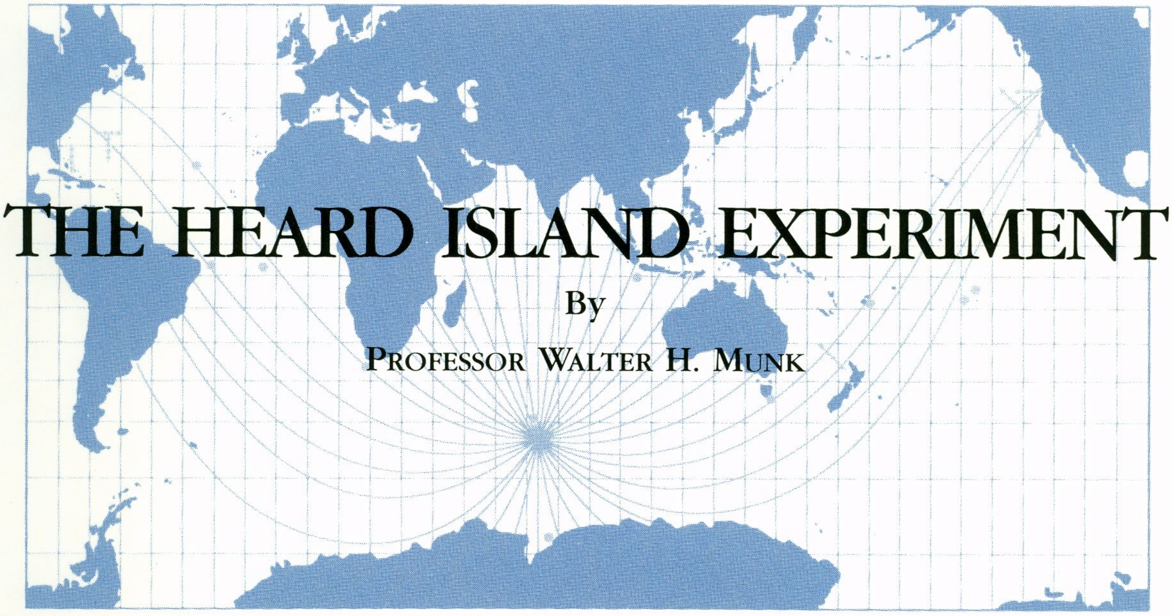
Inaugural Lecture
International Science Lecture Series



THE HEARD ISLAND EXPERIMENT

By

PROFESSOR WALTER H. MUNK

Organized by

The National Academy of Sciences

and

The Office of Naval Research

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PREFACE

At the request of the Office of Naval Research the International Science Lecture Series was established in mid-1990 as a joint endeavor with the National Academy of Sciences-National Research Council for the expressed purpose of advancing communication and cooperation within the international scientific community. A search committee established by the National Research Council is charged with selecting two prominent American scientists each year (beginning in 1991) to lecture on the latest research results in areas of scientific inquiry pre-selected by the two sponsors. The countries in which the lectures are to be given are worked out in consultation with representatives of the international scientific community, with the science attaché in the relevant American embassies, and with senior representatives of Office of Naval Research-Asia and Office of Naval Research-Europe. Wherever appropriate, each lecture is followed by formal and informal discussions with senior representatives of the scientific community in the host country to expand the dialogue on research progress, problems, and plans of common interest. Following each tour, the lecture will be published for wider international distribution.

The inaugural lecture in the series was presented during November 1990 by Professor Walter Munk of the Scripps Institution of Oceanography. Professor Munk lectured on the planned *Heard Island Experiment*—a ten-year research program aimed at monitoring global warming by measuring ocean temperature changes as a function of acoustic travel times across the Atlantic, Pacific, and Indian ocean basins from a sound source near Heard Island in the southern Indian Ocean. The experiment will be preceded by—and largely rest on the outcome of—a ten-day feasibility test in January 1991.

Accompanied on the tour by Bernard J. Zahuranec of the Office of Naval Research, and Lee M. Hunt of the National Research Council, Professor Munk presented the lecture in Paris, France; in Cochin, Goa, Delhi, and Ahmedabad, India; and in Jakarta, Indonesia. In Paris the lecture was sponsored by the French Academy of Sciences. In Cochin it was presented before the annual meeting of the Indian Acoustical Society, and at the Naval Physical and Oceanographic Laboratory. In Goa the lecture was given at the National Institute of Oceanography. In Delhi the lecture was sponsored by the Indian Academy of Sciences, and as the first of a Distinguished Lecture Series sponsored by the Department of Ocean Development. The lecture was given at the National Physical Laboratory. The final lecture in India was presented at the Physical Research Laboratory in Ahmadabad. In Jakarta the lecture was presented before an audience at the Indonesian Agency for the Application and Assessment of Technology. Both Professor Munk and the lecture were received with interest and enthusiasm at each of the above locations, and the formal and informal discussions that followed were well attended and revealed many areas of common interest in oceanographic research.

The sponsors would like to acknowledge the invaluable assistance of the many individuals in France, India, and Indonesia who made the inaugural lecture of the International Science Lecture Series a success. Prominent among these are Dr. James Andrews, Chief Scientist of ONR-Europe; Dr. Willem H. Brakel and Dr. Michael Michaud of the Science and Technology Affairs Office of the American Embassy in Paris; Dr. P. L. M. Heydemann, Dr. S. K. Dutt, Ms. Sundari Kumar, and Ms. Lakshmi Kinger of the American Embassy in Delhi; and Dr. Jeffrey T. Lutz and Ms. Kemala Angraini Ahwil of the American Embassy in Jakarta for both arrangements and participation in meetings. Dr. Sach Yamamoto, Chief Scientist of ONR-Asia and Dr. David Evans of the ONR Washington Office also provided valuable assistance.

The sponsors would also like to thank their scientific colleagues in all three countries for their warm hospitality, and for the many arrangements: Dr. Claude Jablon (French Academy of Sciences) and Dr. Klaus Voigt (Deputy Secretary, Intergovernmental Oceanographic Commission); Dr. V. K. Aatre (Director, Naval Physical and Oceanographic Laboratory), Dr. B. N. Desai (Director, National Institute of Oceanography), Dr. S. K. Joshi (Director, National Physical Laboratory, and Foreign Secretary, Indian Academy of Sciences), Dr. V. K. Gaur (Secretary, Department of Ocean Development), Dr. A. P. Mitra (Director General, Council of Scientific and Industrial Research), Dr. V. R. Gowariker (Secretary, Department of Science and Technology); and Dr. IR. H. Wiryosumarto (Bidang Pengembangan Teknologi).

THE HEARD ISLAND EXPERIMENT

The Technical Director of Office of Naval Research is routing me around the world to talk of an experiment yet to take place. This is a risky mission, like playing the futures. I would much rather be talking here next year about what we have learned.

Atmospheric CO_2. Keeling's three decades of painstaking CO_2 measurements at Mauna Loa Observatory (figure1) have played a major role in an ungoing debate on global energy policy.[1] I wish to raise two issues. First, that no one would today question the value of Keeling's research program. Yet, support for the program was not so readily forthcoming when Revelle and Suess proposed that an important increase in atmospheric CO_2 was taking place even then, in 1956, at a rate measurable with then available techniques. The theme of my talk is that the upper kilometer of ocean may be warming even now, in 1990, at a rate measurable with available techniques.

Second, why does no one question the existence of the CO_2 trend? Because the time series is of sufficient length for the long-term trend to equal 40 sigma (standard deviations). To detect a trend in a noise at the 95% level takes time enough for the trend

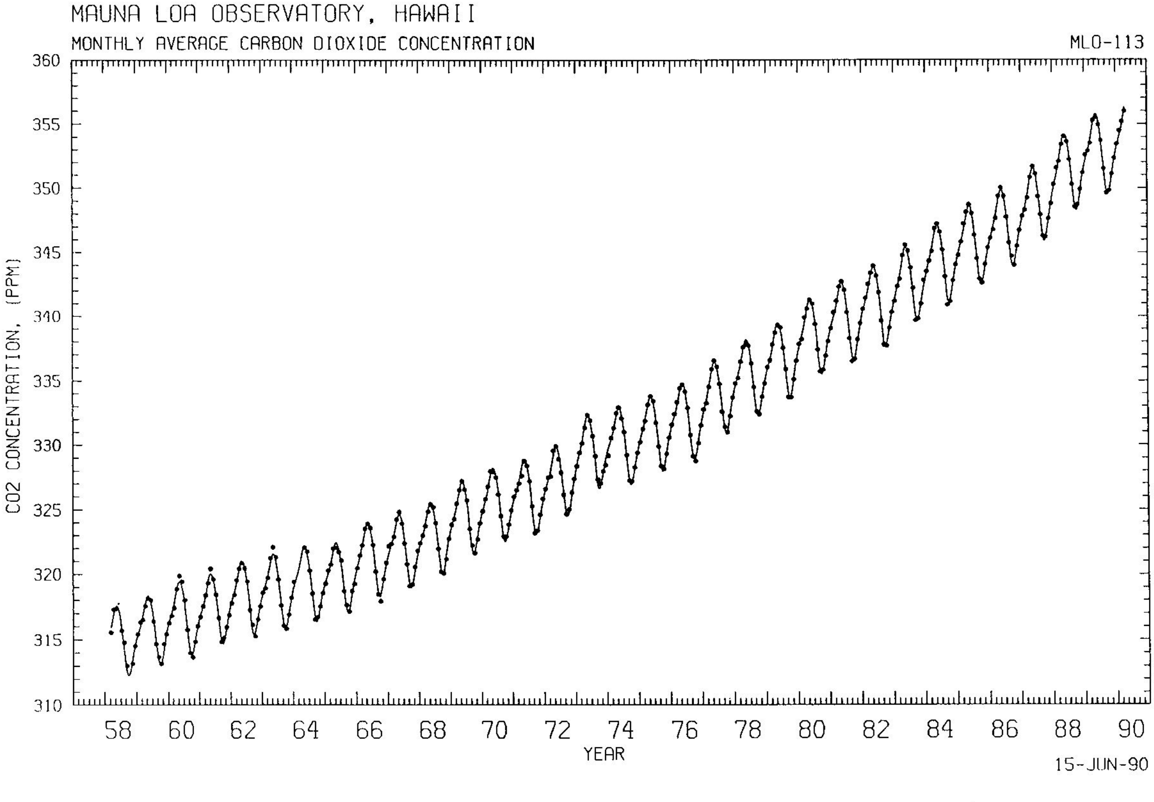

FIGURE 1. The Keeling time series of CO_2 concentration at Mauna Loa.[1]

to reach 4 sigma (under certain assumptions), or 5 years for the CO_2 record. (Most of the variance here is due to seasonal variability; the situation can be much more complicated for a continous variance spectrum.)

Keeling's measurements started in 1958. Antarctic ice cores have made it possible to reconstruct CO_2 history back to 1740, with a good match to Keeling (figure 2).[2] Zero time is taken for the industrial revolution in 1860 with 280 ppm of CO_2. The increase has been by a very respectable 27%. There have been many attempts to reconcile the 27% increase with global fuel consumption. A budget estimate for 1990 is given in table 1. Radiation reaching the outer atmosphere equals 1333 W/m^2 (solar constant), of which 280 W/m^2 gets to the surface, Given the increases in greenhouse gases since 1860, various investigators have computed the associated increase in surface heat flux to be about 2 W/m^2, and the resulting increase in equilibrium surface temperature to be about 1°C. We will show next that the *measured* increase is by only 0.5°C; the difference is attributed to ocean heat storage. The ocean is also a significant sink of CO_2 (the oceanic 2.2 gigatons of carbon per year are based on balancing the budget, not (as yet) on direct

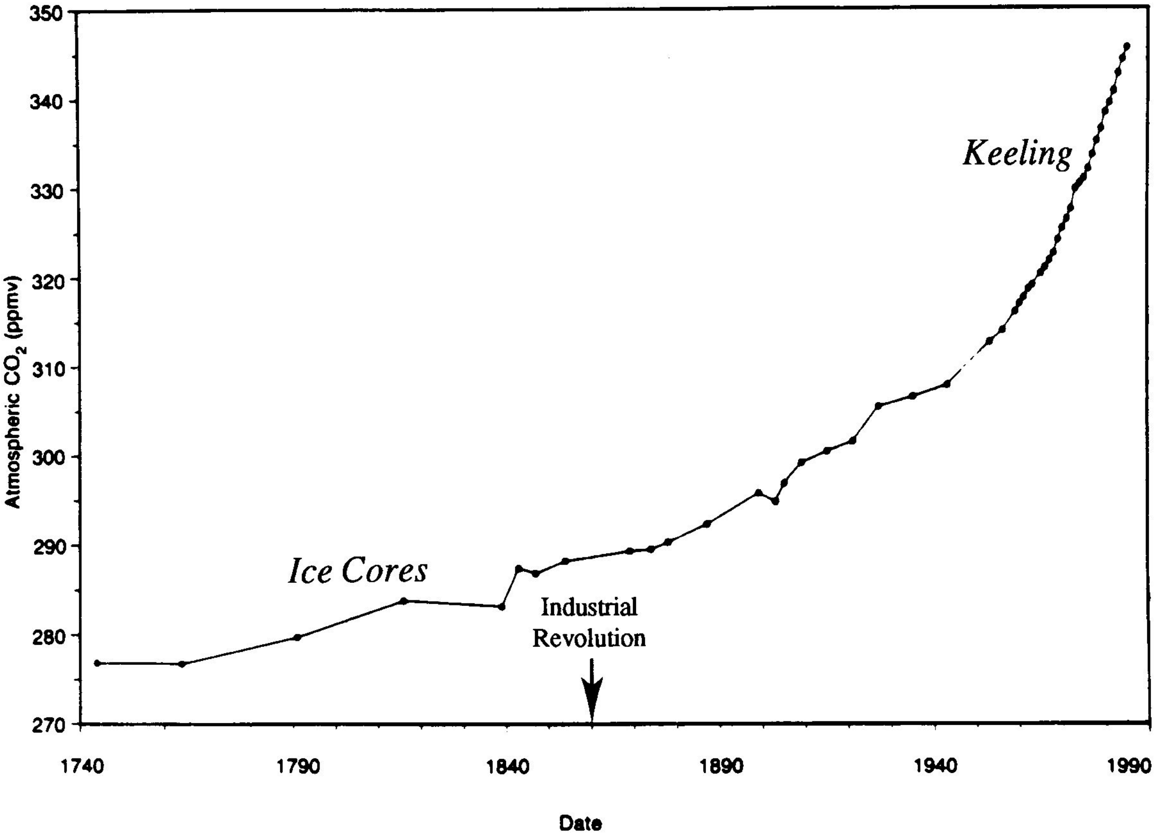

FIGURE 2. An extension of the Keeling annual means back to 1740, using measurements made on Antarctic ice cores.[2]

TABLE 1. Parameters

INDUSTRIAL REVOLUTION

	1860	1990	Δ
CO_2	280	355	+75 ppm
Surface Flux	238	240	+2 W/m^2
T (equilibrium)	15°C	16°C	+1° C
T (measured)	15°C	15.5°C	+0.5° C

1990 CO_2 BUDGET (GTC/year)

SOURCES		SINKS	
FUEL	5.7	ATMOSPHERE	3.7
FORESTS	1.8	BIOSPHERE	2.1
METHANE	0.5	OCEANS	2.2
	8.0		8.0

1990 WARMING (m°C/year)

T_{ATM} (equilibrium)	32		
T_{ATM} (measured)	20	$\rightsquigarrow$	0.03 W/m^2
T_{OCEAN} (surface)	20	$\rightsquigarrow$	1.7 W/m^2 1.8 mm/year
T_{OCEAN} (1 km depth)	4		

measurements). Without ocean heat storage the atmospheric temperature increase 1860–1990 would be 1°C instead of 0.5°C; without ocean CO_2 storage, it would be up 1.6°C instead of 0.5 °C. So the oceans are an important sink for greenhouse gases and an important sink for heat (as well as a sink for ignorance since the ocean changes are not measured but inferred).

