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Historical Perspectives

Walter Munk

(born 1917)

Walter H. Munk, Ph.D., is an American physical oceanographer whose pioneering studies of ocean currents and wave propagation have made significant contributions to geophysics. He has participated in almost all of the significant scientific events and debates related to the oceans and climate in the United States during his lifetime.

Walter Munk was born in Vienna, Austria, and sent by his family to New York in 1932 to be educated as a banker. When banking bored him, he drove to Pasadena, California, and enrolled at the California Institute of Technology where he earned B.S. and M.S. degrees in Physics. In 1939, he met the Norwegian oceanographer Harald U. Sverdrup at the Scripps Institution of Oceanography in La Jolla, California. Sverdrup became his mentor, champion, and scientific model. Munk completed his Ph.D. in Oceanography in 1947.

When his family fled Austria in 1938, Munk enlisted in the U.S. Army ski troops. With his training completed but no war in sight, Sverdrup recalled him to Scripps for work on amphibious warfare and sonar research. Munk and Sverdrup trained military oceanographers and developed rough but effective methods of predicting sea and surf conditions employed for Normandy (D-Day) and other Allied landings. This work was credited for saving many lives and cemented a close and lasting relationship between Munk and the U.S. Navy. In 1946, Munk was on the *U.S.S. Bowditch* studying water circulation at Bikini Atoll in connection with the postwar American atomic tests in the Pacific. This was the first of his many oceanographic expeditions throughout the world. While on a fellowship to the University of Oslo (1949) and later on sabbaticals at Cambridge University, Munk expanded his acquaintance among scientists and his research interests in geophysics to include the study of the Earth's rotation.

Roger Revelle, Munk's friend and a founder of the University of California, San Diego (UCSD), encouraged Munk's broad research in geophysics and supported his effort to create an institute, the Cecil H. and Ida M. Green Institute of Geophysics and Planetary Physics (IGPP), at La Jolla. Munk directed the institute until 1982 and has worked closely with scientists there to study tides, ocean dynamics, waves, ocean currents, and geophysical processes of every kind. In 1957, seeking to invigorate public interest and support for oceanography, Munk and Harry Hess suggested the idea behind Project Mohole: to drill to the Mohorovicic Discontinuity (i.e., the boundary between the crust and the mantle) from a drilling platform at sea. This is expressive of Munk's style, setting groundbreaking and risky research goals that require the development of

Walter Munk in Amsterdam at the international meeting of the Effects of Sound in the Ocean on Marine Mammals, September 2014 (ESOMM-2014) (Photos by Wouter Coomans, StudioBiB) innovative technology and, when successful, test theory and yield new scientific knowledge. Munk and IGPP developed new techniques and applied technologies from other sciences to geophysics. In 1975, Munk and Carl Wunsch (MIT) used acoustic tomography to study the movements of water in the oceans culminating in the 1991 Heard Island Experiment and the subsequent Acoustic Thermometry of Ocean Climate (ATOC) project, which used sound to measure ocean temperature around the world. Both Mohole and ATOC engendered significant public controversy but also created lasting international scientific collaborations focused on important scientific goals.

Munk's publications include *The Rotation of the Earth: A Geophysical Discussion* (1960) with G. J. F. MacDonald; *Ocean Acoustic Tomography* (1995) with Carl Wunsch and Peter Worcester; and *Sound Transmission Through a Fluctuating Ocean* (1979). A full list of all of Walter Munk's publications can be found in Appendix B of the book by Von Storch & Hasselmann (2010). Since 1985, Munk has held the Secretary of the Navy Chair in Oceanography at Scripps Institution of Oceanography, UCSD.

Acoustic Monitoring of Global Ocean Warming: The Very First Encounters with Concern About Marine Mammals and Sound

A Brief Personal Historical Narrative

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Ocean acoustics started with the discovery of the SOFAR (SOund Fixing And Ranging) channel in 1944. It had long been known that sound speed increases with temperature and with pressure. The (almost) trivial consequence is that there must be a minimum at about 1 km depth, with sound velocity increasing upwards with increasing temperature and increasing downwards (into a nearly isothermal ocean) with increasing pressure (see Figure 2.3, lower panels, in Munk et al., 1995, p. 37). It has also been long known that any minimum in phase velocity (light, sound, surface waves) is associated with a wave guide (see Figure 1.1, lower right panel, in Munk et al., 1995, p. 5). In 1944, Maurice Ewing and J. Lamar Worzel (1948) departed Woods Hole aboard the *R/V Saluda* to test the wave guide theory. They hung a deep-water hydrophone and had a second ship drop 2-kg charges at distances up to 900 nautical miles. They heard, for the first time the characteristic signature of the SOFAR channel: "the end . . . was so sharp that it was impossible for the most unskilled observer to miss it" (p. 4). They spoke, even then, of transmissions over 10,000 nautical miles. (See Figure A.1 in Munk et al., 1995, p. 356. This figure is also represented on the DOSITS website: www.dosits.org/science/soundmovement/sofar/sofarhistory.)

