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Reimar Lüst Lecture

Listening to Ocean Climate

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Impressum

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Listening to Ocean Climate

By Walter Munk on behalf of the ATOC Executive Committee*

***Peter Worcester (Principal Investigator),
Robert Spindel (Co-Principal Investigator),
Walter Munk and Carl Wunsch.**

I am pleased for this opportunity to speak in honor of Reimar Lüst whom I met while serving on the Advisory Committee of this Institute. The progress here at the MPI in just twenty-five years is truly astounding. I cannot recall any comparable development elsewhere during my life time. Winston Churchill was speaking for the climate community when he said: "never have so many owed so much to so few".

During the same twenty-five years we have been involved in developing "Acoustic Thermometry of Ocean Climate" (ATOC), a method for measuring ocean variability on a climate scale. Our story has been controversial, with many ups and downs. I will tell the story of ATOC.

1. The Ocean Sound Channel

In the fall of 1944, Ewing and Worzel departed Woods Hole aboard the ***Saluda*** to test the theory of an ocean acoustic waveguide. A deep (1000 m) receiving hydrophone was hung from the ***Saluda***; a second ship dropped 4-pound charges to 1000 m at distances up to 900 miles. They heard, for the first time, the characteristic signature of a SOFAR (sound fixing and ranging) transmission building up to a climatic cut-off, as illustrated in figure 1. This is the only oceanographic experiment I know which confirmed a theoretical prediction.

Ewing and Worzel[1] made two statements: a conjecture about possible transmissions of over 10,000 miles (which we have since confirmed), and that "the end of the ... transmission was so sharp that it was impossible for even the most unskilled observer to miss it". We have yet to find an unequivocal way of measuring the end of a transmission.

For the record, the Russian acoustician Brekovskikh independently discovered the ocean acoustic waveguide soon thereafter (at high latitude where the channel is shallow). Ewing and Brekovskikh did not know about each other's work for many years, for the subject had fallen under a veil of secrecy on both sides of the iron curtain.

The U. S. Navy established a SOund SUrveillance System (SOSUS) at the expense of some $15 billion.

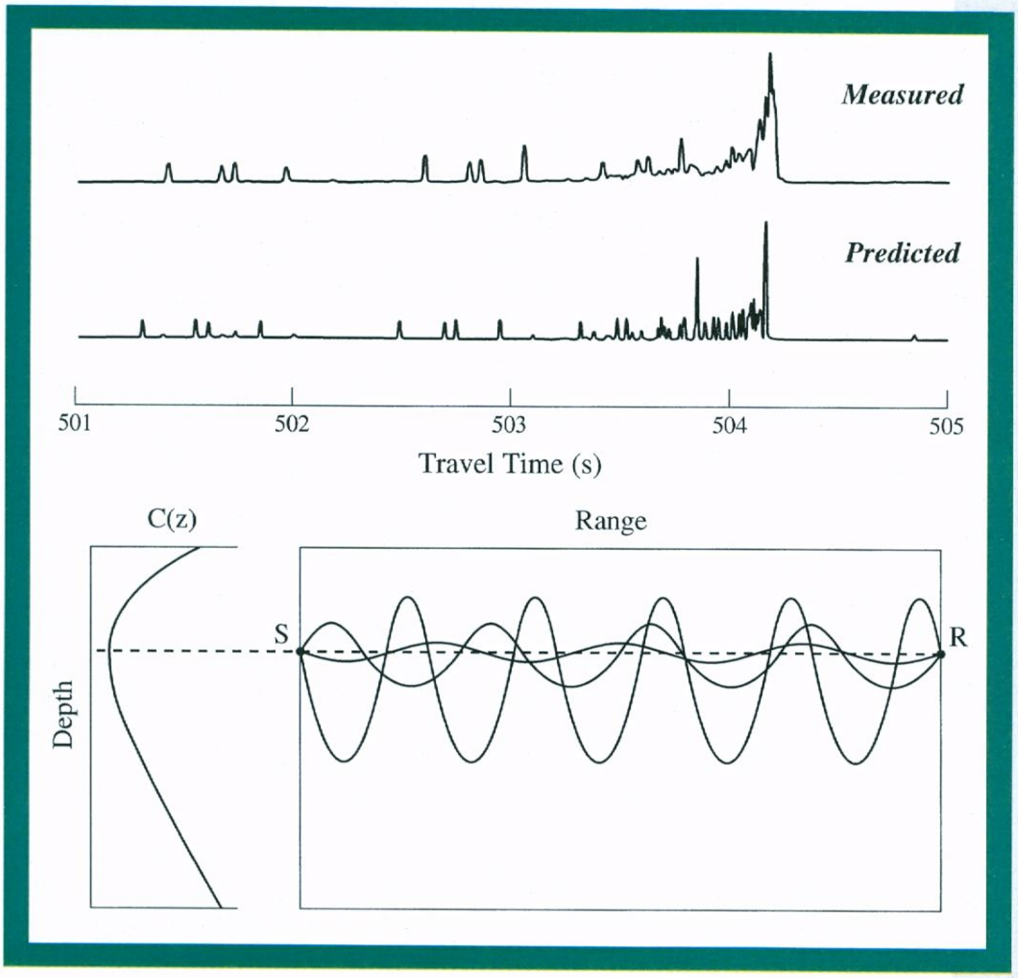


Figure 1. A tomography transmission. Sound speed increases with temperature and pressure. The acoustic wave guide (left) owes its existence to the fact that sound speed increases upwards from the minimum axis because it gets warmer, and increases downward from the axis because the pressure increases. Steep rays oscillate throughtout the water column; flat rays remain near the sound minimum and come in last. The discrepancy between the measured arrival pattern (top) and that inferred from climatology was associated with a colder (slower) than average surface layer.

