# Always count on the oceans

*The great adventure of exploring the world's oceans took place largely in the latter half of the 20th century, when new technology and novel methods of remote analysis had become invaluable tools for oceanographers. This year's Crafoord Prize Laureate,* ***Walter Munk****, is a person who, in his work of explaining ocean circulation, tides and waves, and their role in our planet's dynamics, moved in the absolute forefront of science throughout this period.*

Incessantly curious and remarkably observant, Walter Munk developed innovative syntheses, used new techniques and devised novel methods of analysis and observation. In so doing, he has made a revolutionary contribution to, and inspired, the development of physical oceanography and also of geosciences as a whole. In particular, Munk's recognition of the importance of tides, at various scales, is central to his scientific achievement.

## Surface waves, tides and currents

Even as a young oceanographer, Walter Munk showed his capacity for innovation. During the Second World War, in cooperation with Harald Sverdrup, he devised a new method of forecasting wave conditions on a given stretch of coast at a given time. This method, which took *ocean waves*, *swells* and *surf* into account, was immediately put to use. It served, for example, as the basis for timing the Allied landings in North Africa and was taken into consideration in the Normandy landing as well.

Two decades later, jointly with David Cartwright, Munk devised the radically new 'response method' of predicting *tides*. This was based on calculation of the response function between the observed and the theoretical potential tide in a location. The response method requires only short data series ('gauge records'), and it indirectly involves both local and regional depth conditions and local downward and upward pressures on the Earth's crust due to tidal load.

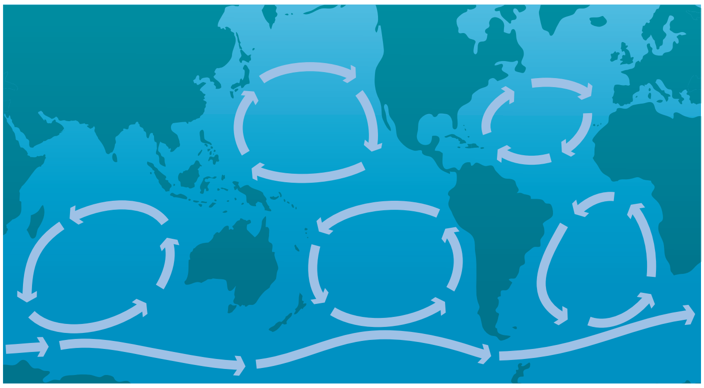
Photo: Michael Dawes

**World-class surfing.** Along the Californian coast and in Hawaii, for example, high waves commonly arise when long swells, after travelling thousands of kilometres from the storm areas where they form, reach the shore.

Walter Munk has also made valuable contributions to knowledge of *swells*. By measuring pressure on the ocean floor, researchers in the 1940s and '50s discovered dispersive waves that must have originated from distant sources. But where did they come from, and how could they move so far? Munk worked on this question in the 1950s with Frank Snodgrass and was able, using field observations and calculations, to describe the characteristics of swells and demonstrated, for example, how storms west of New Zealand actually affect surf conditions in Southern California.

Early on, Munk took the step from waves to global current systems. By building on and developing previous research on wind-driven ocean circulation he was able, in 1950, to present a model of the oceans' wind-driven circulation in which friction was seen as caused by horizontal eddies. The model thus took into account lateral friction (against the edges of ocean basins and within water masses themselves, caused when water currents of different velocities meet), rather than friction against the ocean floor.

Another enigma that Munk undertook to solve was the Antarctic Circumpolar Current, which surrounds the continent of Antarctica like a broad band and is driven by westerly winds. Scientists had long been baffled by the fact that this current was slower than it theoretically should be. Bottom friction was considered but not regarded as a sufficient cause. In 1951, in cooperation with Erik Palmén, Munk proposed a solution: ridges on the ocean floor can exert 'form resistance', which may balance the force of the wind on the surface.



**The five main** 'ocean gyres' – the wind-driven current systems of the North and South Atlantic, North and South Pacific and South Indian Ocean – work similarly. In the Northern Hemisphere, they circulate in a clockwise direction, while in the Southern Hemisphere the circulation is anticlockwise. To the west, the giant rotating eddies are made up of rapid, narrow currents towards the Poles; to the east, broad, slow currents flow towards the Equator. The Antarctic Circumpolar Current encircles the continent of Antarctica.

## Waves beneath the surface

Much of what happens in the oceans is hidden from the human eye. But although they are not always visible on the surface, waves also form at the boundaries between water masses of differing density. These are known as 'internal waves'.

