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TELLUS

The sound of climate change

By WALTER MUNK*, *Scripps Institution of Oceanography, University of California at San Diego, La Jolla, CA 92093-0225, USA*

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ABSTRACT

It came as a great shock in the 1960s that the oceans, like the atmosphere, have an active *weather* (i.e. ocean storms are called eddies). The traditional expedition mode of individual research vessels making independent measurements was no longer adequate. Ocean Acoustic Tomography was developed in direct response to the 'eddie revolution'. Sound travels faster in warmer water; acoustic waves transmitted from ship to ship give information about the temperature and currents in the *intervening* waters. The transmission scale has widened over the years from 100 to 1000 to 10 000 km, approaching the antipodal scale of Ewing's 1960 transmission from Perth (Australia) to Bermuda. In 1991 we successfully transmitted from a source ship on Heard Island in the Indian Ocean to receiver ships in the north and south Atlantic and Pacific Oceans. Brian Dushaw is planning to repeat Ewing's experiment; he expects a reduction in travel time of approximately 10 s as confirmation of global ocean warming over the last 50 yr.

Sea level rose 15 cm in the 20th century. The rate has since doubled; values up to 2 m by 2100 are now being quoted. To make accurate predictions we must understand the melting processes of continental ice sheets. Floating ice sheets from Antarctic and Greenland glaciers cover huge ocean caverns that have not to date been accessible to observation. We propose probing these caverns with sound waves to study the ocean dynamics at the underside of the floating ice sheets: a daring venture.

1. Introduction

In the summer of 1939, I applied to Scripps for an undergraduate student summer job. The Norwegian oceanographer Harald Sverdrup had returned from 7 yr in the Arctic to become the third Scripps director. Some years later I became his Ph.D student (Fig. 1). There is a direct line from being Sverdrup's student to receiving the Crafoord Prize tomorrow.

One of my earliest memories is listening to Sverdrup talk about his arctic experiences and the ill-fated attempts of the submarine *Nautilus* to dive under the ice. He told about glaciers flowing into the sea until they come off the bottom at the 'grounding line' and continue for long distances as floating ice tongues (Fig. 2). In the process they thin from 2 km (say) at the grounding line to $^1/_2$ km at the ice edge, loosing mass by melting on the underside in contact with a warmer ocean cavern. The underice cavern may stretch for a 100 km. And Sverdrup emphasized that we know nothing about this ocean cavern, not a single observation. This was true 60 yr ago, and is nearly so today. I will return to this topic at the end of my talk.

The following summer saw the start of World War II. Following military service, I joined Scripps in the war efforts. In 1942, we were told of the Allied preparations for an amphibious winter landing on the northwest coast of Africa. The winter surf in this region was known to be atrocious. It was important to pick the one out of three days when the waves are suitable for a landing. Sverdrup and I started working on a method for wave prediction, consisting of (i) computing the dimensions of waves leaving a given storm area (using weather predictions); (ii) allowing for the decay of waves between a distant storm and the landing beaches and (iii) computing the major transformation in shallow water leading to wave breaking. The African landing took place during favourable conditions (on hindsight with a strong element of luck). Wave predictions were used in subsequent landings during the Pacific Theatre of War, and ultimately for the landings in Normandy. As far as I know, there had been no previous attempt at predicting *Sea*, *Swell* and *Surf.* This is hard to believe when today, in my home town of La Jolla, every surfer routinely listens to the daily wave forecast to select the surf board most suitable for today's predicted wave character.

With the end of the war I returned to Scripps, and for the next 30 yr worked on waves of increasingly longer period, ending up with waves of tidal period.

2. The mesoscale revolution

Until the 1970s the oceans were generally viewed to be in a near steady state condition. If you asked what would be considered