2. The Discovery of Ocean Weather

The second chapter in our essay is the discovery in the 1960's of mesoscale variability. Since the days of the ***Challenger*** expedition in the 1870's, Oceanography had been conducted by sounding the oceans from a few moving ships. Successive soundings were traditionally attributed to changes in position (rather than time) with the inevitable result of a climatology steady in time and increasingly complex in space. It came as a great shock that the oceans, like the atmosphere, had an active weather at all depths. Using over-simplified terms, in oceanography the study of weather lagged the study of climate by many years. In the atmosphere it was generally the other way around.

My introduction to ocean acoustics came in direct response to the "mesoscale revolution". The fact that 99% of the ocean kinetic energy is associated with scales of order 100 km and 100 days (the ocean weather) implied that one had to rely on something other than the "expedition mode". Carl Wunsch and I proposed "Ocean Acoustic Tomography" as an observational method[2] which takes advantage of the fact (i) that the oceans are transparent to sound but opaque to electromagnetic waves, and (ii) that sound speed is a sensitive function of temperature so that the travel time between an acoustic source and receiver is a function of the temperature profile of the intervening waters.

In the fall of 1978 a signal was transmitted at 10-minute intervals for 48 days from a moored source off Bermuda to a SOSUS receiver array at 900 km range[3]. We were able to resolve and identify a series of stable ray arrivals. The work came just in time to save Acoustic Tomography from an early demise. A reviewer for the National Science Foundation wrote that "travel times along ray paths are meaningless in a saturated environment", hence ray arrivals could not be resolved, and even if resolved could not be identified, and even if identified would not be stable. The proposal was declined. We responded with "we have resolved, identified and tracked 13 rays for 2 months". The proposal was accepted[4,5].

3. Ocean Climate

Starting with Worcester's 25 km reciprocal transmissions[6] (to measure currents) in 1976, the first ten years were largely devoted to the mapping of mesoscale features at typical ranges of a few hundred kilometers[4,5]. Multi-megameter tomography was pioneered by Spiesberger starting in 1983, with a program of transmissions from Hawaii to the mainland[7]. Open ocean vorticity was measured in 1987 with a 1000 km tomographic triangular mooring north of Hawaii[8]. The question naturally arose as to whether one could perform tomography on a basin scale, say 5000 to 10,000 km (remember the Ewing prophesy), to reduce the "mesoscale noise" variance by two orders of magnitude relative to a climate signal.

We have here a case of detecting a trend of order 0.01°C per year in a 1°C to 3°C rms noise. A weak trend in a noisy background is difficult to detect, and even more difficult to interpret. Wunsch[9] has described the sorry state of affairs at the time; there were virtually no adequate interior ocean time series. Discussions of surface temperature trends required heroic corrections for shifts from canvas to metal buckets, and from buckets to engine intake temperatures. With regard to interpretation, the ocean community had not yet come to grips with Hasselmann's historic application of random walk statistics to the climate problem[10].

4. Heard Island Feasibility Test

To settle the problem of how far man-made acoustic signals can be recorded and interpreted, we chose a source site near Heard Island, an uninhabited Australian island in the southern Indian Ocean[11] which has a unimpeded "view" into all ocean basins (figure 2). The American west and east coasts are both in view almost half way around the world, at 19,000 km or 3 1/2 hours of acoustic travel time; the first westward past the Cape of Good Hope, the other eastward past New Zealand.

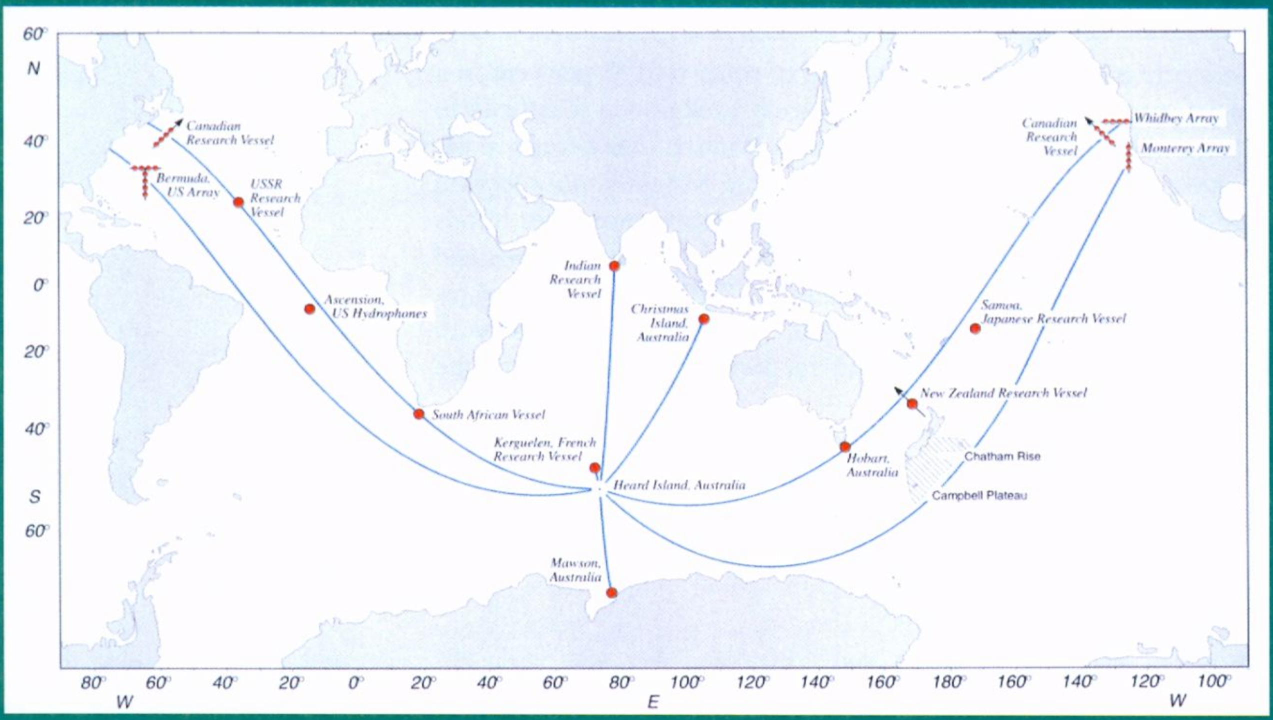
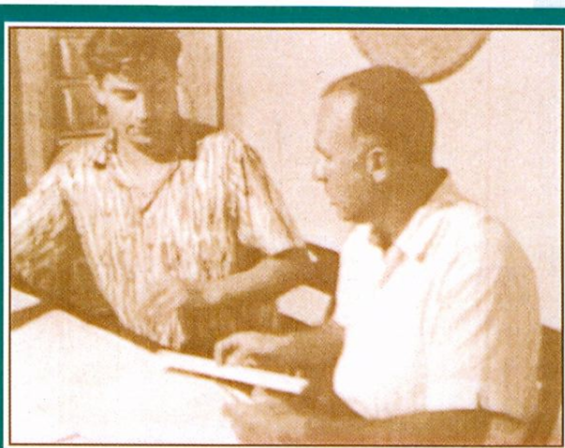


