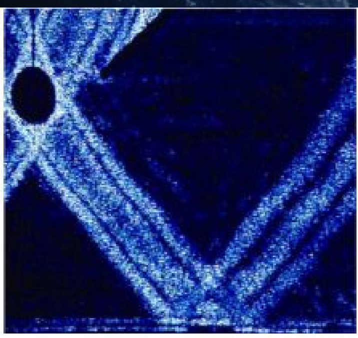
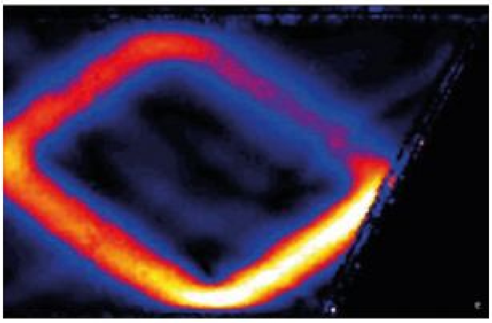
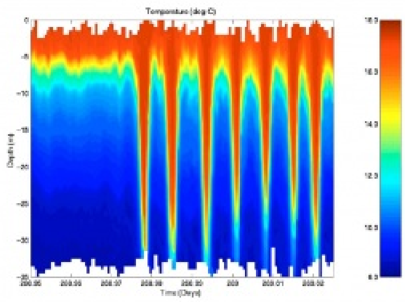
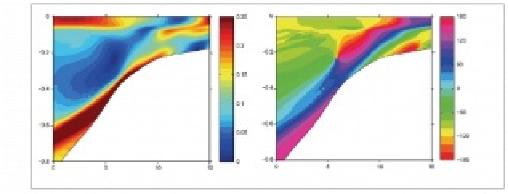
UNCHARTED REALITY?

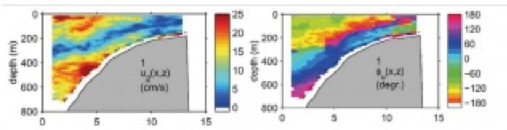
Mysterious Underwater Waves

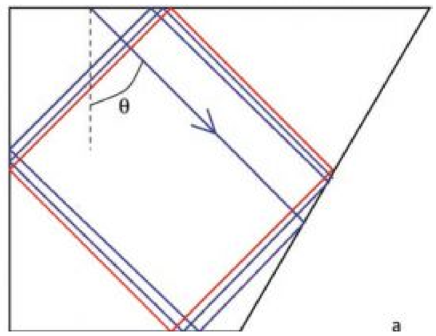












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In addition to surface waves generated by wind, tidal forces or, in case of tsunamis, seismic events, there exists a less well-known class of bigger waves under water. These underwater waves (internal waves) are generated by the same forces, but owe their existence to the ocean's non-uniform density distribution. This paper introduces various underwater waves that appear on interfaces or in continuous density stratification. In uniformly stratified seas, these waves differ from surface waves in nearly every conceivable aspect, creating underwater 'storms' at certain hotspots. These may possibly impact natural and man-made structures, and may transport heat and material vertically.

The ocean's salt and heat content, which determines its density, vary with depth. This stable stratification supports underwater waves. Due to slight differences in density, these waves easily displace fluid parcels vertically over hundreds of metres. Depending on the local rate with which density increases with depth, they propagate either horizontally or obliquely into the abyss. The former, interfacial waves, are partly visible at the surface, but the latter, abyssal waves, remain elusive. Theory and laboratory idealisations provide understanding, but observing their unusual properties at sea remains challenging owing to lack of proper instruments.

Internal Waves

Regular arrays of clouds in the sky are manifestations of waves in the atmosphere, visualised by condensation of water vapour in wave crests. They classify as internal waves as their maximum vertical displacements occur in the atmosphere's interior, away from its boundary. While ocean and atmosphere are dynamically quite similar, we never see such waves in the ocean though, because the ocean is opaque. Light penetrates a mere hundred metres, leaving the remainder of the ocean literally and figuratively in the dark. But oceanographic instruments 'visualise the invisible'. These show temperature and salinity, and hence density, to vary with increasing depth. Below the wind-mixed surface layer this change occurs abruptly, at the so-called thermocline, which supports horizontally propagating interfacial waves. Below the thermocline, density increases gradually, and an entirely different type of waves penetrates obliquely into the deep sea.

