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DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA

REPORT ON THE WORKSHOP:
APPLICATIONS OF OCEAN ACOUSTIC REMOTE SENSING TO CLIMATE MONITORING
BOULDER, COLORADO
7-8 JUNE 1990

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Wave Propagation Laboratory
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REPORT ON THE WORKSHOP: "APPLICATIONS OF OCEAN ACOUSTIC REMOTE SENSING TO CLIMATE MONITORING" BOULDER, COLORADO, 7-8 JUNE, 1990

T. M. Georges and D. R. Palmer

The workshop invitation, reproduced below, states its goals and purpose. The invitation was sent mainly to scientists working directly in the field of ocean acoustic tomography, particularly those involved with the Heard Island Program.

Dear Colleague,

You are invited to attend and participate in a small, informal workshop in Boulder on 7-8 June to discuss "Applications of ocean acoustic remote sensing to climate monitoring."

The focus of this workshop will be on acoustic propagation modeling and experiment simulation, but we expect to discuss broader questions, as well, including climatic needs for monitoring ocean variability and the suitability of ocean acoustics for doing so. Accordingly, we have invited not only propagation modelers, but also some representatives from the experimental-acoustics and climate-modeling communities.

The main outcome we desire is a working, cooperative relationship among NOAA and non-NOAA scientists who want to understand and model the acoustic propagation aspects of basin-scale and global-scale acoustic measurements, such as (but not confined to) the Heard Island Experiment. To this end, we propose to exchange ideas, to keep each other informed, and to join forces, when appropriate, to solve problems of common interest.

The meeting will be small enough (10-15 people) that you needn't make a formal presentation; just be prepared to explain your interests, concerns, recent results, and plans in a roundtable format. Vu-graph and 35-mm projectors will be available.

In lieu of a formal agenda, we propose to structure the workshop around a series of scientific questions, some of which appear on Page 2. We welcome *submissions of your own questions or concerns to add to the list -- not only ones to be answered at this workshop, but also suggested topics for research projects or for other workshops to follow.*

Page 3 contains the distribution list for this invitation, as of this date. You may nominate others you think should attend. Page 4 has information about accommodations, directions and other logistical details.

We sincerely hope that you can contribute your expertise to this workshop; please let one of us know as soon as you can whether you plan to attend.

Participating in the workshop were:

L. Boden, WHOI
B. Chertock, NOAA/WPL
T. J. Eisler, NOAA/NOS
T. M. Georges, NOAA/WPL
R. M. Jones, NOAA/WPL
J. F. Lynch, WHOI
J. H. Miller, NPS
D. R. Palmer, NOAA/AOML
E. C. Shang, NOAA/WPL
J. Wilson, NOAA/WPL

Workshop Conclusions

The workshop was structured around five "Discussion Topics" and associated scientific questions, which were distributed with the workshop invitation and were designed to stimulate discussion. The two days of discussion were divided into five sessions, each moderated by a discussion leader. The principal discussion results and conclusions are arranged below following restatements of each discussion topic:

*1. **RELEVANCE TO CLIMATE STUDIES** -- Questions for Discussion: What aspects of ocean circulation and heat transport are most critical for monitoring climate processes? What acoustic paths would be most sensitive to those aspects? What predictions of climate models could be best tested with long-range acoustics? What do we understand about the "normal" seasonal and interannual ocean variability from which longer-term climate change is to be distinguished?*

1.1 The answers to the first three questions require estimates of the four-dimensional "greenhouse signature" in ocean temperature, which is the domain of climate modeling. The workshop participants believe that there is general agreement in the climate modeling community that an increase in greenhouse gases caused by human activity will cause global warming. Beyond that, the models disagree about quantitative aspects of the warming and about what one might call second-order effects, such as regional climate redistribution. (There is, however, general agreement that high latitudes will experience greater temperature changes than lower latitudes (White, 1990).) Furthermore, much less is known from climate models about the greenhouse signature in the ocean interior than in the atmosphere. **Conclusion: Present disagreement of climate models about the "greenhouse signature" in the ocean does not permit the design of acoustic measurements that test specific regional consequences of greenhouse warming. However, by monitoring global and regional temperature trends, ocean acoustic measurements over the next decade could provide the needed validation and refinement of coupled general-circulation models, which constitute our understanding of climate processes. The most useful validation would include not only global average temperature measurements, but also measurements that sample the oceans on basin and sub-basin scales.** It is possible, for example, that major regional climate redistributions will be accompanied by only minor changes in global averages.