Atmospheric temperature. The reconstruction of global temperature increase over the last 108 years by Hansen and Lebedeff[3] gives 0.5°C, one half the equilibrium warming. There are many difficulties in deriving this estimate (see figure 3).[3,4] The distribution is biased in favor of northern hemisphere land stations. Many of the land stations have suffered the "urban heat-center" effect. Sea surface measurements have gone from "bucket" to "injection" temperature. By coincidence, both effects require a correction of the order of 0.5°C, which is of the same order as the total change. Not a happy

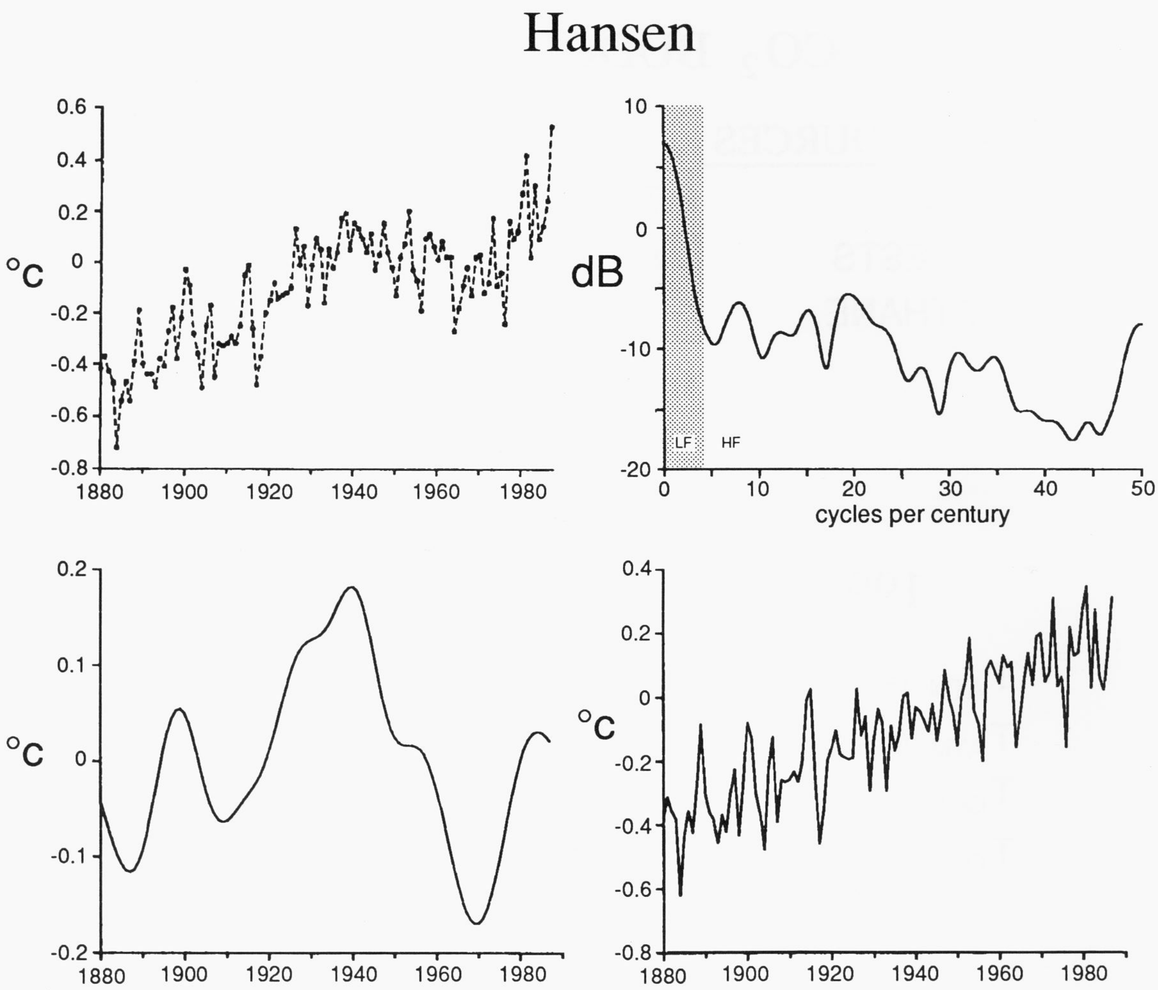

FIGURE 3. The Hansen time series of global average surface temperature[3] (left top) and the MacDonald decomposition[4] into an ambient low frequency component (left bottom) and a trend plus high frequencies (right bottom). The reference frequency is 4 cycles per century (right top).

situation. But all these corrections have been applied with great care, and the Hansen compilation is probably as good as can be done.

The detection of the greenhouse trend is far more difficult than then the detection of the CO_2 trend. The series is too short for the 4 sigma requirement. The spectrum shows a separation into low-freqency and high-freqency "noise" with a demarcation at 4 cycles per century. Gordon MacDonald separates the temperature record into three components: (1) a linear trend by 0.5°C per century, (2) high-frequency variability and (3) low-frequency variability (figure 3). Note the downward trend between 1940 and 1970.

The Hansen data suggest a 1990 rate of warming by 20 m°C/year (compared to 32 m°C/ year for the equilibrium warming). For purposes of discussing the proposed experiment I assume that this rate decreases exponentially with ocean depth to 4 m°C/year at 1 km. This estimate is based on a number of considerations. It is roughly in accord with ocean-atmosphere models at Princeton and Hamburg. Warming of the order of 4 m°C/year is consistent with the observed 1960 to 1980 warming by 0.1°C below 1500 m depth at the Palunirus station off Bermuda,[5] and with the 1960 to 1990 changes in the temperature of bottom water in the western Mediterranean.[6]

Going back to table 1, we note that the assumed profile in ocean warming requires a heat flux of 1.7 W/m^2 which is consistent with the incremental surface flux of 2 W/m^2 produced by the greenhouse gases. Further, that the associated rise in sea level from thermal expansion is 1.8 mm/year at mid-latitude (half this value at 60° latitude); we need to add something less than 1 mm/year from glacial melting, and end up with a rate not inconsistent with global tide gauge records. (We can use sea level as a surrogate of upper ocean heat content.) So we have a model of ocean warming which does not greatly offend a variety of evidence. To those who find fault with these numbers, I respond that the poorer the model estimates, the more important it is to replace them by observation.

How should one go about measuring global ocean warming? The simplest procedure is to install a thermometer mooring and record temperature. At 1 km depth the mesoscale eddies (the "storms" of the sea) are associated with month-to-month changes in temperature of, typically, 0.2°C rms. At the present estimated rate of warming by 4 m°C/year it would take 200 years to produce a change by 4 sigma. For independent measurements from 100 moorings this estimate is reduced to 20 years. An easier way of forming an average over 100 independent samples is to take advantage of the fact that these eddies have typical dimensions of only 100 km (unlike their 1000 km atmospheric sisters), and to form a spatial line average over distances of the order of 100 eddy scales (10,000 km). For multiple independent lines the required record length can be further diminished.

Acoustic thermometry. Acoustics provides a way of forming such large spatial averages. The speed of sound increases by 5 m/s per °C, with a much lesser dependence on salinity. Thus the travel time between two points is a measure of the mean temperature along the acoustic path. The ocean provides a most efficient wave guide centered at the depth (normally 1 km) of the sound speed minimum (sound axis). A stick of dynamite detonated near the axis can be heard by an axial receiver clear across the Atlantic Ocean! Averaging by acoustic integration has some advantage over summing irregularly distributed land stations. There is (as yet) no problem with underwater urban heat centers. On the other hand, the depth of the sound axis varies with latitude, and we have little control over the depth dimension of the measurements.

Figure 4 shows the results of an experiment conducted in 1960; a detonation off Perth was clearly detected at Bermuda half-way around the Earth![7,8] At the time the acoustic path was assumed to follow a great circle but, on an elliptical Earth, the shortest path (the geodesic) differs appreciably from the great circle. Further, one needs to allow for horizontal refraction. Using the profiles from 8000 hydrographic stations (figure 5, you can find your favorite expedition) we constructed a map of the depth of the sound axis and of the sound speed at the sound axis (figure 6). The sound axis is typically at 1 km depth, but shoals towards the high latitudes. Note the sharp gradient associated with the Antarctic Circumpolar Current, which deflects rays to the south. The previous geodesic is refracted to intersect Brazil. A clockwise rotation of the geodesic launch angle leads to an intersection with South Africa prior to reaching Bermuda. (For the moment, I assume that the acoustic energy remains trapped near the axis; the fact that the signal was detected at Bermuda is probably associated with non-axial propagation.)

Heard Island test. We have chosen Heard Island as an ideal site for an unimpeded transmission to Bermuda. As a bonus there is also an eastward path to San Francisco, and possibly a path through the Tasman Sea to Coose Bay, Oregon. (The curves in figure 7 are axially refracted geodesics.) We plan to transmit from Heard Island for a 10-day period beginning 26 January 1991 and to record at the 18 sites shown. This is an acoustic feasibility test, to estimate transmission and coherence losses over these

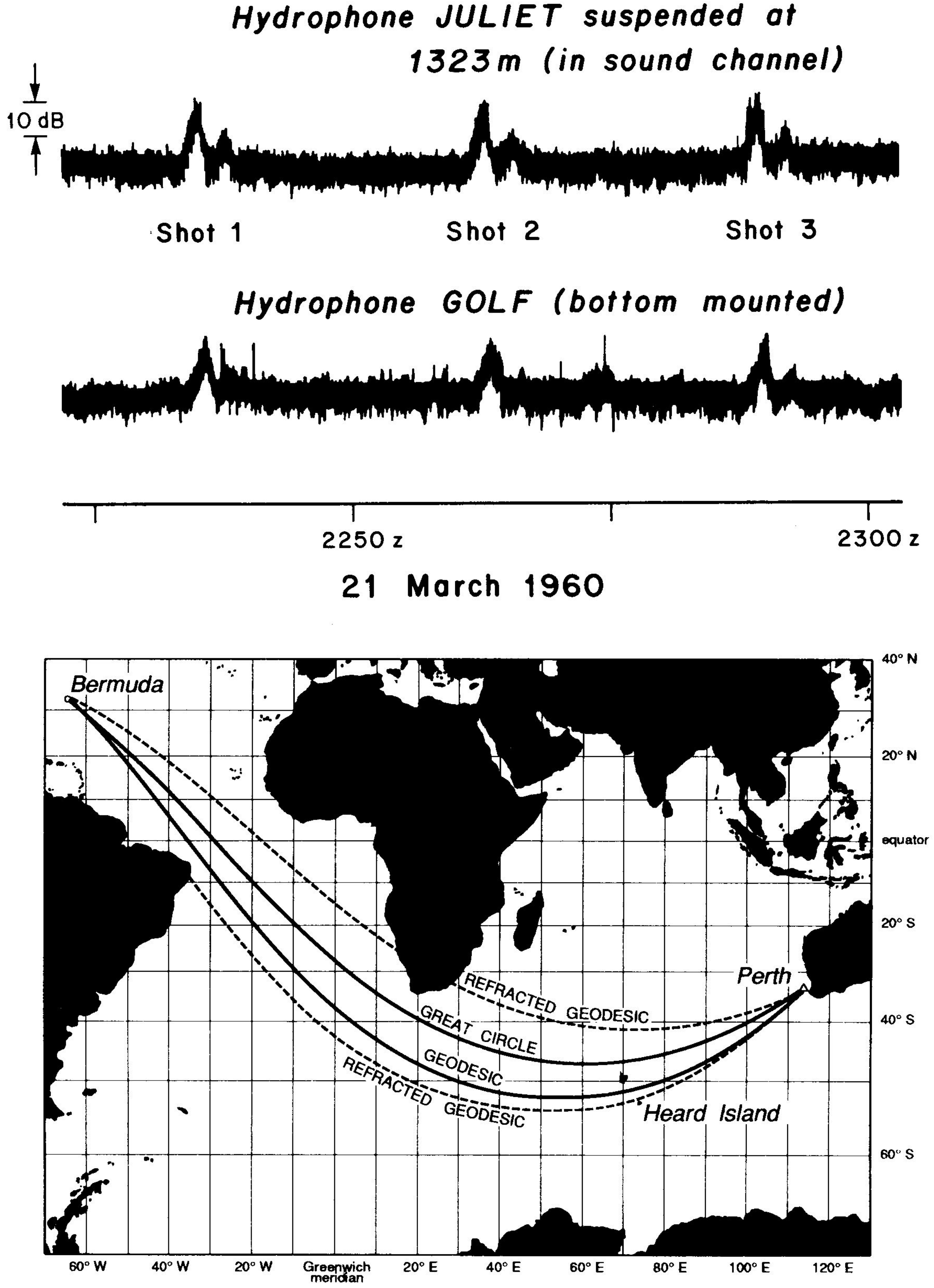

FIGURE 4. Three detonations in the sound channel off Perth were clearly recorded on Bermuda hydrophones half-way around the Earth.[7,8]

