WALTER HEINRICH MUNK
19 October 1917 — 8 February 2019
Born in Vienna, Austria, shortly before the Austro-Hungarian Empire lost its access to the sea, Walter Munk became a leading geophysicist and physical oceanographer after being sent to school in New York State and later moving west to California. He and Harald Sverdrup developed wave prediction schemes that were used by the Allies in World War II to evaluate whether amphibious landings would be feasible. His post-war research included further major contributions to the understanding of ocean waves, as well as ocean circulation, tides, internal waves, mixing processes and many other phenomena. He showed how variations in the Earth’s rotation contained a wealth of valuable geophysical information and was an instigator of the ‘Mohole’ project that failed for political reasons but paved the way for the Deep Sea Drilling Project. Although primarily a theoretician, throughout his career he was an enthusiastic adopter of new technologies and data analysis techniques. He showed how acoustic transmissions could be used to map ocean eddies and currents as well as to monitor temperature changes of whole ocean basins. He was a key adviser to the US Navy and a dedicated member of the science advisory group, JASON, that focuses on national security. As well as his scientific contributions, his legacy includes the La Jolla Institute of Geophysics and Planetary Physics. He was liberal in his political outlook, gregarious, hospitable and treated everyone, from undergraduate to admiral, with the same interest and respect.

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INTRODUCTION

Walter Munk’s 80-year career covered so many diverse but related fields of oceanography and geophysics, and he had so much influence on science, and science related to the military, that giving the flavour of his achievements is a major challenge. We have attempted in what follows to convey to the reader some of the highlights of his life and career; the references provide much greater depth. A full understanding of this complicated, fascinating, person and his family and colleagues calls for an outstanding novelist or movie scriptwriter!

FAMILY BACKGROUND AND EARLY LIFE

Walter’s father, Dr Hans Munk, was born in Vienna in 1886 to Jewish parents who had moved there from Mikuszwice, Galicia, in what is now Poland. The title ‘Dr’ came from a law degree, though he never practised law. Apart from several years of service in the Austro-Hungarian army in World War I, partly spent as chauffeur to Emperor Franz Josef, he never needed to work for a living but enjoyed an aristocratic lifestyle supported by family wealth based on a lumber factory in Silesia. Walter’s mother, Regine (Rega) Pauline, née Brunner, was born in 1892 to a wealthy Jewish banking family (figure 1). Her father, Lucian Brunner, had moved to Austria from Switzerland and founded a bank in his own name, later changing it to Österreichische Volksbank.

Rega spent a year at Cheltenham Ladies College in England, followed by two years, 1911 to 1913, at Newnham College, University of Cambridge, one of very few foreign female students. She studied botany and met the amateur botanist Harold Jeffreys (FRS 1925), later a famous geophysicist whose interests in the Earth’s rotation overlapped with those of Walter. (More than 50 years later Walter presented the Harold Jeffreys Lecture to the Royal Astronomical Society (21).) Rega did not complete a degree but returned to Austria in 1913.

Rega and Hans were married in 1914 and had three children, Gertrude (born 1915), Walter and Alfred (born 1925), but divorced in 1927. In 1928 Rega married Dr Rudolf Engelsberg, Director General of the Austrian Salt Mines, who was a Catholic. In spite of the religious backgrounds of Walter’s mother and stepfather, Walter and his siblings were raised in a non-religious household. The family lived in Vienna but spent the Christmas vacation and three months each summer in Altaussee, near Salzburg, in a farmhouse rebuilt by Lucian Brunner (who had died in 1914).

During the early decades of the twentieth century, Vienna was an artistic and cultural hothouse, the home of Sigmund Freud, Arnold Schoenberg, Gustav Klimt, Alfred Adler, Ludwig Wittgenstein and numerous others of distinction. As members of the wealthy elite, the Munk/Brunner families would have known a great variety of interesting individuals. Maria Munk, the subject of three paintings by Klimt after her suicide in 1911, was Hans Munk’s cousin.

The city and the country as a whole were subject to great upheaval and instability during Walter’s youth. The emperor had abdicated; Vienna lost its role as capital of a great empire, being reduced to the major city in a very small central European country with a radically different non-imperial government. Many of the better-known events in neighbouring Weimar Germany were echoed in Austria—including the creation of private militias, a period of runaway inflation, the rise of Fascist parties, a failed Putsch, serious religious disputes
Figure 1. Walter and his mother, Regine, ca 1918. (Online version in colour.)
involving the government, the world-wide onset in 1929 of the Great Depression. Anxieties were intensified by the rise of the Nazi Party in Germany and its known ambitions for union (Anschluss) with Austria (Holmes & Silverman 2009).

As a boy, Walter was probably unaware of much of this turmoil. He took great pleasure later in saying that he had not been keen on academic studies, preferring to play tennis and ski. He claimed that at age 14 he decided that he wanted to become a skiing instructor and that his mother was so horrified that she exiled him to the United States, planning for him to become a banker. More plausibly, as suggested by his nephew Glenn Clark (pers. comm. 2019), she was alarmed by the rising chaos in Austria and thought to protect her oldest son and his future by getting him out of the country. Her decision was likely driven by both a sense that Austria was becoming unsafe, and that Walter needed a different environment.

AMERICA

The Brunner bank was affiliated with the Cassel bank in New York; Walter’s initial stay in 1932 was with Hugh Cassel in his apartment on Park Avenue. His mother then sent him to Silver Bay Preparatory School for Boys on the shores of Lake George in upper New York State. The school had been founded in 1918 with the plan that ‘The curriculum will include a program of productive work for each boy—work in the garden, workshop or on the premises with farm animals . . . ’. Walter quickly established the Silver Bay Ski Club and was its president.

After just a year at the Silver Bay school, Walter, still a teenager, was sent to work as a low-level employee in the New York bank. He hated it, but used his free time to take a number of serious courses at the Columbia University Extension School, while living at the International House (where he started a ski team!). Most summers he returned to Austria for several months and was thus exposed to the continuing upheavals in that country.

Shortly before he turned 20, Walter persuaded his mother that he should be released from the family business. She gave him US$10 000 (over $170 000 in 2020 dollars), part of which he spent on a DeSoto Phaeton, a luxury convertible, and drove across the country to Pasadena, California, where he had an aunt who took him in. He loved the area and resolved to further his education. A sympathetic dean at Caltech responded to his charm and, partly on the basis of credit for the courses he had taken at Columbia, authorized Walter’s admission as a third-year student provided that he took and passed an entrance exam. He succeeded after a month of intense study and enrolled in courses in mathematics, physics and earth sciences, particularly enjoying field trips into the desert led by geologist Peter Buwalda. He took courses from Charles Richter, Hugo Benioff and Beno Gutenberg, some of the other very distinguished geophysicists and geologists at Caltech. He also enjoyed a course in constitutional law and found time for other pursuits, including captaincy of the Caltech ski team. The 1939 yearbook (figure 2) describes how ‘his adaptability to American ways and his genial friendship have won him a large number of friends’.

In 1938 Hitler’s Germany annexed Austria, causing Walter great concern for his Jewish mother, his sister, brother and stepfather, who had been a low-level member of the Fascist (but anti-Nazi) Schuschnigg government. Rega had long anticipated and prepared for the German annexation. Within one day of the Anschluss she took a train to Switzerland, leaving her other two children behind temporarily but succeeding in arranging false Swiss identification papers
Walter’s sister Gertrude later recalled their dramatic escape, aided by brave Swiss citizens (Clark 2010). It remains a matter of family pride that Rega’s initiation of an escape method, using false papers identifying the bearers as Swiss citizens, helped hundreds of other Austrians with Jewish heritage escape to freedom. Walter had applied for US citizenship, obtaining it in June 1939, and was joined in Pasadena by his siblings, mother and stepfather.

Meanwhile, still a Caltech student, Walter had fallen in love with fellow skier Ruth (‘Bumps’) Andersson, a student at nearby Scripps College. She visited her grandparents in La Jolla in the summer of 1939—and Walter followed.
By then Walter had exhausted the money given to him by his mother and needed a job. The only employment he could find was at what he described as ‘a sleepy Marine Station with a staff of 15 people (including the gardener)’ (30), now the Scripps Institution of Oceanography with a staff of over 1000 and part of the University of California, San Diego (UCSD). The Director of Scripps was the Norwegian polar explorer and physical oceanographer Harald Sverdrup, who agreed to take Walter on as a student assistant. The research sailing schooner *E. W. Scripps* had just returned from an expedition to the Gulf of California, having made measurements of temperature, salinity and oxygen at various depths at 53 oceanographic stations. The data showed that surfaces of constant density were not flat, but varied in depth by many metres. Sverdrup attributed this feature to internal waves. Walter was asked to examine the problem further.