In the 1970s, jointly with Chris Garrett, Walter Munk explored the ways in which internal waves arise, and they devised an empirical model to show how energy is distributed in an 'internal wave spectrum' in the ocean. Their description of this spectrum remains the standard one, and is referred to as *the Garrett–Munk internal wave spectrum*. Munk had paved the way for this understanding of the internal wave spectrum in his research over several decades. Internal waves are vital to an understanding of ocean dynamics since energy in internal waves is converted, through varying degrees of instability, into turbulence, which in turn is crucial for the mixing of different water masses in the ocean's interior.

In cooperation with Ernest Anderson, for example, Munk described back in 1948 how vertical density stratification affects the turbulent exchange; and one of the formulae he then presented has featured in many models of ocean circulation ever since. In a 1966 article entitled *Abyssal*

### A GENERAL DESCRIPTION OF WAVE MOVEMENTS

*A local disturbance in a medium propagates as a wave movement. Examples of wave movements are sound waves, waves in a fluid and electromagnetic waves.*

**Ocean waves** are wind-generated wave movements on the ocean surface. These waves arise because of unstable feedback between the shape of the ocean surface and the movements of air. In brief, wave height may be said to depend on wind strength, duration and fetch length, i.e. the distance over which the wind blows.

**Swells** are ocean waves, often of a long wavelength, that appear outside the area in which they are generated by the wind. They move at a relatively high velocity and can propagate thousands of kilometres from the storm areas where they form.

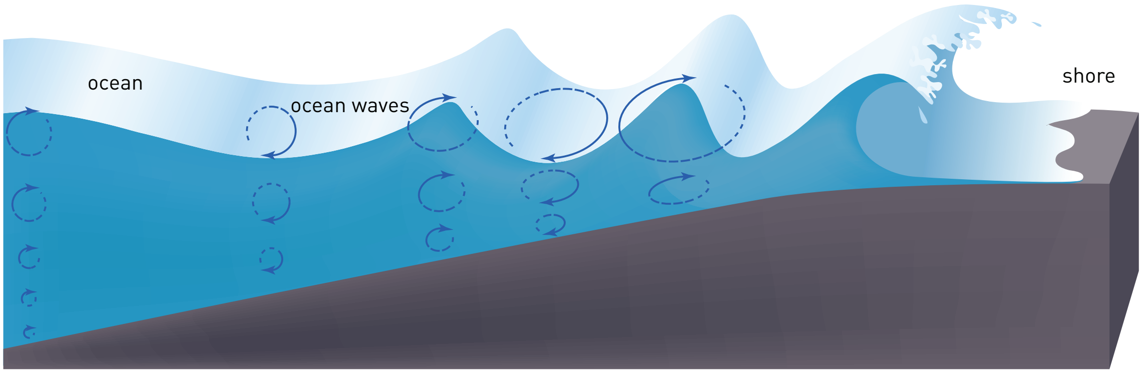
The longest ocean waves are the **tidal waves**, which are generated by the gravitational influences of the Moon and Sun. The strength of the tide depends on the relative positions of the Earth, Moon and Sun.

**→ Arithmetical example 1.**
Tidal-wave velocity, v, is determined solely by water depth, d, as described in the following equation:
$v=\sqrt{g \cdot d}$
where g is the gravitational constant, 9.81 $m/s^2$.

The average depth of the oceans is some 4,000 metres. A tidal wave out at sea then moves at a velocity of approximately 200 metres a second or 720 kilometres an hour.

**→ Arithmetical example 2.**
The velocity of shorter waves is expressed in the following equation:
$v=g \cdot T/(2\pi)$
where T is the period (the time it takes for a wavelength to pass a specific point).

A long swell out at sea may have a period of 10 seconds, giving a wave velocity of 16 metres a second or 58 kilometres an hour.




The illustration shows ocean waves moving towards the shore. In deep water these waves, which are generated by the wind, are unaffected by the ocean floor. Particles in the water move in circles: the water in the wave crests is carried forward in the direction of wave propagation, while that in the troughs is dragged back in the opposite direction. The wavelength is the distance between two successive points in the same state of motion. In shallower water, proximity to the sea bed inhibits vertical movements, making particles in the water move in elliptical instead of circular paths. As ocean waves approach the shore and the depth diminishes, the velocity of wave propagation decreases. A reduction in wavelength results, wave height increases instead and the waves break.