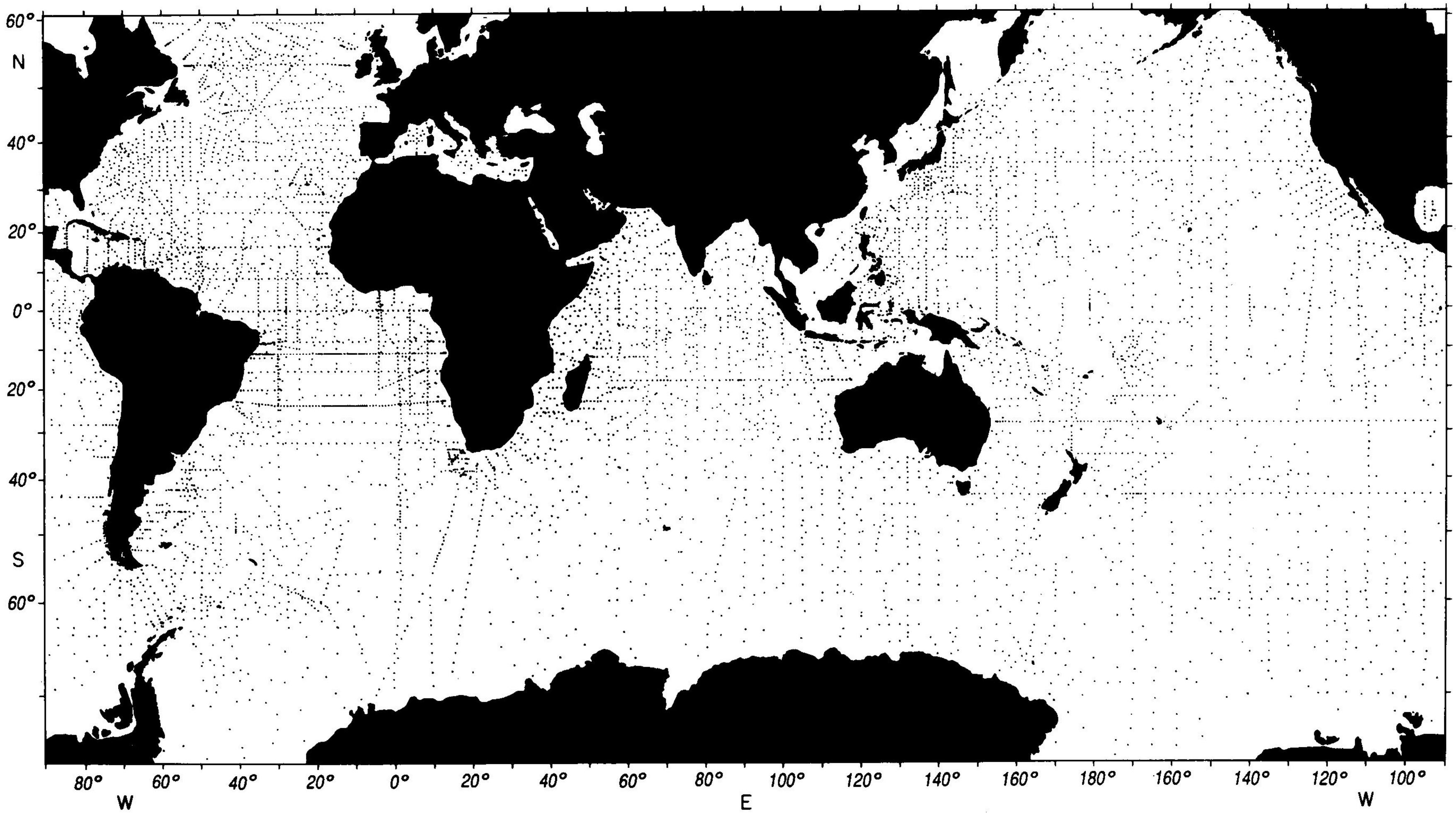

FIGURE 5. Observations used by Reid[8] to compute the global sound channel.

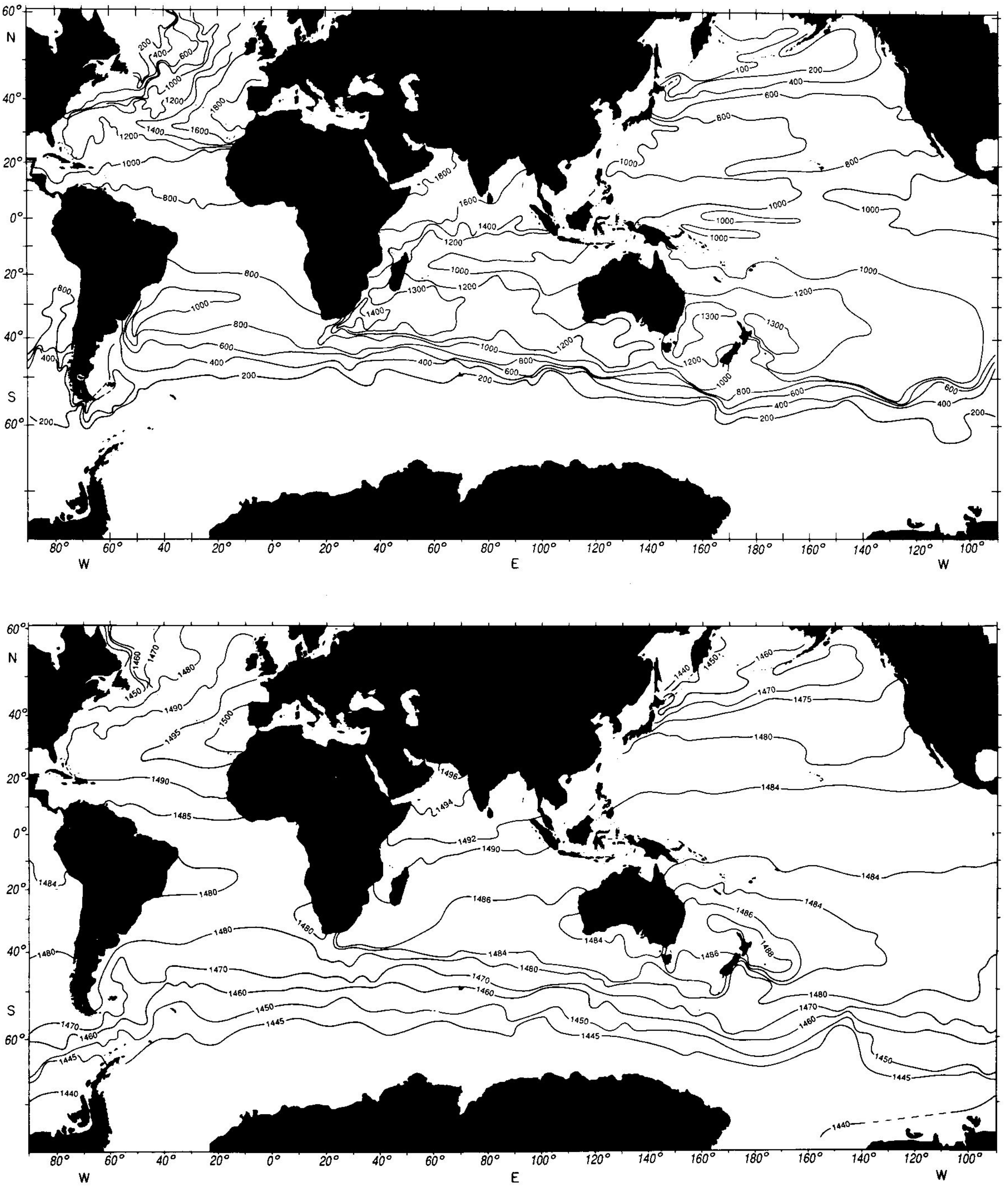

FIGURE 6. Depth (m) and sound speed (m/s) at the sound channel.[8]

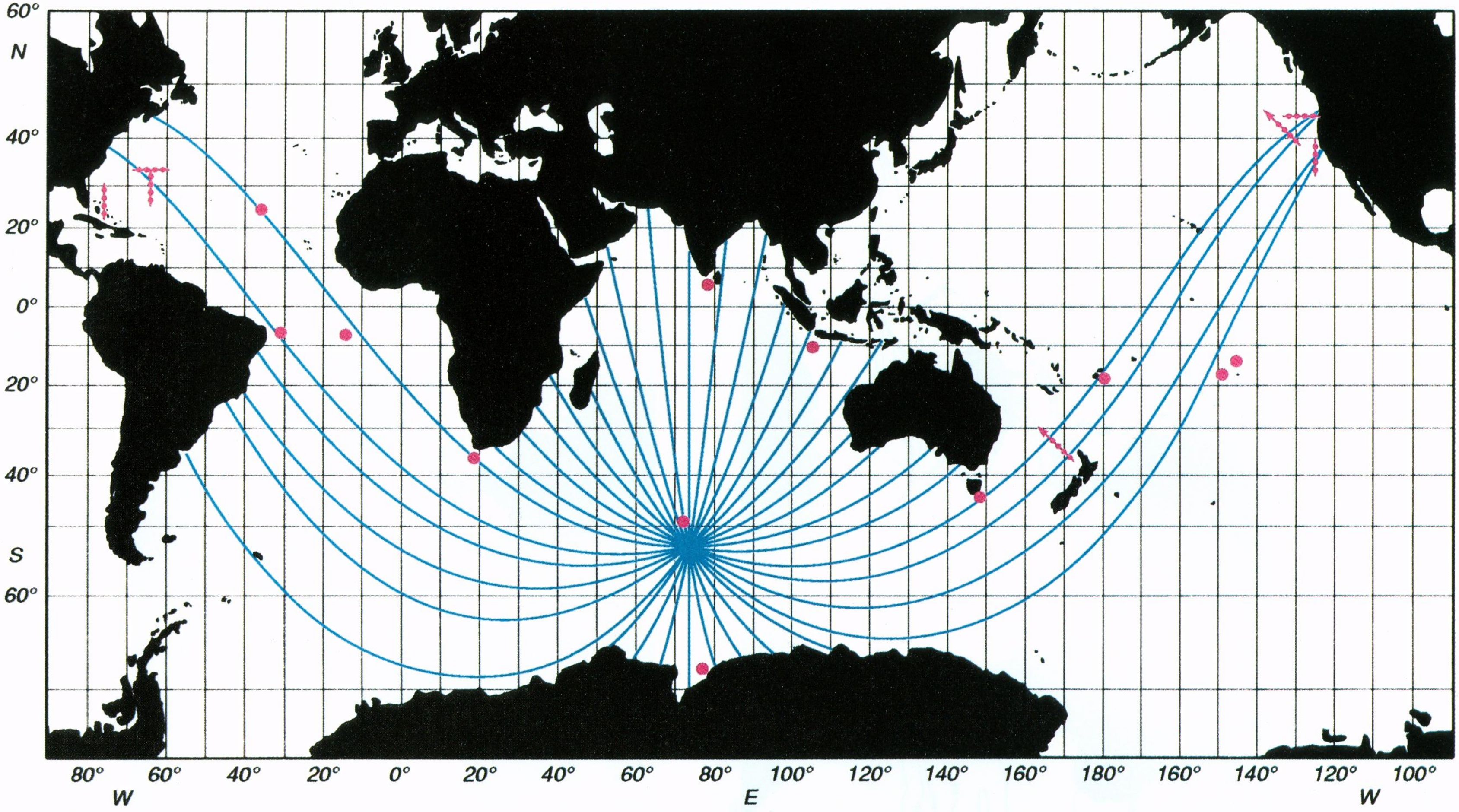

FIGURE 7. Axially refracted geodesics drawn every 10° from the source location at Heard Island.[9] Receiver sites are shown. Horizontal lines represent horizontal arrays off the American west coast and off Bermuda. Vertical lines designate vertical arrays off Monterey and Bermuda. Lines with arrow designate a Canadian towed array off British Columbia and a New Zealand towed array. The Japanese will occupy a station near Fiji island. The Australians (our principal partners) will occupy three stations, one near Christmas Island in the Indian Ocean, one off Tasmania and a third at Mawson Station, Antarctica. There will be a French receiver east of Kerguelen Island, an Indian receiver off Goa, and a station by the University of Cape Town. NOAA will record axial receivers at Ascension Island. A USSR acoustic vessel will record at 25°N in the North Atlantic. There may be a station off Brazil. An attempt will be made to record the signal on land with a high-frequency seismic array on Ascension Island, and possibly in the Tahitian area.

paths. If successful, it is to be followed by a climate experiment extending over at least a decade using fixed sources and receivers with satellite timing.

It is not desirable to use explosive sources for obtaining time series. We will employ a source somewhat akin to a loudspeaker (figure 8). The available source is limited to depths of less than 300 m, and this requires a high-latitude location where the sound channel is relatively shallow. The source strength is 209 dB re 1 micropasqual at 1 m at the resonance frequency of 57 Hz. The source is ideally tuned for global transmissions (figure 9). At higher frequencies the attenuation becomes forbidding, and at lower frequencies the background noise (mainly shipping) is higher.