*Corresponding author
e-mail: wmunk@ucsd.edu
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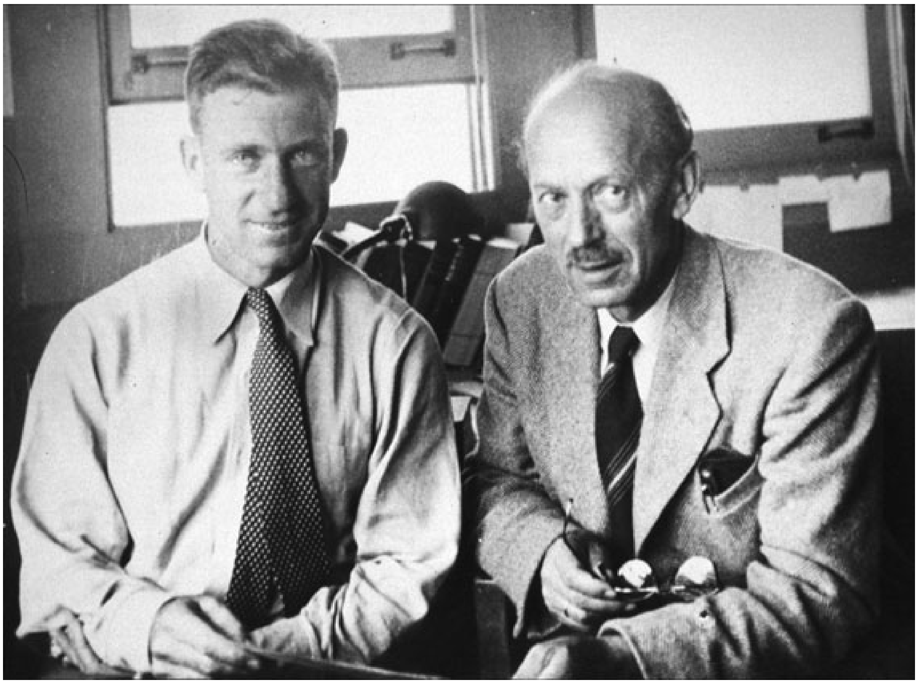

Fig. 1. Harald U. Sverdrup, Director of Scripps Institution of Oceanography, and Walter Munk in George Scripps Hall (1940). Sverdrup was working on his epic 'The Oceans'. There is a direct line from being Sverdrup's student to receiving the Crafoord Prize.

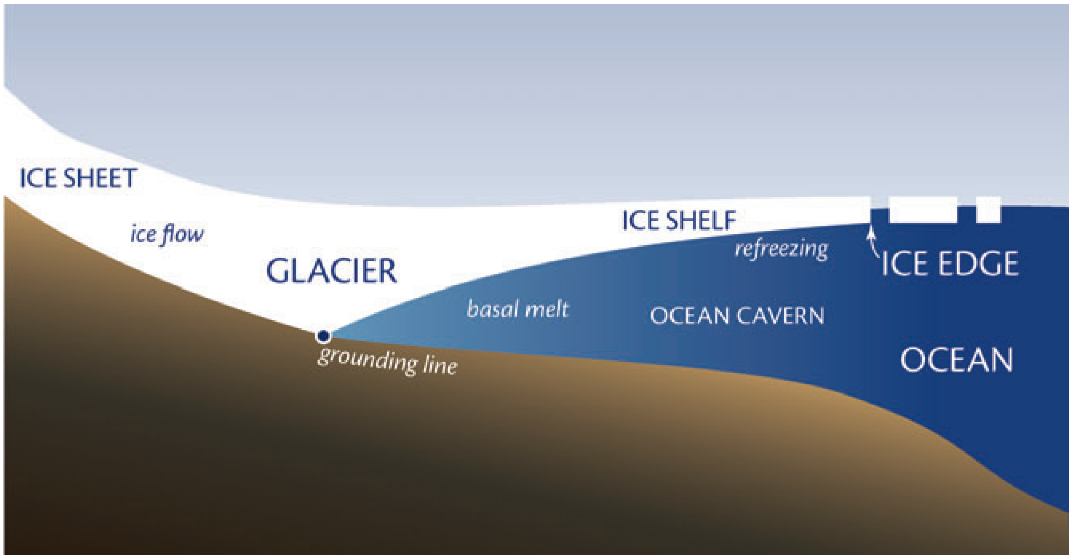

Fig. 2. Cartoon of a glacier sliding into the sea. The glacier comes off the bottom at the grounding line and continues moving seaward as a floating ice shelf covering the ocean cavern.

a typical velocity (away from the intensive boundary currents) you would get an order of magnitude estimate of 10 ± 1 cm s^{-1}. (Today we know that 1 ± 10 cm s^{-1} is more representative.) For a century, since the great *Challenger Expedition*, we had ignored *ocean weather*. Changes from station to station were attributed to changes in position, not changes in time. This point of view was aided by the tradition never to occupy a station twice. And in the rare instances when this happened, one could attribute changes to a malfunctioning of instruments.