*Recipes*, Munk also provided a general principle of deep water ventilation by the downward mixing of lighter surface water. He estimated a typical coefficient of this vertical turbulent mixing as 1 $cm^2/s$ – and this figure has since come to be regarded as the canonical value for the vertical mixing rate of the deep water of the oceans.

Munk also discussed the provenance of the energy in the turbulence, and concluded that the tide was a potential candidate. However, at the time he was unable to demonstrate which mechanisms might be at work. Only in his latter years have mechanisms for the transfer of energy in waves ('internal tides') been described and verified, notably through studies of the tides in threshold fjords. It is now entirely clear that the tide governs mixing in many fjords, and presumably in the deep sea as well.

**INTERNAL WAVES**

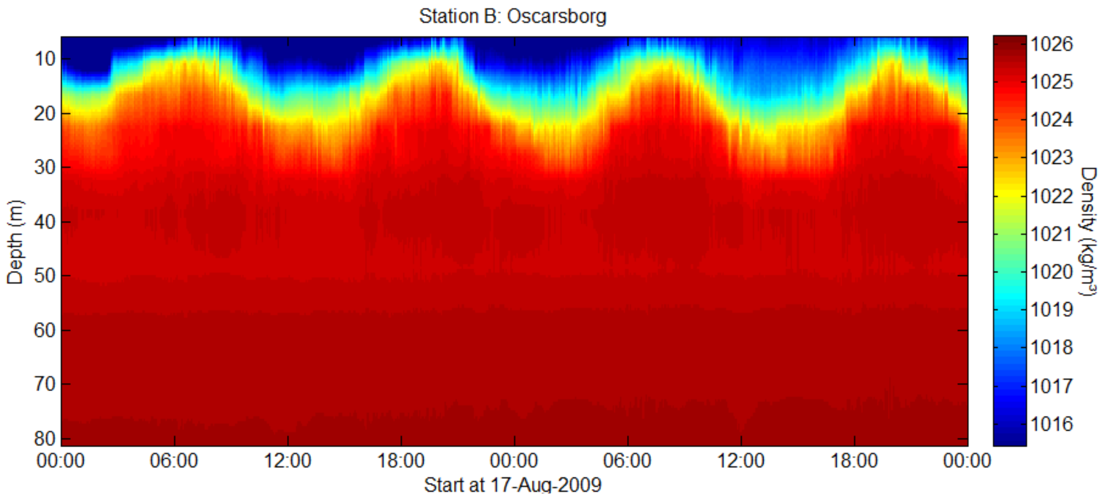
Beneath the ocean surface, 'internal waves' form at the boundaries between water masses of different density. An internal wave arises when the state of equilibrium of a density layer is disturbed. Internal waves, which are not usually visible to the human eye since they appear below the water surface, have a major bearing on ocean dynamics by contributing energy to turbulence, and thereby to mixing.

*The Garrett–Munk internal wave spectrum* is an empirical description of how the energy in oceanic internal waves is distributed as a function of frequency. The minimum frequency of internal waves is the 'inertial frequency', f, which is a consequence of the Earth's rotation. At this frequency, the movement of the internal wave has degenerated into purely horizontal, inertial circulation.

The maximum potential frequency of internal waves is the *Brunt-Väisälä frequency*, N, which is entirely determined by the strength of the vertical layering. At this frequency, all movement takes place vertically. For frequencies between f and N, particles move both horizontally and vertically as a result of internal waves.

Internal waves can be generated by time-dependent currents, such as tidal currents, over a sloping bottom, across a threshold in a narrow sound or across an underwater ridge in the open sea. Internal waves move very slowly compared with the waves on the ocean surface but their amplitude, on the other hand, may be great. In the Strait of Gibraltar, internal waves of up to 100 metres in height occur. The currents associated with internal waves may give rise to large-scale patterns that, in favourable weather conditions, are observable on the ocean surface.

Breaking internal waves contribute to vertical mixing in the interior of the ocean. This has a major impact on the vertical transport of water masses upward from the deep. The more energy that is converted from the tide and other movements into internal waves, the greater the mixing that takes place. This has been possible to demonstrate in fjords, where estimating the scale of energy flux from the tide to the internal tide is relatively easy.