Two years later, Leonid Brekhovskikh (see boxed text) was conducting experiments in the Sea of Japan, but his equipment was not working. Rather than lose ship time, he decided to make some spontaneous measurements of sound transmission: "something very strange was observed" (Brekhovskikh, pers. comm., 1989). Maurice Ewing and Brekhovskikh did not learn of each other's work until some years later because of the communications barrier between American and Russian scientists imposed by the Cold War.

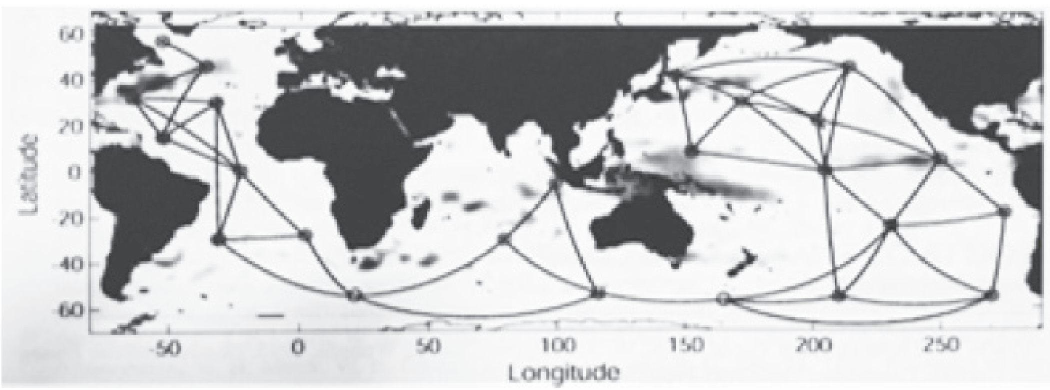
> ***Leonid Brekhovskikh*** (1917-2005)
> The great acoustician and member of the USSR Academy of Sciences was at Lebedev Physical Institute (FIAN) in 1946 at the time of his work in the Sea of Japan, but he was at Moscow State University from 1953 through 1966 when Dr. Munk got to know him, and when he ended his career at the Shirshov Institute of Oceanology.

The next chapter on long-range ocean acoustics was an almost casual add-on to a 1960 geophysical survey off Perth, Australia, by John Ewing when he received a message from his brother Maurice in Bermuda ("looks like I ought to be able to hear you"). Three 300-pound amatol charges were detonated near the sound axis off Perth at five-minute intervals and clearly recorded two hours later by axial hydrophones off Bermuda—nearly halfway around the Earth (see Figure 8.4 in Munk et al., 1995, p. 330). It has been estimated that global ocean warming since 1960 would reduce travel time by something like 10 seconds; Brian Dushaw (APL, University of Washington) has proposed a repeat transmission to confirm this estimate (Dushaw & Menemenlis, 2014).

It came as a great shock in the 1960s that the oceans, like the atmosphere, have an active weather at all depths. This is sometimes referred to as the *mesoscale revolution*. Storms are called *eddies*; typical dimensions are 100 km and 100 days, and typical water velocities are up to a few meters per second. These eddies contain 99% of the oceans' kinetic energy. For 100 years, oceanographers had sampled the ocean with a few ships chasing independently along great circle routes at 10 knots (10 nautical miles per hour, approximately equal to 5 m/s; not much faster than the eddy phase velocity). Water samples of different depths as collected by Nansen bottles at selected stations ("never occupy a station twice") permitted the calculation of dynamic heights and geostrophic currents, which were published on permanent charts (see Sverdrup et al., 1942, p. 353; Figure 87 shows three very nice pictures of the Nansen reversing water bottle: up, halfway reversed, and fully reversed, respectfully, from left to right). These resulting charts are comparable to weather maps in which water currents ("winds") could be derived from the dynamic height ("pressure field"). The mentioned geostrophic currents are linked to the equilibrium of pressure difference and Earth rotation forces, which define wind intensity and direction from the isobars.

The discovery of the intense mesoscale ocean variability called for a new sampling strategy. The interior ocean is opaque to electromagnetic radiation yet transparent to sound. Carl Wunsch and I came up with ocean acoustic tomography to infer from precise measurements of travel time, or other properties of acoustic propagation, the state of the ocean traversed by the sound field (see Appendix 2 in Munk et al., 1995, for a full historic overview of ocean acoustic tomography). The speed of sound under water is typically 1,500 m/s (approximately 3,000 knots) and happily exceeds that of oceanographic vessels. It increases with temperature by 5 m/s per degree Celsius. Ray travel time A- > B is an accurate measure of the mean temperature along the ray from A to B. The difference A- > B minus B- > A is a measure of current velocity. In 1978, in the North Atlantic, we started with a 900-km range (my first experience in ocean acoustics after 35 years of physical oceanography) and gradually increased the range to 19,000 km (antipodal) in the 1991 Heard Island experiment. For this experiment (see Figures 1 & 2 from Munk et al., 1994, pp. 2331, 2333), the U.S. National Marine Fisheries Service (NMFS) requested a two-vessel operation: one for the sound source and the other for monitoring nearby marine life. The experiment was successful. We were able to record the antipodal signal, and there was no evidence of distress on nearby mammals (Bowles et al., 1994; Munk & Baggeroer, 1994; Munk et al., 1994). With the experiments in 1973 by Clark & Kronengold (1974), it was already demonstrated that explosions could be replaced by powerful transducers. For the Heard Island