From solutions of the dynamical equations, Walter showed that Sverdrup’s interpretation was theoretically plausible. The project became the subject of his MS thesis when he returned to Caltech later in 1939, leading to his graduation in 1940 and his first published paper (1). The project involved discussion with Roger Revelle, then a young assistant professor, who became a close life-long friend of Walter’s. Walter returned to Scripps in 1940 and persuaded Sverdrup (figure 3) to take him on as a PhD student, although Sverdrup held out little hope for any future jobs.

The war years

Walter anticipated that the US would eventually be involved in the war with Germany, and in September 1940 he enlisted in the 146th Field Artillery of the Washington State National Guard. He found the peacetime service distasteful and boring, apart from a month training with the new 41st Division Ski Battalion. Meanwhile, Sverdrup and Revelle had formed a Scripps group to work on anti-submarine warfare (ASW) and successfully applied for Walter to join them. He was honourably discharged from the army on 12 November 1941, just a few weeks before the Japanese attack on Pearl Harbor on 7 December 1941 and US entry into the war.

The Scripps ASW group was provided with offices at a US Navy Laboratory on Point Loma in San Diego, 20 km south of Scripps. The work of the group was interrupted, however, when on 1 March 1942 Sverdrup was denied entry as his security clearance had been suspended. Walter also lost his clearance later, in July 1942, largely because of his association with Sverdrup. A freedom of information request decades later revealed that Sverdrup had been subject to investigation by the FBI since May 1940 on unfounded suspicion of Nazi sympathies (39). The one humorous episode brought to light in the secret FBI files concerned the interview with Walter’s landlady, who vouched for his loyalty but said that she would never rent to him again because he was so untidy! Walter’s clearance was eventually restored, but Sverdrup’s never was, thus depriving the US war effort of the full services of one of the world’s leading oceanographers.

Walter remained deeply disturbed by the way in which Sverdrup was treated but, fortunately, these two immigrants did manage to collaborate on a vital contribution to the war effort.
Surf forecasts

Although he had been denied security clearance by the Navy, in October 1942 Walter was able to accept a position as assistant oceanographer in the Army Air Force (AAF) Directorate of Weather, based at the Pentagon in Washington DC. He heard about Operation Torch, an Allied amphibious landing on the North African coast planned for November, and was permitted to observe practice landings on North Carolina beaches. Senior officers had become aware that wave breaker heights of more than 1.5 to 2 metres would cause landing craft to broach and swamp. Practices were postponed in such conditions. Returning to the Pentagon, Walter assembled data showing that wave heights on the Atlantic coast of North Africa typically exceeded this limit in winter.

The challenge was thus to forecast conditions accurately enough to predict days on which amphibious landings would be possible. Walter assembled meteorological and oceanographic data and thought about possible empirical relations connecting storm parameters to wave heights on distant shores. He concluded that useful predictions could be made, but that further work would benefit greatly from the involvement of Sverdrup. The AAF agreed to this suggestion, as Sverdrup’s confirmation of the calculations of the 25-year-old Walter Munk would add considerable weight to any recommendations.
The Sverdrup and Munk report (3), published much later, examined data on the wave height and period as functions of wind-fetch (the distance over which the wind blows) and storm duration, with different data sets being combined through suitable non-dimensionalization. Attenuation of the swell as it travelled away from the storm area was also based on observations rather than rigorous theory, but paved the way for post-war studies (Hasselmann 1984). Walter and Sverdrup later added an important component to their scheme to allow for the transformation of swell into breakers and surf and continued this research after the war (2).

As it turned out, wave conditions during the North African landings were unusually benign, but this could not be expected for future landings elsewhere. The Sverdrup and Munk scheme was taught to over 200 military and naval officers in courses at Scripps in 1943, and used in the planning of later operations in Sicily, Normandy and the Pacific (e.g. Crowell 2011). The forecasts were particularly critical for the D-Day landings, with a 24-hour postponement from the originally planned date of 5 June due to stormy conditions (Fleming 2004). A risky decision was made to proceed with the invasion on 6 June, when a lull in the weather was anticipated, and it seemed that both the weather conditions and the waves and surf, according to the Sverdrup and Munk wave-forecasting scheme, would be marginally acceptable (Parker 2010).

Apart from the sad treatment of Walter and Sverdrup from a security point of view, the development and use of their scheme was a major component of the adoption by the military of civilian scientific expertise, and set the stage for collaboration after the war.

**POST-WAR EXPEDITIONS**

After the war, Walter’s research branched out into different areas, but his involvement with the military continued (44). In 1946, Scripps was asked by the US Navy to investigate the flushing rate of the lagoon at Bikini Atoll, Marshall Islands, where the US was conducting a series of nuclear weapons tests. Walter and William von Arx, from the Woods Hole Oceanographic Institution, dropped dye markers in the entrances to the lagoon and estimated that it would take about a week for radioactivity from an underwater explosion within the lagoon to be flushed out.

A few years later, the US responded to the first Soviet nuclear test by accelerating its development of a fusion device—with the first test, Ivy-Mike, at Enewetak Atoll in the Marshall Islands, in 1952. Scripps scientists expressed a concern that the explosion might trigger an underwater landslide that would generate a significant surge and cause destruction on other islands. To provide some advance warning, Willard Bascom and Walter were stationed on two rafts moored at a seamount some 130 km from the test site, with pressure gauges to monitor any tsunami. None was observed and Walter and Willard were picked up by the Scripps ship *RV Horizon*, which then left the area at top speed, though still experiencing some radioactive fallout. Not surprisingly, the experience and seeing the mushroom cloud from the explosion left a deep impression on Walter (40).

**OCEAN CIRCULATION**

In 1948 Walter spent six months visiting Harald Sverdrup, who had returned to Oslo after the war. Harald had earlier elucidated the physics of what is now known as
‘Sverdrup transport’, linking the net equatorward or poleward transport of water in ocean basins to the patterns of the wind stress at the ocean surface and leading to the first basin-scale estimates of water movement. The basic problem is that, in the North Atlantic for example, the high latitude westerlies and the low latitude easterlies (trade winds) exert a clockwise torque on the ocean, but the water clearly does not respond with an ever-increasing clockwise spin. Instead, it is the angular momentum of the water relative to an inertial frame that matters, and this motion involves the Earth’s rotation, specifically the locally vertical component, which is anticlockwise and decreases equatorward. Thus, the wind stress torque can be balanced by a net movement of the water southward.

But the North Atlantic (or similarly the Pacific) does not empty; the southward Sverdrup transport must somehow return northwards. The acquisition of an increasing clockwise spin relative to the Earth is avoided through the effect of friction at the western boundary, with the friction supplied at the sea floor in an initial model by Henry (Hank) Stommel (ForMemRS 1983), another giant of twentieth-century oceanography. In a now-classic paper (6), Walter made the more appropriate assumption that the friction is applied at the lateral boundary. Although still not particularly realistic, Walter’s theory, along with those of Stommel and Sverdrup, provided the crucial physical explanation of why there is a Gulf Stream and why it is on the western side of the ocean basin (and similarly for the Kuroshio Current in the North Pacific and in similar situations in the southern hemisphere). George Carrier of Brown University worked with Walter to generalize the problem (7), using analytically-new boundary layer theory that was also applicable to other oceanographic problems.

The models represented lateral momentum exchange, accomplished by transient oceanic eddies with horizontal scales of tens of kilometres, by assuming a constant ‘eddy’ viscosity, vastly greater than the molecular viscosity. While useful, this assumption is an oversimplification, particularly in taking a constant value for the eddy viscosity. Investigations continue.

Walter recognized that the Southern Ocean circulation had to have a very different force balance than was appropriate for the ocean basins that had meridional continental boundaries. He and Finnish meteorologist Erik Palmén, then visiting Scripps, elucidated the dominant role of irregular bottom topography in providing drag in the Southern Ocean (8), also a topic of intense continuing research.

Apart from the wind-driven circulation, the nature and control of the stratification of oceanic density (determined by temperature and salinity) had begun to interest Walter. With E. R. Anderson he proposed a simple one-dimensional model (5) in which surface wind stress and heating are mixed down into the ocean by turbulent mixing processes, again represented mathematically by assuming greatly amplified versions of the molecular viscosity and diffusivity. The proposed formulae are really more relevant to coastal and estuarine situations, as in later studies by various authors, but it was a pioneering effort.

