OCEANOGRAPHY

Ripples run deep

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Tiny, wind-generated ripples on the sea surface can interact and produce pressure changes felt on the ocean floor. The same line of study points to a basic distinction between two types of surface wave.

The sea floor is a vibrant place — earthquakes, volcanoes, man-made explosions and ships are all causes of disturbances that can be monitored by instruments on the ocean bottom. Data from arrays of sea-floor seismometers also provide information about the structure of Earth's interior[1], but in this case in particular, intricate analysis is required to separate the desired signal from 'noise'. One source of such noise is the pressure fluctuations arising from wind-generated waves on the ocean surface. Despite the attenuation caused by the water column, the pressure signals from surface waves can reach the sea floor even in the deep ocean. A new and unexpected angle on this general phenomenon comes in a paper by Farrell and Munk just published in *Geophysical Research Letters*[2].

Even during a hurricane, it is fairly calm not far beneath the surface of the sea. The powerful swells are attenuated by the water between the surface and the bottom, with long waves decaying more slowly than those with shorter wavelengths. For example, the pressure signals from long-wavelength tides, with lengths of some 1,000 kilometres and periods of 12 hours or so, reach the floor of even the deep ocean. But the signals from ocean swells 150 metres long and with a 10-second period have lost about 97% of their energy when they arrive at 100 metres depth. And wind-generated surface ripples (10 centimetres long, with a period of less than 1 second) lose 99.99% of their energy in just a few metres of water.

Nonetheless, as Farrell and Munk[2] show, these wind-generated, thumbnail-sized ripples on the ocean surface can produce pressure signals that pass through the water column to the sea floor with little attenuation. When two such waves travel in opposite directions on the ocean surface, for instance after a sudden shift in the wind direction, they can interact nonlinearly with each other. The result can be the generation of a third wave with half the period of the wind waves, but with a much longer wavelength (Fig. 1). Given that attenuation in the water column decreases with increasing wavelength, the pressure signal from the nonlinearly generated long wave can reach the sea floor with little decay.

Farrell and Munk[2] demonstrate that nonlinear interactions between short (order 1 centimetre wavelength), small (heights of order 1 centimetre) waves travelling in opposite directions on the ocean surface produce waves with long wavelengths of some hundreds of metres. These nonlinear waves create extremely rapid pressure fluctuations, with periods of less than a tenth of a second, that are detectable on the sea floor more than 5 kilometres below the surface. These deep-sea pressure fluctuations are probably common, because winds shift from one direction to another as storms cross the ocean surface.

To reach their conclusions, Farrell and Munk combined theoretical work with analysis of observations[3] made over the course of a year with a sea-floor hydrophone at 5.5 kilometres depth near Wake Island in the North Pacific Ocean. Not only do the authors demonstrate that the pressure effects of interacting surface ripples can reach this depth, but their mathematical models also show that the observations suggest a fundamental difference between gravity and capillary waves. Gravity waves are long waves that are caused by gravitational restoring forces when the water surface is displaced, for example by wind. In contrast, capillary waves are so short that the associated curvature of the water surface is restored by surface tensile forces. The fundamental difference between them, proposed by Farrell and Munk, is that their spectral shapes — that is, the amount of wave energy associated with each wave period or wave frequency, f — decay as f^{-7} (gravity waves) and f^{-3} (capillary waves). The ocean-bottom data suggest that a transition from gravity to capillary waves occurs at periods of about a third of a second.

It is remarkable that Farrell and Munk[2] were able to estimate the separation between gravity and capillary waves from measurements made more than 5 kilometres below the surface. Although high-frequency 'noise' has been observed in ocean-bottom seismometer records for many years, an explanation was lacking until Farrell and Munk combined nonlinear wave theory with careful analysis of a nearly 20-year-old data set.

Taking their work further will require other developments, however. Studies[4–6] using extensive arrays of pressure gauges have provided measures of the periods, wavelengths and directions of the 150-metre-wavelength surface swells that cause ocean-bottom microseisms. But that has not been done for short waves. It would be difficult to deploy a sufficiently extensive array of sensors to estimate the distribution of short-wave parameters over the oceanic surface area (estimated at two to three times the water depth[2]) that contributes to the pressure fluctuations on the sea floor. The array would have to be huge in overall extent yet have sensors spaced at the centimetre scale to detect the wavelengths of interest.

Direct verification of Farrell and Munk's hypothesis will thus require innovative observational techniques, perhaps using high-resolution remote sensing of the sea surface combined with bottom-mounted pressure sensors. Meanwhile, even as they stand, their results are remarkable: they explain a complex geophysical phenomenon and will prompt many further studies. ■

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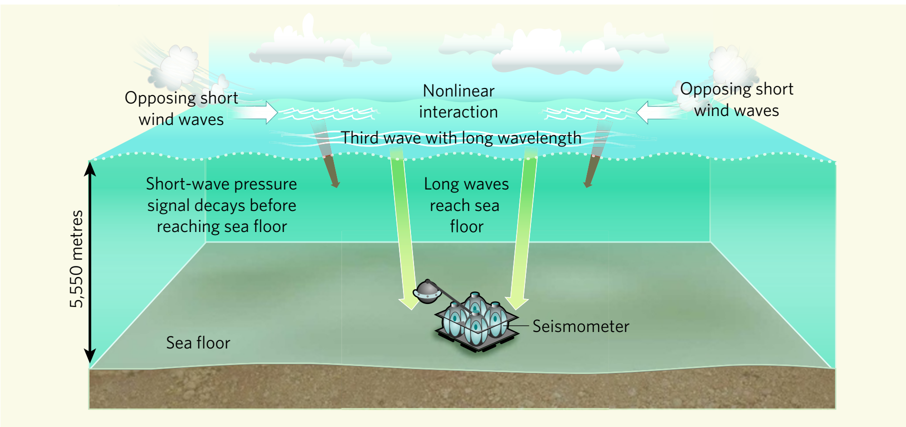

Figure 1 | Interaction of short-wavelength surface waves to create a long wave[2]. Wind-generated ripples travelling in opposite directions on the sea surface interact non-linearly with each other to generate waves with twice the period and much longer wavelengths. Unlike the pressure signal from the ripples, which decays rapidly with depth, the signal from the long-wavelength non-linear waves propagates to the sea floor with little attenuation, and is detected with ocean-bottom instruments.