FIGURE 8. The acoustic source is shown to the right.

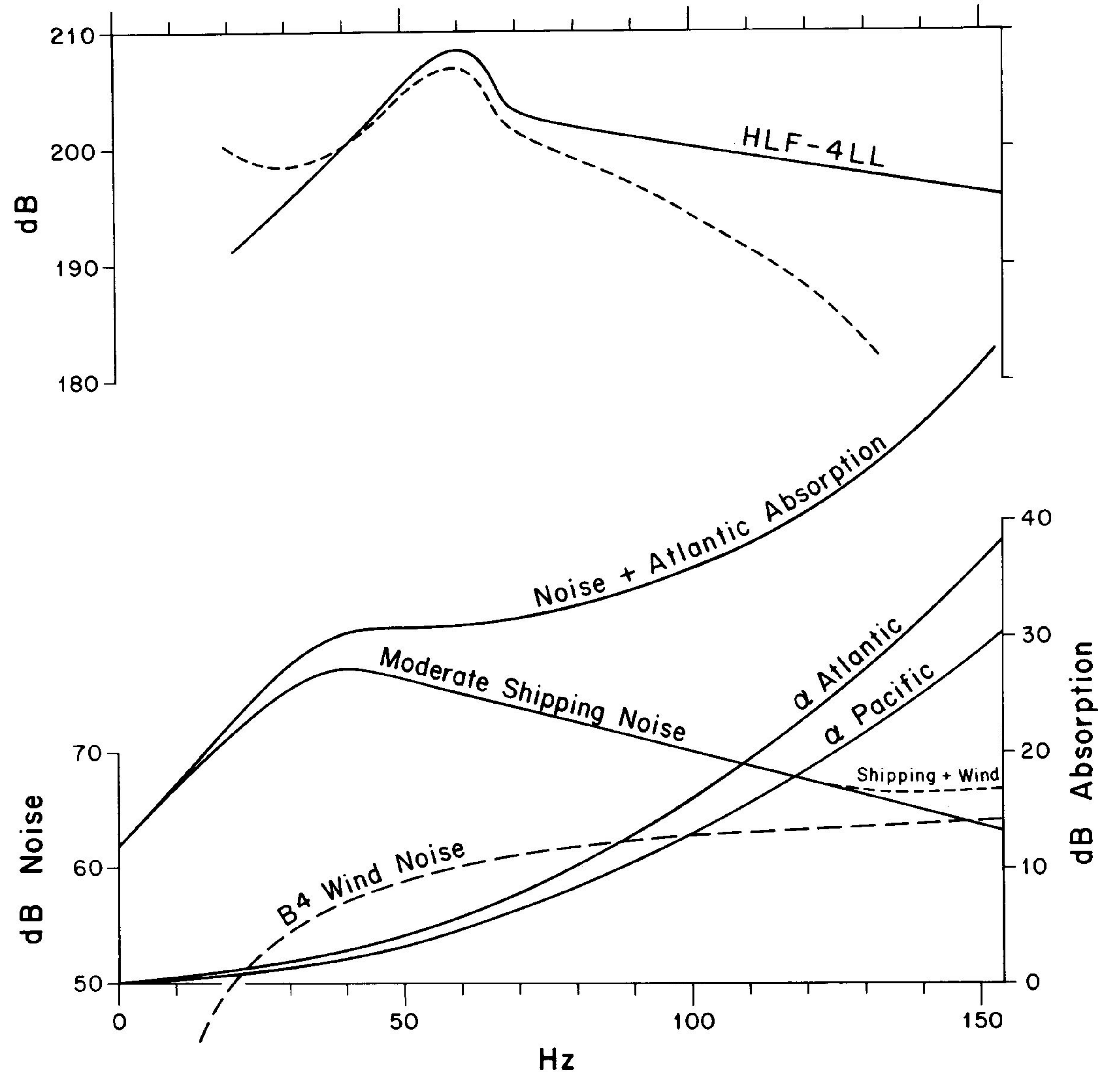

FIGURE 9. The source strength is peaked at about 60 Hz. Absorption and ambient noise limit the transmission to a 50 Hz to 70 Hz band.[9]

Over the past 10 years we have conducted experiments in "ocean acoustic tomography" with up to 1000-km ranges. The arrival pattern (figure 10) consists of a series of sharp pulses each identified with a given ray: steep rays arrive early; axial rays (which stay near the sound speed minimum) come in last. The predicted pattern is based on the climatological sound speed profile. The measured pattern resembles the climatological pattern, but differs in an important way. This difference permits tomographers to contour the field of sound speed (temperature) as perturbation from the mean field. (Vive la petite difference!) In the case of figure 10 the measured pattern is late and so the ocean is colder than average. It should be added that the source does not emit pulses, but rather a pseudo-random signal with a uniquely pulse-like autocovariance. The plotted arrival pattern is the correlation of the received signal with a replica of the transmitted signal.

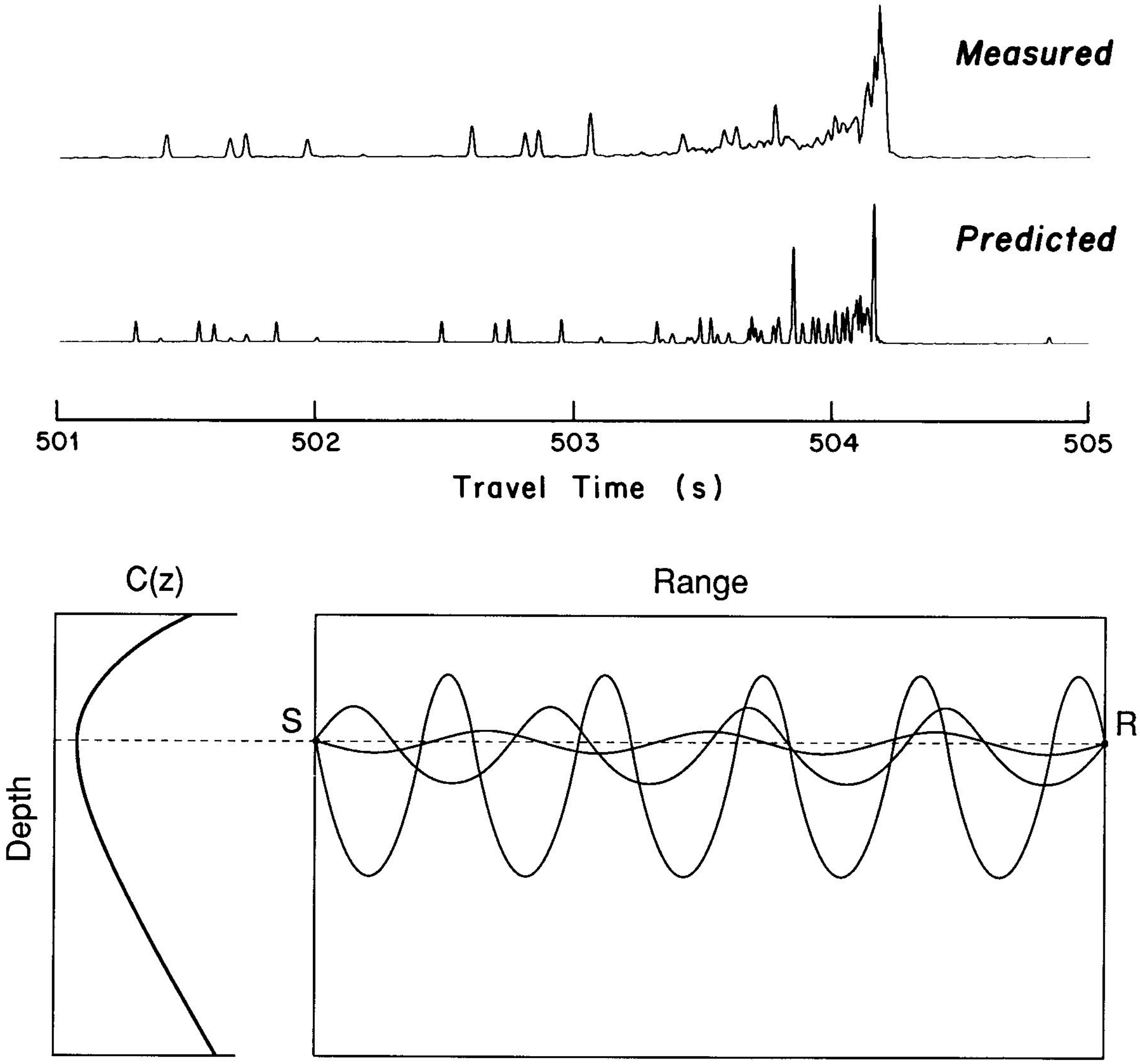

FIGURE 10. A ray diagram for an idealized sound channel (bottom) is associated with an arrival pattern (top) of early steep rays and late flat rays. The diagram is shown for a 700 km tomographic transmission.[10]

At 1000-km ranges the pulse-like arrival pattern permits the determination of travel time with millisecond precision. At very large ranges the pulses broaden and merge, and may disappear entirely. The final cut-off is more robust. We are hoping for a precision of 10 milliseconds at 10,000 km ranges, and an intensity corresponding to at least 10 dB signal to noise ratio.

Some unsolved acoustic problems. An interpretation in terms of modes may be more fruitful (figure 11). Steep rays correspond to high modes, flat (axial) rays to low modes. Modes remain trapped along the deepening axis from Heard to Bermuda,[11] provided the change is gradual (adiabatic). The lowest mode (corresponding to the axial ray) extends about 100 m above and beneath the axis, mode 8 extends more than 500 m and intersects Conrad Rise. This results in "mode stripping" for mode numbers 8 and above. There is an interesting question whether these higher modes (steeper rays) are repopulated in 15 megameters of further travel to the most distant stations. For this purpose two vertical arrays with mode-resolving capability will be deployed off California and Bermuda (figure 12).

For glancing incidence on islands and seamounts, the sound waves are bent away from shore (opposite to surface waves, figure 13). We do not know whether the sound transmission can bounce through the rough terrain of the Tasman Sea and the western Pacific (figure 14). The Heard Island experiment is to provide information on "global acoustics" which will determine whether a global acoustic thermometer is feasible. There are many unknowns, this is truly a feasibility experiment.

Detection of greenhouse trend. The most severe problem facing a global system of acoustic monitoring is the problem of signal to geophysical (not acoustic) noise, of detecting greenhouse warming in the presence of a large natural variability. This is the same problem that has made the atmospheric determination controversial even after a century of measurements.

Using the values for ocean warming in table 1 yields a change in travel time typically by 0.25 s per year at a 15,000 km range. The straight lines in figure 15 were computed by Manabe, Spelman and Bryan (MSB) by computing the greenhouse temperature changes along the x,y,z-coordinates of the three geodesics, based on their three-dimensional atmosphere-ocean model. The superposed wiggles were computed in a similar manner by Semtner and Chervin using their multilevel primitive-equation model, which exhibits

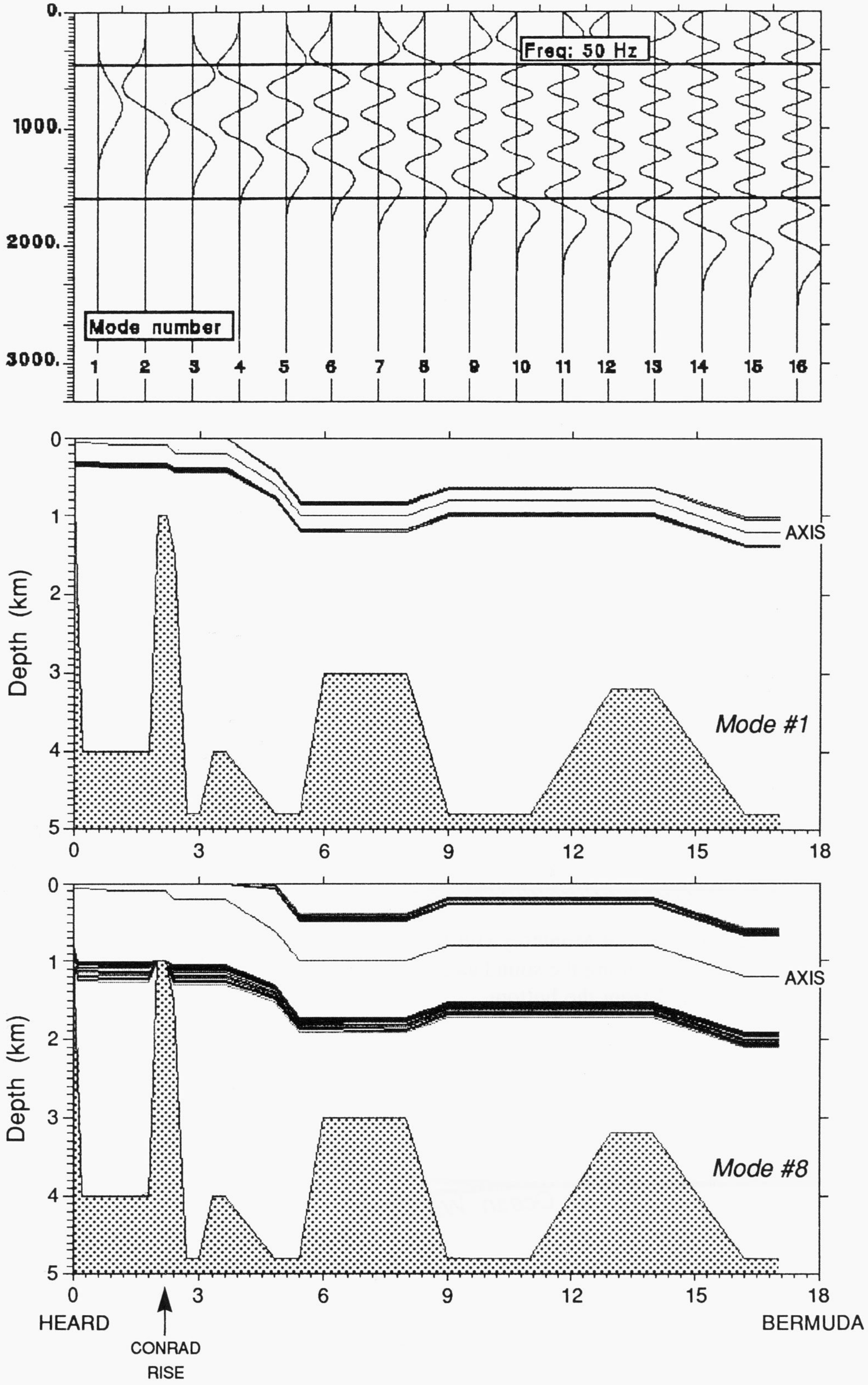

FIGURE 11. A modal representation of the transmission from Heard Island to Bermuda.[11] Acoustic energy is trapped within the vertical strip between the heavy lines to both sides of the sound axis. Low modes can follow the axis without bottom interaction. High modes are "stripped" by bottom interaction.