Walter returned to the question of the nature of ocean mixing in a 1966 paper (20) with the evocative and typically provocative title of ‘Abyssal recipes’. The basic (though oversimplified) scientific issue is that cold, dense, water is created in polar regions, principally around Antarctica, sinks to the sea floor, spreads through the world’s oceans and slowly upwells at a rate of about one metre a year. Without any downward mixing of heat from the surface, the ocean would be filled with very cold water all the way to the sunlit upper layers, contrary to observations. Walter examined representative observed vertical profiles of
temperature in the open ocean, and fitted them with a simple model that balanced the upwelling of cold water with the downward diffusion of heat. He estimated the effective eddy diffusivity as $10^{-4}$ m$^2$/s, some 700 times greater than the molecular value.

Walter’s comparatively simple model of a one-dimensional steady balance for heat and other quantities was widely and perhaps over-enthusiastically embraced by the physical, chemical and biological communities. With newer technologies and better understanding of ocean circulation and oceanic turbulence, the picture has become considerably more complex, but Walter’s abyssal recipes still provide a useful framework. Decades later, Walter and one of us (C.W.) returned to the problem and showed the applicability of the older theory on a global ocean integral basis, and emphasized the need to account explicitly for the energy sources for ocean mixing (36).

We will return to these physical oceanographic topics later, but first describe some of Walter’s involvement in more geophysical questions.

**Project Mohole**

One of the major issues in geology and geophysics was (and remains) the character of the discontinuity in the solid Earth between the crust and the underlying mantle. Named for the Croatian scientist Andrija Mohorovičić, it is characterized by a marked change in the speed of seismic waves above and below. Usually referred to as the ‘Moho’, the generally accepted explanation for its existence is a change in composition from crust to mantle. A desire to confirm that conjecture has existed for decades.

In 1957, evidently at an end-of-day relaxation gathering following a meeting of a US National Science Foundation Earth Science Panel, of which Walter was a member, discussion turned to the possibility of a major, ‘big-science’, programme in geophysics and geology. Walter, with the support of the prominent geophysicist, Harry Hess, proposed that drilling to the Moho in the deep ocean, where the oceanic crust is generally thinnest, would be a major worthwhile endeavour directed at an important problem: the actual composition change.

What followed was a well-documented attempt to use the existing deep-sea drilling technology to drill a test hole. Initial success, led by the brilliant engineer Willard Bascom, was encouraging (Bascom 1961), but considerable mismanagement, misunderstandings, technical issues and a brutal encounter with the Texas petroleum–political nexus later led to cancellation of the project.

The later Deep Sea Drilling Project, studying sediments recovered from shallower depths, has led to the new field of paleoceanography and greatly expanded knowledge about Earth’s climatic past, but reaching the Moho remains elusive. This is, however, within the scope of subsequent programmes, including Japanese plans to drill to the Moho using the large drilling ship *Chikyu*. Walter was an invited guest in November 2012, arriving by helicopter when the *Chikyu* was 80 km offshore. He received a warm welcome as a scientist who had been well ahead of his time.

**Earth rotation and lunar evolution**

By 1950, Walter had developed a strong interest in changes in the Earth’s spin rate, particularly on seasonal time-scales as the solid earth exchanges momentum with the wind. He was also
intrigued by observations of the movement of the rotation axis within the Earth (the Chandler wobble).

Astronomers were very aware of movements of the rotation pole, as it introduced a serious noise into their observations of extra-terrestrial objects. Earlier pioneering studies by George Darwin (FRS 1879), Harold Jeffreys and others had strongly suggested that the ‘noise’ arose as signals of geophysical processes. The subject crosses a bewildering array of processes and time-scales, including the large-scale behaviour of the atmosphere, the ocean, earthquakes, ice sheet growth and decay, the response of the solid Earth and its fluid outer core to all of those changes, the origin of the Moon and its orbital evolution and the statistics of time series.

A series of papers on various aspects of Earth rotation and polar motion culminated in the remarkable book (16) co-authored with geophysicist Gordon MacDonald. This elegantly-written monograph is nearly a ‘handbook’ of the analysis and interpretation of a very wide range of geophysical, meteorological, oceanographic and astronomical processes. It includes a discussion of changes in the Earth’s rotation rate and the Moon’s orbit over long periods and the relationship to energy losses from ocean tides, and hence to ocean mixing and circulation, thus linking the topic to Walter’s physical oceanographic interests. Walter returned to the subject later as new data and ideas became available (21,35).

Walter later described the difficulty in reconciling slow changes in the Earth’s rotation rate (other than the contribution from tidal friction) with direct estimates of sea level rise from tide gauge and ocean temperature data (38). What became known as ‘Munk’s enigma’ appears to have been resolved recently (Mitrovica et al. 2015), partly through careful attention to the role of viscous coupling between the Earth’s liquid outer core and its mantle.

Surface waves

In 1953 Walter was granted the use of a B17 (Flying Fortress) for an investigation, with his student Charles (Chip) Cox, of mean square sea surface slopes as a function of wind speed. The project was based on aerial photos of the size and shape of ‘sun glitter’. With no wind, the sun’s reflection is from a single point but, as the wind speed increases, so does the area containing parts of the sea surface, tilted in such a way as to reflect the sunlight towards the camera. In a successful flight near Hawaii, Chip and Walter found that the mean square slope of the sea surface in the crosswind direction is 60% of the mean square downwind slope, with both increasing linearly with wind speed (11). These remarkably simple results called out for a simple explanation, but one remains elusive (45). Although not understood, the Cox–Munk results remain widely important in many remote-sensing applications, including, particularly, those based on orbiting spacecraft.

Walter contributed to many other studies of ocean surface waves, but one deserves particular mention. Waves with a long period travel faster than those with a short period, so measurements of changes in wave period at a receiving station provide estimates of the distance from a storm. In 1956, engineer Frank Snodgrass and Walter developed a new instrument to measure and record pressure at the sea floor. While testing it off the Mexican island of Guadalupe, they found signals of surface waves with a period decreasing at a rate that indicated a distant source that had to be in the southern Indian Ocean, with swell entering the Pacific Ocean past New Zealand (13).
This work led to a study documented in the movie *Waves Across the Pacific* (https://www.youtube.com/watch?v=MX5cKoOm6Pk), describing an observational programme to track swell all the way from the Southern Ocean to Alaska, with bottom pressure recorders installed at New Zealand, American Samoa, Palmyra, Hawaii and Alaska. Scripps’s new Floating Instrument Platform (FLIP) made measurements in mid ocean between Hawaii and Alaska. The results showed the propagation of swell just as expected from theory with, contrary to Walter’s expectation, very little loss of energy through interactions with the waves in the trade winds of the equatorial region.

**TIME SERIES ANALYSIS**

As is evident above, much of Walter’s research in geophysics and physical oceanography from the mid 1950s onwards relied on what has become known as time series analysis, based upon Fourier series methods combined with statistics. That unintuitive combination of probability and mathematics had led to much confusion in the geophysical literature in the time since Sir Arthur Schuster (FRS 1879) had introduced the periodogram in the nineteenth century. Following World War II, a number of people began to grapple with the ideas of surface wave spectra—a natural sequel to the Sverdrup–Munk efforts to understand surface wave generation and propagation. One group was Walter’s, another the surface wave group at the British National Institute of Oceanography, which had come together during World War II under the leadership of Sir George Deacon (FRS 1944). The two groups collaborated on an important review paper (14). Remarkably, the 1960s system known as BOMM (17), that Walter worked out with Teddy Bullard (FRS 1941) and computer-savvy colleagues, anticipated such recent ‘black box systems’ as Matlab® and Mathematica®.

Walter’s expertise, nearly unique at the time (Tukey 1984), led his colleagues to seek out his help (e.g. (15), a study with colleagues Bernard Haurwitz and Hank Stommel) and was crucial to his work on the Earth’s rotation as well as all aspects of surface and internal waves.

**OCEAN TIDES**

Frank Snodgrass’s skill in measuring pressure fluctuations at the sea floor had led him and Walter into an investigation of the low energy waves, near the coast, with periods in minutes (12) and ultimately to the even longer period tides. Frank developed instruments that could be dropped to the sea floor and take pressure readings for several months. He was a pioneer of deployments that avoided the use of an umbilical cord to the surface but relied on acoustic signals from the surface to release the instrument package from an anchor, usually an old railway wheel, that would be left behind on the sea floor. Frank and Walter also pioneered the use of portable laboratories that could be loaded with equipment on land and then transported to the dock to be bolted to the deck of the research ship (figure 4).

