

The Ocean's Seismic Hum

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The first seismometers capable of measuring ground vibrations with periods of several seconds were installed in the early 20th century. Since then, the devices have recorded a continuous seismic hum, called “ocean microseisms.”

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This hum is not the result of tectonic forces, but rather the response of the solid Earth to ocean wave-wave interactions, which have an annual global cumulative seismic energy comparable to that from earthquakes.

Long considered noise by seismologists, ocean microseisms have recently been found to be a useful resource for the interdisciplinary study of our planet. They provide a record of the state of the oceans since the early 20th century and are a passive seismic source for probing the geological structure of Earth's upper crust (0 to 20 km). Origins, applications, and future studies of ocean microseisms were discussed at the Fall 2004 meeting of the American Geophysical Union (1).

Early studies showed that ocean microseism signals are linked to ocean swell conditions (such as wave direction, amplitude, and period) but have half the swell period. The debate over their origins was settled by Longuet-Higgins, who showed in 1950 that the interaction of water waves with similar frequencies but opposing directions generates a second-order pressure wave with half the period and an amplitude proportional to the product of the wave heights (2). Unlike the pressure field generated by traveling waves, this pressure wave does not wane with depth and efficiently couples with the solid Earth to generate seismic surface waves.

The conditions for generating these wave-wave interactions probably occur at cyclonic depressions and along steep coastlines. Until recently, information about the source of ocean microseisms was inferred from laboratory experiments, analysis of seismic data, and sporadic ocean observations from buoys and ocean-bottom pressure sensors (3–5). In recent years, the combination of seismic data and improved

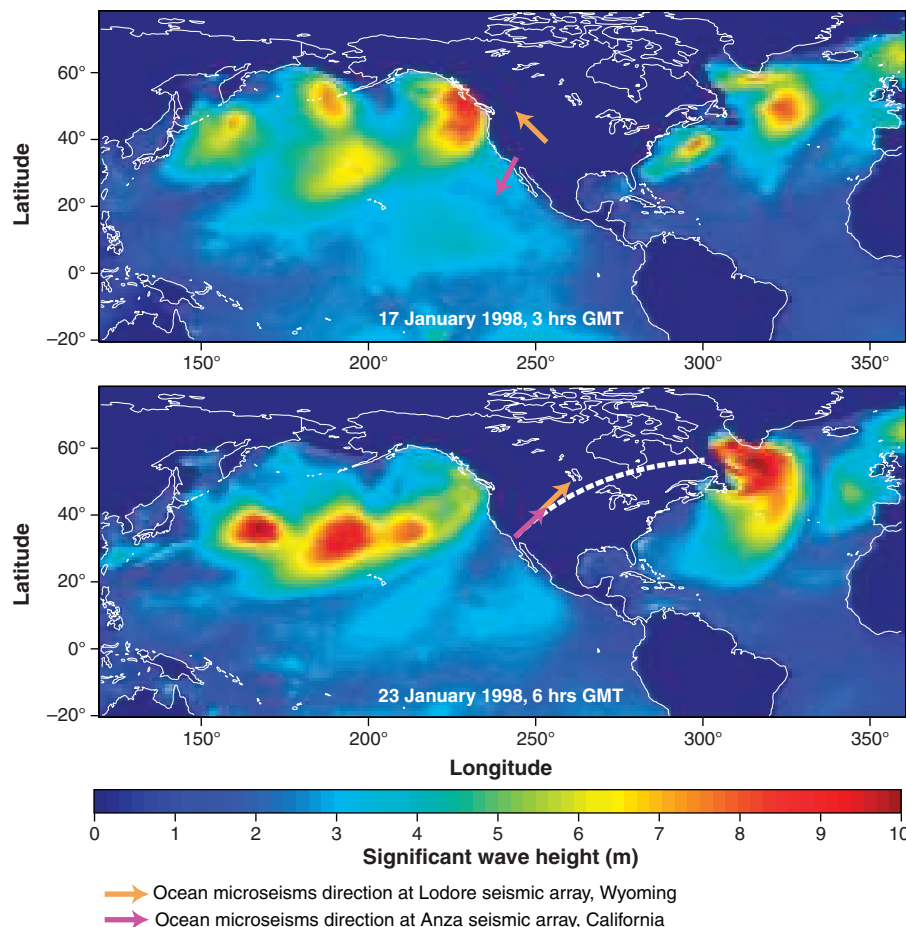
global ocean-wave observations and models has led to new insights into the origins of ocean microseisms and new Earth science applications of these signals.

Potential oceanographic applications were considered as early as the 1960s, when Haubrich *et al.* showed that storms can be located and tracked with seismic data (4). This method has been improved upon in recent years. Bromirski and Duennbier (6) have shown that the wave climate (that is, the ocean conditions that give rise to and sustain ocean waves) can be reliably reconstructed with archived seismic data. This

approach allows, for example, the strengths of El Niño conditions to be assessed for times when ocean data were largely unavailable.

Other researchers are combining remote sensing data from ocean satellite altimeters and data from the global seismic network to investigate global interactions between the oceans and the solid Earth. Rhie and Romanowicz (7) have discovered that the ocean's hum extends to periods of several minutes and have shown that background vibrations of the solid Earth are excited in the northern Pacific ocean in Northern Hemisphere winter, and in southern oceans in the summer. Ocean microseisms thus act as a meter by which global-scale ocean activity can be monitored.