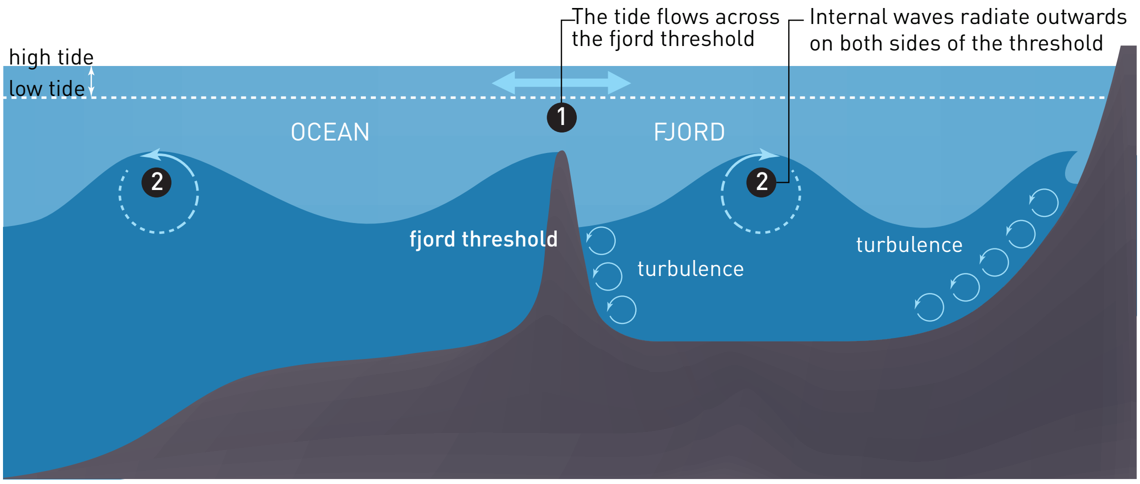



The illustration shows density in a vertical profile in Oslo Fjord, where the internal waves that form at the threshold, at Drøbak, generated by semidiurnal tides (two periods daily), propagate inwards into the fjord. Salinity and temperature, which together determine density, were measured every five minutes by means of instruments anchored on a vertical line between the surface and the bottom. Wave height is up to ten metres, which is 30 times higher than the difference in water level between high and low tide. *Source: Anders Stigebrandt, Department of Earth Sciences, University of Gothenburg, Sweden.*

Although, step by step over the years, oceanographers have revealed several of the hidden characteristics of oceans, much marine exploration remains to be done. Present-day global models of ocean circulation are still, for example, too sketchy to include internal waves. But as their resolution is raised, models of ocean dynamics will improve by taking into account the mixing caused by internal waves.

## The vulnerable Earth

Walter Munk has made extremely valuable contributions not only to oceanography, but also to our understanding of the Earth's entire dynamics. In the 1950s, Munk studied irregularities in its rotation. His evaluation included the movement of the poles, which has a 14-month period and causes small pole tides – the only kind of tide that is not connected with the gravitational forces of the Moon and Sun.




1. When the tide flows in and out over a fjord threshold, internal waves (the internal tide) are generated in density layers in adjacent basins.

2. The internal waves radiate outwards from the threshold. When the internal waves break, their energy is converted into turbulence, which mixes the water.

The energy loss of the tide at the threshold results in reduced amplitude and a phase shift of the tide (the surface wave) inside the fjord; but this is not depicted in the illustration. This fjord example may also be seen as a model of how internal waves are generated across ridges on deep-sea bottoms.