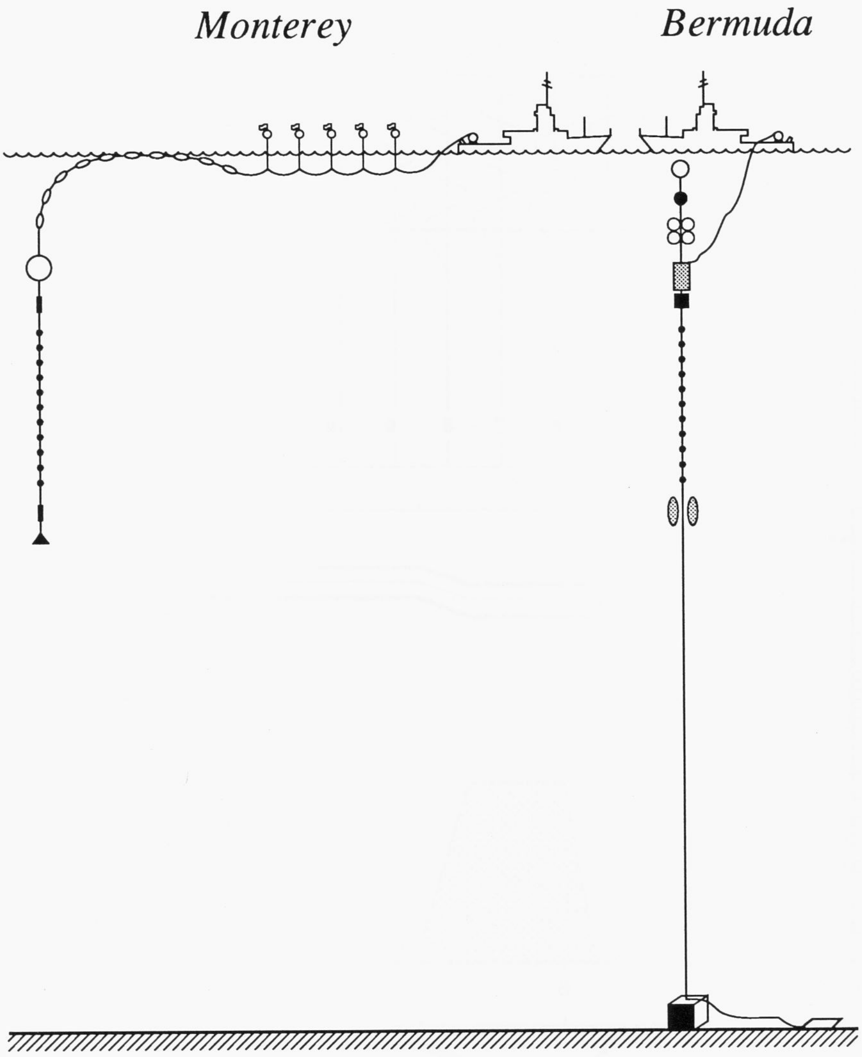

FIGURE 12. The vertical arrays at Monterey and Bermuda.[11] Both arrays consist of 32 elements with a 1300 m vertical aperture subtending the sound axis. The Monterey array is suspended from the surface, the Bermuda array is tethered from the bottom.

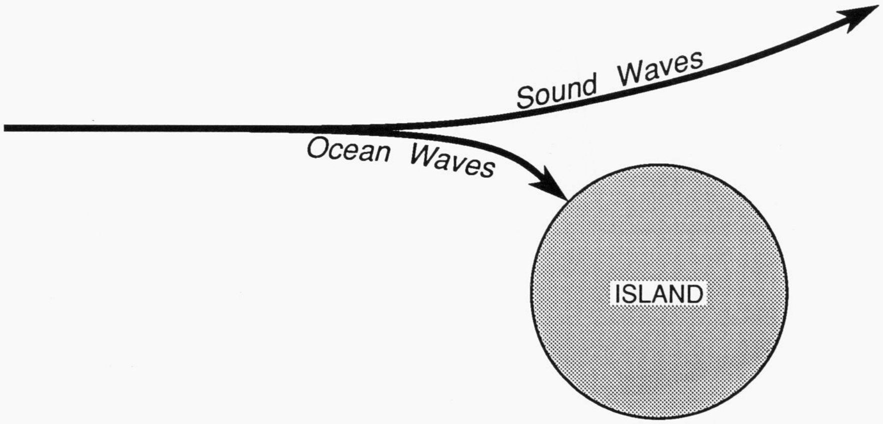

FIGURE 13. Unlike ocean surface waves, sound waves are *repelled* by islands and seamounts.

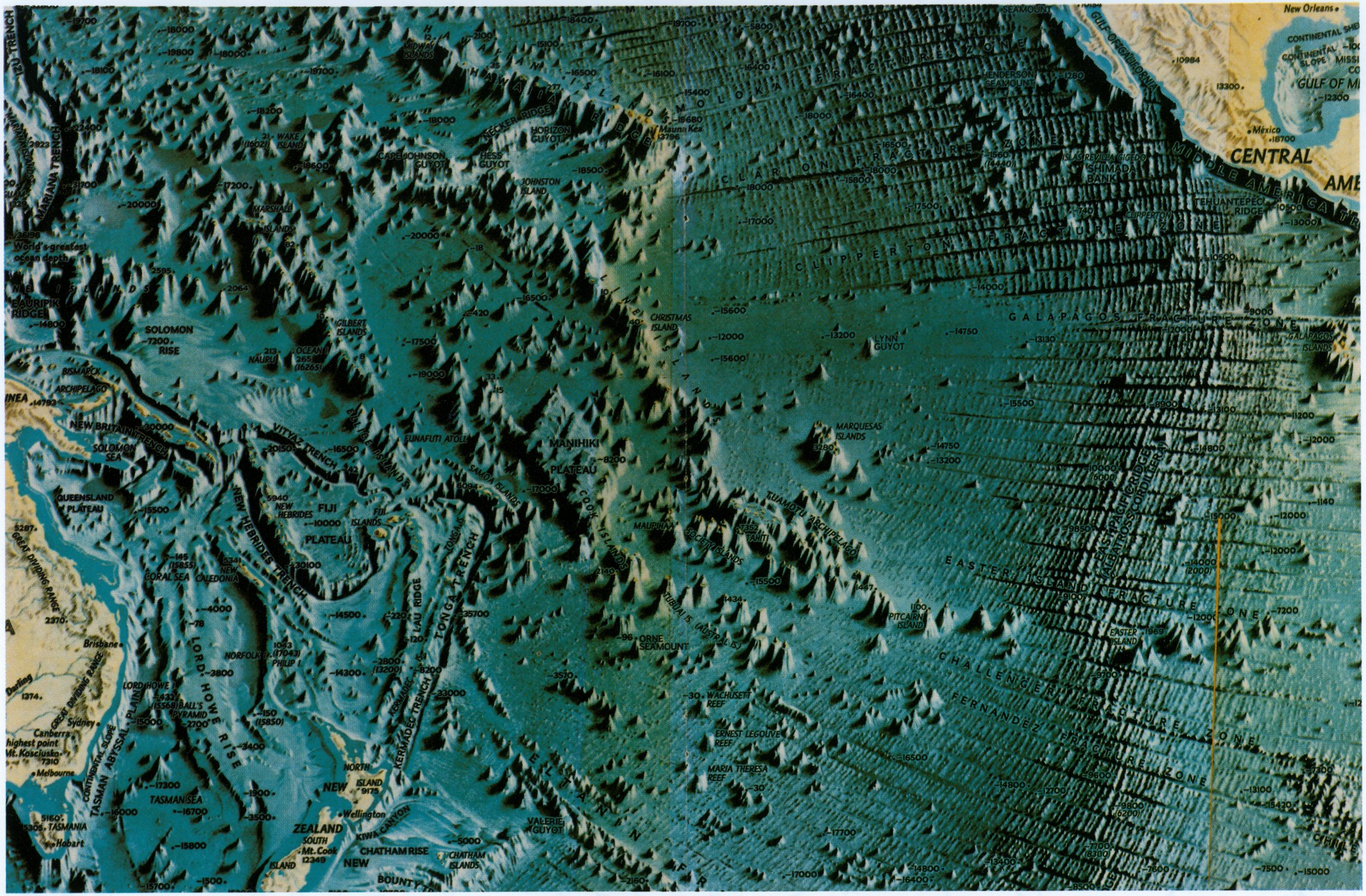

FIGURE 14. It is not known whether the acoustic signal can "bounce" through the chains of islands and seamounts of Tasman Sea and the western Pacific. The bottom topography of the eastern Pacific is relatively smooth. Reproduced, by permission, from National Geographic (1969), Face and floor of the peaceful sea, pp. 496-499.

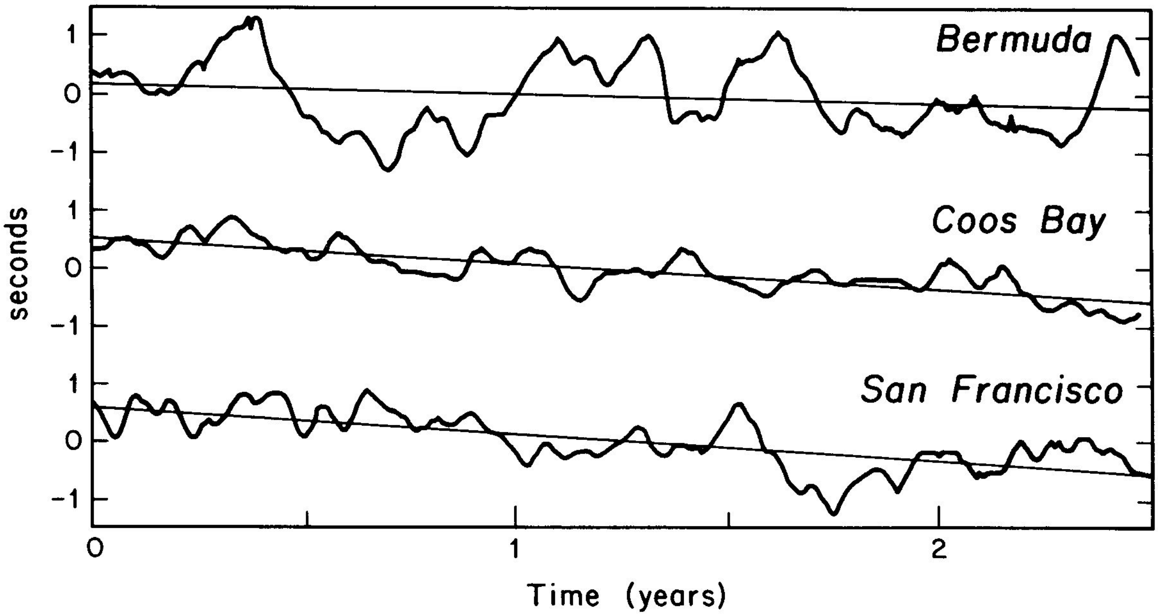

FIGURE 15. A computer simulation of travel time versus calendar time along stated paths, assuming the Princeton model of greenhouse warming (straight sloping lines) and the Semtner model of mesoscale variability.[9]

mesoscale variability. The MSB model has a definite calendar time associated with the CO_2 scenario of Wuebbles *et al.*[12] The SC mesoscale wiggles are for model years 20 to 23 and have no such absolute time reference. (The SC magnitudes are strongly supported by the fact that the global distribution of the inferred mesoscale surface level oscillations is in good agreement with satellite altimetry.) For San Francisco and Coos Bay the trend is evident in only 2.5 years.

Gyre scale variability. I suspect that the variability of the oceans on a larger time and space scale is a more limiting factor then mesoscale variability. Unfortunately there is very little data concerning the large scale variability. During the El Niño year 1977 the entire northeast Pacific was higher by 100 mm than in 1975, indicating a temperature change of the upper ocean by 0.5°C (figure 16). A decadal cooling centered at Bermuda extended over most of the North Atlantic subtropical gyre (figure 17). But the North Atlantic is the only place with a sufficient database to produce maps of year-to-year changes in temperature.

