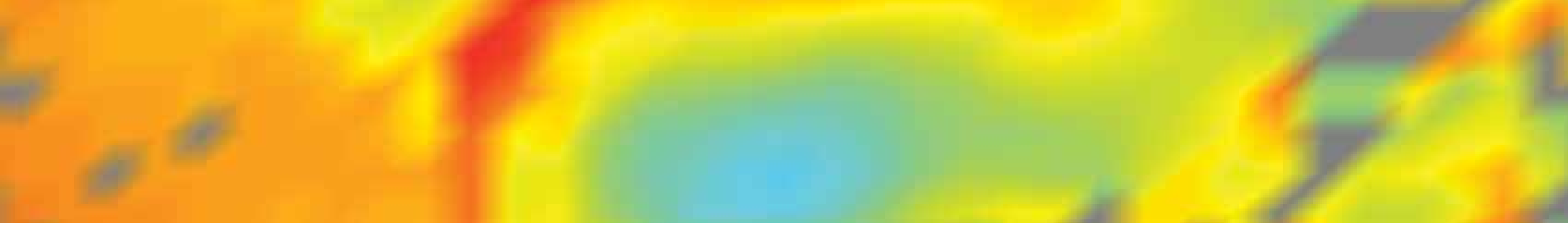
# Finding Oceanic Hot Spots

The ocean is a dynamic and, at times, a dangerous place, responding to wind stresses, heating and cooling, and gravitational attraction from the Sun and the Moon.

Knowing the state of the ocean — where it's hot, or very active, and where it's not — is crucial for optimal Naval operations. That means the Navy needs to know all the hot spots, those places in the ocean where large surface ("rogue") waves might endanger ships and where large internal waves might seriously damage submarines and other submersible platforms (such as oil rigs). Unexpectedly hitting one of these hot spots could seriously impact Naval operations.

NRL scientists have been working with University of Michigan researchers to simulate ocean tides concurrently with ocean circulation at very high resolution anywhere in the world and at any time. Comparison with observations from satellite altimeter, drifting buoy, and moored current meter data have proven the accuracy and reliability of the simulation's ocean current and tide height estimates.



# Oceanic Hot Spots — Internal Tides in the Global Ocean

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The ocean flows and undulates in response to wind stress, heating and cooling, and the gravitational attraction of the Sun and Moon. For the first time, Naval Research Laboratory scientists, in collaboration with university colleagues, have simulated ocean tides concurrently within the ocean circulation over the entire globe at very high resolution.[1] The surface tides interact with bottom topography to generate internal waves. Surprisingly, the strongest internal tide generation is not where the surface tides are the largest. The strongest interactions occur in limited regions, oceanic internal wave "hot spots." The internal waves radiate away from the hot spots as focused beams, which propagate for thousands of kilometers, and are an important source of energy for mixing the ocean interior. Both the ocean circulation and the tidal flow of the model compare well to a new set of global observations consisting of satellite altimeter tidal heights, historical moored current meters, and drifting buoys. The new model allows estimates of the ocean currents and tidal elevations anywhere on the globe at any time.

## FORECASTING THE OCEAN ON A MULTITUDE OF SCALES

The Navy needs to know the state of the ocean — quantities such as the strength of currents, height of the water, clarity of the water, and sound propagation properties, amongst others — on a range of time and space scales at diverse locations around the globe. Large surface waves can affect the operation of ships, and the interaction of the waves with ocean currents can lead to extremely large "rogue waves" that can damage and even sink ships, as seen in Fig. 1(a). The density of the ocean varies in the vertical, which allows internal waves as well as surface waves. These internal waves can have displacement amplitudes greater than 50 m and current speed greater than 2 m $\mathrm{s}^{-1}$. These large internal waves can damage structures and ground submarines. For example, in October 1997, the semisubmersible oil platform *Stena Clyde* was hit by a set of internal waves in the Andaman Sea, which broke the drill pipe, damaged the mooring lines and flotation, and left the platform with a 4-degree list, as seen in Fig. 1(b). Naval operations can occur anywhere on the globe at any time, and the Navy needs to know the changing ocean conditions that can affect operations.

