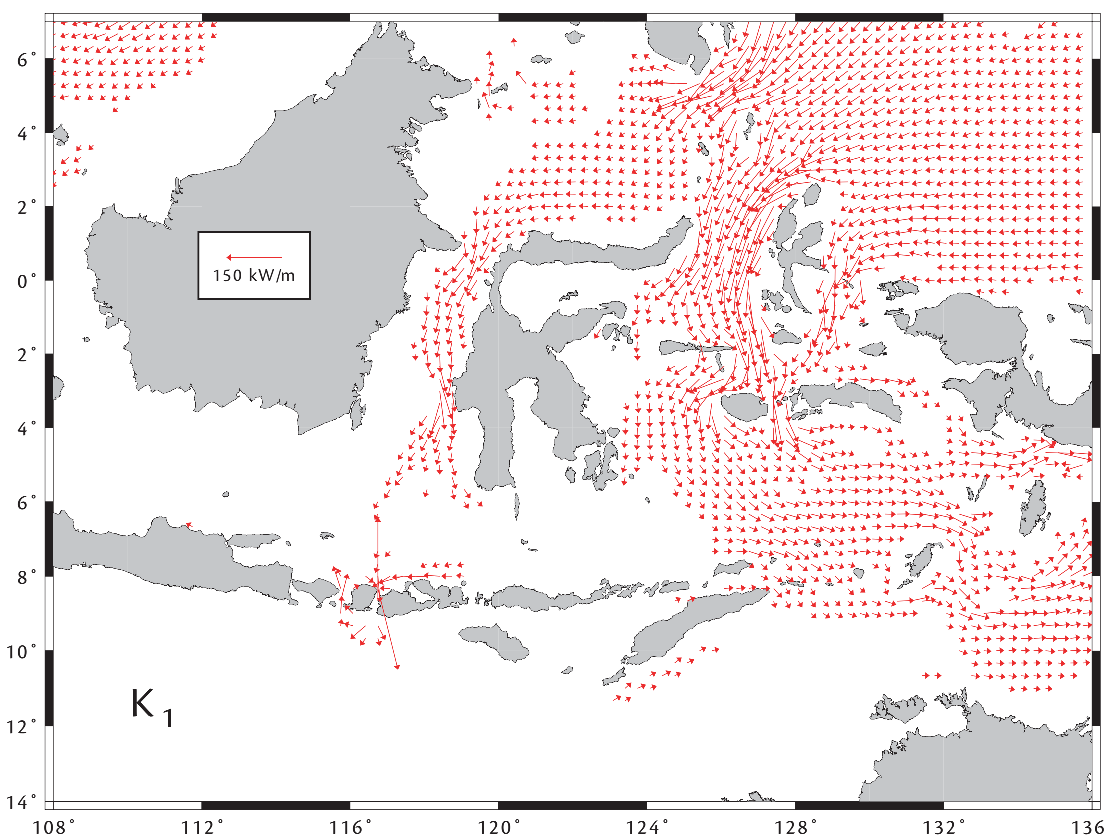

Figure 6. Mean barotropic energy flux vectors for the K_1 tide. Fluxes smaller than 20 kW m^{-1} are not drawn. Note scale differences between Figures 5 and 6. Unlike the semidiurnal tide, the diurnal tide in the Indonesian seas is powered primarily by energy from the Pacific Ocean.