Figure 2. The Heard Island Feasibility Test conducted in January 1991. An acoustic source was located near Heard Island in the Southern Indian Ocean. The blue lines are refracted geodesics (great circles corrected for Earth flattening and horizontal refraction). Signals were recorded on hydrophores tended by eleven nations at the location shown by red circles.

There was no theoretical guidance; estimates of the attenuation distance[12] ranged from a few thousand to ten thousand kilometers. For months we had anticipated the crucial moment of commencing transmissions at 0000 GMT 26 January 1991 (Australia Day). The answer, when it came, was in the form of a resounding anticlimax. On the preceding evening technicians aboard the ***R.V. Cory Chouest*** requested a routine 5-minute checkout of the sources. Three and one-half hours later the ***Cory*** received an incredulous message from Bermuda that they had received an unmistakable signal one day in advance. What was going on? A few minutes later an annoyed message asking for confirmation came from Coos Bay, State of Washington. Both arrivals had traveled almost half around the world (19,000 km), the first westward past the Cape of Good Hope into the South and North Atlantic, the other eastward through the Tasman Sea into the South and North Pacific. The feasibility of global transmission had been established, and it was not yet Australia Day! I was reminded of Sir Edmond Hillary's comment when he finally made it to the top of Mount Everest: "I suddenly realized that I was no longer going uphill".

Five days into the transmission the ***Cory*** encountered a gale and all sources were demolished. By then we had collected enough data from the fifteen global receiving sites to come to grips with some of the problem. I am convinced that if the storm had come a few days earlier, we would never have had another chance. Sheer luck! [I should have known better than to select the Heard Island site; in 1963, a 28 year old Klaus in Hawaii recorded a dispersive wave train from which he deduced a very severe storm centered over Heard Island[13] (figure 3 lower, right). It is one thing to detect an event at 15,000 km; it is another thing to be in the middle of it.]



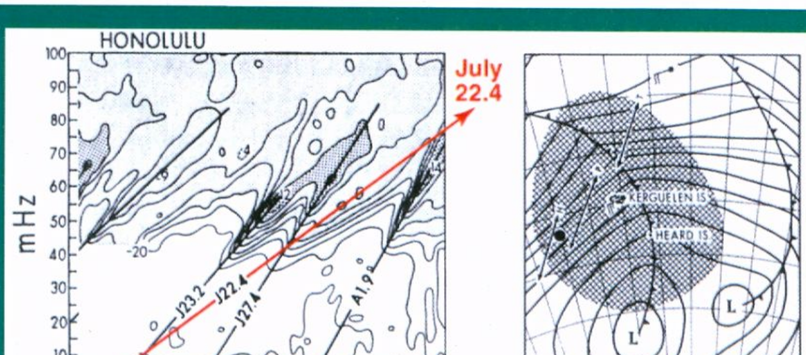


Figure 3. Waves Across the Pacific . Klaus Hasselmann and Frank Snodgrass at the recording site in Honolulu in July 1963. The dispersion diagram (left, bottom) shows the characteristic frequency signature of an "event" on 22.4 July 1963 at a distance of 15,300 km from Honolulu. The inferred wave origin is centered on Heard Island[13].

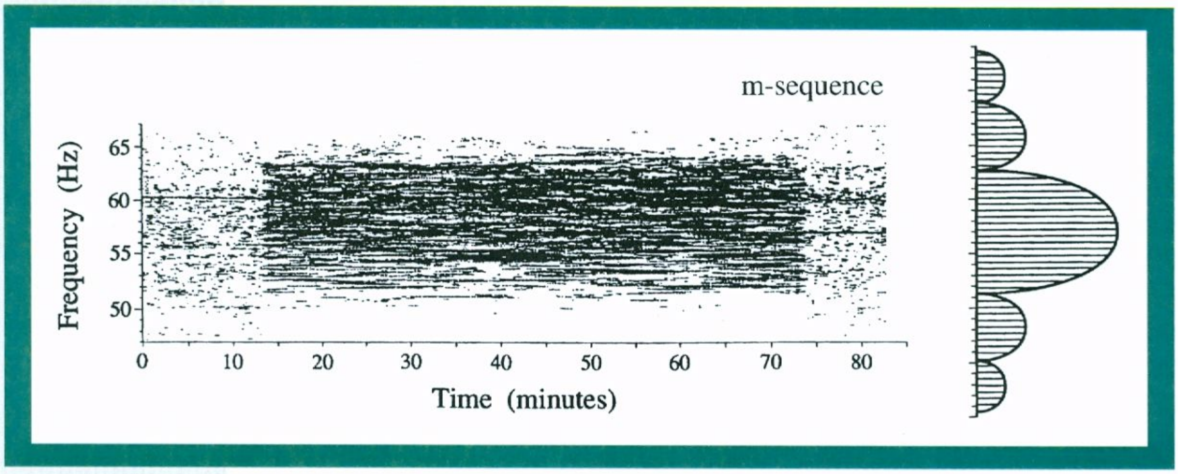


Figure 4. Recorded spectrogram at Ascension Island 9200 km from Heard Island. Some 60-Hz noise is evident before and after the 1-hour transmission.