To fill this need, Naval Research Laboratory scientists, in collaboration with university researchers, have developed a hierarchy of ocean forecast systems from global scales to river estuaries. The global ocean forecast system is built around the HYbrid Coordinate Ocean Model[2,3] (HYCOM). The model is forced by fluxes obtained from the Navy Operational Global Atmospheric Prediction System[4] (NOGAPS) and assimilates satellite altimetric sea surface height, radiometric sea surface temperature, and in situ ship, float, and profile temperature and salinity data using the Navy Coupled Ocean Data Assimilation system[5] (NCODA) to provide a statistical blending of model and observations. The global ocean model runs on a combination Mercator and tripolar grid with an equatorial grid resolution of 0.08° (8.9 km) and is coupled to a sea ice model at high latitudes. The model reproduces the general circulation of the global ocean, the strength and variability of the western boundary currents, such as the Gulf Stream and Kuroshio, and the mesoscale eddies generated by instabilities of the major currents. The model is validated by comparison to in situ observations not used in assimilation.[6,7] The global model performance is not as good near the coasts, where smaller scale features in the bathymetry and new phenomena, such as tides, become important in determining the state of the ocean.

To obtain forecasts in the coastal ocean, another model with finer grid resolution, typically 1 to 3 km, is

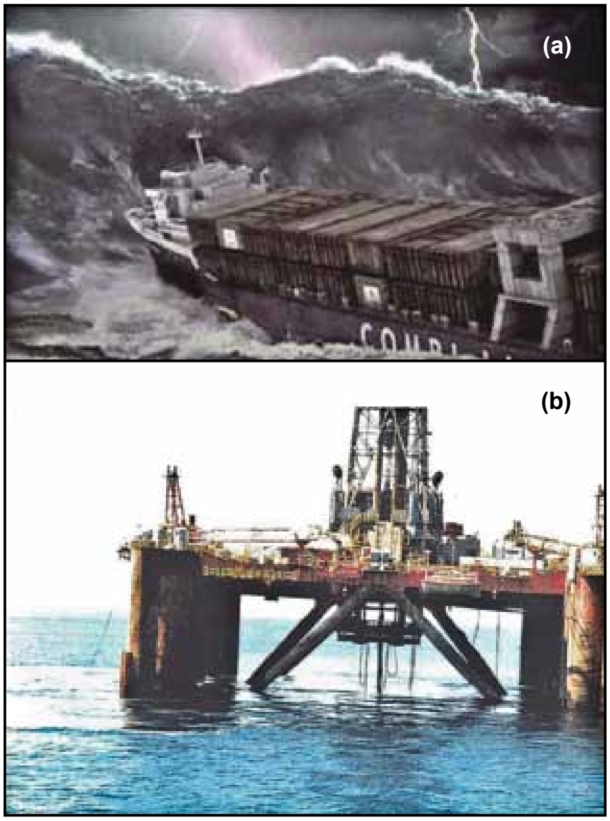

**FIGURE 1**
(a) A rogue wave with over 20 m height about to strike a container ship south of Africa. Rogue waves damage and sink several ships each year. (b) The semisubmersible oil rig *Stena Clyde* was damaged extensively by an internal wave in the Andaman Sea, October 18, 1997. The rig was left with a 4° list after the internal wave strike and required extensive repairs and a lengthy period of suspended operations.

nested within the global model. Boundary conditions are obtained from the global model to force the nested model. If higher resolution forecasts for beaches or estuaries are needed, then the process can be repeated with another even finer model obtaining boundary conditions from the first nested model, as depicted schematically in Fig. 2. The hierarchical nested scheme is complicated when the outer model, such as the global model, does not include the same physics needed for the inner model forecast. For the present hierarchical forecast system used by the Navy, the tidal height and currents forced by the gravitational attraction of the Moon and Sun are not included in the global ocean forecast model. For the nested model, the tides are added to the boundary conditions using an independent model.

