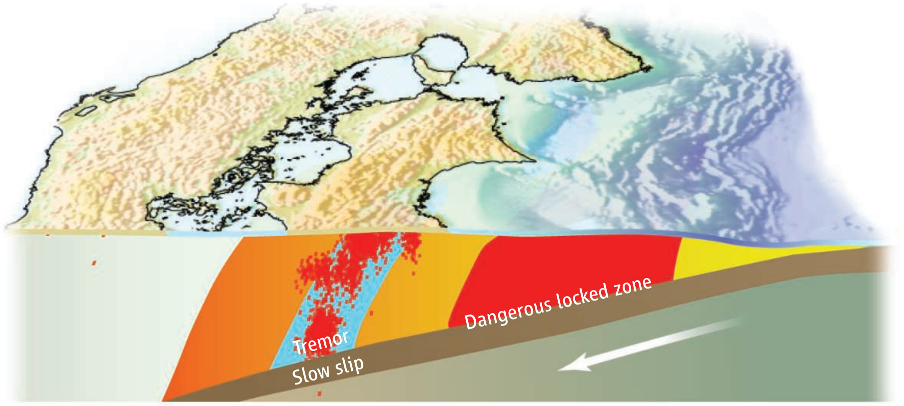

At fault. Perspective view of subduction of the Philippine Sea Plate under southwest Japan. Blue zone with red dots shows the location tremor and slow earthquakes under Shikoku; shallower orange area is the dangerous, locked zone that last ruptured in two large earthquakes in 1944 and 1946.

tremor in California occurs under some faults but not others.

Given the variable seismic network coverage in these areas, and the fact that tremor occurs near the detection threshold of seismic networks, we have to check carefully whether the absence of tremor in some areas is simply due to the inability of existing monitoring networks to detect it. The same is true for slow slip: Most slow-slip events in Cascadia and Mexico are large enough to be detectable by Global Positioning System, whereas in Japan the smaller observed slow-slip events are only visible on more sensitive tiltmeters and strainmeters, which suggests a detectability problem. Nevertheless, it seems clear that there are strong variations in the distribution of tremor and slow slip in areas of similar tectonics. What causes these variations?

Finally, there is the central question of why slow earthquakes are slow. Ordinary earthquakes grow at a large fraction of the medium velocity because stresses transmitted by seismic waves efficiently promote failure in the direction of propagation. This failure mechanism is common from the laboratory scale to the scale of the largest earthquakes. But slow earthquakes clearly have something else going on.

Tremor and slow slip occur on parts of faults where the behavior is transitional between fast, brittle rupture and slow, steady deformation. Depth-dependent friction laws can model repeated deep slow earthquakes to some extent (*17*). Moreover, tremor can migrate fairly rapidly, but not as fast as ordinary earthquakes. How can it be that so many small, slow earthquakes should be starting and stopping in quick succession?

Simple friction laws by themselves do not provide an explanation for this complex behavior. Petrology and seismic tomography both suggest a role for pore fluids in tremor, but exactly what that role is has yet to be worked out. Much remains unclear, but one thing is clear: A better understanding of slow earthquakes has the potential to fundamentally change our understanding of the earthquake process.

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GEOPHYSICS

Earth Vibrations

Peter D. Bromirski

Seismic "noise" can be used to monitor climate change effects, locate storms, and elucidate the structure of Earth's crust.

Intense cyclonic storm systems generate strong ocean-surface winds that transfer atmospheric energy into ocean gravity waves. Some of the ocean wave energy couples to the solid earth, causing what seismologists have long considered as ambient "noise," because it interferes with the study of earthquake signals measured by seismometers. However, rising ambient noise levels imply increasing oceanic storminess (*1*), which is linked to climate change. In this context, the roles are reversed, with earthquakes being the noise that needs to be excluded from the climate-related signals. Studies of long-term seismic records suggest that wave-generated ambient noise is increasing globally (*2*).

Historic paper seismograms produced by classic drum recording systems have been archived at select locations since about 1930. Treasure troves of these archived seismograms are now being tapped for climate change information. The length of these seismic records and the stability of the recording platforms are advantages over many climate-related records, which often have large gaps and changes in measurement methodologies that make reliable long-term trend assessment difficult.

At periods shorter than 30 seconds, the ambient noise spectrum is dominated by microseism energy (see the figure). Microseisms are generated by two mechanisms. Single-frequency (SF) microseisms, observed at the period of the forcing waves, are generated only in shallow coastal waters by direct

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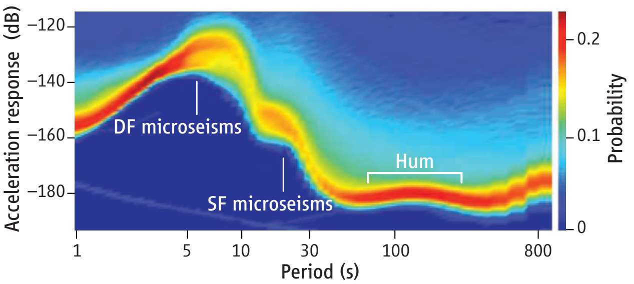
pressure fluctuations on the ocean bottom from shoaling and/or breaking waves (*3*). The dominant double-frequency (DF) peak, observed at half the period of the ocean waves, results from the nonlinear interaction of waves traveling in nearly opposite directions (*4*). This "wave-wave" mechanism generates a pressure pulse that propagates nearly unattenuated to the sea floor, where it is transformed mainly into seismic Rayleigh waves that can propagate long distances.