Interfacial Waves

Interfacial waves, propagating along a thermocline, are similar to surface waves. But, since the density contrast between underwater layers is much less than that between water and air, the acceleration of gravity that a displaced fluid parcel senses is reduced by approximately a factor thousand, the ratio of the cross-thermocline density difference to mean density. Therefore, interfacial waves attain larger amplitudes (up to hundreds of metres), have longer periods (longer than 10 minutes, say) and have wavelengths (up to kilometres) that are short compared to those of surface waves of identical period. Interfacial waves of tidal period (internal tides), for instance, are much shorter than the thousands of kilometres long surface tides.

Underwater interfacial tides steepen and form trains of solitary waves (see Figure 1, showing temperature as a function of time-depth). Strong accelerations in these solitons have likely caused reported submarine crashes. Because of the proximity of the interface to the surface, converging and diverging currents associated with solitary waves strain short surface wind waves, leaving an imprint at the surface that can be spotted from satellite or, as in Figure 2, airplane. Here, a front marks the transition between salty North Sea water on the left and fresh river Rhine water on the right that flows out on top of it. At the interface between the two, internal solitary waves are present. These are imaged at the surface while propagating towards the reader and quite distinct from the short familiar wind waves. Compare also to the tanker in the upper right of this photo.

Deep-sea Underwater Waves

Internal gravity waves propagating in the continuously-stratified deep sea may however go unnoticed. At present, there is no instrument that can give us a good spatio-temporal view of the internal wave field. We have to do with a collection of contact instruments, like thermistors, current meters, or with remotely-sensing instruments, such as the Acoustic Doppler Current Profiler (ADCP) shown in Figure 3, instruments that are either deployed or employed on a moving ship (Figure 4). The intensity and Doppler-shifted frequency of the ADCP’s back-reflected, previously transmitted sound can be used to determine density surfaces and to measure currents along the line of view. Figure 4 shows numerically computed (top) and observed (bottom) cross-topography velocity amplitude (cm/s, left) and phase (degrees, right) of the internal tide generated near the shelf edge in the Bay of Biscay as a function of cross-topography distance (km) and depth (m). Needless to say, that neither moored nor ship data yield a complete view of the (four-dimensional!) internal wave field. The sparse data leave voids, voids often filled with model results. For this reason internal waves are studied in conceptual theoretical, laboratory and more realistic numerical models, leaving the discovery of their spatio-temporal patterns in nature for future work.

Laboratory Experiments

A laboratory model of a uniformly-stratified ocean can be created by adding successively more salt to a fluid when filling a tank from the bottom upwards. Perturbations of this quiescent, undisturbed state are produced by oscillating a cylinder vertically (Figure 5). Using the fact that light refraction depends on fluid density, underwater waves change brightness and reveal their oblique propagation. The beam inclination relative to the direction of gravity, g, turns out to be uniquely determined by the ratio of the oscillation frequency to a frequency characterising the stratification rate. It produces four internal wave beams (one shown here) along which energy propagates obliquely up and downward and left and rightwards. Phase (crests and troughs) propagate perpendicular to these beams (white arrow) and sheared currents (red arrows) are parallel to the beams.

Since reflection of an underwater wave does not change its rate of incidence, neither will its inclination . Therefore, when this beam undergoes multiple side wall reflections (blue lines Figure 5) it focuses onto a periodic orbit, called an internal wave attractor (red line). Since the wave beam’s energy flux is preserved when the underwater waves reflect from sloping walls intense beams result. As in the laboratory experiment in Figure 6, in semi-enclosed seas this may lead to ‘hotspots’ where underwater wave energy piles up.

Conclusion

Because the ocean is three-dimensional, of complex shape, non-uniformly stratified, and ‘large’, it is currently impossible to predict whether and where ocean attractors exist. Internal waves might follow paths that are perhaps too long to overcome viscous and frictional damping. On the other hand, this decay might be counterbalanced by re-amplification due to intermediate reflections from sloping bottoms. Thus, generally speaking, we expect the appearance of localised regions where internal wave activity is large. These hotspots may be perceived as locations subject to underwater storms, which may prove hazardous to e.g. risers, submarines or exploitation platforms. The presence of localised regions of intense internal wave activity may also be keeping the oceans healthy as it may offer a fast track along which oxygen, plankton and nutrients may be transported from surface to bottom or vice versa. A widely-spaced array of conventional, seafloor-tethered ADCPs will still not provide the horizontal spatial resolution required to capture these hotspots. But, perhaps a new type of ADCP that ‘watches’ in all kind of directions will allow us to measure three-dimensional velocities within a spherical domain, enabling us to ‘see’ underwater waves (Figure 7).

More Information

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