In the next few years, we plan to move the global ocean forecast system to higher resolution (0.04° or 4.4 km at the Equator). This higher resolution for the global model is close to the present nested coastal model resolution. The question arises: Can the tides be modeled within the global ocean model to provide even better boundary conditions for even higher resolution nested coastal ocean models? We present the results from our first attempt to model concurrently the ocean circulation and ocean tides. The tides in the global ocean circulation model require different numerical modeling techniques compared to the tide-only models. We show that our global tides compare favorably with the tide-only models and a new altimetric tidal model. In particular, we confirm recent results by other researchers that the surface or barotropic tide interacts strongly with bathymetry to generate internal tides at a few locations — called oceanic hot spots — and that the internal tides generated at these locations travel for thousands of kilometers. The presence of these remotely generated tides affects the boundary conditions for the nested models, which is now a subject of active research.

## TIDES IN THE OCEAN

In the coastal ocean, the ebb and flow of the tidal currents and the twice daily changing height of the water tend to dominate one's view of the ocean. Tides have a rich history of study by mariners and scientists.[8] Sir Isaac Newton was one of the first to realize that the tides are driven by the gravitational attraction of the Sun and Moon. He presented a static equilibrium theory of the tides in his famous *Principia* in 1687. In his equilibrium theory, the amplitude of the lunar semidiurnal tide would be 0.5 m. A problem with the equilibrium theory is that the Earth rotates faster than a water wave can propagate, so that the gravitational bulge and the water forced by the bulge cannot travel together. Laplace in 1728 recognized that the ocean is a thin layer on top of the Earth and tides could be treated as shallow water waves, leading to Laplace's Tidal Equations as a mathematical model of the tides. Modern calculations of the tides with bathymetry and coastlines were done by G.I. Taylor and Joseph Proudman in the 1920s to 1940s. Advances in tidal analysis were made by William Thompson (Lord Kelvin), who recognized that the tides could be harmonically analyzed with discrete frequencies related to the geometry of the Sun and Moon. Thus, the principal semidiurnal lunar tide has a period of 12.42 h. The tidal variability can be calculated independently for each distinct tidal constituent with a distinct frequency. The tidal amplitudes can be increased dramatically from the equilibrium levels by geometric resonances, such as found in the Bay of Fundy.

The tides dissipate approximately 3.5 TW of energy (1 TW is a million megawatts). The energy dissipation can be measured by monitoring the distance between the Earth and Moon and the length of day. Most of this energy is dissipated by the ocean tides. Early tidal models assumed that the energy dissipation occurred over