The MODE expedition in the late 1970, made the steady-state view untenable. We now know that over 90% of the ocean kinetic energy is associated with ocean weather (mesoscale dynamics). The traditional expedition mode of a few oceanographic vessels chasing independently through the worlds oceans was not up

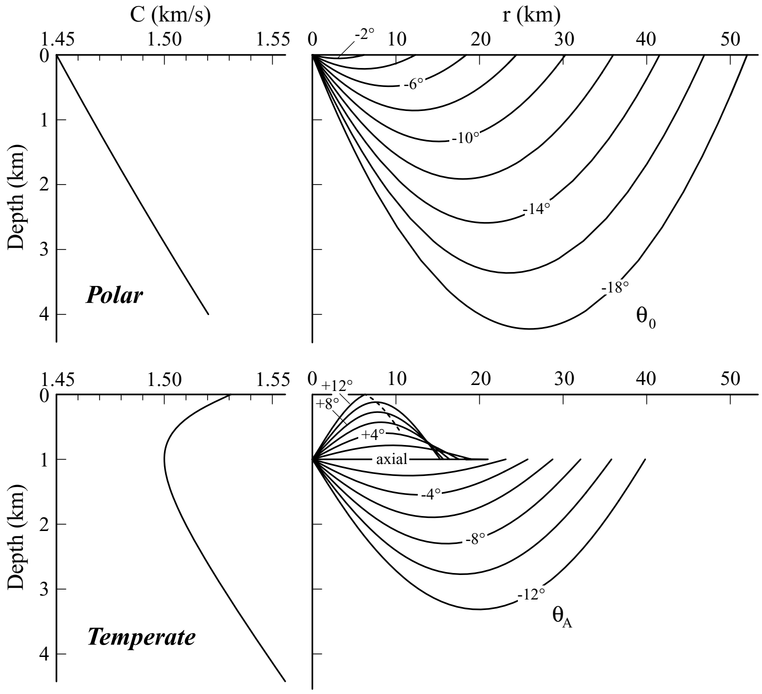

Fig. 3. Ray diagrams for the polar and temperate sound-speed profiles. The vertical launch angles θ_0 are indicated. Sources are at the surface and axis, respectively. Rays tend to focus at various ranges, giving rise to 'convergence zones'(Munk et al., 1995, p. 37). Ocean Acoustic Tomography, by Walter Munk, Peter Worcester and Carl Wunsch. Copyright © 1995 Cambridge University Press. Reprinted with permission.

to the charge. Carl Wunsch and I agonized about the challenge and came up with 'Ocean Acoustic Tomography' (the name was deliberately obscure so people would be curious of what it was all about). The speed of sound increases by 5 m s^{-1} per °C; so the time it takes to go from A to B is a measure of the temperature of the intervening water. There are a multitude of ray paths (Fig. 3); early arrivals sample the ocean from top to bottom, late arrivals are increasingly concentrated along the 'sound axis' (a sound speed minimum typically at 1 km depth). In polar latitudes (Fig. 3. upper panel) rays are surface reflected and bottom refracted. In the case of propagation in ocean caverns covered by floating ice sheets there is additional horizontal refraction; a sound beam injected at the ice edge will eventually be turned back towards the ice edge. The multitude of ray traveltimes can be 'inverted' to provide the depth *profile* of the intervening water temperature. Subtracting travel times A → B from B → A yields the depth profile of *velocity* of the intervening water. Further, the speed of sound in water (3000 knots) greatly exceeds that of mesoscale eddies, so the measurement is virtually synchronous. The same cannot be said for oceanographic vessels moving at 10 knots.

Figure 4 compares AXBT mapping with tomographic mapping using a receiver ship making 135 receiving stops. Medical CAT scans (for computer aided tomography) typically consist of 10^4 to 10^5 scans leading to high-resolution images. (The 'tomography theorem' proves that the error goes to zero for an infinite number of scans.)

But the important consideration here is that the low attenuation of low frequency sound in the ocean permits long transmission ranges. We soon went from 100 km acoustic ranges (suppressing internal wave 'noise') to 1000 km (suppressing mesoscale noise) to 10 000 km climate scale experiments. Here acoustics is at its best. The horizontal averaging inherent in the acoustic transmissions favours the detection of the large scale climate signals; 'noise' associated with small scale internal waves and mesoscale is traditionally suppressed by the square-root of *n* averaging.