We came back from Heard Island fully expecting to put what we had learned to early practice for monitoring ocean climate variability. We had in mind some loose global configuration of half a dozen sources and a few dozen receivers. Uwe Mikolajewicz and E. Maier-Reimer of MPI made some calculations based on the Hamburg Climate Model[14].

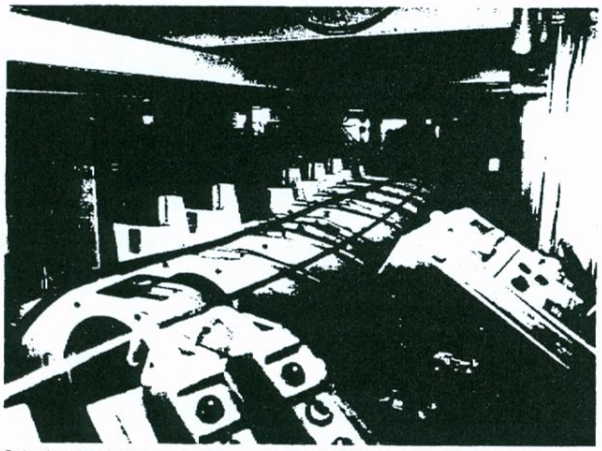
By now we had conducted open-sea tomography experiments for fifteen years (though at much lower acoustic source levels) without anyone paying much attention. But the Heard Island test had caught the public eye, and the problem arose as to whether our acoustic transmissions would be harmful to marine life. An article in ***Der Spiegel*** entitled "Radau in der Tiefe" (figure 5) gave another early storm warning, a storm of opposition. It was not until December 1995, five years later, that a limited program got underway.

Treibhauseffekt

Radau in der Tiefe

Mit Donnerschall unter Wasser wollen Meeresforscher den Treibhauseffekt messen. Tierschützer fürchten Gefahren für Robben und Wale.

Die mächtigen Meeressäuger plauderten wie immer und ließen ihr vielstimmiges Grunzen, Stöhnen, Zirpen, Pfeifen und Singen vernehmen. Doch plötzlich mischte sich ein ungewohnter Ton in das Unterwasser-Geschwätz der Wale: Ein ohrenbetäuben-



Schallquelle auf der „Cory Chouest": Disco-Dröhnen über 1000 Kilometer

der Knall, synchron aus drei Lautsprechern, erschütterte die Idylle.

Eine Stunde lang dröhnten die Lautsprecherboxen in rund 200 Metern Tiefe mit der Schallstärke eines Düsenjets. Dann hatten die Wale eine Stunde Ruhe, bis der Krawall von neuem begann.

Die Idee, den Ozean zu beschallen, war dem amerikanischen Meeresforscher Walter Munk schon vor zehn Jahren gekommen. Für das Vorhaben wählte er einen gottverlassenen Ort: die unbewohnte Heard Insel, ein vergletschertes Vulkaneiland mitten im antarktischen Meer zwischen Südpol und Australien.

Die unwirtliche Insel hat eine geographische Eigenschaft, die sie von jedem anderen Ort der Erde unterscheidet: Von der Heard Insel lassen sich direkte Linien in alle Ozeane der Erde ziehen, ohne daß dabei irgendwo Land berührt würde. Schnurgerade durchs Wasser geht es von dort nach San Francisco, Sri Lanka, São Paulo oder New York.

Das macht die Insel zum Idealort für den Plan des Ozeanforschers: Er will den Krach vom Südpolarmeer rund um die Erde schicken und sein Echo in rund einem Dutzend Lauschstationen auf allen Kontinenten abhorchen.

In einer dünnen Wasserschicht wandert der Schall in etwa 1000 Metern Tiefe fast ungedämpft über gewaltige Entfernungen. Oben wird er von einer wärmeren Wasserschicht, unten von einer besonders komprimierten Schicht in den Schallkanal gezwungen und gelangt so zum Ziel wie die Herzgeräusche eines Patienten im Stethoskop zum Ohr des Arztes. Der Zweck dieser „akustischen Meeres-Tomographie": Der US-Ozeanograph will die Erwärmung der Erdatmosphäre messen.

Kein Klimaforscher zweifelt mehr am globalen Treibhauseffekt, der durch Spurengase wie Kohlendioxid ausgelöst wird. Doch keine Temperaturmessung ist bislang zuverlässig genug, um die von Computermodellen vorhergesagte Erwärmung zu überprüfen. Natürliche Klimaschwankungen verwirren das Bild, zudem liegen die meisten Meßstationen in der Nähe von Städten, deren Wärmeabstrahlung die Messungen stark verfälscht.

Mit der Meeres-Tomographie glaubt Munk nun die Temperatur dort messen zu können, wo es derartige Störungen nicht gibt: 1000 Meter unter dem Meeresspiegel. Computermodelle schätzen die Erwärmung dieser Ozeanschicht auf etwa ein halbes Hundertstel Grad Celsius pro Jahr.

Um diese Prognose zu überprüfen, nutzen die Krachmacher in der Antarktis eine einfache physikalische Tatsache: Schall bewegt sich in warmem Wasser schneller als in kaltem. Wenn die Vorhersagen der Klimaforscher zutreffen, müßte sich die dreieinhalbstündige Reise des Schalls von der Antarktis bis nach San Francisco Jahr für Jahr um ein oder zwei Zehntel Sekunden verkürzen.