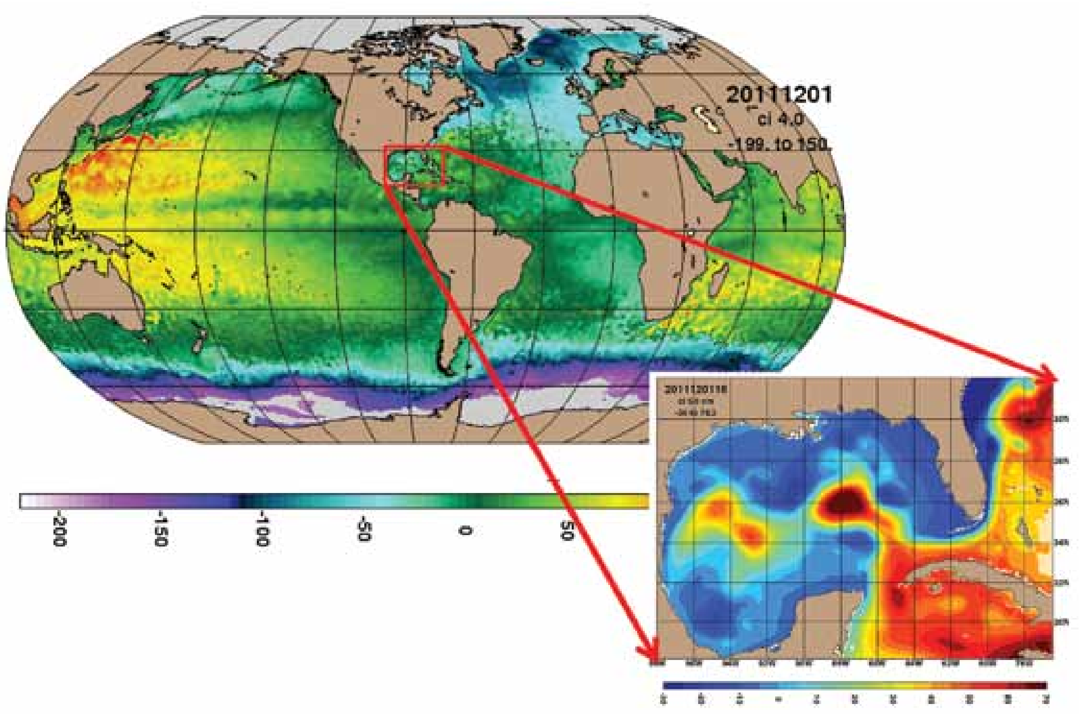

**FIGURE 2**
Forecasts from one model can be used to provide initial and boundary conditions for higher resolution models nested inside the larger model. The forecasts for the surface height (in cm) over the entire globe are produced each day. A forecast from a higher resolution model of the Gulf of Mexico also is produced each day. The initial and boundary conditions for the higher resolution Gulf of Mexico model are obtained from the global ocean model.

shallow continental shelves. With the advent of satellite altimetry, showing strong conversion of the barotropic surface tide into baroclinic internal waves,[9] a different picture emerges, with approximately 40% of the tidal dissipation occurring in deep water. The internal tides propagate long distances from the oceanic hot spots[10] and represent a significant source of energy for deep ocean mixing.[11] The generation of the internal tide occurs through an interaction of the barotropic flow over topography in the presence of density stratification.

For the barotropic shallow water tidal models with a constant density ocean, the dissipation of the surface tide by internal wave generation must be parameterized. However, the density of the ocean is predicted by the global ocean forecast model. Thus, concurrently estimating the tides with the global ocean circulation can provide predictions of the internal tide generation for the ocean. The global forecast model is modified to add the physics required to simulate the tides.[1] First, the gravitational attraction of the Sun and Moon are added as a body force via the equilibrium tidal potential, which was first computed by Newton. The astronomical tidal potential is corrected for the solid Earth body tides. The effects of ocean self-attraction and the loading of the solid Earth by ocean tides are also accounted for in the ocean tide model.

The conversion of the barotropic surface tide into internal tides depends upon the roughness of the sea floor and the density stratification at the sea floor. The global model, presently, has 32 layers in the vertical and runs at a horizontal resolution of approximately 9 km at the Equator. Thus, only part of the conversion of the barotropic surface tide into internal tides can be directly estimated in the model, and the internal waves with small vertical and horizontal scales must be parameterized as in the barotropic shallow water model.