Tides in the open ocean could not easily be inferred from measurements at the coasts or at islands. Two-dimensional numerical models were starting to be developed with predictions that required observational checks. The mapping and modelling exercises were related to Walter’s interest in the role of the dissipation of tidal energy in slowing the Earth’s rotation, and to the possible role of the tides in producing the vertical mixing needed to maintain the oceanic temperature and salinity structure (e.g. (36)). Observational focus has shifted to
Figure 4. Walter standing at the entrance to a sea-going portable laboratory, developed with Frank Snodgrass (third from left), during a 1968 expedition to measure deep-sea tides. (Online version in colour.)

altimetric measurements from satellites, which provide global coverage but benefit from the spot-checks available from precise measurements obtained from deep-sea pressure sensors deployed by Walter’s team, a similar British group led by David Cartwright (FRS 1984) and others.

Tidal prediction at a particular location usually involves analysing data for the amplitude and phase of astronomically-prescribed frequencies and extrapolating the periodic motions to make predictions; the methodology was originally developed by William Thomson (Lord Kelvin, FRS 1851) and George Darwin. Walter and David Cartwright developed a ‘response method’ (19), in which the observed tides are assumed to be associated with the generating forces at a number of earlier times, each assigned a different weight determined from fitting the model to observations. The advantage over the traditional technique is its much readier connection to the physics of tidal response.

The Munk and Cartwright study, and an earlier paper (18), included Fourier analysis of long records, revealing the presence of what they termed ‘tidal cusps’, energy contained in frequencies very close to, but not right at, the frequencies of the main tidal constituents and previously ignored. These cusps are a manifestation in frequency space of a slow modulation of the tidal signal. In most coastal seas this modulation is largely caused by weather-induced changes in the friction experienced by the surface tide on the continental shelf. However, in some coastal locations, and particularly in the deep open ocean, a significant contribution to tidal changes in sea level can come from the internal tide (which has a small surface
displacement), the generation and propagation of which can be modulated by changing water stratification (42).

One minor tidal study concerned ‘the age of the tide’, the name given by William Whewell (FRS 1820) in 1833 to the delay between full or new moon, when the tidal forcing is maximum, and the maximum response—so-called spring tides. Whewell attributed the age, typically a day or two in Northern Europe, to the time taken for the tide to travel from the Southern Ocean, where he supposed that the tide was generated. An older theory, by Pliny the Elder, drew a parallel to thunder and lightning, perhaps providing a spurious oceanographic proof that gravitational forces travel at much less than the speed of light! More plausibly, the effect is a simple consequence of the response to forcing of a simple damped harmonic oscillator near resonance (22).

In another minor and light-hearted investigation of sea level oscillations and associated flows, Walter and his wife Judy accompanied Adrian Gill (FRS 1986) and his family on an expedition in 1981 to Chalcis in Greece, where Aristotle is alleged to have despaired of understanding the fluctuating currents through Euripus Strait and have thrown himself into the water to drown. Adrian provides an entertaining account (Gill 1984) of how to conduct a scientific investigation, culminating in an interview with the local harbour master who told Walter where bodies wash ashore. Thus, Adrian claimed, Walter’s greatest achievement will eventually be recognized as his discovery of the last resting place of Aristotle!

INTERNAL WAVES

In 1970, Walter turned to internal waves in the deep open ocean. Water parcels experience typical vertical displacements of 10 m and horizontal excursions of 1 km, with oscillation periods between the local buoyancy period, associated with the stable stratification of the water column, and typically 10 minutes in the upper ocean, longer at depth, and the Coriolis period associated with the Earth’s rotation. The motions are forced by wind at the sea surface and flow over topographic features on the sea floor. Vertical shear of the associated horizontal currents can occasionally lead to what is known as Kelvin–Helmholtz instability, leading to turbulence and vertical mixing. It was this possible connection to his ‘abyssal recipes’ that was Walter’s primary motivation for undertaking a study.

Even describing internal waves is difficult. For surface waves, a record of sea surface displacement is sufficient to define the frequency spectrum of the waves, and hence the wavenumbers (reciprocals of the wavelengths). For internal waves, however, a wave of a given frequency may be associated with any spatial scale. Similarly, vertical profiles of horizontal currents provide the wavenumbers of the waves, but not the frequencies at each vertical scale.

Working with one of us (CG) as a postdoc, Walter made the extremely bold assumption that, unlike surface waves for which there are periods and places of storm and calm, internal waves in the ocean have a universal spectrum in frequency–wavenumber space, so that different types of observation, at different times and locations, could be fitted with a single model. Valuable input was obtained by Walter’s student, Jim Cairns (Cairns 1975; Cairns & Williams 1976). Jim adapted the group’s deep-sea capsule to bob up and down in the water column, tracking a particular temperature surface by adjusting its buoyancy, a technique now used extensively in global oceanic monitoring programmes.
Walter Heinrich Munk

Walter insisted in being second author of the resulting papers (23,26), largely out of his characteristic generosity to a junior colleague, but also so that the resulting ‘GM’ spectrum could be compared with the typical product of the US automobile industry, represented by General Motors, with neither reliability nor durability to be expected (‘planned obsolescence’). Nonetheless, the sequence of models (see reviews (27) and (29)) has provided a valuable benchmark and theoretical provocation. It seems that, insofar as universality is valid, it is associated with the time to drain the energy from the waves being much longer than the time interval between generation events. Furthermore, the vertical mixing to be expected from instabilities for the canonical spectrum appears to be at least an order of magnitude less than Walter’s requirement for the abyssal ocean (Gregg 1989). Mixing there may partly be associated with the intensification of current shear as internal waves are reflected and scattered at the rough, sloping, sides of ocean basins, but is also largely associated with internal waves of tidal frequency, generated by tidal flow over bottom features and omitted from the GM spectrum. Research continues.

Although Walter had purely scientific reasons for his internal wave studies, he was also motivated by the problem of submarine detection. Submarines generate internal waves, which, like the wake at the sea surface of a surface vessel, could lead to their location if the waves could be distinguished from the natural wave field. Moreover, the use of both active and passive acoustic detection methods is complicated by the presence of fluctuations in sound speed due to the presence of internal waves. But, surprisingly, until Walter joined the discussion in the early 1970s, it had been erroneously assumed that fluctuations in sound speed were associated with homogeneous isotropic turbulence. The situation was well, and poetically, described by Stanley Flatté in his presentation at Walter’s sixty-fifth birthday celebration in 1982 (Flatté 1984).

Detailed analysis of the situation led to new understanding of sound transmission in the ocean and marked Walter’s adoption of acoustic oceanography as his major research interest for the next three decades.

**Ocean acoustics and tomography**

Although exposed to ocean acoustics from working with the Scripps ASW group during World War II, Walter’s revived interest in the field arose through his interactions with the national security consulting group JASON. Many of the details of this work remain classified or at least inaccessible, but with an available summary (28) focusing on propagation through random media.

The ocean is, in practice, nearly opaque to electromagnetic wave propagation at useful signalling frequencies. Acoustic propagation had long been used for depth sounding and, by about 1970, had also become conspicuous in oceanographic research as a tool for tracking drifting floats and as a way for ships to communicate with acoustic devices used to release moorings from seabed anchors. At the time, sound signals were not used as a way of measuring the fluid behaviour itself. Later on, starting in the 1980s, currents have been measured by acoustic Doppler current profilers (ADCPs) that rely on the Doppler shift of high-frequency sound reflected from particles in the water, but with a range limited to a few hundred metres.

At larger scales, in the mid 1970s Walter began experiments with Frank Snodgrass and then graduate student Peter Worcester on the use of reciprocal acoustic transmissions
between deeply submerged instruments A and B, separated horizontally by about 25 km. With sufficiently high accuracy in the measurement of the difference of the travel time from A to B, compared with B to A, a large-scale integrating current meter exists. Although reciprocal transmission remains an important potential application, the extreme demands on time-keeping and the complexity of oceanic flow fields over hundreds or thousands of kilometres led to a focus on one-way transmissions and their temporal variability.

An important feature of ocean acoustics is that the speed of sound is an increasing function of both temperature and pressure, with the vertical gradient of temperature dominating in the upper ocean and that of pressure in the deep ocean. A minimum sound speed at a depth of typically 1 km results in a waveguide, permitting sound to travel almost unattenuated over long distances. Different acoustic paths within a single source-receiver pair sample different depth ranges.

Exploitation of this phenomenon began when one of us (CW) became a member of JASON to help with the study of non-acoustic ASW. After a number of informal discussions, it was realized that the combination of (primarily) one-way acoustic transmissions with the use of inverse methods could lead to a system for large-scale, integrating measurements of oceanic temperature. The horizontally averaged vertical profile of temperature is obtainable between a single source and receiver. With several sources and receivers, it is possible to map 3D structures and their changes, particularly over a horizontal scale of 100 km or so. Parallels with medical computerized axial tomography (CAT) gave a name to the approach.