3. Perth to Bermuda transmission of 1960

In March 1960, in an almost casual add-on to a geophysical survey, the R/V *Vema* and the HMAS *Diamantina* fired 3000-pound charges off Perth, Australia (Fig. 5). The three detonations at 5-min intervals, were clearly recorded at Bermuda, halfway around the globe, each consisting of two pulses separated by 30 s. As first reported by John Ewing (Maurice Ewing's brother) in *Notes and Personalia* (Ewing, 1960), the recording was considered particularly remarkable as the great circle is blocked by Kerguelen Bank and the Crozet Islands. The expedition report (Shockley et al., 1982) followed in 22 yr. Munk et al. (1988) replaced the great circle by geodesics to allow for the Earth's equatorial bulge. The resulting path is up to 4° latitude south of the great circle and avoids the Kerguelen collision but comes uncomfortably close to the South American continent. But when refraction by the mean climatological north–south temperature gradient is taken into account, the geodesic is moved way up north and collides with South Africa. The path constructions ignored refraction in shallow water and its dependence on

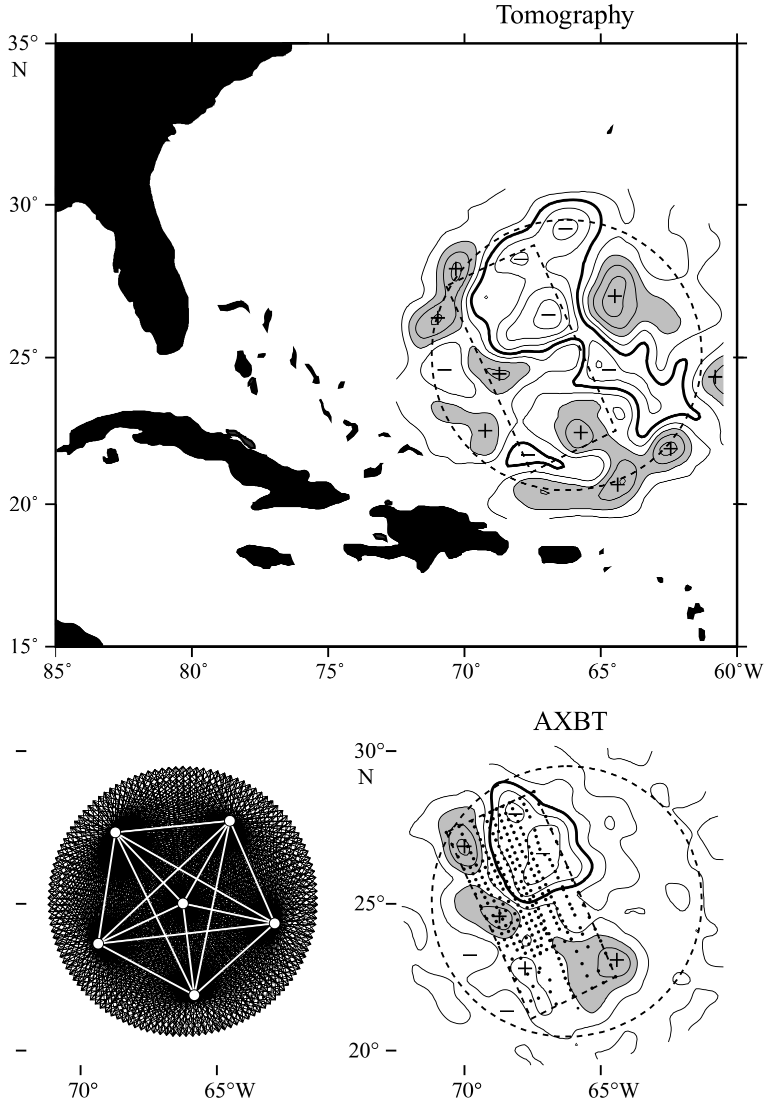

Fig. 4. Sound-speed perturbations from the climatological mean in 1-m s^{-1} (0.25 °C) contours at 700 m depth, as measured during the Moving Ship Tomography Experiment, 15–30 July 1991 (AMODE-MST Group, 1994). Five of the moorings are in a pentagon 700 km in diameter, with the sixth mooring in the center. The receiving ship moved around a 1-Mn circle, making 135 receiving stops. Rays from each of the moorings to the receiving stops are shown to the lower left. For comparison with the tomography map (using acoustic data only), a map using only AXBT data at 700 m is shown at the lower right (Munk et al., 1995, p. 26). Ocean Acoustic Tomography, by Walter Munk, Peter Worcester and Carl Wunsch. Copyright © 1995 Cambridge University Press. Reprinted with permission.