In what follows we shall depend on the Hamburg ocean-atmosphere model for both the greenhouse signal and for the ambient ocean variability. Changes in sea level in 50 years following CO_2 doubling gives an indication of the spatial pattern of greenhouse

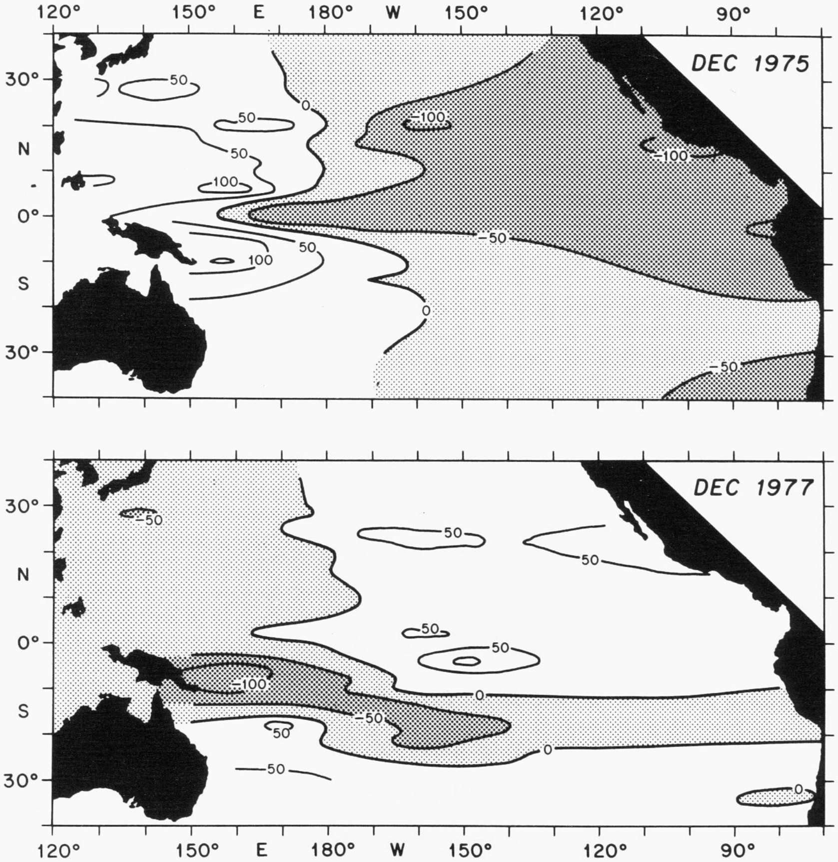

FIGURE 16. Wyrtky's compilation of sea level topography.[13] In December 1975 the Pacific slopes downward to the east by about 200 mm, the opposite holds in December 1977 (an El Niño year). Sea level is a surrogate for upper ocean heat content.

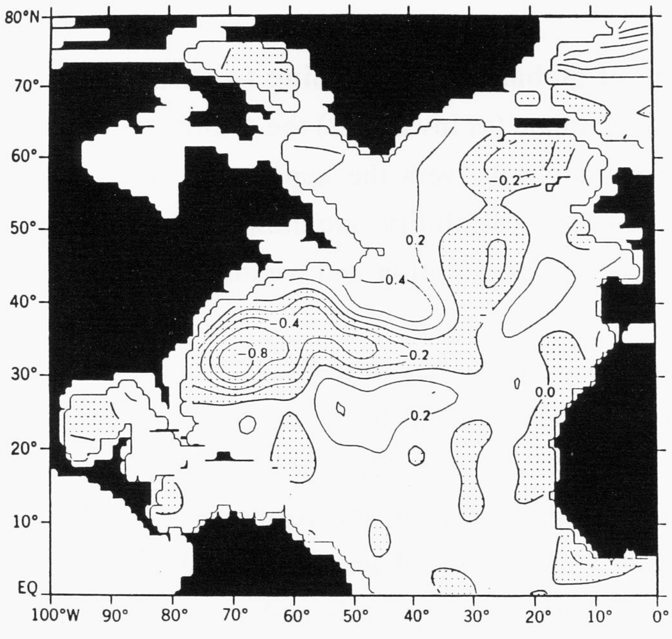

FIGURE 17. Temperature anomaly (°C) at 1 km depth in 1975.[5]

ocean warming. Figure 18 shows two regions of level changes exceeding 30 cm (large warming), and many areas with changes of less than 10 cm (small warming) or even negative values (cooling). It is totally misleading to visualize a uniform greenhouse warming. Evidently warming takes place on a gyre and ocean basin scale.

Using the same model, Uwe Mikolajewicz has computed the greenhouse induced change in soundspeed at the axis for years 10 to 30 following CO_2 doubling, as well as the natural variability in 3000 model years (figure 19). The close resemblance between the mean fields of axial depth and axial sound speed in the model (figure 19) and from ocean observations (figure 6) lends credence to the model calculations.

For optimum detection of the greenhouse trend one would wish the fields of the greenhouse signal and of the natural variability to be orthogonal. Unfortunately this is not the case, but there are important differences between the two fields in the North Atlantic and the North Pacific. (The fact that both fields are high near Antarctica is the result of the shallow sound axis.) Figure 20 shows the probability density of 10-year trends in travel time from natural variability only (300 samples from 3000 model years) as compared to the greenhouse warming by 0.4 s/year for reception only at Coos Bay. The probability of detection is not high. However, for an imagined 36 stations at the coastal intersections of the great-circle routes, and collapsing these 36 records to two empirical orthogonal functions, the trend is well determined. From this zero'th order estimate I tentatively conclude that greenhouse warming can be detected with a suitable receiver array in something like 10 years.

Acoustic monitoring of global ocean warming (AGLOW). With a single source all that could be done is to validate (or invalidate) the estimates based on model calculations. For an array of sources and receivers the application of tomographic inverse theory leads to a mapping of ocean variability, including greenhouse warming. Ideally one would like an array with gyre resolution and mesoscale averaging.

Figure 21 shows the refracted geodesics from five fictitious southern hemisphere sources. The distribution of oceans and continents lends itself to such a southern strategy. But there is some real activity under way (figure 22). Spiesberger has worked for five years with 4000 km transmissions from Hawaii to the American continent. Some experimental transmissions from Bermuda northward across the Gulf Stream were initiated this year. A proposal for a trans-arctic transmission is under consideration, and there have been preliminary discussions concerning a transmission from Vladivostok across the Pacific.

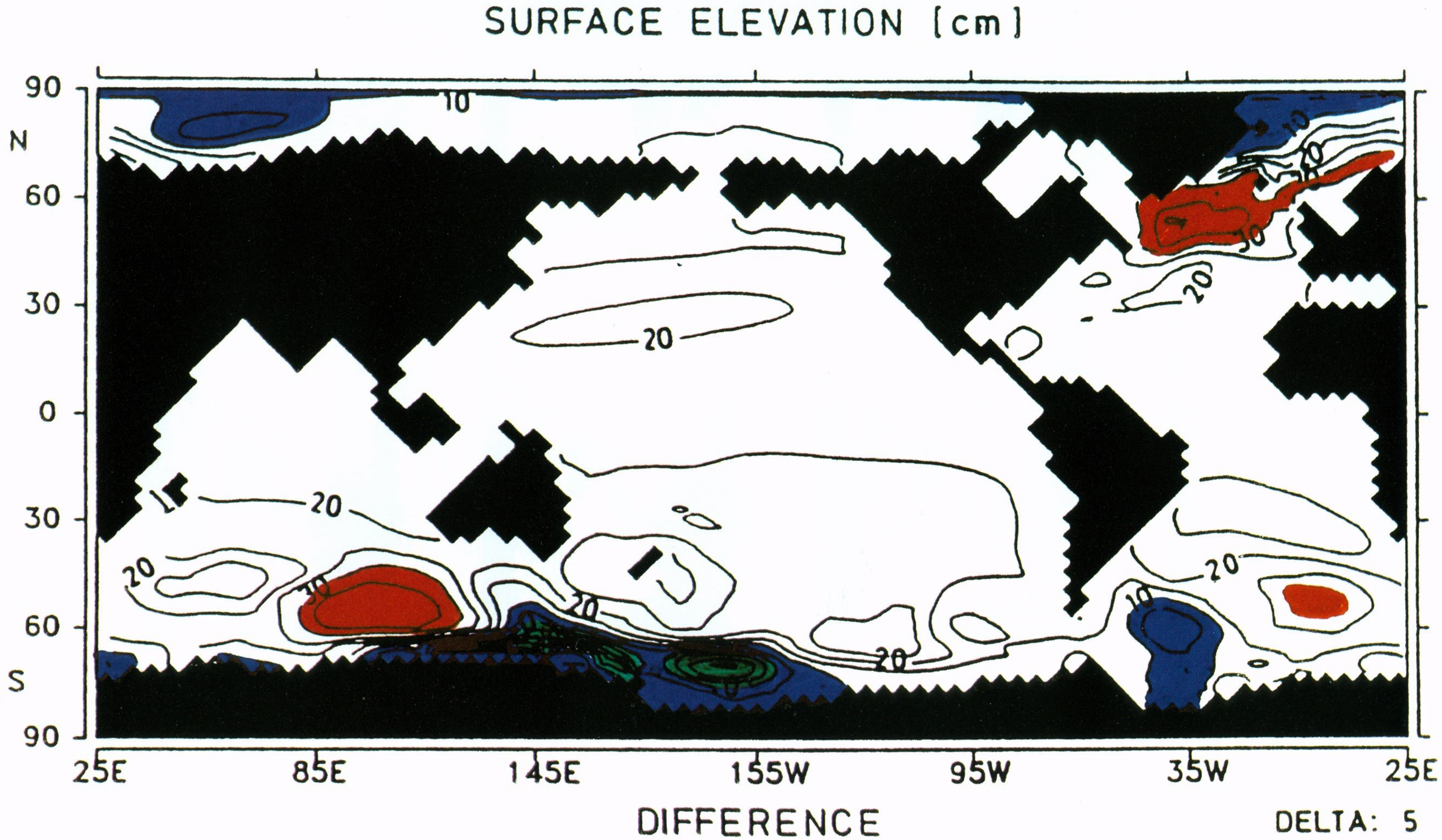

FIGURE 18. The change in sea level 50 years following CO_2 doubling.[14]

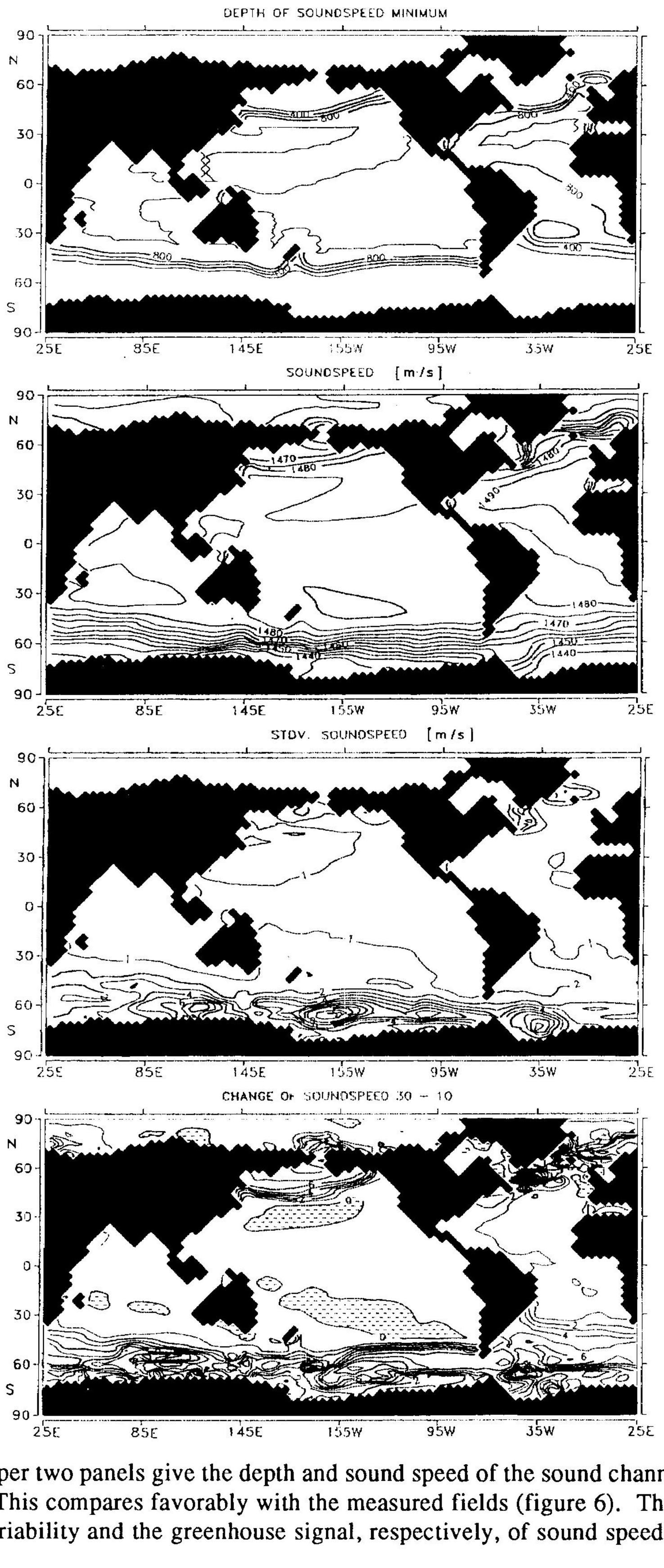

FIGURE 19. The upper two panels give the depth and sound speed of the sound channel according to the Hamburg model.[15] This compares favorably with the measured fields (figure 6). The lower two panels show the ambient variability and the greenhouse signal, respectively, of sound speed (m/s) at the sound axis.

The central challenge is to design an affordable array of sources and receivers that optimizes the probability of detecting the greenhouse trend against the background of natural ocean variability. Most of the atmospheric work has dealt with a detection in the time domain only. An extension to the space-time domain would constitute a significant advance in our efforts to secure a timely and reliable warning.