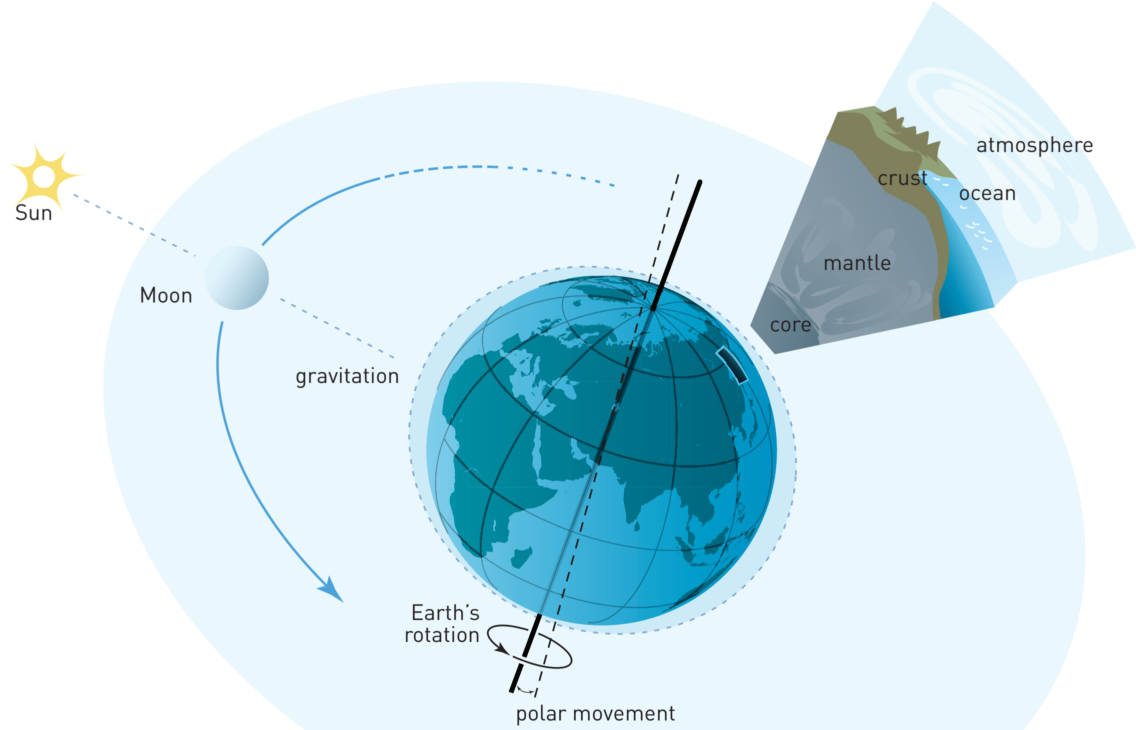
In their book *The Rotation of the Earth: A Geophysical Discussion* (1960), Munk and Gordon MacDonald then adopted a comprehensive approach, by dealing with polar movement and variations in the Earth's rotation speed in geophysical terms.

This geophysical approach proved to be a key. The research community had long been able, through calculations and measurements alike (meticulous determination of latitudes and times), to demonstrate that irregularities existed. But they had been unable to provide an entirely satisfactory explanation of why this was so.

Munk and MacDonald present arguments in their book about how irregularities in shorter timescales depend on winds, air masses, sea levels, underground water, movements in the interior of the Earth, and tides in the ocean and their counterparts in the solid Earth ('bodily tides') and the atmosphere. They also discuss the Earth's rotation in a historical and geological perspective.

The authors find that, over a century or more, tidal friction is the force that affects the Earth's rotation most. This is because, as a result of this friction, a gradual deceleration of the Earth's rotation speed takes place. The gradual lengthening of the day that this causes is included nowadays in the calculation of Coordinated Universal Time (UTC), with the addition of an extra 'leap second' in certain years. Looking back on the geological timescale, we see that the length of a day at the time when life on Earth began – at the beginning of the Palaeozoic era, more than 500 million years ago – was an estimated 21 hours.

Owing to the deceleration of the Earth's rotation, the Sun and Moon are also moving away from the Earth. The increase in our distance from the Sun is virtually negligible compared with that from the Moon. The annual increase in the Earth–Moon distance is about four centimetres.




Munk and MacDonald discussed the irregularities in the rotation of the Earth. They studied how polar movements and changes in the Earth's rotation speed depend on winds, air masses, sea levels, underground water and movements in the Earth's interior, along with ocean tides and their counterparts in the solid Earth (bodily tides) and the atmosphere.

## New ways of measuring

In the 1970s, Walter Munk began studying the acoustic properties of the oceans. He developed *acoustic tomography*, a method of remote analysis based on how low-frequency sound propagates in the ocean, with reference to temperature and currents. By measuring the time it takes for sound to travel between acoustic transmitters and receivers, for example, the mean temperature between the instruments can be determined with high accuracy, and current velocities are also measurable. Using acoustic tomography, both the Pacific and the North Atlantic have been investigated. In the early 1990s, a global experiment was conducted under the direction of Munk and Andrew Forbes, with an acoustic transmitter sited in the southern Indian Ocean and receivers placed on board 12 ships deployed around the five oceans. This acoustic measurement could serve as a point of reference for global ocean warming, but the experiment has not been repeated to date.


Photo: Ian Britton, FreeFoto.com

Sun glitter tells us much about wave properties.

Another area in which Munk has been a pioneer is in how to obtain information on wave properties by measuring solar reflection from the ocean surface. Munk first wrote articles on this subject jointly with Charles Cox in 1954. These articles described how to use photographs of solar reflection (glints or 'glitter points') on the ocean surface to calculate its roughness, i.e. the probability distribution of the surface slope. If the ocean surface was completely horizontal, there would be a single glint only: an image of the sun. With just a light breeze, the sunlight splits into patterns composed of glints by the thousand. Each glint represents a facet at the correct angle for reflecting the sun in a camera lens. The outer edges of each glitter pattern contain the steepest slopes, and the slopes increase with rising wind velocity.