frequency and mode number of the explosion signal. Taking all this into account, Heaney et al. (1991) was able to construct two bundles of geodesics, a northern bundle passing near South Africa, and a southern bundle passing near South America. Computed travel times are not inconsistent with the recorded first and second pulse arrivals. In a final calculation, Brian Dushaw (personal communication, 2010) allowed for refraction by mesoscale eddies in accordance with the Ecco2 numerical model (acoustic rays are repelled by warm water and by shallow water). His monthly snapshots record occasional hits on Bermuda. Dushaw has proposed a repeat of the 1960 transmission. The expected 10 s reduction in travel time would be a nice confirmation of 50 yr of global ocean warming (Fig. 6).

As a result of my work with the Perth-Bermuda transmission I had developed an antipodal obsession. Could we monitor large-scale climatic temperature changes with nonexplosive acoustic devices?

4. The Heard Island feasibility test 1991

At 0000UTC on 26 January 1991 the acoustic source ship R/V *Cory Chouest* started transmitting from the south side of Heard Island, and uninhabited Australian island in the southern Indian Ocean (Fig. 7). The location had been selected because of its unique global access. Oceanographers from nine countries participated informally but very effectively. The signal was received at 15 sites distributed in the North and South Atlantic, the North and South Pacific, the Indian Ocean and the southern Oceans. (A site in the Tasman Sea encountered unexpected bathymetric blockage.) Pre-expedition

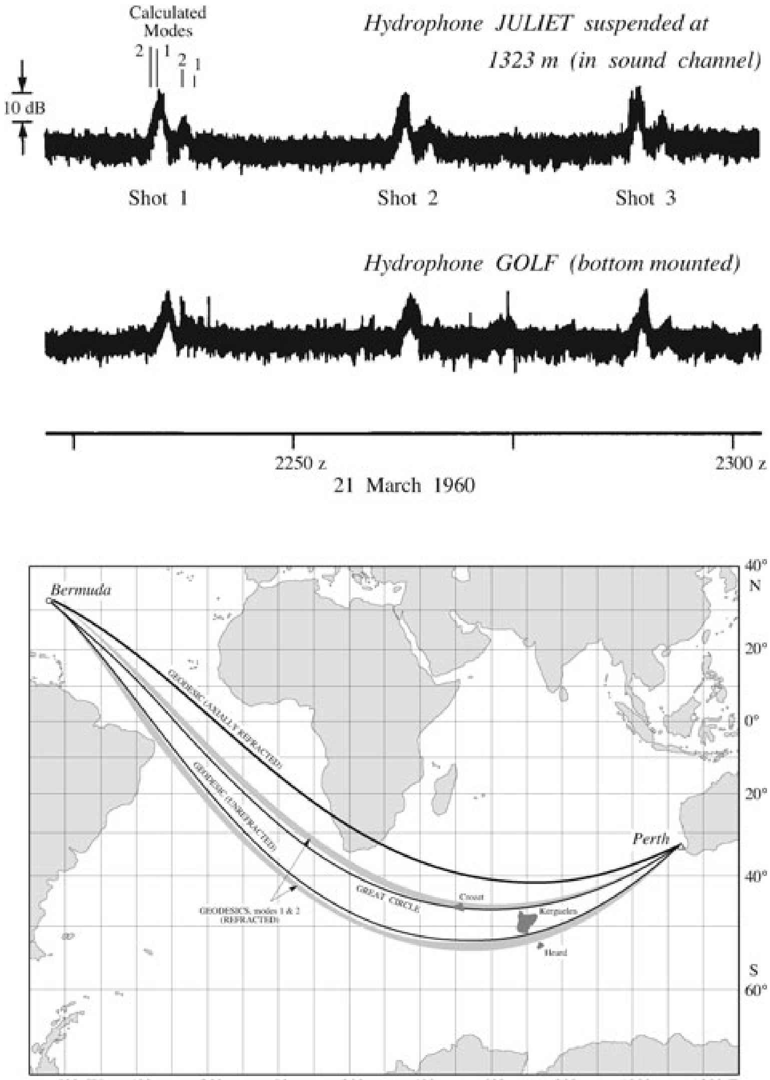

Fig. 5. Three detonations at 5-min intervals off Perth, Australia, were clearly recorded at Bermuda, halfway around the globe. The computed arrival times for modes 1 and 2 are indicated in the upper left corner (Munk et al., 1995, p. 330). Ocean Acoustic Tomography, by Walter Munk, Peter Worcester and Carl Wunsch. Copyright © 1995 Cambridge University Press. Reprinted with permission.

estimates of detection had ranged from impossible to barely possible.