What followed was a series of experiments, many based at Scripps but with French, Scandinavian and other US laboratories taking part, deployed over different ranges and physical settings. Much of the background physics and the field and theoretical work was summarized in the 1995 book (34) and a later semi-popular article (41).

Although the acoustic tomography experiments were led by others, Walter was the instigator and inspiration. He enjoyed the work at sea, though his colleagues agreed with the much earlier assessment by Frank Snodgrass that Walter was best kept away from equipment. Spindel and Worcester (2016) commented on his preference for finding a convenient corner of the lab or deck where he could sit with pencil and paper (figure 5), thinking deep thoughts and carrying out key calculations while taking in everything that was happening around him.

While tomographic techniques are useful for mapping oceanic structures with limited horizontal scales, acoustical transmission on the scale of ocean basins is most useful for measuring the changes in average temperature between source and receiver and is sometimes called ‘thermometry’ rather than ‘tomography’. The exploratory use of ocean acoustic transmissions reached a culmination in the so-called Heard Island Experiment, in which a specially instrumented ship was stationed in close proximity to Heard Island, a location in a remote part of the Southern Ocean west of Australia. With widespread international cooperation, the signals emitted by the ship were detected at great distances, all round the world, including antipodal positions and farther (figure 6). Walter described it as the high point of his career when even the test signal, prior to the main transmission, was detected at receiving stations on Bermuda and near Seattle. The viability of the use of sound to integrate through oceanic properties at immense distances was clearly demonstrated (31,32,33).

A less-happy experience, however, was the Acoustic Thermometry of Ocean Climate (ATOC) project, intended by Walter and numerous colleagues to begin the deployment of a long-lived acoustic measuring system on the scale of the Pacific Basin. Owing to fears concerning potential damage to marine life, and something of a culture clash between the
Figure 5. Walter in his favourite sea-going modus operandi, during an acoustic tomography experiment in 1981. (Photograph: Bob Spindel.) (Online version in colour.)

Figure 6. Acoustic paths from Heard Island to receiving stations around the world. (Reprinted with permission from (33); copyright: Acoustical Society of America.)
marine mammal community and the physical acousticians, a public uproar ensued. Newspaper headlines about potential harm to marine animals erupted, public hearings were called and Walter’s normal ebullience and optimism about the rationality of the world began to fail him. Some of the scientific funding had to be used for legal support, attendance at numerous hearings and for demonstrations of benign biologic effects—the latter having been one of the goals from the outset. At the end of the day, useful measurements were obtained ((41), Worcester and Spindel 2005) but, at the time of this writing, acoustic tomography and related ideas have not blossomed in the way the participants had hoped.

ATOC did give rise to a great deal of insight into biological sound, the remarkable ongoing temperature and salinity profiling done today by instrumented marine mammals (Treasure et al. 2017; hundreds of thousands of profiles now exist), the most-widely used oceanic general circulation numerical model (Marshall et al. 1997) and considerable understanding of low-frequency acoustics and ocean physical properties generally. Tomographic applications under the ice-covered Arctic Sea remain an active area of use (46) (Mikhalevsky & Gavrilov 2001). Howe et al. (2019) provide a review of the current state and prospects for acoustic observations of the oceans, a field to which Walter contributed so much.

OTHER RESEARCH INTERESTS

Walter believed that asking the right question is much more important than providing the right answer. Combined with his sense of fun, this stimulated research by others and opened new fields. For example, his tongue-in-cheek proposal that biological processes such as schools of fish could substantially mix the ocean (20) later proved to be the subject of a serious literature. His sense of humour was apparent even in the titles of several of his papers, such as the ‘Abyssal recipes’ (20), the ‘Once again...’ (21) and ‘Once again, once again...’ (35) papers on tidal friction.

Walter also contributed to the work of colleagues in other oceanographic disciplines, with one example being an early paper with Gordon Riley on nutrient uptake by aquatic plants (9). It bears re-reading. Another topic that caught Walter’s (and Judy’s) attention during a sabbatical leave in Venice was the use of lasers to clean ancient sculptures (24,25). Roger Revelle liked to call attention to Walter’s paper on ‘The delayed hot-water problem’ (10) as perhaps a classic of plumbing science. (The paper is a very simple theoretical analysis of the reduction in the speed of advance of hot water from heater to tap caused by the heat loss to a cold pipe.)

Walter’s research continued long after normal retirement age. In his ninth decade, he enjoyed collaborating on a study of spirals at the sea surface, revealed in sun glitter patterns as waves steepened in the current patterns of eddies (37). Even later, he pursued the idea that surface waves, even short ones, propagating in opposing directions, could lead to pressure fluctuations at the sea floor (43), following earlier studies by Michael Longuet-Higgins (FRS 1963).

THE INSTITUTE OF GEOPHYSICS AND PLANETARY PHYSICS (IGPP)

The institute that Walter founded in 1959 is a very important and valuable part of his legacy. A state-wide Institute of Geophysics had been founded by the University of California, which
offered to provide half the funds needed for a branch associated with Scripps. Walter and colleagues were successful in raising the other half, from federal government agencies but with a major contribution from the Fleischman Foundation. ‘Geophysics’ was part of Walter’s original scientific interests, and this period was that of the plate tectonics revolution. This post-Sputnik period was one of a rapidly growing space programme and so the word ‘planetary’ was incorporated.

Judy Munk was heavily involved in plans for the building and chose Lloyd Ruocco as the architect. The resulting redwood structure sits on the edge of the cliffs (figure 7), halfway up a hill from the then main Scripps campus, with a seminar room and most of the offices overlooking the Pacific. Walter, as the Director, eschewed the rather grand front office, and assigned himself a modest one on a lower level, above a laboratory and equipment assembly area.

In a nice touch, Walter and Judy insisted that the offices should not have numbers, but be identified by photos of eminent scientists. One such photo is of a young Teddy Bullard, later Sir Edward Bullard and close friend of the Munks, wearing no more than a pith helmet. Another office has been assigned to Green Scholars, scientists from other institutions who visit for a few months at a time, with support from the Green Foundation, established by Cecil Green, a founder of Texas Instruments and close friend of the Munks. At the time of writing, there have been nearly 200 Green Scholars. The research undertaken at IGPP has always been a mix of geophysics, planetary physics and ocean physics, allowing for frequent and effective collaboration.
In 1993 IGPP was renamed the Cecil and Ida Green Institute of Geophysics and Planetary Physics, with the original building now the Judith and Walter Munk Laboratory and an elegant redwood expansion across the street being the Roger and Ellen Revelle Laboratory.

**JASON AND THE NAVY**

We discussed earlier Walter’s involvement with US Navy issues during and after the war. Much, but not all, of Walter’s later interaction with the military occurred in the context of JASON, apparently beginning with an evaluation of the possibilities of non-acoustic ASW. That organization had begun in 1960 as an advisory group on matters of national security, though in the last 15 years or so it has also studied some non-military issues. It originally consisted largely of physicists who had been involved with the US government during World War II, many of them in the nuclear weapons and radar programmes. Although Walter was not a founder, he was brought in very early as many of the JASON members recognized their need for expertise on the fluid ocean. One notable contribution that Walter made to JASON was his insistence that each report be accompanied by a ‘child’s guide’, written in even simpler terms than an executive summary, as he recognized that the reports would be sent to people with very limited time and no scientific expertise.

The involvement of JASON in Vietnam War military advising, and upheavals on US university campuses in the late 1960s, did sometimes leave Walter (who for part of the time was faculty chairman at UCSD) in an awkward position, though he always readily admitted his involvement with the military. Later, the prominence of some JASON physicists in the climate-sceptics drama led Walter to stand aside as far as possible. A history of JASON, including some of Walter’s role, can be found in Finkbeiner (2006).

It seems that Judy constantly challenged Walter over his involvement with JASON and the Navy, but his defence was that ‘if you’re going to have a Navy, you ought to have a good one’ (Aaserud 1986).

Walter also brought oceanographic considerations into project MEDEA, initiated by Vice-President Al Gore in 1990 in an effort to declassify as much military surveillance data as possible for use in civilian efforts to monitor global environmental change. MEDEA was later taken to be an acronym for Measurements of Earth Data for Environmental Analysis, but was a name originally assigned to recognize the close connection to Jason, Medea’s husband in Greek mythology (Baker & Zall 2020).

Walter persuaded the Navy to join in by releasing previously classified data and partner with the intelligence community in monitoring not only sites of interest to the military, but also key ocean regions (known as ‘Fiducials’). Interestingly, the unfreezing of US data led the Russians to release large data sets from the Arctic. An archive of the photographic images of the ocean and land surfaces is maintained by the US Geological Survey as its Global Fiducials Library.