1.2 With regard to the fourth question about "normal" ocean variability, Semtner and Chervin (1990) have recently discussed in detail the effects of mesoscale and annual ocean variability on global-scale acoustic measurements. They estimate the travel-time fluctuations of "axial rays" caused by the temperature fluctuations produced by an eddy-resolving numerical model of the global ocean. (J. Miller reported on similar work by Chiu at NPS using the HARPO 3D ray-tracing program.) They concluded that the expected acoustic path-average greenhouse signal would not be masked by mesoscale and annual variability. An important question remains about how the greenhouse signal can be distinguished from non-greenhouse interannual variability (such as ENSO). **Conclusion: Semtner and Chervin's and Chiu's work illustrate the utility of joining ocean-model predictions with simple acoustic estimates. Adding greenhouse forcing and modeling basin-scale acoustic effects would be logical next steps in incorporating climatology into acoustic simulations.**

***2. THE HEARD ISLAND PROJECT** -- Questions for Discussion: Is the goal of the Heard Island Project to detect climate trends or to understand climate mechanisms? How would the answer affect the way the experiment is designed? What are the modeling requirements (if any) of the Heard Island Feasibility Study? What are the feasibility criteria? How will experimental parameters like source and receiver depth and geographic location be decided?*

2.1 Although the stated goal of the Heard Island Project (Munk and Forbes, 1989) is to monitor global temperature trends in the ocean, interpreting the experimental results will certainly require comparisons with the predictions of climate models. Furthermore, monitoring Heard Island transmissions for a decade will test models of the background (mesoscale and annual) "noise" levels. Climate modeling and the interpretation of acoustic measurements are thus interdependent. **Conclusion: To assess the regional variability of the climate as well as the mesoscale and annual signals, the design of the Heard Island receiving network could include more basin- and sub-basin-scale paths, in addition to those already**

planned. The number of paths probed using a single source could be increased by considering travel-time differences among receiving stations that line up along acoustic ray paths. For example, could one monitor North-Atlantic temperature variability by receiving the Heard Island signal in Nova Scotia and subtracting the travel time to Ascension?

2.2 Acoustic paths from Heard Island that pass through an Antarctic environment (particularly those to the U. S. west coast) are of concern, because of the possibility of excessive path loss by surface scattering. Where the sound channel lies close to the surface, all but near-axial rays could experience multiple surface reflections and suffer very large scattering losses, which would depend on sea state. These paths are also complicated by abrupt vertical displacements of the sound channel and by horizontal refraction at the Circumpolar Front. **Conclusion: Propagation loss estimates (as a function of sea state) for Antarctic paths out of Heard Island would help determine whether only axial rays survive surface scattering. The effects of horizontal refraction at the front on travel time could be studied using simple 3D analytical ocean models. If only axial rays (modes) survive, reception only near the axis may be possible. Even for axial rays, travel-time sensitivity to the location of the front for Antarctic paths could unduly complicate the "background" variability. Satellite SST measurements during both the feasibility and ten-year studies could help locate oceanographic features (such as the Circumpolar Front), which would be useful in data interpretation.**

2.3 Although most of the receiving-station parameters for the Feasibility Study have been decided, a few choices with regard to locating hydrophones on or near complicated bathymetry can still be made that could improve the experimental outcome. Because reception near a steeply sloping or very rough bottom or in canyons is complicated by 3D multipath and is difficult to model, data from hydrophones located on or over smooth, gently sloping bathymetry will be less distorted and easier to interpret. **Conclusion: Estimates of acceptable bottom roughness and slope for the frequency of the Heard Island source would be useful in guiding receiver placement.**

2.4 Dave Palmer summarized NOAA's plans to man an acoustic receiving station at Ascension Island in the South Atlantic during the Feasibility Study. The island is located at 8 deg S, 14 deg W on the mid-Atlantic ridge and is roughly half-way along the acoustic path between Heard Island and Bermuda. Signals will be recorded from bottom-mounted, Missile Impact Locating System (MILS) hydrophones cabled to the island. Some of the hydrophones are near the sound-channel axis (about 800-m depth) and have uninterrupted paths to Heard Island, approximately 9500 km away. **Conclusion: Modeling the acoustic propagation from Heard Island to Ascension Island would help to assess any propagation or interpretation problems associated with that path and to predict what arrivals to expect. The ability of the four hydrophones to monitor horizontal direction of arrival could be investigated.**

3. PROPAGATION MODELING -- THEORY *-- Questions for Discussion: What is the simplest way to model acoustic propagation to megameter ranges that reproduces the essential features of the acoustic measurables? What are the limi-*

tations of ray, mode, PE and hybrid models with respect to range, frequency, complex bathymetry, 3D structure, etc.? What uncertainties do (unknowable) small-scale ocean structure and motions (e.g., eddies and internal waves) impose on acoustic measurements of large-scale structure? How should information from fluctuation models and measurements be combined?