## VERIFYING THE TIDES IN THE GENERAL CIRCULATION MODEL

The global ocean circulation model with tidal potential forcing for the four leading semidiurnal ($M_2$, $S_2$, $K_2$, $N_2$) and four leading diurnal ($K_1$, $O_1$, $P_1$, $Q_1$) constituents and realistic atmospheric wind, heat, and freshwater forcing has been run for a 7-year period (2004 to 2010). The performance of the model for time scales longer than a day has been extensively validated against in situ and satellite observations. Validating the tides for the global ocean is much more challenging. Most of the tidal observations are collected in shallow, coastal regions, where the performance of a relatively coarse resolution global model is poor. In deep water, only 102 tide gauges and bottom pressure gauges are available. However, with the launch of satellite altimeters in 1992 — which are capable of measuring the sea surface height with an accuracy of a few centimeters — observations of the global tides were realized. The satellite altimeters do not make direct observations of the tides, but allow a statistical estimate to be obtained. In Fig. 3, we compare the lunar semidiurnal tidal amplitudes and phases for a shallow water model assimilating the altimetric tidal amplitudes and tide gauge observations (TPXO) with the global ocean model (HYCOM), which does not assimilate any data. The white lines on the amplitude maps are the phases of the tide. The surface tide propagates as a wave around approximately 15 amphidromes. The spacing of the phase lines and amplitudes around the amphidromes agree well between the two maps. The global ocean model reproduces 95% of the variance at the 102 bottom pressure gauges and 97% of the variance in the TPXO shallow water model. The largest errors in the global ocean model tides occur in the Southern Ocean. The global ocean model converts approximately 1 TW of barotropic tidal energy into baroclinic internal tides through the parameterized internal wave drag and generation of resolved internal waves.

Internal waves have their largest amplitudes deep in the ocean. However, the internal waves have expressions that are visible at the ocean surface and can be

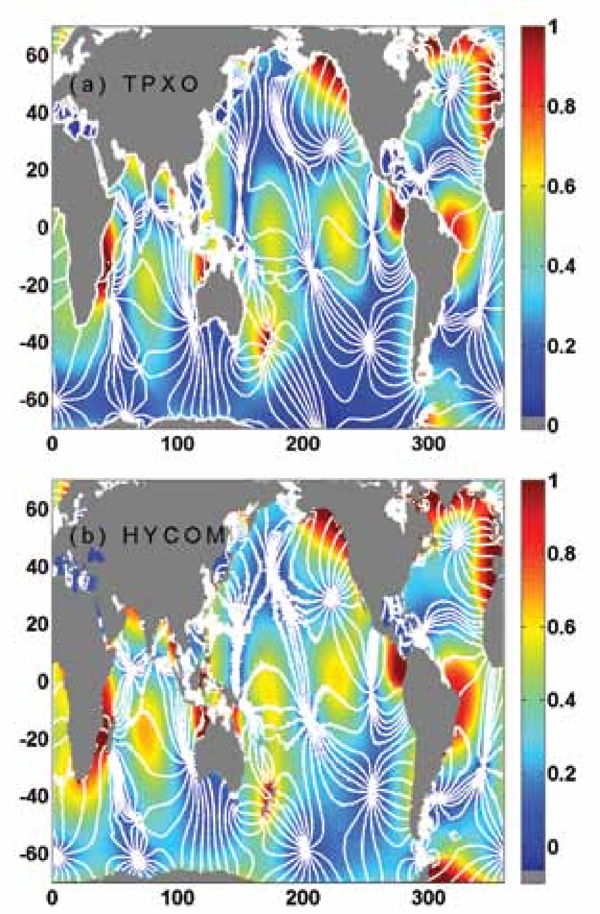

**FIGURE 3**
The ocean sea surface elevation (m) and phase for the principal lunar semidiurnal tide as predicted by (a) the current best forecast from a shallow water model assimilating all available tide data and as predicted by (b) the new global ocean circulation model with astronomical tidal forcing and internal wave generation. Open ocean tidal heights are typically less than 1 m. The amplitudes and phases of tidal elevation in the two maps are very similar, with the largest differences found in the Southern Ocean. Compared to 102 deep-sea pressure gauges, the tides in the ocean circulation model capture 94.5% of the observed tidal variability.