**PERSONALITY AND DOMESTIC LIFE**

Although several of his most important papers were single-authored, Walter enjoyed working with other people, and liked to say that his approach was always to identify a good problem and then find someone who could help him solve it. However, anyone arriving at his house at 8 or 9
in the morning would find that he had already been busy at his work-table in the house entrance for a couple of hours. Most of his papers had at least one co-author, but whether his co-authors were established experts or young colleagues, he was an inspiration and leader, generous with unselfish collaboration and joint authorship. He put significant effort into helping younger scientists find career opportunities and achieve recognition.

Although a product of the very wealthy interwar Viennese banking and artistic culture, Walter clearly distanced himself from any close connections with it after he discovered the Southern California way-of-life, scientific and otherwise, described by Sargent (1979). He was a firm believer in the international nature of science but refused to speak German unless it served a useful purpose, such as at a 1959 oceanographic conference in New York when he spoke directly in German to Russian scientists to avoid mistranslation by their KGB minders.

In 1945, long after the cooling of his romance with Bumps Andersson, Walter married La Jolla resident Martha Chapin, a writer for the movie industry. The couple drifted apart and divorced on Walter’s return from the nine-month *Horizon* expedition in February 1953. A few months later he married Judith Horton (1925–2006) who was then working at Scripps as a scientific illustrator. The phrase ‘Walter and Judy’ came to be a label for an internationally known marital unit. They epitomized the gregarious interaction of science, arts and philosophy of the region, and actively sought the company of almost any individual who promised to provide interesting conversation. It was difficult to imagine Walter without Judy. They had three daughters, Lucian (1954–1960), who tragically died very young of a heart defect, Edith (Edie), born in 1956, and Kendall, born in 1959 (figure 8). Kendall had three sons (Walter, Maxwell and Lucien) (figure 9) with her husband, Paul Weiss.
One of Walter and Judy’s first enterprises after their marriage was to build a house on one of the lots on a parcel of land 1 km up the hill from Scripps. Their elegant home, Seiche, has a spectacular view of the Pacific down a community-owned canyon. As designed by Judy (who had some training as an architect), the house was eminently suited for entertainment, and thousands of scientists, students, government officials, artistic people and just friends came to cherish their invitations. Walter’s colleagues were welcomed to the Munk home with such great hospitality that they almost felt part of the family. His skill at mountaintop yodelling, however, was a talent that was never revealed to a scientific audience, though remembered fondly by his daughters.

The Munks made Seiche available for large-scale parties for the wider academic and artistic communities and installed a stage and amphitheatre for community dance, theatre and non-profit events. In designing the house, Judy included a private office, hidden away below stairs, intended for Walter’s use. But he quickly made it known that he was not going to use it—and set his workspace at a large, heavily cluttered table right in the entrance area of the house so that he would be privy to any comings and goings. He would happily work through all kinds of distractions and only objected when people whispered to avoid distracting him!

Judith Horton Munk was a talented artist and architect (although not licenced, she played a major role in the design of IGPP and other buildings on the UCSD campuses). She grew up in the Los Angeles area as part of a Hollywood family (‘Uncle Ed’ was Edward Everett Horton, a well-known film and stage actor of the 1930s to 1970). After arranging to study architecture at the Harvard University Graduate School of Design, she suffered a catastrophic attack of poliomyelitis and spent several months in an iron lung. She was then able to walk
Walter and Judy lived for months in an open fale on American Samoa during the Waves Across the Pacific project. In 1962, at the height of the Cuban missile crisis, they undertook a trip across the Soviet Union in their own handicapped-equipped Land Rover, entering at the Finnish border and departing by sea from Odessa. This trip had ostensible scientific purposes, but it was really just an adventure. They lived for many months in Venice (24), where Judy coped with the endless bridges and stairs. Walter also had physical problems in his later life, but even while recovering from his own surgeries it was very unusual for him to allow anyone else to push Judy’s wheelchair.

As one of us (CW) wrote in the foreword for von Storch and Hasselmann (2010), ‘In their house in La Jolla hangs a double portrait of Walter and Judy back-to-back, facing outward to whatever the world would bring, watching out for each other, for something fun to do together, and ever alert to the well-being of the other’ (figure 10).

After Judy’s death in 2006, Walter was fortunate to meet Mary Coakley, a La Jolla resident active in many local environmental and artistic endeavours. They married in 2011, while Walter was in hospital following ventricular tachycardia brought on by his foolishly attending and speaking passionately at a faculty meeting to discuss the proposed closing of the Scripps library! Mary carried on the Munk tradition of hospitality and made it possible for Walter to continue with the scientific travel that he enjoyed so much. She also updated the earlier account of Walter’s career (von Storch & Hasselmann 2010) to include recent documentation of Walter’s extensive activities between 2010 and his centennial in 2017.
Mary provided support for Walter’s interests, but he also took great interest and pride in her enterprises, which included the installation of a 2450 sq. ft. mosaic, the *Grand Canyons of La Jolla*, installed next to Walter Munk Way in La Jolla Shores, along the beach to the south of Scripps Pier (figure 11).

The mosaic contains 120 life-sized images of species found just offshore and an illustration from Walter’s 1947 paper (4) showing how waves refract as a result of the submarine canyons.

Although Walter tended to discard notes and letters once a project was completed, he donated some personal correspondence and other personal papers to UCSD, where they are now in UCSD Library Special Collections. He gave his later papers to the American Philosophical Society, of which he was a member and enthusiastic supporter.

Walter is survived by Mary, his daughters, Edie and Kendall, and three grandsons. As well as his family legacy, he leaves an immense and enduring scientific legacy of not only scientific discovery but also institutions and a style that combined hard work with a sense of fun and an optimistic outlook. He treated everyone with respect and interest, regardless of their status in science or society.

Walter was also a generous benefactor. In 2014 he arranged that, two years after his death, Seiche would become the property of Scripps Institution of Oceanography, with the understanding that it would be used as the home of the Director or serve whatever purpose the Director felt would benefit Scripps the most. Shortly after Walter’s 100th birthday, he and Mary founded the Walter Munk Foundation for the Oceans to continue his legacy of daring exploration and discovery through scientific research, education and ocean conservation. Plans
include an exchange programme that will bring high school students from Austria to San Diego, repeating the journey that Walter made himself in the 1930s. A continuing goal of the Foundation is to reach across boundaries between generations, nations and disciplines to recognize and promote talent in ocean science and conservation, especially in the next generation.

**RECOGNITION**

We list below many of the awards that Walter received. Concerned about the difficulty of obtaining funding for risky research, he donated his Kyoto Prize of more than $400 000 to Scripps to support 'students engaged in daring research with significant probability of failure', with the further stipulation that the fund be administered by a committee of one: the Director.

Receiving awards and lecturing around the world continued into Walter’s 101st year. He was delighted to be appointed a Chevalier of the French Légion d’honneur in Paris in 2018 and combined the trip with presenting the Roger Revelle Memorial Lecture at UNESCO’s Paris headquarters.

Walter took particular pleasure in having the *Mobula munkiana* (Munk’s Devil Ray) named after him as a tribute by his student and friend, conservationist Giuseppe Notarbartolo di Sciara, who discovered the ray in 1979 in the Gulf of California. The photo of this remarkable fish soaring above the sea (figure 12) somehow conveys the essence of Walter’s spirit and style.

Figure 12. Munk’s Devil Ray (*Mobula munkiana*). (Photograph: Octavio Aburto.) (Online version in colour.)
SIGNIFICANT HONOURS AND AWARDS

1948, 1955, 1962  Guggenheim Fellow
1956  Member, National Academy of Sciences
1957  Fellow, American Academy of Arts and Sciences
1965  Member, American Philosophical Society
1965  Arthur L. Day Medal, American Geological Society
1966  Harald Sverdrup Gold Medal, American Meteorological Society
1968  Gold Medal, Royal Astronomical Society
1970  Member, Deutsche Akademie der Naturforscher Leopoldina
1975  Doctor Philosophiae Honoris Causa, University of Bergen, Norway
1976  Foreign Member, The Royal Society, London
1976  Agassiz Medal, National Academy of Sciences
1976  Maurice Ewing Medal, American Geophysical Union and US Navy
1981  Fulbright Fellow, UK
1985  National Medal of Science
1986  Doctor Philosophiae Honoris Causa, University of Cambridge, England
1989  William Bowie Medal, American Geophysical Union
1993  Vetlesen Prize, Columbia University
1994  Foreign Member, Russian Academy of Sciences
1996  Doctor Philosophiae Honoris Causa, University of Crete, Greece
1999  Kyoto Prize, Inamori Foundation, Japan
2001  Prince Albert I Medal, International Association for the Physical Sciences of the Oceans
2004  Foreign Member, European Academy of Sciences
2010  Crafoord Prize, The Royal Swedish Academy of Sciences
2010  Österreichisches Ehrenzeichen für Wissenschaft und Kunst (Austrian Decoration for Science and Art)
2014  Medal of Honour of the French Navy
2018  Chevalier, Légion d’honneur, France