Each transmission consisted of 1 h of M-code at 57 Hz with source level of 221 dB re 1 μPa at 1 m (Munk et al., 1995, p. 194). The coded signal permitted coherent processing gain not available in the analysis of the explosive Perth source.

The Heard Island Test afforded the opportunity to compare the computed geodesics with observations. The source ship was steered as closely as possible to a straight and steady course, necessarily directed into the prevailing wind and sea. If the ship's heading were directly along the geodetic launch azimuth, we would expect a positive Doppler consistent with the ship's total speed; at right angle this would give zero Doppler. We derived a launch azimuth to a station on Ascension Island (at 10 000 km distance) of $268.1^\circ \pm 0.1^\circ$ compared with 268.05° for the refracted geodesic of mode 1 at 57 Hz. The corresponding angle for the nonrefracted geodesic is 265.9°.

After 6 d of transmission we encountered a gale and all ten sources were demolished. Still from the point of view of the feasibility of acoustic global ocean temperature monitoring, the test was a success. (In order to stay within a given climate province, ranges beyond 10 000 km should be avoided). Eighteen publications under the heading 'The Heard Island Papers: A Contribution to Global Acoustics' were collected in a special volume of the *Journal of the Acoustical Society of America* (1994, **96**(4)). Mode stripping and mode repopulation associated with the crossing of the Antarctic Circumpolar Front and other major oceanic and bathymetric features were recognized as fundamental features in global acoustics.

From the point of view of establishing a global network, Heard Island was a failure. We should have been on guard; 4 months after our return, *Der Spiegel* reported on the expedition under the heading 'Radau in der Tiefe'. And some years later, the Los

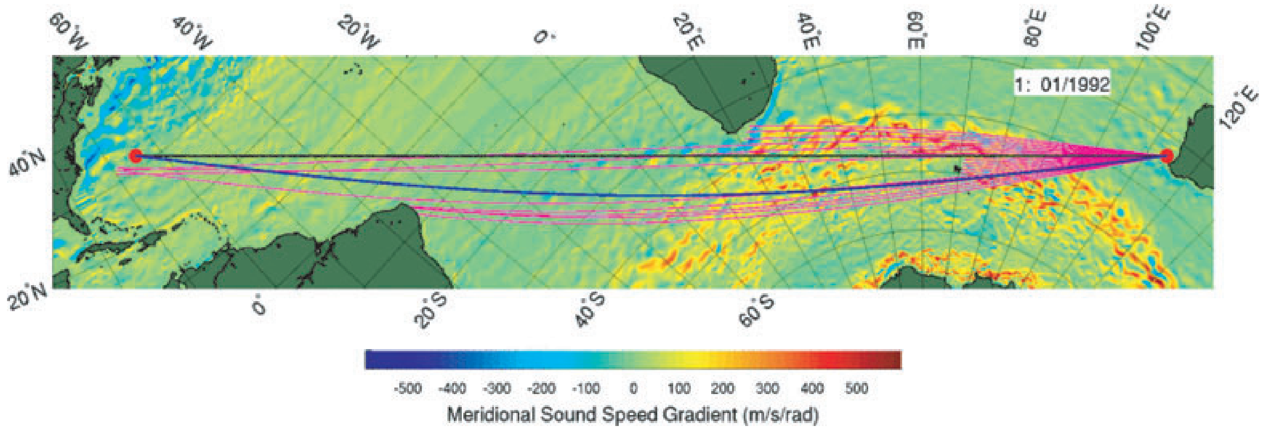

Fig. 6. The 1960 acoustic transmission from Perth Australia to Bermuda. The great circle path (black) is blocked by Kerguelen Bank. The geodesic (blue) allows for the earth equatorial bulge; it avoids Kerguelen Bank but comes uncomfortably close to the South American Continent. When the mean climatological temperature gradient is taken into account, the geodesic path is moved north and collides with Africa. A movie of consisting of monthly snapshots gives occasional arrivals at Bermuda.