High-amplitude DF microseisms observed by seismometers on the sea floor in the deep ocean are caused by wave activity under nearby storms (*5*); these microseism signals should be observable on land. However, even extreme storms approaching the coast generate microseisms that are detected on land only when their waves reach nearshore locations (*1*, *6*, *7*), where shore-reflected/scattered waves provide opposing wave components at swell periods (*6*). To date, there is no unambiguous evidence that deep-ocean-generated microseisms are observed on land.

The ubiquitous microseism vibrations are sensed at seismic stations globally, even deep in continental interiors (*1*, *8*). Their integrative quality allows assessment of trends in coastal wave activity at regional and global spatial scales using the global seismic network (GSN). The close relationship between near-coastal measurements of DF microseisms and the nearby wave climate allows an accurate estimate of historical near-coastal wave variability from archived seismograms (*9*), important for investigating changes in storm wave frequency, intensity, and duration associated with climate change. Upward trends in the number of strong microseism events indicate that coastal wave intensity is increasing globally (*2*).

Microseism measurements may also have other uses beyond climate studies. Because microseisms are generated continuously at multiple source areas along coastlines, compared with infrequent earthquake signals arriving along single azimuths, they provide useful signals for seismic array tomography (*10*) to probe the structure of Earth's crust. Storm tracking using microseism noise is also getting renewed interest. In addition to generating Rayleigh waves, a portion of the DF microseism pressure pulse produced under storms is converted at the ocean bottom to seismic *P* waves that can be observed by land-based seismic arrays, allowing the locations of storms to be determined (*11*).

Microseisms should not be confused with Earth's "hum," a term referring to bell-like ringing associated with the fundamental resonant spheroidal oscillations of Earth (*12*) at periods between 1 and 8 minutes (see the figure). Initially it was thought that hum was forced by direct coupling of atmospheric pressure fluctuations to the solid Earth (*12*), but recent studies favor hum excitation by ocean infragravity (IG) waves (*13*–*16*). A portion of ocean swell that reaches coastlines is transformed into much longer period (>50 second) IG waves (*17*), partly through the same wave-wave mechanism that produces DF microseisms. IG-wave amplitudes depend on swell amplitudes impacting coasts, which in turn depend on climate factors affecting storm track and storm intensity. Consequently, the locations of dominant hum excitation and hum levels, both seasonally and longer term, are climate-related.



Distribution of seismic noise energy. The data, obtained at a "quiet" seismic station (TUC in Tucson, Arizona) between 6 November 1998 and 30 December 2008, show the observed range of variability over the 10-year record for the DF and SF microseisms and for the hum band (*21*). The highest probability obtained means that these levels were observed >20% of the time at this inland location, an indication of the persistence and ubiquitous nature of wave-generated signals.

Early analyses suggested that hum modes are excited by IG waves in the deep ocean (*13*). However, because IG-wave amplitudes are much higher over the shelf than the deep ocean, shallow continental shelf waters are more likely to be the dominant source regions (*15*, *16*). Hum modulation has been associated with changing source regions as storm waves arrive at different coastal locations (*18*), locally generating IG waves. Whether low-amplitude background hum levels are excited by IG waves over the deep ocean remains uncertain. Newly available USArray (*19*) data, which provide an unprecedentedly dense large-aperture network of broadband seismic stations, may help to identify the dominant hum source regions.

Recent analysis of horizontal motions recorded by seismometers suggests the existence of "toroidal" hum modes (*20*). The cause of these modes is unknown, but Kurrle and Widmer-Schnidrig (*20*) suggest that the horizontal forces needed to excite these modes may result from coupled wind energy along mountain range fronts or long period ocean waves impacting steep oceanic topographic features such as island chains or continental shelves. Alternatively, the toroidal modes may be a consequence of the wave-wave hum forcing mechanism. The USArray data may also advance our understanding of toroidal hum sources and their characteristics.

The direct association of storm-driven ocean waves with microseisms and hum shows that the solid Earth is not independent of the global "climate system." Microseisms and nonearthquake hum levels are regional and/or global integrators of storm intensity that complement near-coastal oceanographic observations. As rising sea levels allow more wave energy to reach farther shoreward, changes in microseism and hum levels could provide a useful proxy for wave energy reaching coasts.

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