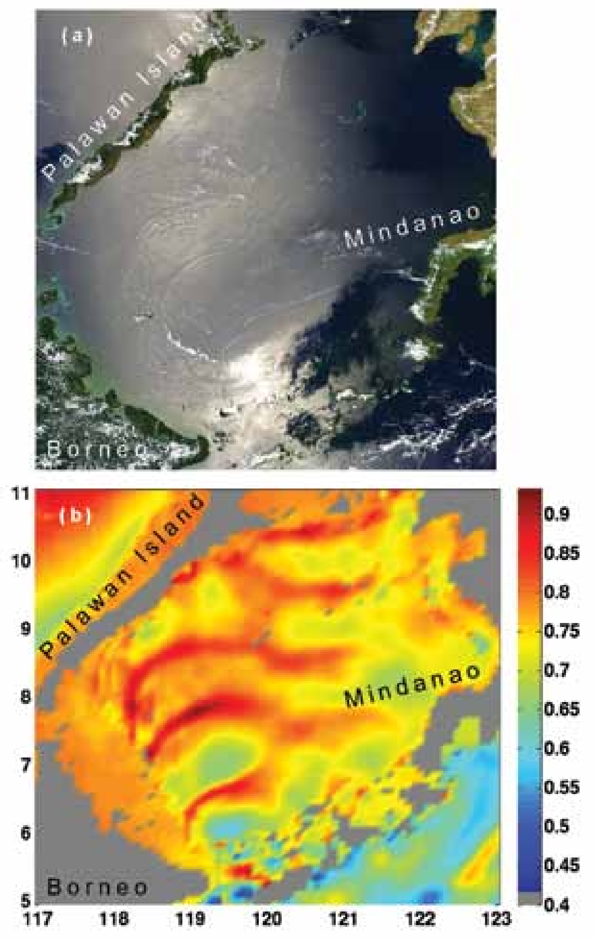

**FIGURE 4**
While the amplitudes of internal tides are largest in the ocean interior — often exceeding 20 m — the surface of the ocean shows the impression of the internal tide. (a) This image is a true-color scene obtained by the Moderate Resolution Imaging Spectroradiometer (MODIS) showing internal waves propagating toward Palawan Island in the Sulu Sea between Borneo and Mindanao in April 2004. The currents from the internal waves affect the surface roughness of the ocean, changing the reflection of sunlight and sunglint, and causing curving light and dark bands in the image. (b) The model sea surface height (cm) shows the same curving bands of elevation as seen in the sunglint image of the Sulu Sea for the same time.

viewed by satellites. Figure 4(a) presents a true-color image obtained by the Moderate Resolution Imaging Spectroradiometer (MODIS) over the Sulu Sea near Borneo. The surface tide sloshing through the Sibutu Passage at the bottom of the image generates internal tides that propagate toward Palawan Island in the northwest of the image. The surface currents of the internal tides affect the roughness of the ocean waves, which, in turn, changes the specular reflection of sunlight from the ocean surface, the sunglint. Three curving dark bands can be seen in the image associated with the crests of the internal wave. The internal waves can have interior amplitudes greater than 20 m, while the surface height variations are approximately a centimeter. A map of the model sea surface height for the same time period (Fig. 4(b)) is shown below the MODIS image. Three curving bands similar to the MODIS image are seen in the model sea surface. Despite the small amplitude, the sea surface height variability due to internal tides can be measured from space and provides a set of global observations to verify the model performance.

The horizontal wavelength of the internal tide is proportional to the vertical wavelength. For very large vertical wavelength internal tides, the horizontal wavelength is approximately 150 km. Inspecting the amplitude maps in Fig. 3, we observe that the surface tide is dominated by extremely long wavelengths, exceeding 1000 km in deep water. Thus, we can separate the surface and internal tides in the sea surface height by filtering the very long wavelengths to remove the barotropic tides. The picture in Fig. 5 for the internal