Projektleiter Robert Spindel glaubt fest daran, auf diese Weise „in fünf bis zehn Jahren den Treibhauseffekt nachweisen" zu können. Skeptiker wie der Meeresforscher Russ Davis, der die Einladung zur Seefahrt in die Antarktis ablehnte, äußern sich hingegen pessimistischer. Davis: „Bis die Messungen klappen, wird die Welt ohnehin für jeden spürbar wärmer sein."

Noch heftiger als der Widerwille von Fachkollegen sind die Proteste der Meeresbiologen. Sie sehen durch den Radau unter Wasser Robben und Wale gefährdet. „Mich beunruhigt dieses Experiment mehr als jeder andere menschliche Einfluß, mit Ausnahme der Giftabfälle", beschwert sich einer von ihnen.

Walforscher belauschen und studieren seit langem die Sprache der Meeressäuger: die Schreie der Blauwale, die noch in Entfernungen von 100 Meilen zu hören sind; die manchmal zweistimmigen Gesänge der Buckelwale, die sieben

Ozeanforscher Munk
Furchteinflößender Gegner

Oktaven übergreifen; oder das morseartige Knattern der Pottwale.

Doch erst neuerdings fangen die Wissenschaftler an, die Bedeutung der einzelnen Klänge in der Unterwasser-Symphonie zu verstehen. Vermutlich orientieren sich die Zahnwale ähnlich wie Fledermäuse durch Echolot, etwa wenn sie sich zwischen Eisschollen hindurchmanövrieren. Sie scheinen auch ihr Fut-

Figure 5. August 1991 issue of Der Spiegel.

5. The whaling years.

Men were not the first to discover that the oceans are opaque to light and transparent to sound. A vast array of marine organisms depend on active and passive sonar for their existence (figure 6). In the last few decades the low frequency ambient noise (due to shipping) has increased by 20 dB in the northern hemisphere. [One can save 99% of power by placing sources in the northern and receivers in the Southern Hemisphere rather than the other way around (e.g.Heard Island)].

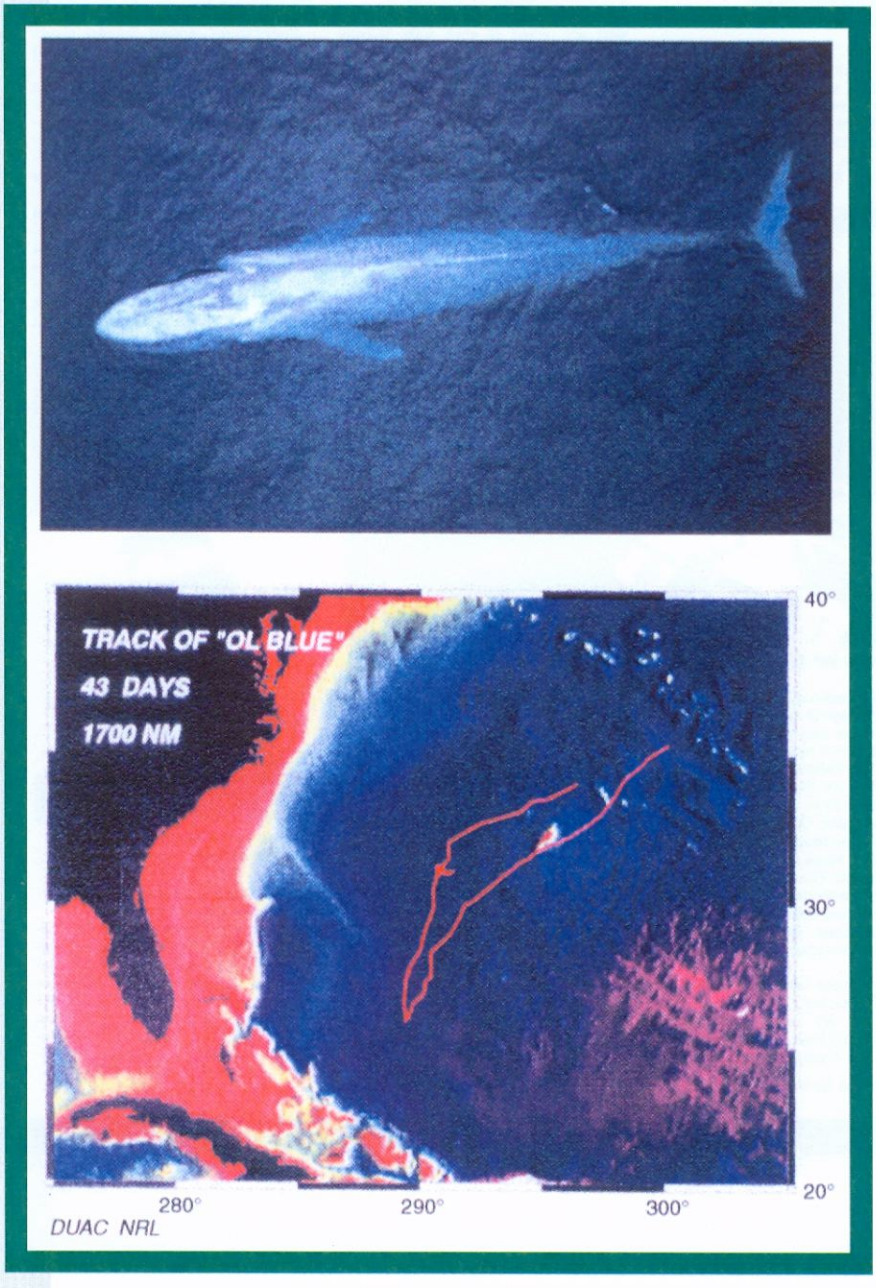


Figure 6. The Blue Whale is the largest marine mammal. It transmits a characteristic chirp of very low frequency and intensity up to 190 dB re 1 μPa. The track of one particular individual was traced acoustically for 43 days.

