

Walter Munk

9.1 Introduction

Gravity waves in the ocean's interior are as common as waves at the sea surface—perhaps even more so, for no one has ever reported an interior calm.

Typical scales for the internal waves are kilometers and hours. Amplitudes are remarkably large, of the order of 10 meters, and for that reason internal waves are not difficult to observe; in fact they are hard not to observe in any kind of systematic measurements conducted over the appropriate space-time scales. They show up also where they are not wanted: as short-period fluctuations in the vertical structure of temperature and salinity in intermittent hydrocasts.

I believe that Nansen (1902) was the first to report such fluctuations;¹ they were subsequently observed on major expeditions of the early nineteenth century: the *Michael Sars* expedition in 1910, the *Meteor* expeditions in 1927 and 1938, and the *Snellius* expedition in 1929–1930. [A comprehensive account is given in chapter 16 of Defant (1961a)]. In all of these observations the internal waves constitute an undersampled small-scale noise that is then “aliased” into the larger space-time scales that are the principal concern of classical oceanography.

From the very beginning, the fluctuations in the hydrocast profiles were properly attributed to internal waves. The earliest theory had preceded the observations by half a century. Stokes (1847) treated internal waves at the interface between a light fluid overlaying a heavy fluid, a somewhat minor extension of the theory of surface waves. The important extension to the case of a vertical mode structure in *continuously* stratified fluids goes back to Rayleigh (1883). But the discreteness in the vertical sampling by hydrocasts led to an interpretation in terms of just the few gravest modes, with the number of such modes increasing with the number of sample depths (giving j equations in j unknowns). And the discreteness in sampling time led to an interpretation in terms of just a few discrete frequencies, with emphasis on tidal frequencies.

The development of the bathythermograph in 1940 made it possible to repeat soundings at close intervals. Ufford (1947) employed three vessels from which bathythermograph lowerings were made at 2-minute intervals! In 1954, Stommel commenced three years of temperature observations offshore from Castle Harbor, Bermuda, initially at half-hour intervals, later at 5-minute intervals.² Starting in 1959, time series of isotherm depths were obtained at the Navy Electronics Laboratory (NEL) oceanographic tower off Mission Beach, California, using isotherm followers (Lafond, 1961) installed in a 200-m triangle (Cox, 1962).

By this time oceanographers had become familiar with the concepts of continuous spectra (long before

routinely applied in the fields of optics and acoustics), and the spectral representation of surface waves had proven very useful. It became clear that internal waves, too, occupy a frequency continuum, over some six octaves extending from inertial to buoyant frequencies. [The high-frequency cutoff had been made explicit by Groen (1948).] With regard to the vertical modes, there is sufficient energy in the higher modes that for many purposes the discrete modal structure can be replaced by an equivalent three-dimensional continuum.

We have already referred to the measurements by Ufford and by Lafond at horizontally separated points. Simultaneous current measurements at vertically separated points go back to 1930 (Ekman and Helland-Hansen, 1931). In all these papers there is an expression of dismay concerning the lack of resemblance between measurements at such small spatial separations of oscillations with such long periods. I believe (from discussions with Ekman in 1949) that this lack of coherence was the reason why Ekman postponed for 23 years (until one year before his death) the publication of "Results of a Cruise on Board the 'Armauer Hansen' in 1930 under the Leadership of Björn Helland-Hansen" (Ekman, 1953). But the decorrelation distance is just the reciprocal of the bandwidth; waves separated in wavenumber by more than Δk interfere destructively at separations exceeding $(\Delta k)^{-1}$. The small observed coherences are simply an indication of a large bandwidth.

The search for an analytic spectral model to describe the internal current and temperature fluctuations goes back over many years, prompted by the remarkable success of Phillips's (1958) saturation spectrum for surface waves. I shall mention only the work of Murphy and Lord (1965), who mounted temperature sensors in an unmanned submarine at great depth. They found some evidence for a spectrum depending on scalar wavenumber as $k^{-3/3}$, which they interpreted as the inertial subrange of homogeneous, isotropic turbulence. But the inertial subrange is probably not applicable (except perhaps at very small scales), and the fluctuations are certainly not homogeneous and not isotropic.

Briscoe (1975a) has written a very readable account of developments in the early 1970s. The interpretation of multipoint coherences in terms of bandwidth was the key for a model spectrum proposed by Garrett and Munk (1972b). The synthesis was purely empirical, apart from being guided by dimensional considerations and by not violating gross requirements for the finiteness of certain fundamental physical properties. Subsequently, the model served as a convenient "straw-man" for a wide variety of moored, towed and "dropped" experiments, and had to be promptly modified [Garrett and Munk (1975), which became known

as GM75 in the spirit of planned obsolescence]. There have been further modifications [see a review paper by Garrett and Munk (1979)]; the most recent version is summarized at the end of this chapter.

The best modern accounts on internal waves are by O. M. Phillips (1966b), Phillips (1977a), and Turner (1973a). Present views of the time and space scales of internal waves are based largely on densely sampled moored, towed, and dropped measurements. The pioneering work with moorings was done at site D in the western North Atlantic (Fofonoff, 1969; Webster, 1968). Horizontal tows of suspended thermistor chains (Lafond, 1963; Charnock, 1965) were followed by towed and self-propelled isotherm-following "fishes" (Katz, 1973; McKean and Ewart, 1974). Techniques for dropped measurements were developed along a number of lines: rapidly repeated soundings from the stable platform FLIP by Pinkel (1975), vertical profiling of currents from free-fall instruments by Sanford (1975) and Sanford, Drever, and Dunlap (1978), and vertical profiling of temperature from a self-contained yo-yoing capsule by Cairns and Williams (1976). The three-dimensional IWEX (internal wave experiment) array is the most ambitious to date (Briscoe, 1975b). These experiments have served to determine selected parameters of model spectra, none of them so far, not even IWEX, has been sufficiently complete for a straightforward and unambiguous transform into the multi-dimensional (ω, \mathbf{k}) -spectrum. The FLIP measurements come closest, giving an objective spectrum in the two dimensions ω, k_x , with fragmentary information on k_y, k_z . Otherwise only one-dimensional spectra can be evaluated from any single experiment, and one is back to model testing. Yet in spite of these observational shortcomings, there is now evidence for some degree of universality of internal wave spectra, suggesting that these spectra may be shaped by a saturation process (the interior equivalent of whitecaps), rather than by external generation processes.

Internal waves have surface manifestations consisting of alternate bands of roughened and smooth water (Ewing, 1950; Hughes, 1978), and these appear to be visible from satellites (figure 9.1). High-frequency sonar beams are a powerful tool for measuring internal wave related processes in the upper oceans (figures 9.2, 9.3). The probing of the deep ocean interior by acoustics is ultimately limited by scintillations due to internal waves (Flatté et al., 1979; Munk and Wunsch, 1979) just as the "diffraction-limited" telescope has its dimensions set by the small-scale variability in the upper atmosphere.

It will be seen that internal waves are a lively subject. The key is to find the connections between internal waves and other ocean processes. The discovery of ever finer scales, down to the scale of molecular processes,