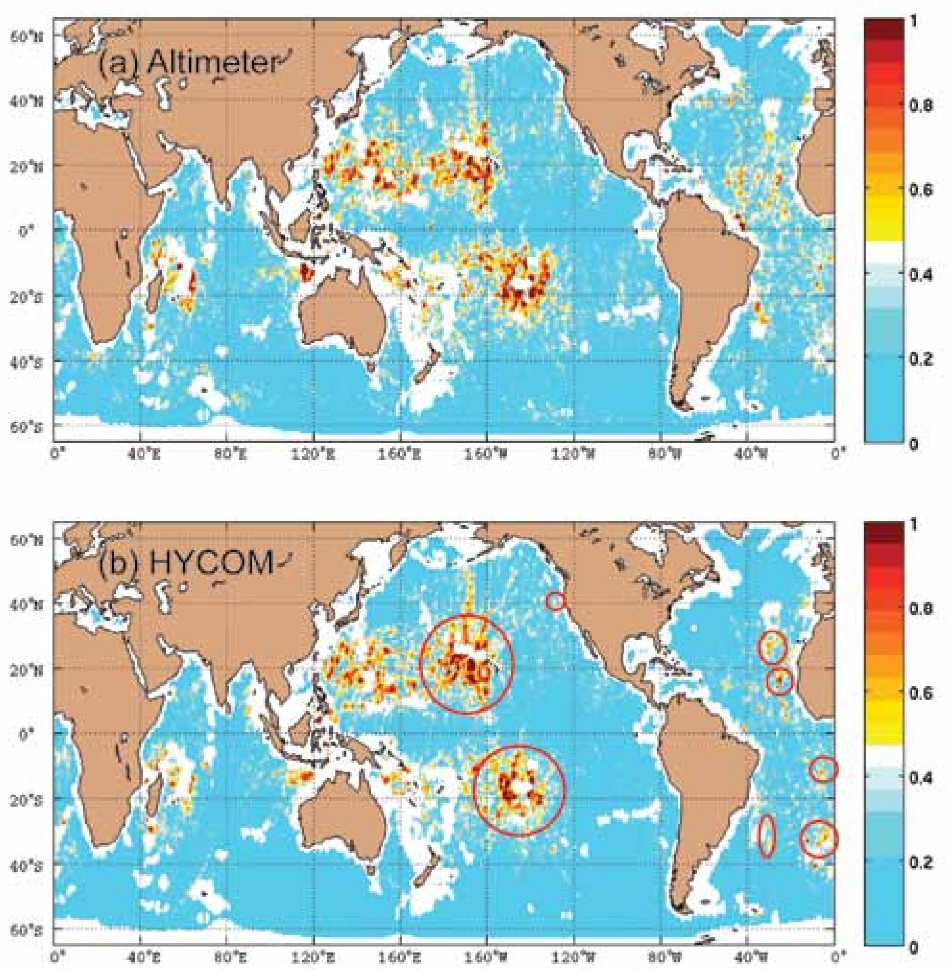

**FIGURE 5**
The amplitudes (cm) of the principal lunar semidiurnal tide, $M_2$, obtained from long-term fits to the satellite altimetric sea surface height (a) and the hourly HYCOM sea surface height (b). The data are filtered to show only short wavelength variations, thus removing the barotropic surface tide. The visual similarity between the model and altimetric estimates is very good, showing the “oceanic hot spots,” circled in red, of internal tide generation around major bathymetric features in the deep ocean. Internal tides also are generated at straits and passages, particularly in the western Pacific around the Indonesian and South China Seas, and at the continental margins, for example, off Spain and Northwest Australia. The internal tides can propagate for thousands of kilometers away from the generation regions.

tide amplitudes is very different from the barotropic tide. The strong internal tide generation at the straits and passages into the Indonesian and South China Seas in the western Pacific Ocean and off the continental margins of Spain and Northwest Australia are clearly visible. However, the largest amplitude internal tides are not found only around the continental margins and near straits, such as seen in Fig. 4, nor where the surface tide is largest in Fig. 3. The largest internal tides are observed near major bathymetric features in a limited number of regions, the oceanic internal wave hot spots. Inspection of Fig. 5 reveals large amplitude internal tides generated around the major island groups, the Hawaiian–Emperor Seamount Chain and Tuamotu–Society Archipelagos in the Pacific Ocean and the mid-ocean ridge in the Atlantic Ocean. Even small bathymetric features, such as the Mendocino Escarpment off northern California, can generate large internal tides.