The Heard Island transmissions were up to 16,000W of acoustic power (221 dB re 1 μPa averaged across the beam) for 1 out of every 3 hours at a depth of 150m. We encountered no evidence of mammal ***distress*** but some changes in the behavioral pattern. The proposed ATOC schedule was reduced to six 20-minute transmissions every fourth day (2% duty cycle) at 195 dB (260W) at 1 km depth. We were at sea installing a source when a front-page article in the Los Angeles Times claimed that ATOC would lead to the death of 3/4 million California Grey Whales. The Times' problem was that the decibel scale is different in air than in water: 195 dB in air corresponds to 260 **million** watts, which would indeed be fatal. Although the error was later corrected, the international newspaper and e-mail outcry following the initial announcement has led to years of legal proceedings.

Finally, in December 1995, we were able to commence transmission from a source on Pioneer Seamount off California. An independent Committee was appointed to conduct a Marine Mammal Research Program and placed in control of the acoustic source. MMRP proceeded along two lines: (i) on the effect of the ATOC transmissions on the whale **distributions**, and (ii) on the mammal **behavioral** response. Aerial surveys of the source area accompanied the transmissions, for a total of 2400 sightings of marine mammal groups consisting of an estimated 44,000 individual animals[15]. Not a negligible database!

I will show only two results. The **distribution** of humpback whales near Pioneer Seamount was judged to be 'significantly' affected (figure 7); similar distributions for sperm, blue and fin whales and for other marine mammals showed no statistically significant effect. The **behavioral** pattern of elephant seals showed no obvious effect (figure 8).

A committee of the National Academy of Sciences appointed in 1994 issued a progress report early this month[15]. There is agreement on three points: (i) no obvious catastrophic short-term effects were observed; (ii) scientific use of sound (such as ATOC) is a minor component of human-generated sound pollution, and (iii) the observations do **not** prove that there are **no** harmful effects (especially with regard to long-term processes).

ATOC has been heavily taxed to prove a negative, with negative results. I believe we have neither the human nor the financial resources to provide such a proof, now or ever in future.

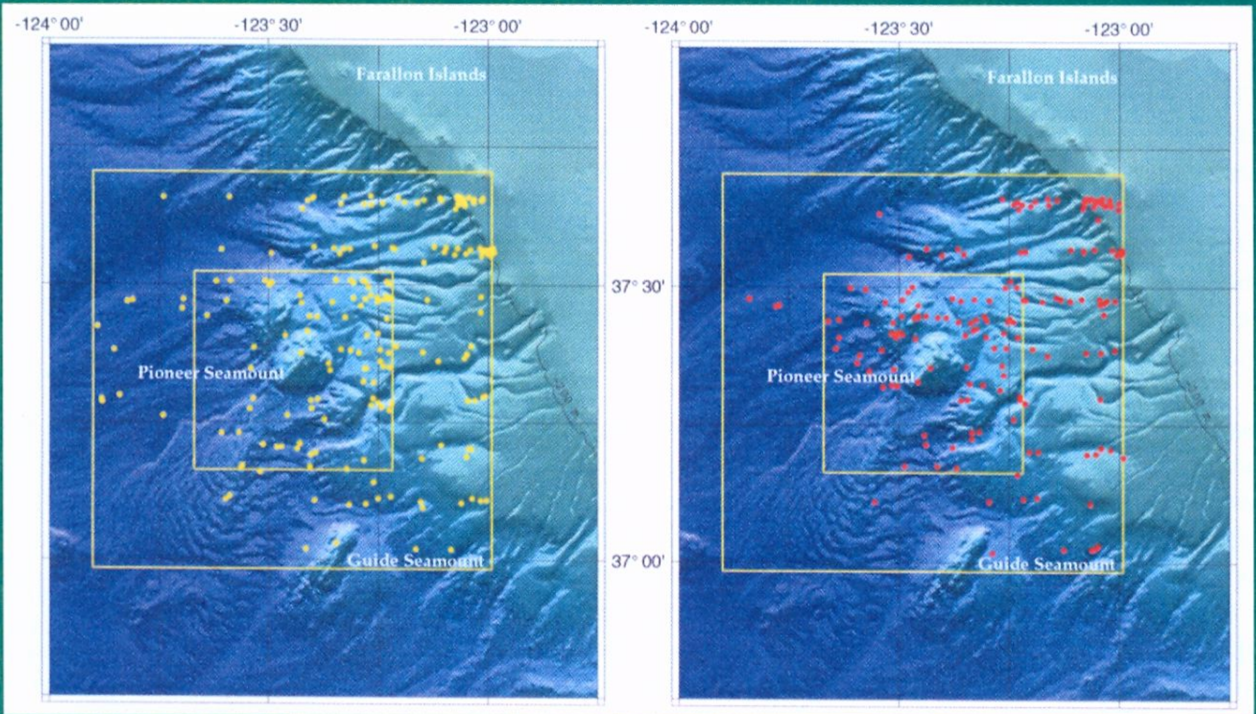
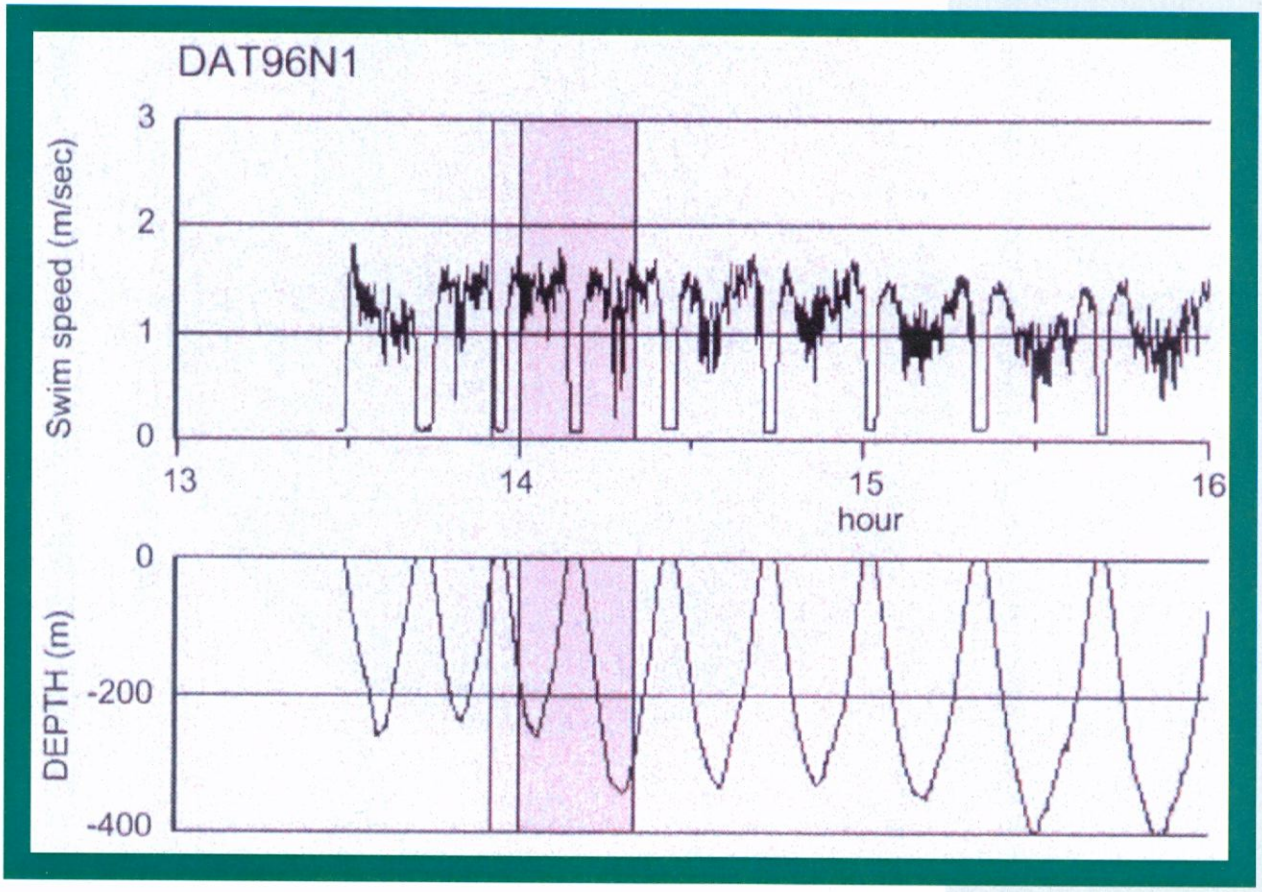