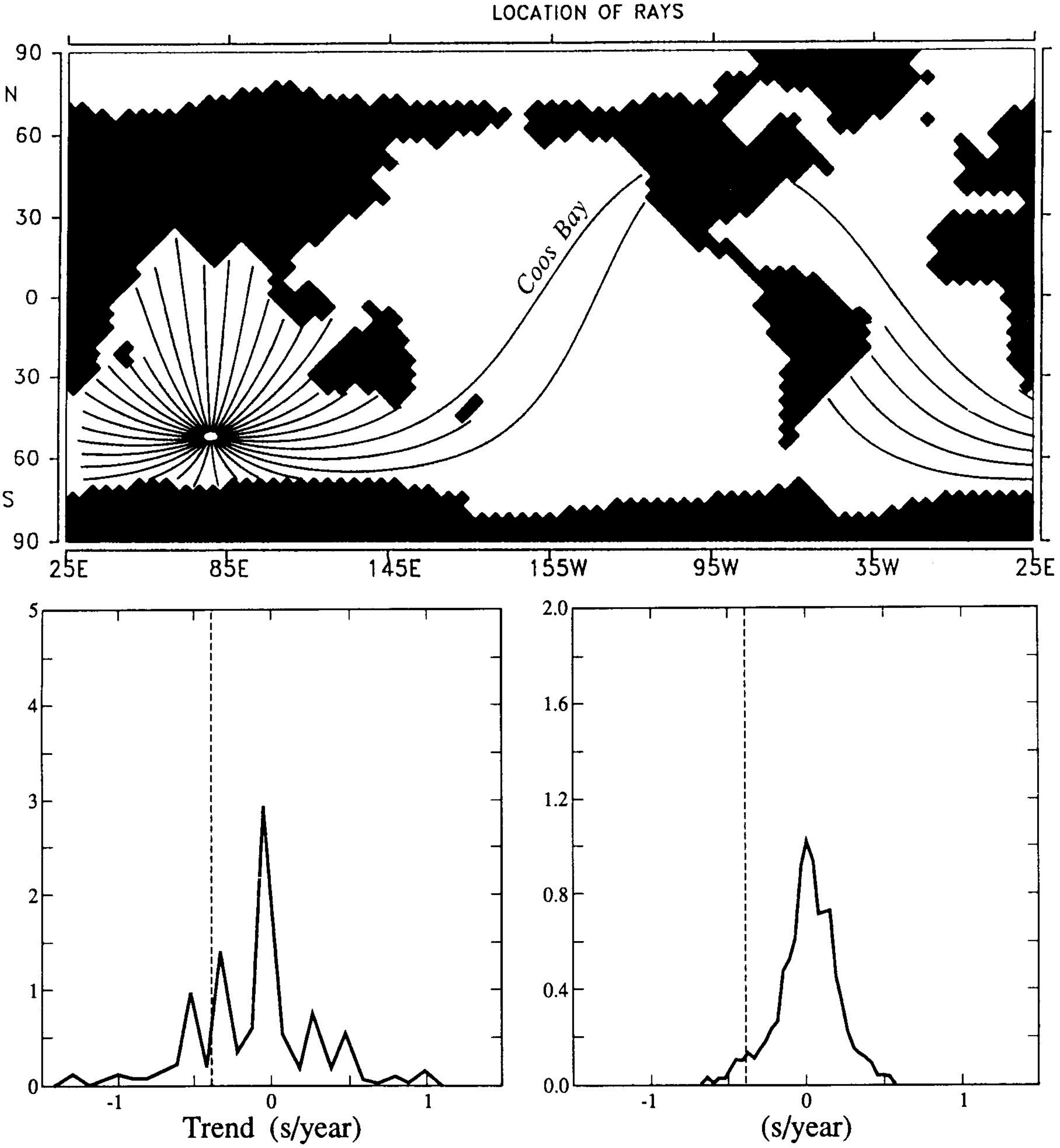

FIGURE 20. The vertical dashed line corresponds to a deterministic change in travel time by –0.4 s/year as a result of greenhouse warming. This is to be compared to the probability distribution of travel time changes (heavy line) from ambient ocean variability, based on 300 decade samples of the Hamburg model.[15] For a single path from Heard Island to Coos Bay (lower left) the signal is not significantly above the noise background, but for many paths (lower right) the greenhouse signal can be detected at about the 95% level. This result is very preliminary.

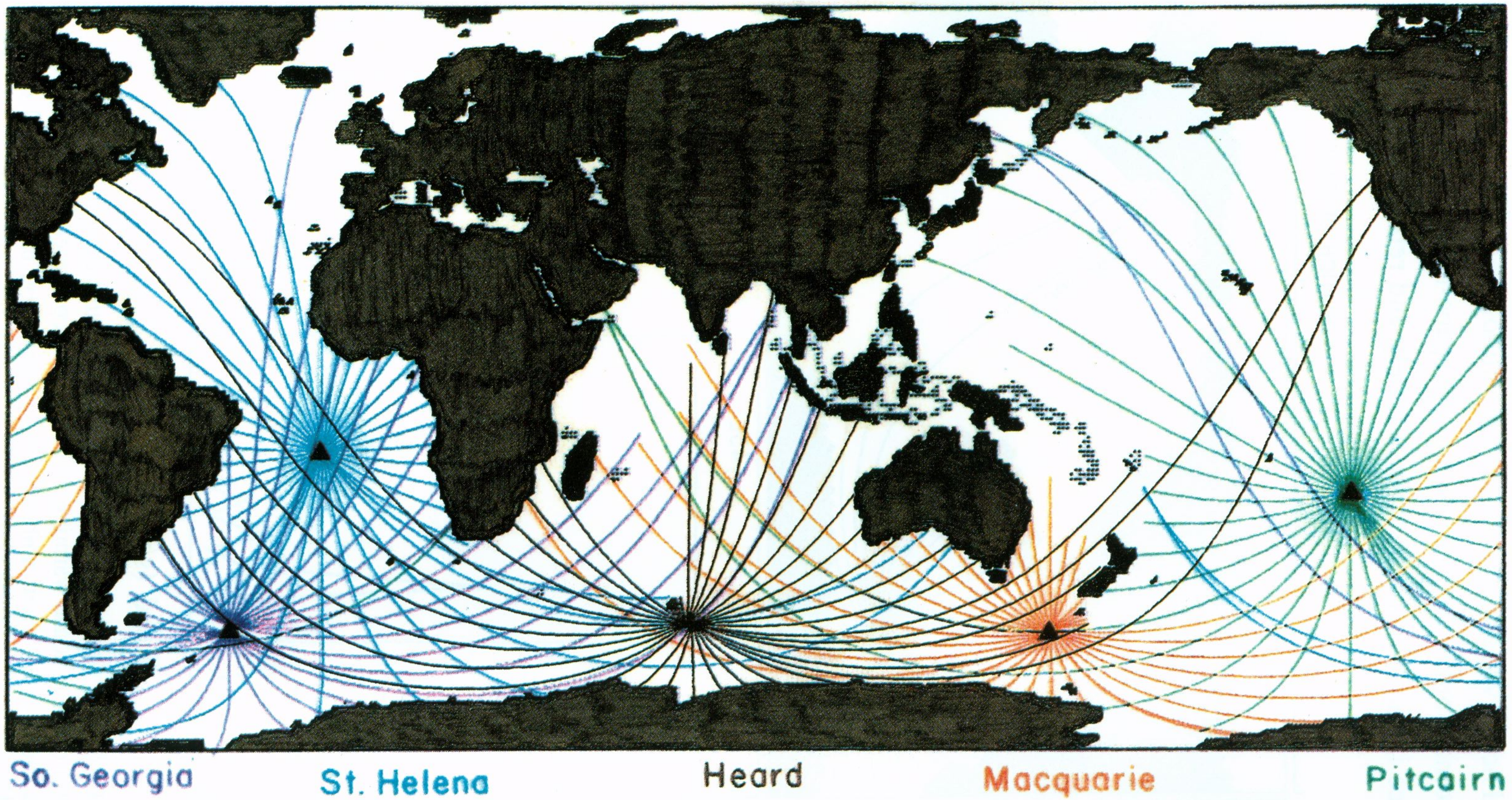

FIGURE 21. Axially refracted geodesics from 5 southern source locations. With such an array (purely fictitious) and 20 well placed receivers, one might begin to resolve basin temperature variability.

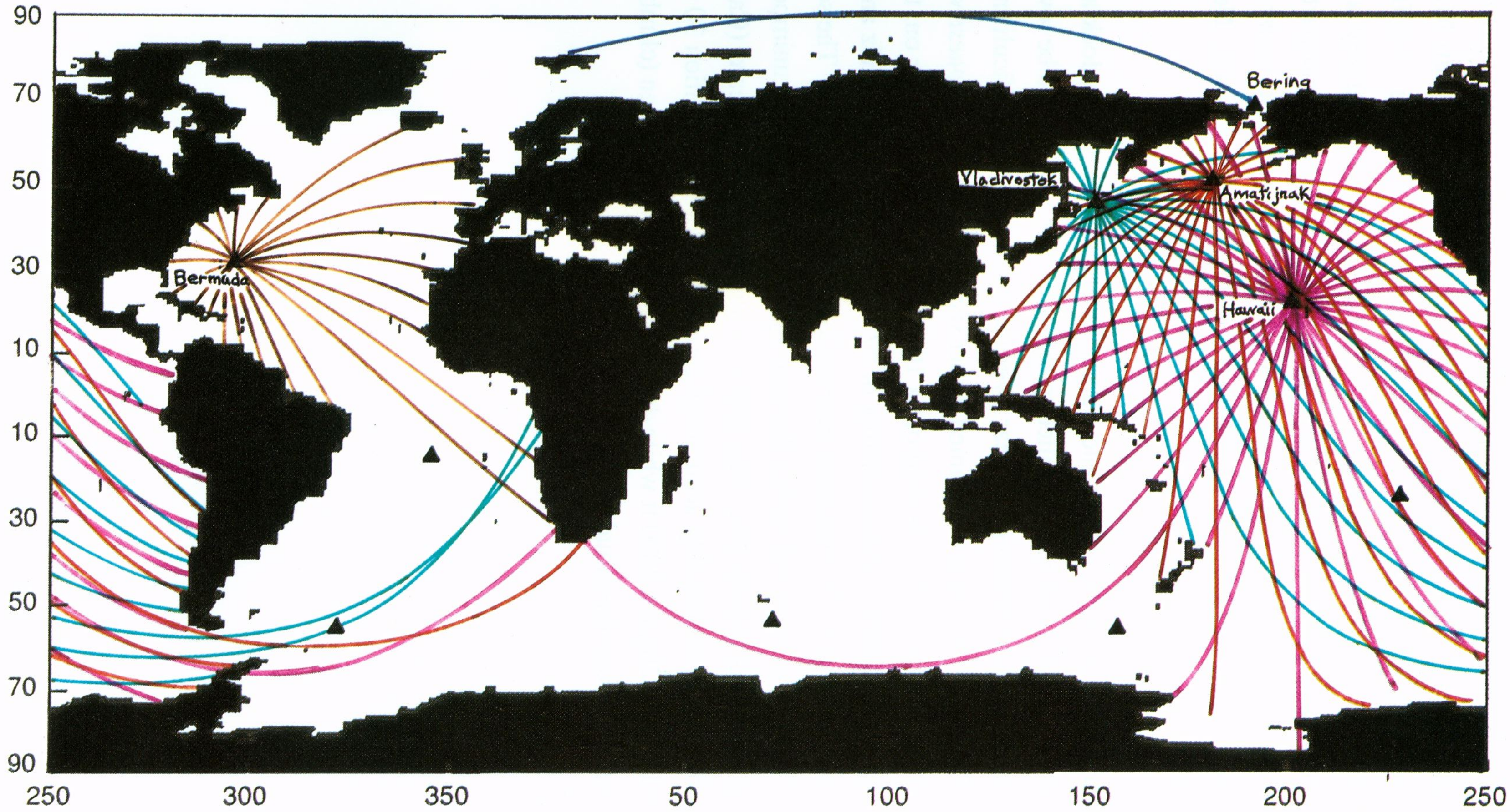

FIGURE 22. Some Northern Hemisphere transmissions that are under way or have been proposed. Spiesberger[16] has been studying a transmission from Hawaii to the West Coast for a number of years. There have been some transmissions from Bermuda northward across the Gulf Stream.[17] A transmission across the arctic has been proposed, and there have been Canadian-USSR discussions[18] of a Vladivostok source transmitting across the Pacific.

Heard Island. The Heard Island test is to get under way in mid-January. Robert Spindel who has built most of the equipment will be at the message center at Applied Physics Laboratory, University of Washington. Ted Birdsall and Kurt Metzger will be manning the horizontal receiver arrays off Bermuda and California. Art Baggeroer and Peter Mikhalevsky will be manning the vertical arrays of Monterey and Bermuda. Andrew Forbes and I will be on the source ship, and Mel Briscoe (our partner before he came to ONR) will be holding his breath back home. There are so many others whose help has been vital, Fred Saalfeld, Admiral Pittenger, John Knauss, Ned Ostenso, I cannot begin to name them.

On 9 January 1991, Andrew Forbes and I are scheduled to leave the dock at Perth. The *Corey Chouest* (figure 23) is ideally suited to the task. The sources can be lowered midship through a center well. Handling the gear over the stern could be difficult in the expected high seas. The *Corey* will be accompanied by her sister ship the *Ami Chouest* with biological observers aboard. Birdsall has worked out a 10-day schedule (one hour on, two hours off) commencing on 26 January, and consisting of 57 Hz CW (avoiding 50 Hz and 60 Hz) plus various coded sequences. Transmission time to Coose Bay is 3.5 hours. The source position 53°15'S, 73°40'E was surveyed earlier this year by Andrew Forbes for unimpeded access to the receiving stations (figure 24). The previous survey by Mrs. Heard (Captain Heard's wife) in 1853 proved remarkably accurate (figure 25). From our position 30 nmi southeast of the island (figure 26), the 9000 ft white dome of the volcano Big Ben (climbed only once) will be towering above the clouds.