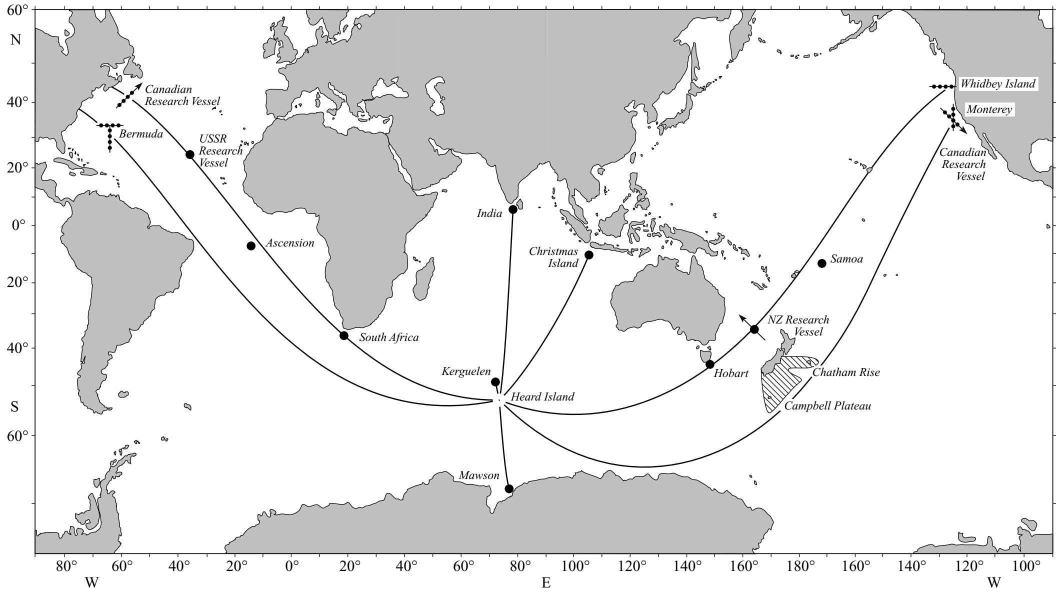

Fig. 7. Heard Island Feasibility Test. The sources were suspended from the center well of the R/V *Cory Chouest* 50 km southeast of Heard Island. Black circles indicate receiver sites. Horizontal lines represent horizontal receiver arrays off the American West Coast and off Bermuda. Vertical lines designate vertical arrays off Monterey and Bermuda. Lines with arrows off California and Newfoundland indicate Canadian towed arrays. Ray paths from the source to receiver are along refracted geodesics, which would be great circles but for the Earth's non-spherical shape and the ocean's horizontal sound-speed gradients. Signals were received at all sites except the vertical array at Bermuda, which sank, and the Japanese station off Samoa (Munk et al., 1995, p. 337). Ocean Acoustic Tomography, by Walter Munk, Peter Worcester and Carl Wunsch. Copyright © 1995 Cambridge University Press. Reprinted with permission.

Angeles Times wrote in a headline article (later retracted) that our plans for acoustically monitoring the North East Pacific Ocean would lead to the death of 750 000 California Gray Whales. As far as we can ascertain, we have not harmed a marine mammal in 30 yr of seagoing experiments. Although we have been able to continue our research, we have not been able to put to rest the opposition from a significant component of the environmental community.

5. Caverns measureless to man

In Xanadu did Kubla Khan
A stately pleasure-dome decree:
Where Alph, the sacred river, ran
Through caverns measureless to man
Down to a sunless sea.
Coleridge 1816