Half a century later, Munk returned to solar reflection from the ocean surface. In 2008, he examined statistical data from eight million worldwide satellite images of sun glitter, which resulted in the article *An Inconvenient Sea-Truth: Spread, Steepness and Skewness of Surface Slopes*. This research field is judged to have great future potential for the evaluation of wave structures, for which oceanographers have lacked measurement parameters to date.

## Plankton too

Walter Munk has the ability to perceive the Earth's dynamics holistically. He also sees contexts and nuances that few others detect, and readily undertakes interdisciplinary work to tackle problems from new angles. One example was Munk's discussion, in a 1952 publication coauthored with the biologist Gordon Arthur Riley, of the bearing of physics on the availability of nutrients to phytoplankton. Munk and Riley estimated nutrient uptake by the plankton as a function of their shape, size and sinking speed, but also of nutrient concentration in the water and other factors. (Nutrient uptake occurs through a physical, 'diffusive' process. If the water is stagnant around plankton, they empty it of nutrients. To sustain a high concentration of nutrients in their surroundings, phytoplankton can sink or rise.) This work in biological oceanography was 'ahead of its time', but in recent years it has been cited fairly often in ecological modelling. This shows how Munk's great scientific breadth has been influential not only within, but also beyond the scope of physical oceanography and geophysical hydromechanics.

## LAUREATE

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***Scripps***: *http://sio.ucsd.edu/Profile/wmunk*
***IGPP***: *www.igpp.ucsd.edu/people/detail.php?name=Munk_Walter*

Walter Munk. Born in 1917 in Vienna, Austria. PhD in oceanography in 1947 and full Professor in 1954, both at Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA, USA. Cofounder (in 1959) and director (1959–82) of the Cecil H. and Ida M. Green Institute of Geophysics and Planetary Physics (IGPP).

## LINKS AND FURTHER READING

More information about this year's prize is to be found at the Royal Swedish Academy of Sciences' website *http://kva.se* and at *www.crafoordprize.se*.

### *BOOKS*

**Munk, W. and MacDonald, G.J.F.** (1960): *The Rotation of the Earth: A Geophysical Discussion*. Cambridge University Press, 323 pp.

**Munk, W., Worchester, P. and Wunsch, C.** (1995): *Ocean Acoustic Tomography*. Cambridge University Press, 450 pp.

**von Storch, H. and Hasselmann, K.** (2010): *Seventy years of exploration in Oceanography. A prolonged week-end discussion with Walter Munk*. Springer Verlag, 250 pp.

### *SCIENTIFIC KEY ARTICLES*

**Munk, W.** (1950): On the wind-driven ocean circulation. *Journal of Meteorology* 7(2): 72–93.

**Munk, W. and Palmén, E.** (1951): Notes on the dynamics of the Antarctic Circumpolar Current. *Tellus* 3(1): 53–55.

**Cox, C. and Munk, W.** (1954): Measurement of the Roughness of the Sea Surface from Photographs. *Journal of the Optical Society of America* 44(11): 838–850.

**Munk, W.** (1966): Abyssal recipes. *Deep-Sea Research* 13: 707–730.

**Munk, W. and Cartwright, D.E.** (1966): Tidal Spectroscopy and Prediction. *Philosophical Transactions of the Royal Society of London* Ser. A, No. 1105, 259: 533–581.

**Garrett, C. and Munk, W.** (1972): Oceanic mixing by breaking internal waves, *Deep-Sea Research* 19, 823–832.

**Munk, W. and Wunsch, C.** (1998): Abyssal recipes II: energetics of tidal and wind mixing. *Deep-Sea Research I* 45:1977–2010.

**Munk, W.** (2003): Ocean freshening, sea level rising. *Science* Vol. 300, No. 5628: 2041–2043.

**Munk, W.** (2008): An Inconvenient Sea Truth: Spread, Steepness, and Skewness of Surface Slopes. *Annual Review of Marine Science* Vol. 1: 377–415.

## *LINKS*

Deborah Day's Walter Heinrich Munk Biography: *http://escholarship.org/uc/item/2tw4z5zs*

Read more about the irregularities of the Earth's rotation at the International Earth Rotation and Reference Systems Service site: *www.iers.org/*