FIGURE 23. Source Ship *Corey Chouest.*

Endnotes

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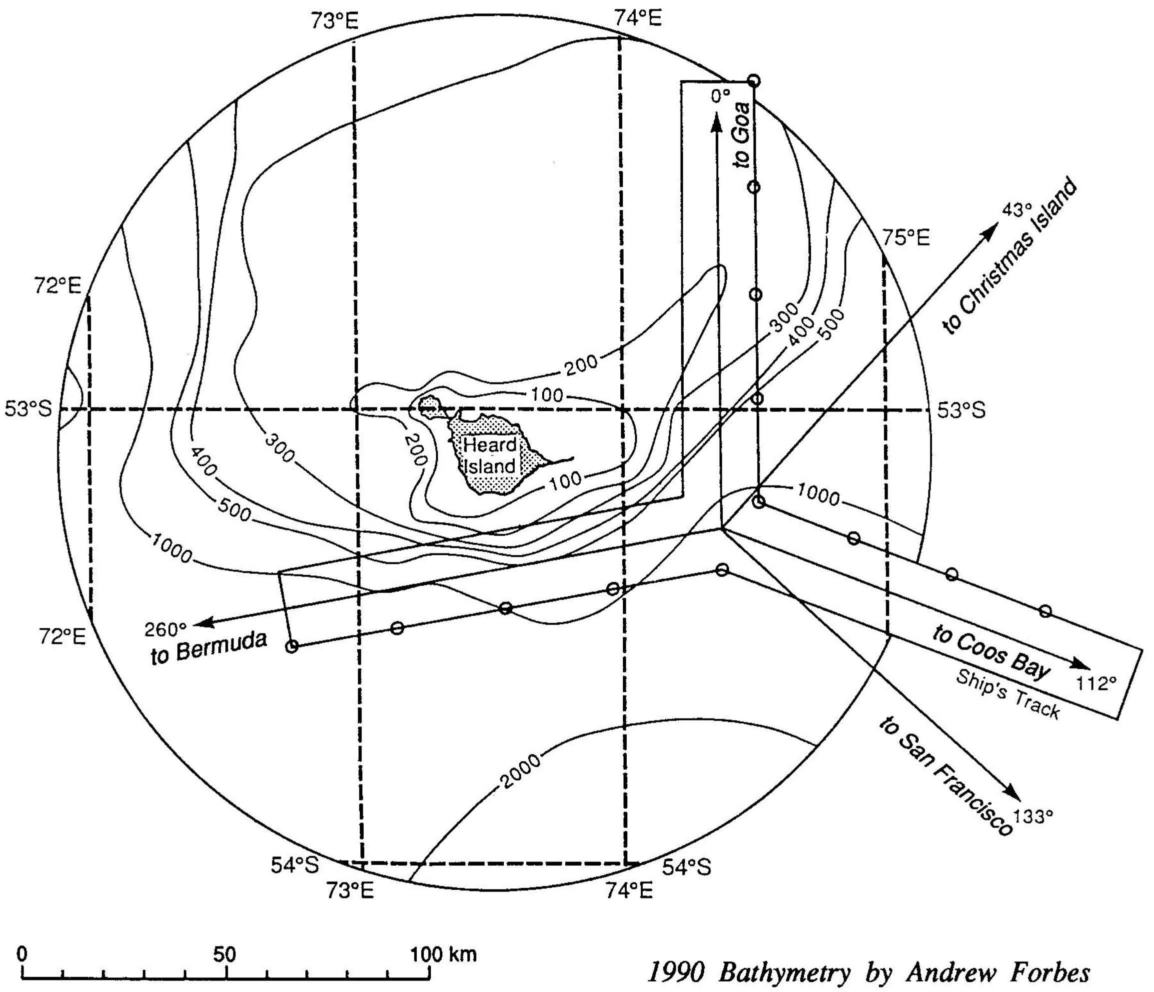
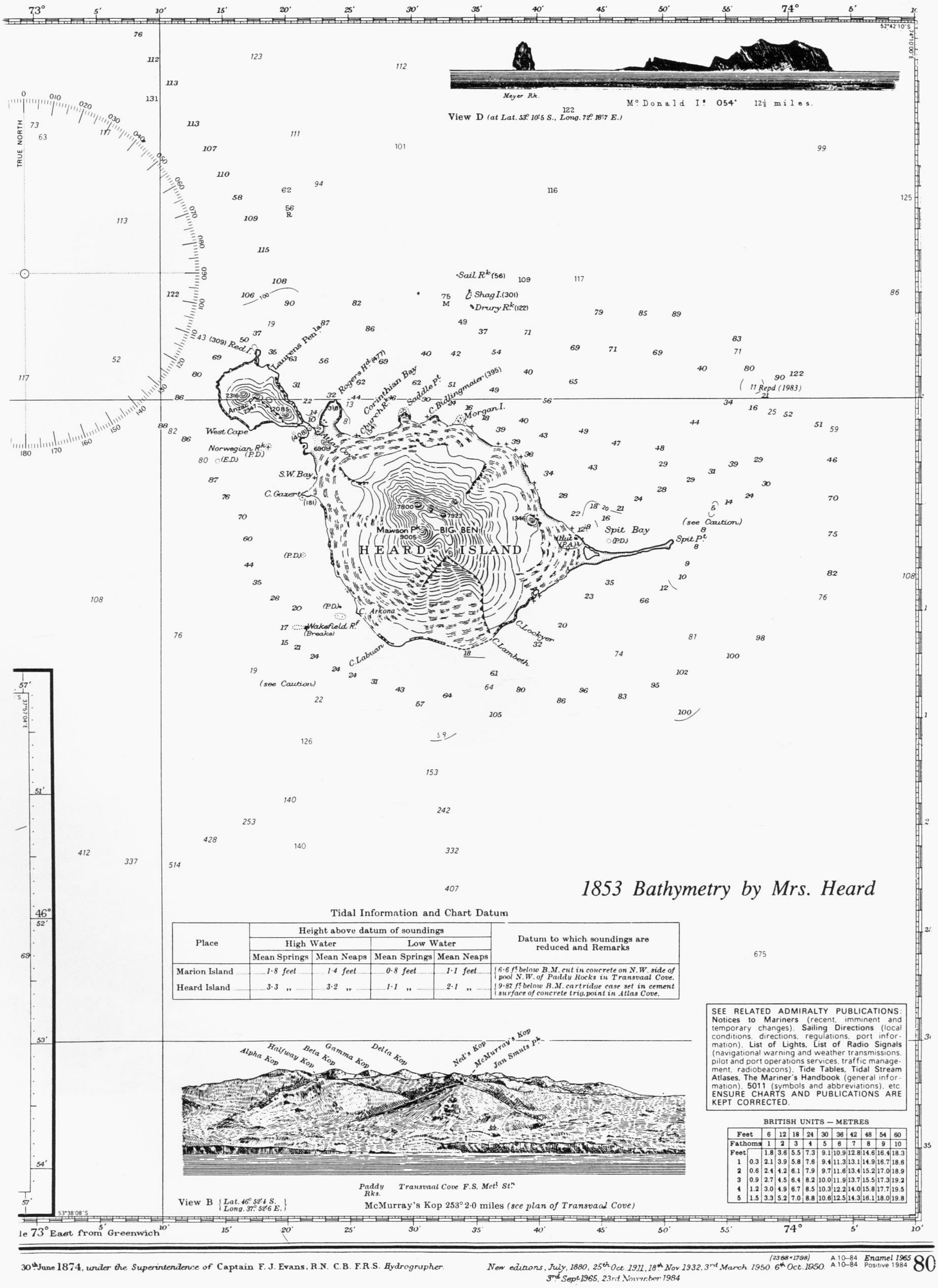


1990 Bathymetry by Andrew Forbes

FIGURE 24. Bathymetry in the vicinity of the source location surveyed by Andrew Forbes early in 1990.



Tidal Information and Chart Datum

Place	Height above datum of soundings				Datum to which soundings are reduced and Remarks
	High Water		Low Water		
	Mean Springs	Mean Neaps	Mean Springs	Mean Neaps	
Marion Island	1·8 feet	1·4 feet	0·8 feet	1·1 feet	6·6 ft below B.M. cut in concrete on N.W. side of pool N.W. of Paddy Rocks in Transvaal Cove.
Heard Island	3·3 ,,	3·2 ,,	1·1 ,,	2·1 ,,	9·87 ft below B.M. cartridge case set in cement surface of concrete trig. point in Atlas Cove.

SEE RELATED ADMIRALTY PUBLICATIONS: **Notices to Mariners** (recent, imminent and temporary changes), **Sailing Directions** (local conditions, directions, regulations, port information), **List of Lights, List of Radio Signals** (navigational warning and weather transmissions, pilot and port operations services, traffic management, radiobeacons), **Tide Tables, Tidal Stream Atlases, The Mariner's Handbook** (general information), **5011** (symbols and abbreviations), etc. ENSURE CHARTS AND PUBLICATIONS ARE KEPT CORRECTED.

BRITISH UNITS — METRES

Feet		6	12	18	24	30	36	42	48	54	60
Fathoms		1	2	3	4	5	6	7	8	9	10
Feet		1.8	3.6	5.5	7.3	9.1	10.9	12.8	14.6	16.4	18.3
1	0.3	2.1	3.9	5.8	7.6	9.4	11.3	13.1	14.9	16.7	18.6
2	0.6	2.4	4.2	6.1	7.9	9.7	11.6	13.4	15.2	17.0	18.9
3	0.9	2.7	4.5	6.4	8.2	10.0	11.9	13.7	15.5	17.3	19.2
4	1.2	3.0	4.9	6.7	8.5	10.3	12.2	14.0	15.8	17.7	19.5
5	1.5	3.3	5.2	7.0	8.8	10.6	12.5	14.3	16.1	18.0	19.8

FIGURE 25. Based on a survey by Mrs. Heard in 1853. Chart of the Indian Ocean No. 802 is reproduced with the permission of the Hydrographer of the Navy, United Kingdom.

FIGURE 26. Heard Island with Big Ben.

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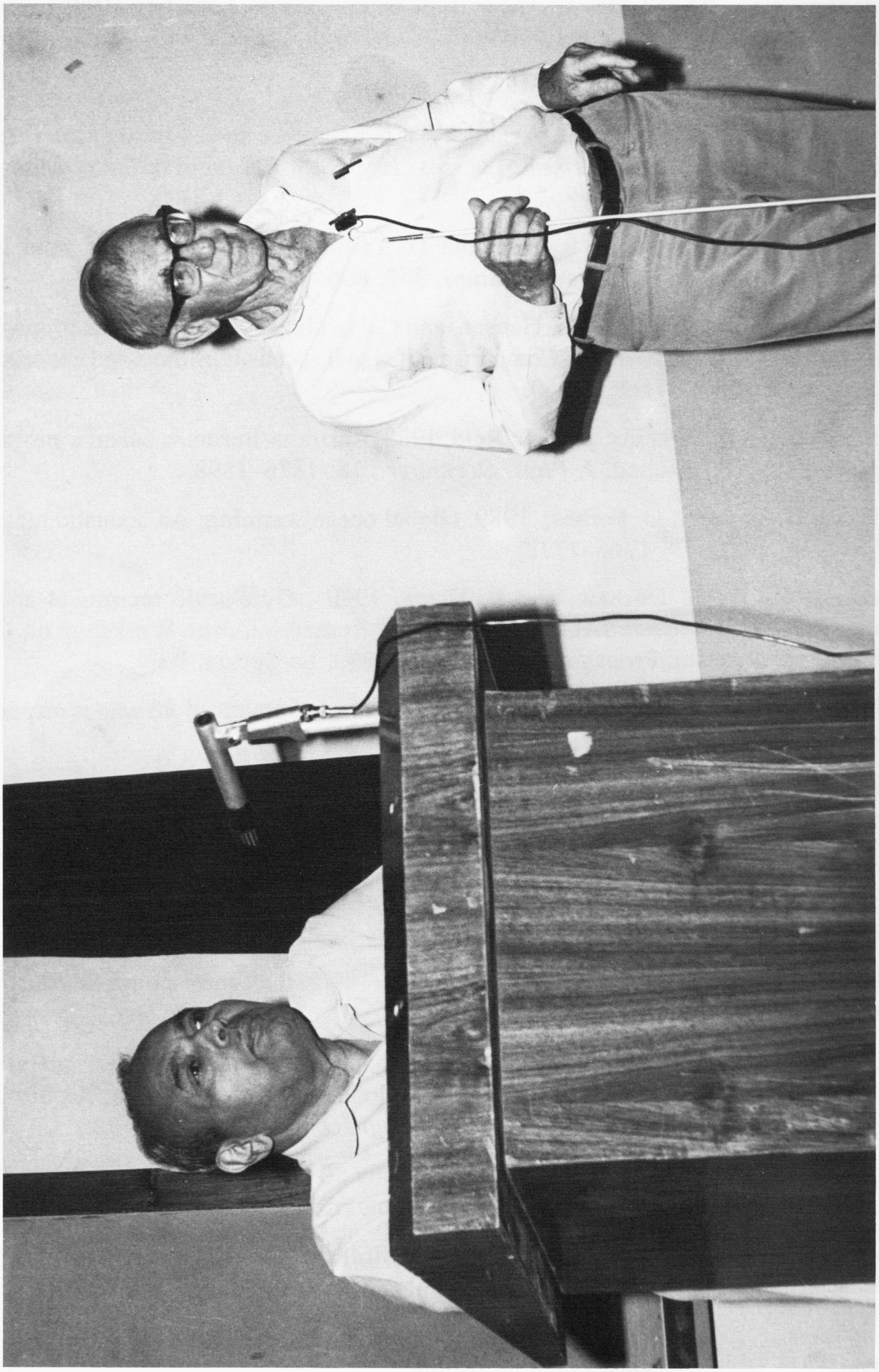

Dr. B. N. Dosai presides over the question and answer period following Professor Munk's lecture at the National Institute of Oceanography in Goa, India.

PROFESSOR WALTER H. MUNK

Professor Munk received his bachelor of science and master of science degrees from the California Institute of Technology in 1939 and 1940 respectively, and his doctorate in oceanography from the University of California in 1947. He has spent the greater part of his professional career at the University of California in San Diego, and the Scripps Institution of Oceanography. He rose from assistant professor to full professor in the period 1947-1954. In addition to Professor of Geophysics, Professor Munk has served as Associate Director of the Institute of Geophysics.

Today, Professor Munk holds the Secretary of the Navy Research Chair in Oceanography at the Scripps Institution of Oceanography, University of California, San Diego. In 1985 he received the National Medal of Science from President Reagan. He is a member of the National Academy of Sciences, the American Philosophical Society, and the Royal Society of London. He holds honorary degrees from the University of Bergen and Cambridge University. Last year he received the Bowie Medal of the American Geophysical Union.