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Walter’s career and accomplishments have been described in many places listed in the references (30,39,40,44) (Doel 1997; von Storch & Hasselmann 2010; Spindel & Worcester 2016), which have provided much of the information in this memoir. Walter’s own accounts of his life were sometimes unreliable due to inevitable lapses of memory or his enjoyment of good stories, but we have tried to correct inaccuracies. We are grateful to archivists Rachel Roberts of Cheltenham Ladies College and Anne Thomson of Newnham College, Cambridge, for information on Rega’s life. We thank Loma Karklins for accounts of Walter’s time at Caltech. Jennifer Martinez Wormser, library director at Scripps College, kindly dug out information on Ruth Andersson. Walter’s nephews, Peter Munk and Glenn Clark, and his great-niece, Liza Munk, generously provided information on their family, particularly on Walter’s mother, Rega Brunner. Her life deserves a separate account. We also thank Mary Munk, Mary Ellen Paci (née Revelle), Edie and Kendall Munk and Deborah Day for providing helpful information, and them and many scientific colleagues for providing feedback and advice.

Unless otherwise indicated, all photographs were from Walter’s personal collection, and used with kind permission from the family. The portrait photograph was kindly provided by Special Collections & Archives, UC San Diego.
Walter Heinrich Munk

REFERENCES TO OTHER AUTHORS

Aaserud, F. 1986 Oral history interview of Walter Munk for the American Institute of Physics. Transcript available at https://www.aip.org/history-programs/niels-bohr-library/oral-histories/4790.

Baker, D. J. & Zall, L. 2020 The MEDEA program: opening a window into new Earth science data. Oceanography 33(1), 20–31. (https://doi.org/10.5670/oceanog.2020.104)

Bascom, W. 1961 A hole in the bottom of the sea: the story of the Mohole Project. Garden City, NY: Doubleday & Company, Inc.

Cairns, J. L. 1975 Internal wave measurements from a mid water float. J. Geophys. Res. 80, 299–306. (doi:10.1029/JC080i003p00299)

Cairns, J. L. & Williams, G. O. 1976 Internal wave observations from a mid water float: part 2. J. Geophys. Res. 81, 1943–1950. (doi:10.1029/JC081i012p01943)

Clark, G. 2010 An autobiography (abbreviated and slightly revised by Rega Wood). In touch: the newsletter of the American friends of the Jewish Museum Hohenems, Inc. 11(2), 12–16.

Crowell, J. 2011 Surf forecasting for invasions during World War II. Santa Cruz, CA: Marty Magic.

Doel, R. 1997 Interview with Walter Munk. Transcript available at https://library.ucsd.edu/speccoll/siooralhistories/Doel-Munk.pdf.

Finkbeiner, A. 2006 The Jasons: the secret history of science’s postwar elite. New York: Viking Penguin.

Flatté, S. M. 1984 Sound transmission through internal waves, including internal wave tomography. In A celebration in geophysics and oceanography – 1982: in honor of Walter Munk on his 65th birthday, October 19, 1982 (ed. C. Garrett & C. Wunsch), pp. 104–112. Scripps Institution of Oceanography Reference Series 84–85. La Jolla, CA: University of California San Diego. (https://igpp.ucsd.edu/sites/default/files/65th_munk_volume_0.pdf)

Fleming, J. R. 2004 Sverre Petterssen and the contentious (and momentous) weather forecasts for D-Day. Endeavour 28(2), 59–63. (doi:10.1016/j.endeavour.2004.04.007)

Gill, A. 1984 Walter, Aristotle and the tides of the Euripus. In A celebration in geophysics and oceanography – 1982: in honor of Walter Munk on his 65th birthday, October 19, 1982 (ed. C. Garrett & C. Wunsch), pp. 96–99. Scripps Institution of Oceanography Reference Series 84–85. La Jolla, CA: University of California San Diego. (https://igpp.ucsd.edu/sites/default/files/65th_munk_volume_0.pdf)

Gregg, M. C. 1989 Scaling turbulent dissipation in the thermocline. J. Geophys. Res. 94 (C7), 9686–9698. (doi:10.1029/JC094iC07p09686)

Hasselmann, K. 1984 The science and art of wave prediction: an ode to HO601. In A celebration in geophysics and oceanography: 1982: in honor of Walter Munk on his 65th birthday, October 19, 1982 (ed. C. Garrett & C. Wunsch), pp. 31–37. Scripps Institution of Oceanography Reference Series 84–85. La Jolla, CA: University of California San Diego. (https://igpp.ucsd.edu/sites/default/files/65th_munk_volume_0.pdf)

Holmes, D. & Silverman, L. (eds). 2009 Interwar Vienna: culture between tradition and modernity. Rochester, NY: Camden House.

Howe, B. M., Miksis-Olds, J., Rehm, E., Sagen, H., Worcester, P. F. & Haralabus, G. 2019 Observing the oceans acoustically. Front. Mar. Sci. 6, 426. (https://doi.org/10.3389/fmars.2019.00426)

Marshall, J., Adcroft, A., Hill, C., Perelman, L. & Heisey, C. 1997 A finite-volume, incompressible Navier Stokes model for studies of the ocean on parallel computers. J. Geophys. Res. 102, 5753–5766. (doi:10.1029/96JC02775)

Mikhailovsky, P. N. & Gavrilov, A. N. 2001 Acoustic thermometry in the Arctic Ocean. Polar Res. 20(2), 185–192. (doi:10.3402/polar.v20i2.6516)

Mitrovica, J. X., Hay, C. C., Morrow, E., Kopp, R. E., Dumberry, M. & Stanley, S. 2015 Reconciling past changes in Earth’s rotation with 20th century global sea-level rise: resolving Munk’s enigma. Sci. Adv. 1(11), e1500679. (https://doi.org/10.1126/sciadv.1500679)

Parker, B. 2010 The power of the sea: tsunamis, storm surges, rogue waves, and our quest to predict disasters. New York: St Martin’s Press.

R. C. & Worcester, P. F. 2016 Walter H. Munk: seventy-five years of exploring the seas. Acoust. Today 12(1), 36–42.
Treasure, A. M., Roquet, F., Ansorge, I. J., Bester, M. N., Boehme, L., Bornemann, H., Charrassin, J.-B., Chevalier, D., Costa, D. P., Fedak, M. A., Guinet, C., Hammill, M. O., Harcourt, R. G., Hindell, M. A., Kovacs, K. M., Lea, M.-A., Lovell, P., Lowther, A. D., Lydersen, C., McIntyre, T., McMahon, C. R., Mueltbert, M. M. C., Nicholls, K., Picard, B., Reverdin, G., Trites, A. W., Williams, G. D. & de Bruyn, P. J. N. 2017 Marine mammals exploring the oceans pole to pole: a review of the MEOP consortium. Oceanography 30(2), 132–138. (doi:10.5670/oceanog.2017.234)

Tukey, J. W. 1984 Styles of spectrum analysis. In A celebration in geophysics and oceanography – 1982: in honor of Walter Munk on his 65th birthday, October 19, 1982 (ed. C. Garrett & C. Wunsch), pp. 99–103. Scripps Institution of Oceanography Reference Series 84–85. La Jolla, CA: University of California San Diego. (https://igpp.ucsd.edu/sites/default/files/65th_munk_volume_0.pdf)

von Storch, H. & Hasselmann, K. 2010 Seventy years of exploration in oceanography: a prolonged weekend discussion with Walter Munk. London: Springer. (https://doi.org/10.1007/978-3-642-12087-9)

Worcester, P. F. & Spindel, R. C. 2005 North Pacific Acoustic Laboratory. J. Acoust. Soc. Am. 117(3), 1499–1510. (doi:10.1121/1.1854780)

BIBLIOGRAPHY

The following publications are those referred to directly in the text. A full bibliography is available as electronic supplementary material at https://doi.org/10.6084/m9.figshare.c.5107165.