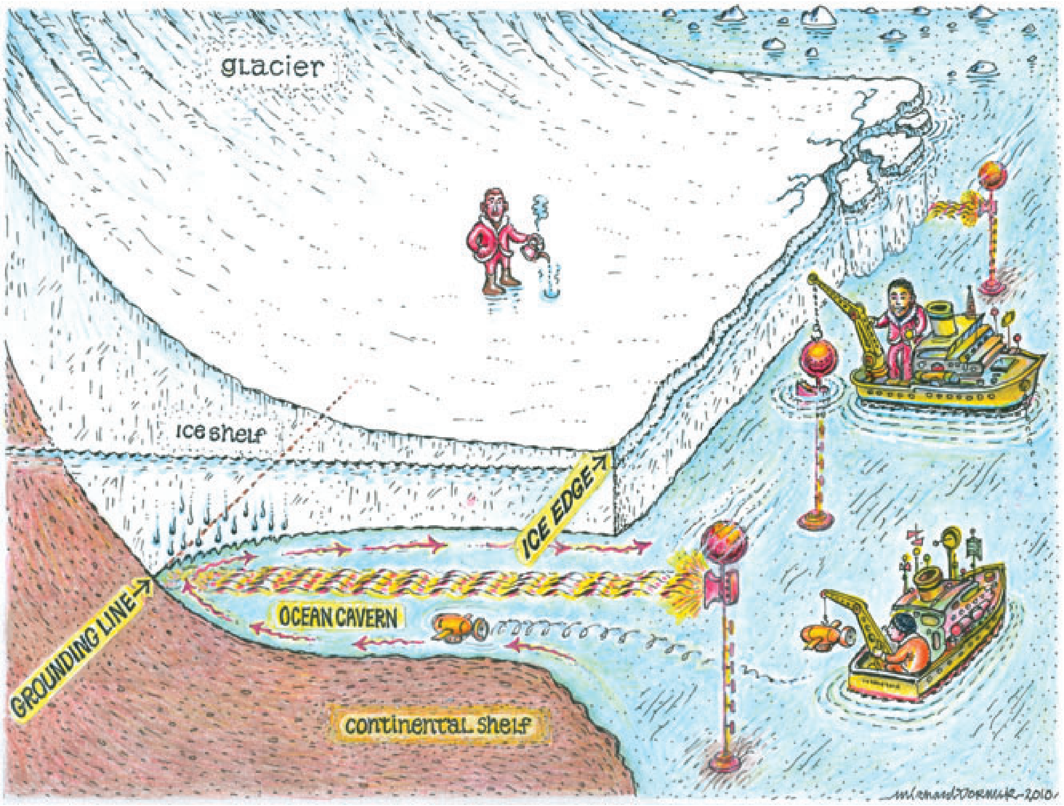

Fig. 8. A cartoon of measurements of the ocean cavern. A hole is being drilled from above by for lowering instruments into the cavern. AUV's are being released at the ice edge for penetration into the cavern. Finally, two acoustic arrays are transmitting sound waves into the cavern (Cartoon by Michael Dormer).

Back to the future (Fig. 2). When Harald Sverdrup vented his frustration that nothing was known about the ocean caverns underneath the floating ice sheets, he had in mind the effect of climate change on sea level. A rise by 1m would displace 100 million people!

The 20th century rise by 15 cm consisted of two parts: 5 cm due to thermal expansion of the oceans and 10 cm from melting of continental ice sheets. The present rate is by 30 cm per century with thermal expansion playing a minor role. Antarctic and Greenland glaciers migrate into the sea, coming off the bottom at the grounding line and continuing their seaward migration as floating ice sheets to an ice edge. The distance from the grounding line to the ice edge can be hundreds of kilometres. By the time the ice sheet reach the ice edge to disintegrate into floating icebergs, its thickness is but a fraction of the thickness at the grounding line. Most of the discharge is associated with melting at the underside of the ice seaward of the grounding line and not with carving at the ice edge. Melting of floating ice does not, of course, directly contribute to sea level rise. But it is part of the dynamics governing the location of the grounding line. Each coastward displacement by 1 km of the Antarctic grounding lines raises global sea level by 10 cm.

When Sverdrup returned from 7 yr in the arctic, the ocean caverns were 'measureless to man'. Now, 60 yr later, not much has changed. A few holes are being drilled into the floating ice sheets (Fig. 8). Instruments lowered into the ocean caverns will provide some welcome information about the melting process. A few instrumented AUV's have been launched into the caverns at the ice edge. GPS through the ice is not possible, and navigation is a bit of a nightmare.

I propose that these efforts be augmented by acoustic monitoring, with source and receiver arrays deployed just seaward of the ice edge (but reaching no higher than the underside of the ice sheets). Sound rays transmitted into the caverns are refracted by the converging cavern and eventually reach a coastal turning point from which they return seaward. (This is related to the coastal 'reflections' by South Africa and South America of the Perth-to-Bermuda transmissions.) To assure that multiple reflections from the bottom and ice boundaries are beyond the critical angle (nonabsorbing), source and receiver must be substantially separated. There are more problems than I could possibly recount (as there were for Heard Island). But there is the challenge to learn about this last piece of unknown ocean. The cavern near the grounding line will be low, cold, dark and noisy. What else will we find (Fig. 9)?

Fig. 9. A cartoonist view of what is encountered near the grounding line (Cartoon by Michael Dormer).

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