The internal tides propagate away from the generation regions for extremely long distances. Again, the comparison between the altimetric observations and the model predictions are very good. Small scale differences in the amplitudes are observed, since the coarse vertical resolution of the model does not represent the actual scattering geometry observed by the altimeter. However, when we average the amplitudes over regions around the hot spots, we find that the model overestimates the internal tide generation near Hawaii by about 10% and underestimates the internal tides by less than 10% at the other hot spots. Thus, a picture emerges from the ocean circulation model with tides in which the dissipation of the barotropic surface tide is split between bottom drag on the continental shelves and conversion into baroclinic internal tides in a few hot spots near major bathymetric features. The internal tides potentially represent approximately half of the energy needed for mixing in the global ocean. Most of the internal tidal energy is dissipated near the hot spot generation regions, but approximately 20% of the internal tidal energy propagates away from the generation regions as low vertical mode and long horizontal wavelength internal waves that are dissipated far from the hot spots. The hot spots of internal tide generation play an important role in providing kinetic energy for ocean mixing.

## THE CHALLENGES AHEAD

For the first time, NRL scientists have shown that tides can be predicted concurrently with the eddying ocean circulation. The ocean circulation model without tides is the operational forecast model for the Navy. The present resolution of the operational model and the preliminary model with tides is about 9 km at the Equator, but will move to 4 km in the near future. At this resolution, the operational global forecast model will be close to the resolution of the regional models. The barotropic tidal heights in the global ocean model compare well with the observed deep water tides, but not as well near the coasts. The semidiurnal tides in the global ocean model have smaller errors than the diurnal tides. The parameterization for the barotropic to baroclinic tidal energy conversion presently is set to minimize the semidiurnal tidal error. A new formulation that properly models the spatial and frequency characteristics of the topographic interaction of the tides is needed. The self-attraction and loading of the tides in the global model is a simplified scalar approximation to the actual self-attraction and loading, which could be improved. The data assimilative shallow water barotropic tidal heights have a much smaller root mean square error (1.6 cm) compared to the global ocean model barotropic tidal heights (5.8 cm). However, the techniques used to assimilate tidal heights in the shallow water models cannot be used in the global ocean circulation model. The present data assimilation scheme for the global ocean forecast model, NCODA, improves the low frequency circulation in the presence of the tides, but does not improve the tides. New techniques must be developed to assimilate tidal information into the global ocean forecast system. The internal tides generated at the oceanic hot spots propagate for long distances and potentially can impact the coastal circulation far from the hot spots. Errors in the barotropic tide will affect the generation of the internal tide, which, in turn, can affect the remote impacts of the propagating tide.

Evaluating and improving the performance of the tidal forecasts within the global ocean forecast system is the challenge ahead. Improvements in the numerical model for the tides and new data assimilation techniques are needed to move the global tides and circulation model forward as the operational forecast system for the Navy.

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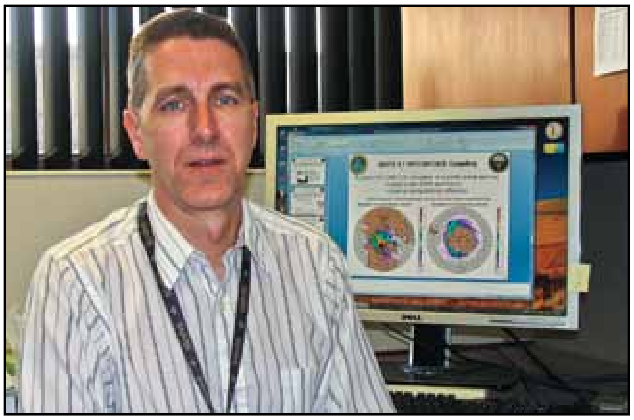

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