(a)



(b)

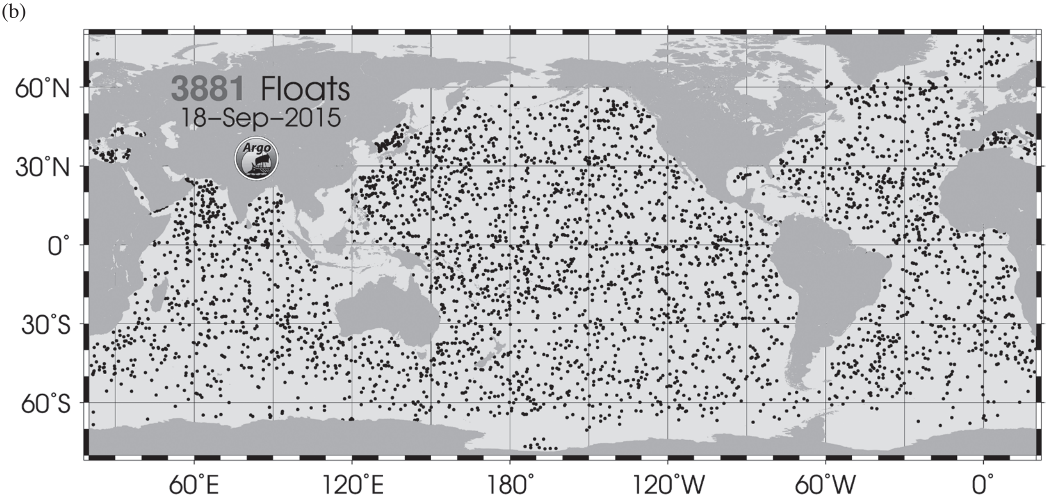


Figure 1. (a) Example of a global acoustic array, and (b) recent overview of ARGO floats in the ocean (Sketch by W. Munk for [a] and weblink: www.argo.ucsd.edu for [b])

Note that an error in this article was corrected (also on the front page of the *Los Angeles Times*) on 3 May 1994. See Section 8.5 of Von Storch & Hasselmann (2010). There are more examples of confusion with terminology, especially for the use of dB scale (e.g., Chapman & Ellis, 1998). Confusion of the dB scale is a typical example that demonstrates the need for proper terminology for scientific language.

experiment, powerful transducers were also used (see Figures 1 & 2 from Munk et al., 1994, pp. 2331, 2333), transmitting coded signals.

The Heard Island Experiment had been widely publicized under the unfortunate slogan: "The Shot that was heard around the World." It caught the attention of the *Los Angeles Times* (Paddock, 1994; see boxed text) with a headline on 22 March 1994 that it could lead to the death of 250,000 California gray whales. This was based on the fact that 195 dB is associated with 250 million Watts in air (250 Watts in water).

There is an urgent need (e.g., see Blunden & Arndt, 2015; National Oceanic and Atmospheric Administration [NOAA], 2015, for recent reports) for monitoring the climate-induced warming of the global oceans, especially the deep oceans. (See Figure 1a for a suggested set-up.) Here, the integrating property of acoustic tomography over global ranges is a unique asset. The concern of damage to the marine environment has greatly limited the use of acoustics to measure ocean warming. In contrast, measuring global temperature with the deployment of thousands of ARGO floats (see Figure 1b) has been a great success story. The floats pose no danger to marine life, and they are associated with a small start-up cost. The best solution is a combination of the two methods.

How do we design a global acoustic array that meets two conflicting requirements—acoustic frequencies and intensities—that are (1) clearly recorded at 10,000-km ranges and (2) not damaging to populations of marine mammals in the source area? This problem will be left as an exercise for the reader. But it is inconceivable that oceanographers (like other marine mammals) should not take advantage of the fact that the oceans are transparent to sound.

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ESOMM-2014 International Meeting Organizing Team

Organizing team surrounding Walter and Mary Munk at the start of the ESOMM-2014 International Meeting, 7 to 12 September, at the Naval Barracks in Amsterdam. *From left to right:* Marije Siemensma, Sacha van Zanen, René Dekeling, Walter Munk, Mary Munk, Frans-Peter Lam, Mathieu Colin, and Kristianne Dreteler. (Photo: Wouter Coomans, StudioBiB)

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