Microseisms are also used to probe Earth's structure through seismic tomography. Crustal-scale tomography typically



Tracking wave-wave interactions. The maps show global wave heights [from the NOAA Wave Watch III model (12), see color scale at bottom] and arrival directions of ocean microseisms at U.S. seismic arrays (from seismic data; colored arrows). **(Top)** Microseisms recorded in Wyoming are dominated by wave-wave interactions near the British Columbia coast, and those recorded in southern California by interactions off the coast of Baja California. **(Bottom)** A North Atlantic storm swell hitting the steep Labrador coast triggers transcontinental microseisms.

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employs energetic, sporadic sources such as large explosions or earthquakes. Because ocean microseisms are almost continuous, they offer the possibility to monitor temporal changes in the crust (induced, for example, by tectonic stresses and fluid flow) on much shorter time scales than is possible with sporadic sources. Suggested in 1964 (8), this method has become a reality with the proliferation of digital seismic data. At the meeting, Stehly *et al.* (9) showed that ocean microseisms can be used reliably for tomographic imaging.

To better understand and use this ocean–solid Earth interaction, better knowledge of the state of the ocean wave field that generates the ocean microseisms is required. Combining seismic observations and wave action models, Schulte-Pelkum *et al.* (10) have analyzed oceanic source regions and conditions for ocean microseism generation (see the figure). Typically, ocean microseisms are generated

locally in coastal regions. However, several times a year, cross-continental seismic waves are excited when swell is reflected off a coast that is prone to ocean microseism generation (10). Rodriguez *et al.* (11) have proposed that microseism-generating regions both in the open ocean and in coastal regions should be directly observable and identifiable from space- and airborne instruments. They pointed to synthetic aperture radar as the prime candidate for identifying regions of interaction between swells of similar periods and opposing directions, which are necessary for the excitation of ocean microseisms.

Ocean wave-wave interactions and the seismic energy they generate have largely been forgotten by oceanographers and swept aside as noise by seismologists. The emerging interdisciplinary effort of the two communities to understand and use this fundamental interaction, taking advantage of the riches of modern ground- and space-

based measurements, is promising. This joint effort is likely to benefit ocean and solid Earth science alike.

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GENETICS

A Century of Corn Selection

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Using conventional selection methods, plant and animal breeders have made many beneficial changes to the yields and composition of crops and livestock (1). Yet we know little about the numbers, effects, and mode of action of the genes that account for these long-term changes. A recent paper about maize selection in the journal *Genetics* demonstrates that such information is slowly becoming available (2).

Since 1896, in one of the longest experiments ever, biologists at the University of Illinois have continuously selected maize (corn) to change the oil composition of its kernels (1, 3). Separate maize lines have been selected for more than 100 generations according to whether the kernels contain high or low amounts of oil, a trait of agronomic importance (3). Typically, mean oil concentration was estimated in 60 or so ears (cobs) of maize, and seeds from only 12 were selected to propagate the next generation. The change in oil concentration was almost continuous (3) and substantial: From a base of about 5%, the high oil-producing line now has about 20% oil in the kernel, and the low oil-producing line has almost none (see fig. S1). The two maize lines differ by about 32 standard deviations (SD, 0.42% in the base population).

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Divergent selection in separate lines for kernel protein concentration gave similar responses, except that the low line reached a plateau at about 5% protein (3).

To explain the large response in terms of changes at the level of individual gene loci, Laurie, Dudley, and colleagues from the Monsanto Company and the University of Illinois recently reported an analysis of the maize data that itself took much time and work (2). Their goal was to identify quantitative trait loci (QTLs)—regions of the genome where genes influence the trait—by testing the association between markers and the trait, a standard technique of QTL analysis (4).

A cross between high and low oil-producing maize lines from generation 70 was randomly bred for 10 generations in a large population (2) to reduce the effects of linkage disequilibrium. From each of 500 inbred lines subsequently derived by self-pollination, DNA was extracted for genetic analysis and oil concentration was estimated in the ears of inbred plants and of hybrid plants obtained by outcrossing. The single-nucleotide polymorphisms (SNPs) chosen as markers of whether a region of the genome came from either the high or low oil-content line differed substantially in allele frequency between the lines or, exceptionally, filled gaps in the genetic map. After eliminating markers with strong linkage disequilibrium, the investigators focused their analysis on 440 SNPs. Because markers more than 20 cM apart were essentially in linkage

equilibrium, real associations would be expected only between close markers and the trait of interest.

An analysis of variance that fitted each marker locus individually and in pairs in separate analyses of inbred and hybrid data showed that both dominance within loci and epistatic interactions between pairs of loci were weak relative to additive effects. This means that the oil concentration in heterozygotes was intermediate between that of the two homozygotes, and that effects at different gene loci did not interact. The high correlation (0.75) of QTL effects on oil content estimated from inbred and hybrid plants is a further indication that they act additively. With the use of a stepwise multiple regression analysis to select markers linked to QTLs and to account for linkage disequilibrium between them, 50 markers were selected for the inbred data and 39 for the hybrids (where differences are smaller). Significant effects were found on all 10 chromosomes, with some clustering in the genome.

A major problem in QTL analyses comprising many tests of significance is to compromise between declaring false associations while missing real ones. To assess their findings, Laurie *et al.* simulated data with effects distributed similarly to what they observed, and subjected these data to the same analysis. They concluded that they had detected about 63% of the QTLs and that about 33% of markers selected were not QTLs. Consequently, they calculated the correct number of QTLs to be about 50.

The estimated effects of the QTLs on oil concentration were all much less than the line divergence of 15% at generation 70. Indeed, the largest had an effect (half homozygote