(1) 1941 Internal waves in the Gulf of California. J. Mar. Res. 4(1), 81–91.
(2) 1946 Theoretical and empirical relations in forecasting breakers and surf. Trans. Am. Geophys. Union 27(6), 828–836. (doi:10.1029/TR027i006p00828)
(3) 1947 (With H. U. Sverdrup) Wind, sea and swell: theory of relations for forecasting. Scripps Institution of Oceanography new series no. 303, HO publ. no. 601. Washington DC: United States Navy Department, Hydrographic Office.
(4) 1947 (With M. A. Traylor) Refraction of ocean waves: a process linking underwater topography to beach erosion. J. Geol. 55(1), 1–26. (doi:10.1086/625388)
(5) 1948 (With E. R. Anderson) Notes on a theory of the thermocline. J. Mar. Res. 7(3), 276–295.
(6) 1950 On the wind-driven ocean circulation. J. Meteorol. 7(2), 79–93.
(7) 1950 (With G. F. Carrier) The wind-driven circulation in ocean basins of various shapes. Tellus 2(3), 158–167. (doi:10.3402/tellusa.v2i3.8550)
(8) 1951 (With E. Palmén) Notes on the dynamics of the Antarctic circumpolar current. Tellus 3(1), 53–55. (doi:10.3402/tellusa.v3i1.8609)
(9) 1952 (With G. Riley) The absorption of nutrients by aquatic plants. J. Mar. Res. 11(2), 215–240.
(10) 1954 The delayed hot-water problem. J. Appl. Mech. 21(2), 193.
(11) 1954 (With C. Cox) Statistics of the sea surface derived from sun glitter. J. Mar. Res. 14(1), 63–78.
(12) 1956 (With F. Snodgrass & G. Carrier) Edge waves on the continental shelf. Science 123(3187), 127–132. (doi:10.1126/science.123.3187.127)
(13) 1957 (With F. E. Snodgrass) Measurements of southern swell at Guadalupe Island. Deep-Sea Res. 4, 272–286. (doi:10.1016/0146-6313(56)90061-2)
(14) 1957 (With M. J. Tucker & F. E. Snodgrass) Remarks on the ocean wave spectrum. In Symposium on naval hydrodynamics, publ. no. 515, pp. 45–60. Washington DC: National Academy of Science and US National Research Council. (https://doi.org/10.5962/bhl.title.38156)
(15) 1959 (With B. Haurwitz & H. Stommel) On the thermal unrest in the ocean. In The atmosphere and the sea in motion: scientific contributions to the Rossby memorial volume (ed. B. Bolin), pp. 74–94. New York: The Rockefeller Institute Press. (https://math.nyu.edu/~gerber/courses/2018-fruhling/bolin_et_al-atmosphere_sea_in_motion-1959.pdf)
(16) 1960 (With G. J. F. MacDonald) The rotation of the Earth: a geophysical discussion. Cambridge University Press.
(17) 1964 (With E. C. Bullard, F. E. Oglebay & G. R. Miller) A user's guide to BOMM: a system of programs for the analysis of time series. La Jolla, CA: Institute of Geophysics and Planetary Physics, University of California.

(18) 1965 (With E. C. Bullard, F. E. Oglebay & G. R. Miller) Tidal cusp analysis. Geophys. J 10, 211–219. (doi:10.1111/j.1365-246X.1965.tb03062.x)

(19) 1966 (With D. E. Cartwright) Tidal spectroscopy and prediction. Phil. Trans. R. Soc. Lond. A 259(1105), 533–581. (doi:10.1098/rsta.1966.0024)

(20) 1966 Abyssal recipes. Deep-Sea Res. 13, 707–730. (doi:10.1016/0011-7471(66)90602-4)

(21) 1968 Once again – tidal friction (Harold Jeffreys Lecture). Q. J. R. Astron. Soc. 9(4), 352–375.

(22) 1969 (With C. J. R. Garrett) The age of the tide and the ‘Q’ of the oceans. Deep-Sea Res. 18, 493–503. (doi:10.1016/0011-7471(69)90073-8)

(23) 1970 (With C. Garrett) Space-time scales of internal waves. Geophys. Fluid Dyn. 2, 225–264. (doi:10.1080/030919270283682)

(24) 1972 (With J. Munk) Venice hologram. Proc. Am. Phil. Soc. 116(5), 415–442.

(25) 1974 (With J. F. Asmus & C. G. Murphy) Studies on the interaction of laser radiation with art artifacts. Proc. SPIE Conf., 27–29 Aug. 1973, San Diego 41, 19–27.

(26) 1975 (With C. Garrett) Space-time scales of internal waves: a progress report. J. Geophys. Res. 80(3), 291–297. (doi:10.1029/JC080i003p00291)

(27) 1977 (With C. Garrett) Internal waves in the ocean. Ann. Rev. Fluid Mech. 11, 339–369. (doi:10.1146/annurev.fl.11.010179.002011)

(28) 1977 (With S. M. Flatté, R. Dashen, K. M. Watson & F. Zachariasen) Sound transmission through a fluctuating ocean. Cambridge University Press.

(29) 1980 Internal waves and small scale processes. Evolution of physical oceanography: scientific surveys in honor of Henry Stommel (ed. B. A. Warren & C. Wunsch), pp. 264–291, Boston: MIT Press.

(30) 1981 Affairs of the sea. In A celebration in geophysics and oceanography – 1982: in honor of Walter Munk on his 65th birthday, October 19, 1982 (ed. C. Garrett & C. Wunsch), pp. 3–23. Scripps Institution of Oceanography Reference Series 84–85. La Jolla, CA: University of California San Diego. (https://igpp.ucsd.edu/sites/default/files/65th_munk_volume_0.pdf)

(31) 1990 (With A. Baggeroer) The Heard Island feasibility test. Phys. Today 45(9), 22–30. (doi:10.1063/1.8131)

(32) 1992 (With A. Baggeroer) The Heard Island papers: a contribution to global acoustics. J. Acoust. Soc. Am. 96(4), 2327–2329. (doi:10.1121/1.411316)

(33) 1993 (With R. Spindel, A. Baggeroer & T. Birdsall) The Heard Island feasibility test. J. Acoust. Soc. Am. 96(4), 2338–2342. (doi:10.1121/1.410105)

(34) 1994 (With P. Worcester & C. Wunsch) Ocean acoustic tomography. Cambridge University Press.

(35) 1997 Once again: once again – tidal friction. Prog. Oceanogr. 40, 7–35. (doi:10.1016/S0079-6611(97)00021-9)

(36) 1998 (With C. Wunsch) Abyssal recipes II: energetics of tidal and wind mixing. Deep-Sea Res Part I. 45, 1977–2010. (doi:10.1016/S0967-0637(98)00070-3)

(37) 2000 (With L. Armi, K. Fischer & F. Zachariasen) Spirals on the sea. Proc. R. Soc. Lond. A 456, 1217–1280. (doi:10.1098/rspa.2000.0560)

(38) 2002 Twentieth century sea level: an enigma. Proc. Natl Acad. Sci. USA 99, 6550–6555. (doi:10.1073/pnas.9902704599)

(39) 2002 (With D. Day) Harald U. Sverdrup and the war years. Oceanography 15(4), 8–29.

(40) 2004 (With D. Day) IVY-MIKE. Oceanography 17(2), 96–105. (doi:10.5670/oceanog.2004.53)

(41) 2005 (With P. F. Worcester & R. C. Spindel) Acoustic remote sensing of ocean gyres. Acoust. Today 1, 11–17. (doi:10.1121/1.2961121)

(42) 2006 (With J. A. Colosi) Tales of the venerable Honolulu tide gauge. J. Phys. Oceanogr. 36(6), 967–996. (doi:10.1175/JPO2876.1)

(43) 2008 (With W. E. Farrell) What do deep sea pressure fluctuations tell about short surface waves? Geophys. Res. Lett. 35, L19605. (https://doi.org/10.1029/2008GL035008)
(44) 2008  (With D. Day) Glimpses of oceanography in the postwar period. *Oceanography* **21**(3), 14–21. (doi:10.5670/oceanog.2008.30)

(45) 2009  An inconvenient sea truth: spread, steepness and skewness of surface slopes. *Ann. Rev. Mar. Sci.* **1**, 377–415. (https://doi.org/10.1146/annurev.marine.010908.163940)

(46) 2015  (With P. N. Mikhalevsky, H. Sagen, P. F. Worcester, A. B. Baggeroer, J. Orcutt, S. E. Moore, C. M. Lee, K. J. Vigness-Raposa, L. Freitag, M. Arrott, K. Atakan, I. A. Besczczyska-Möller, T. F. Duda, B. D. Dushaw, J. C. Gascard, A. N. Gavrilov, H. Keers, A. K. Morozov, M. Rixen, S. Sandven, E. Skarsoulis, K. M. Stafford, F. Vernon & M. Y. Yuen) Multipurpose acoustic networks in the integrated Arctic Ocean observing system. *Arctic* **68**, Suppl. 1. (https://doi.org/10.14430/arctic4449)