3.1 The workshop participants seemed at first to disagree about how much ocean-model detail is appropriate in modeling acoustic propagation, particularly to megameter ranges. Some felt that there is a tendency to "over-model" small-scale sound-speed and bathymetric structure, the result being computational inefficiency and loss of insight. Others felt that only very detailed models of mesoscale structure (such as EOF models) can reveal the expected mesoscale-induced acoustic fluctuations. The discussion seemed to resolve itself in the general observation that the models that provide the most insight are the simplest ones that reproduce the desired acoustic properties. Modeling time-dependent small-scale structure is appropriate if its acoustic effects are being specifically studied. All agreed that, for ray calculations in particular, it is useless to model structure smaller than an acoustic Fresnel zone. **Conclusion: Care in deciding how much ocean detail is appropriate in models pays off in computational efficiency as well as insight about acoustic sensitivity to model parameters. For many purposes, low-order analytical sound-speed and bathymetry models avoid artificial structure, reproduce the essential acoustic features, and are computationally more efficient. On the other hand, simulating the acoustic "noise" due to eddy fields or other mesoscale structure may require 3D acoustic computations using very detailed models derived from ocean GCMs or observations.**

3.2 There is no indication that existing propagation programs (for example, 3D ray tracing, adiabatic normal modes, pulse PE) cannot adequately model most of the sound-channel propagation paths of interest for climate monitoring. It will be necessary to better understand the range and frequency limitations of each model, however, and some may require refinements and modifications. The ambiguity diagram used by Munk and Wunsch (1983) is a useful tool for determining whether a ray or mode representation of the propagation (and inversion) is appropriate. In the vicinity of steeply sloping or complicated bathymetry, near features like the Circumpolar Front, or for diffraction by continents, seamounts, etc., full-wave "patches" may be necessary. However, it may sometimes be easier to avoid these situations experimentally than to include them in models. **Conclusion: Existing propagation programs are adequate for describing most of the acoustic propagation of interest for ocean climate monitoring; problems with specific paths may require hybrid models.**

3.3 Discussion of the effects of small-scale structure is in paragraph 5.6.

***4. INTERPRETING ACOUSTIC MEASUREMENTS** -- Questions for Discussion: What can we infer about proposed global measurements from existing megameter-path data? What ocean properties do path-averaging acoustic measurements (like travel time) really average? What kind of global network of "acous-*

tic thermometers" is required to infer global ocean circulation and heat transport? Can travel-time spreading and wander be interpreted in terms of the "internal-wave tomography" concept proposed by Flatté?

4.1 The recent measurements by Spiesberger et al. (1990) of WHOI using bottom-mounted hydrophones in the northeastern Pacific Ocean demonstrate the long-term stability of ray arrivals over long (3000-km) acoustic paths using 300-Hz sound sources. He also showed that temperature changes near the surface could be monitored using the methods of vertical-slice tomography. This long-term stability is good news for acoustic climate monitoring, because it implies a lack of sensitivity to small-scale structure. Just before this workshop, WPL and AOML staff met with John Spiesberger and agreed to cooperate in analyzing his North Pacific data set. **Conclusion: Existing megameter-path data, such as Spiesberger's, should be analyzed further and if possible inverted, to find out what basin-scale ocean features can be monitored. The implications of data obtainable over such paths for global climate monitoring should be assessed as soon as possible. The data-analysis process would be greatly accelerated and simplified if aspects of the data set that are now classified could be declassified.**

4.2 Vertical-slice tomography measures path-average sound slowness at ray turning points, but for small changes, it approximately measures path-average temperature.

4.3 The question of an optimum configuration for an acoustic thermometer network was implicitly addressed in paragraphs 1.1 and 2.1.

