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Acoustic-gravity wave transmission through air-water interfaces

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It is often assumed that the sharp contrast of material parameters at the air-sea interface makes transmission of acoustic-gravity waves (including sound and internal gravity waves) through the interface negligible. In particular, the air-water interface is usually modeled as a pressure-release surface in underwater acoustics and marine seismology. The interface is modeled as a rigid surface in analyses of Lamb waves in the atmosphere and internal gravity waves in the ocean. However, it has been found recently [O. A. Godin, Sound transmission through water-air interfaces: New insights into an old problem, Contemporary Physics, 49, 105–123 (2008)] that low-frequency acoustic fields in the ocean and atmosphere are much more closely connected than was previously believed possible. Under normal conditions, when a monopole, point underwater sound source with a fixed magnitude of the volume velocity oscillations approaches the air-water interface, the acoustic power flux into the air increases by a factor of about 40 compared to the power flux from the same source at depths of a wavelength or more. The transparency of the interface, which is defined as the ratio of the power transmitted to the interface to the total radiated power, increases by a factor of 3400 and closely approaches unity. Thus, contrary to the conventional wisdom based on ray-theoretical predictions and observations at higher frequencies, most of the acoustic energy emitted by a shallow, compact, underwater source is radiated into the air. In this paper, we study analytically a simplified model of the ocean and atmosphere and show that the very strong wave coupling across the water-air interface persists at low frequencies, where fluid compressibility and buoyancy simultaneously act as restoring forces and mechanical waves in fluids should be treated as acoustic-gravity waves (AGWs). The physics of the anomalous transparency for AGWs proves to be much richer than for sound. In addition to refraction of body waves at the interface, generation of surface waves plays a crucial role in the AGW transmission. For air-water interfaces, transmitted power can exceed the total power emitted by the same point source in unbounded water by an order of magnitude or more, depending on wave frequency. The relative significance of the body waves and surface waves varies with frequency and depends on the depth of the wave source. Particularly strong transmission of AGWs from a compact underwater source into air is predicted to occur in two narrow frequency bands around about 1 mHz (wave period $\sim$18 min) and 4 mHz (wave period $\sim$4 min). These "transparency windows" are related, respectively, to the proximity of two cut-off frequencies of an interface wave and to near-intersection and resulting hybridization of the Lamb and surface gravity waves.