4.4 Tomography inversion could more fully incorporate available independent information about the ocean, in particular, constraints imposed by satellite sea-surface-temperature measurements (Chiu et al., 1987) and knowledge of the long-term stability of the deep ocean temperature structure. However, it is important that inversion methods retain the ability to separate the parts of the recovered ocean structure that are derived from the acoustic measurements from those which depend on independent measurements and assumptions. **Conclusion: Continue developing acoustic inversion methods that incorporate independent knowledge about the ocean, but make sure that the relative contributions of acoustic vs. other measurements to the recovered ocean structure remain identifiable.**

***5. EXPERIMENT SIMULATION** -- Questions for Discussion: What limits our ability to simulate long-path data: the propagation model or the ocean model? Where should ocean-model and propagation-model improvements focus? To what extent do only near-axial rays (or modes) survive propagation over megameter ranges? What are the implications for vertical-slice inversion? When are three-dimensional simulations necessary? Of what use are bottom-reflected and surface-reflected signals over very long paths? What are the implications of acoustic chaos simulations for inherent measurement uncertainties?*

5.1 There was a consensus that, at present, it is the ocean models that limit our ability to simulate long-path data. The most important question about experiment simulation with respect to climate monitoring is: "What is the greenhouse signal that we are tying to identify?" Unfortunately, there isn't yet a consensus among climate modelers about the effects of greenhouse warming on ocean circulation and heat transport, except near the surface. This ignorance stems mainly from the sparseness of observations of the ocean interior. Acoustic tomography can therefore help validate climate models, which in turn are needed for better experiment simulation. **Conclusion: This interdependence of climate modeling and acoustic propagation modeling suggests that closer working research ties between the the two communities would be productive.**

5.2 When only near-axial rays/modes survive to long ranges, it is because non-axial rays/modes are blocked by bathymetry, and not because higher rays/modes are attenuated in the sound channel. Vertical-slice inversion is not possible for high-angle rays/modes that are cut off. **Conclusion: Proposed climate-monitoring acoustic paths should be assessed for blockage of higher-order rays/modes by intervening bathymetry. When possible, paths that are the least blocked should be selected.**

5.3 Simulations have shown that three-dimensional effects on travel time cannot automatically be ignored for many long paths in realistic ocean models. Computation of eddy-noise statistics is an example of a problem that may require 3D modeling. **Conclusion: Rules-of-thumb devised from simulations could help determine from transverse refractive-index gradients whether full three-dimensional modeling is required for a given case.**

5.4 Bottom- and surface-reflected rays/modes are of little use for monitoring the vertical structure of ocean temperature changes, because they do not reveal the depth where temperature changes occur. (The depth-weighting function has a stronger depth dependence for refracted than for reflected rays.) However, some paths that consist of only short segments with bottom or surface reflections can still be used in vertical-slice inversions. **Conclusion: For recovering path-average sound-speed profiles using vertical-slice inversion, it would be useful to better understand the effects of bottom and surface reflections that occur only over short path segments, such as near a source and/or receiver.**

5.5 Mike Jones summarized the mathematical basis for vertical-slice tomography inversion in the adiabatic-invariant approximation. Once the pulse arrivals are identified in terms of the number of loops and direction of transmission (up or down), the path-average symmetric part (thickness) of the sound channel can be recovered from the pulse-arrival sequence, even if the source and receiver are not on the sound-channel axis. The antisymmetric part (vertical displacement) of the profile cannot be recovered (by any inversion method) without using independent information, such as SST constraints or the constancy of the lower part of the profile.

5.6 Acoustic chaos, or extreme sensitivity of acoustic ray paths to small-scale structure of the environmental model, has been observed in simulations of range-dependent sound channels and bathymetry (Palmer et al., 1988a,b). Its consequence for acoustic tomography is a "blurring" of the effective ray paths corresponding to resolved pulse arrivals and thus an inherent uncertainty about the portion of the medium being probed. Although the conditions that produce truly chaotic acoustic fields are not fully understood, it seems likely that the exponential proliferation of micro-multipaths associated with complicated ocean and bathymetry models corresponds to observed signal complexity in certain experimental environments, such as the Florida Straits (Palmer et al., 1988b, 1990). Since chaotic effects increase exponentially with range, some ray properties at long ranges (such as amplitude and ray position) are very sensitive to small-scale model parameters. However, integrated effects, such as travel time, are known to be less sensitive to those details in simulations than other wave properties, supporting the advantage claimed for long-path-integrated measurements that they inherently low-pass filter the effects of small-scale structure, leaving only the climate signal. **Conclusion: The present controversy about the existence of "wave chaos" (i.e., is ray chaos an artifact of the ray approximation?) must be resolved. It would be useful to model the sensitivity of acoustic travel time and recovered sound-speed profiles to realistic models of small-scale structure.**

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