Figure 7. Distribution of humpback whales near Pioneer Seamount. The source is located at the center of the inner box. Yellow circles designate whale sightings (all species) during transmission days, red circles during non-transmission control days. The difference is judged to be statistically significant.

	all species	*# sightings*	*# animals*
Aerial	Transmissions	1,284	20,864
	No Transmissions	1,132	22,934

Figure 8. The depth-time history of an elephant seal passing by the source during a 20 minute transmission (magenta rectangle).



6. Acoustic thermometry of the northeast Pacific

A good way of observing the oceans on a basin scale is by combining the necessarily sparse interior measurements with well-sampled satellite surface coverage[16], for example combining acoustic tomography with satellite altimetry. Figure 9 shows the results of a year's transmission from Pioneer Seamount (off California) to eleven SOSUS horizontal arrays[17]. (Two Scripps vertical arrays are also shown). Our original hope had been that the ATOC measurements would cover the 1993 to 1997 interval of Topex/Poseidon; there is only one year of overlap, to our great disappointment. The irregular sampling intervals arise from the requirement of simultaneous aerial monitoring in the source area (probably the only geophysical experiment with whale-controlled sampling).

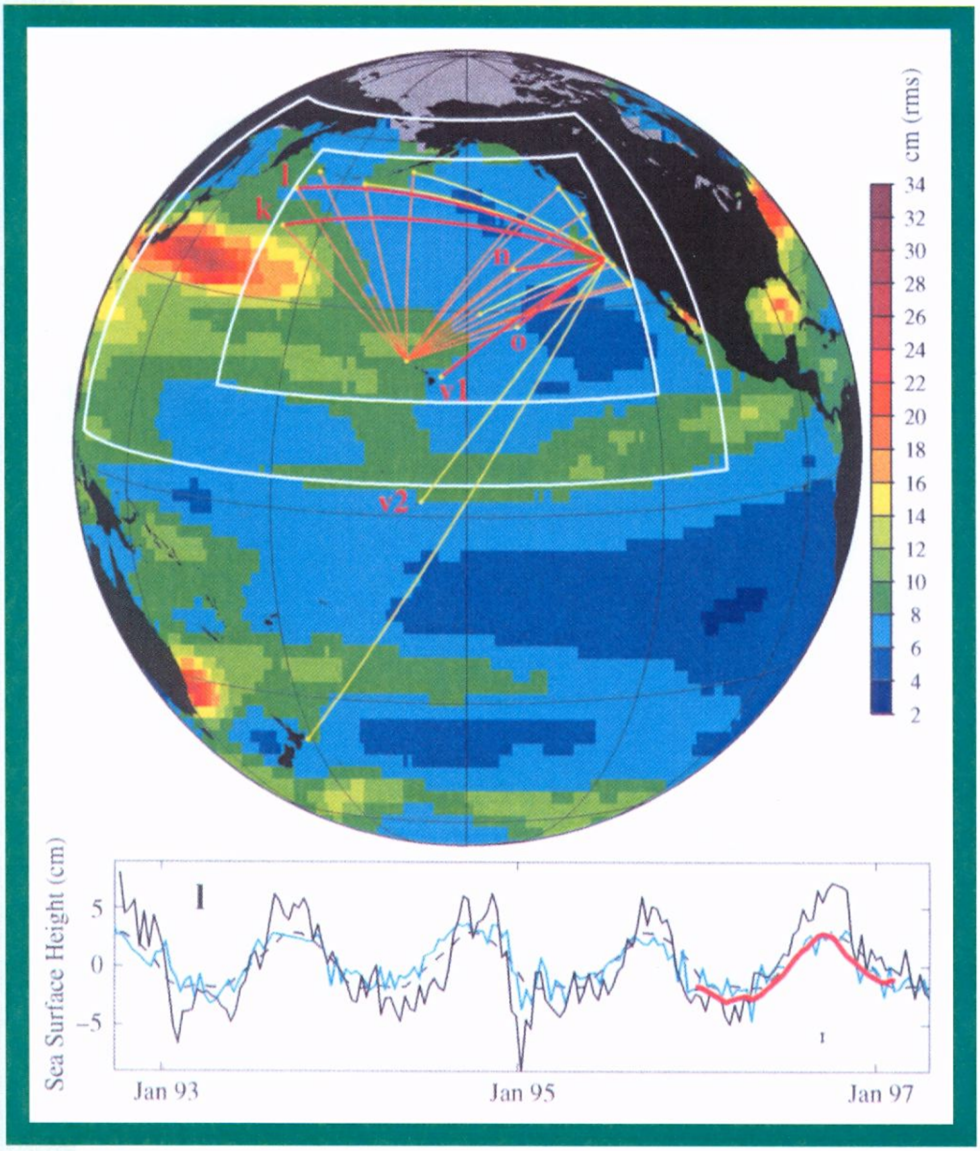
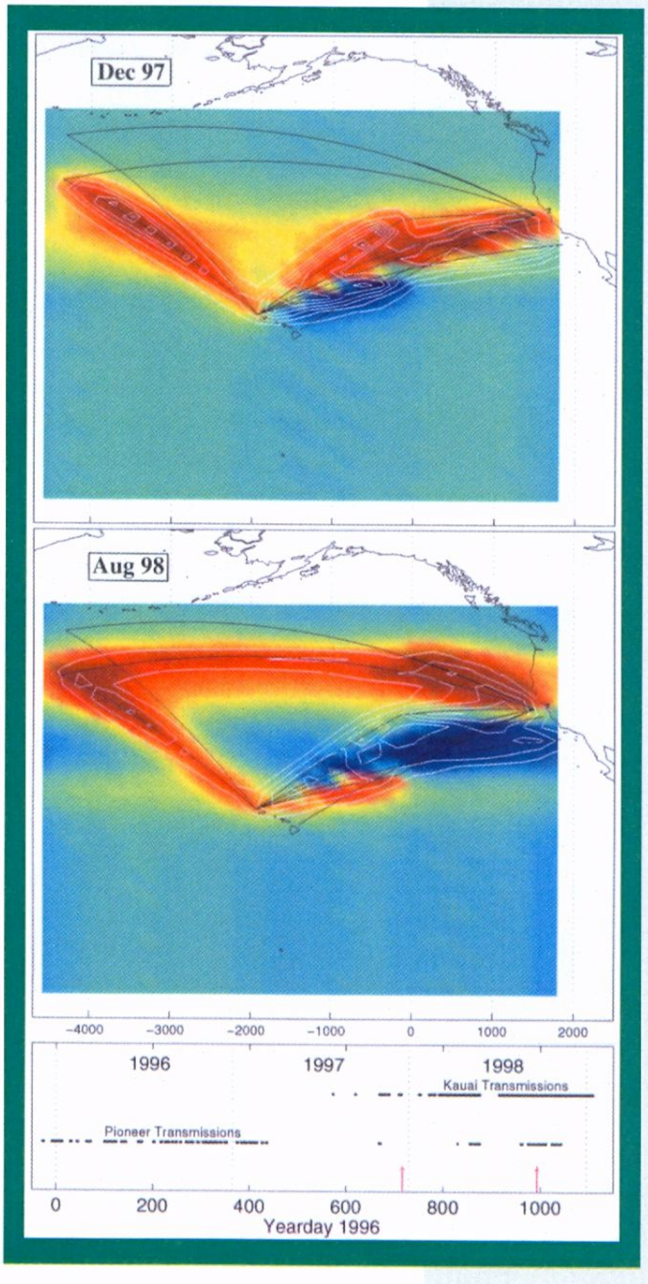


Figure 9. TOP: Transmission paths from Pioneer Seamount and Kauai sources[14]. Receiving sites are horizontal Navy SOSUS arrays. Sites V1 and V2 are vertical receiver arrays deployed by Scripps Institution. BOTTOM: Fluctuations in range-averaged sea level along path 1. Solid black line: satellite altimetry; dashed: from climatological temperature fluctuations; red: sea level inferred from acoustic tomography; blue: GCM estimates. The tomography measurements had been scheduled to overlap with the entire time series of the Topex-Poseidon satellite measurements, but was delayed by permit requirements. Colours show rms sea level variability.

The sea level variations inferred from the acoustic measurements are smoother and of smaller seasonal amplitude than those measured by Topex/Poseidon satellite altimetry. We attribute the differences to a barotropic component in the sea level changes. The combined measurements yield estimates of basin heat content with accuracy corresponding to about 25 W/m^2 of surface flux. Figure 10 gives another view of the changes in oceanic heat storage[18].

Figure 10. Anomalies of heat content in the north-east Pacific at indicated times, based on acoustic tomography (Dushaw, unpublished). Ray paths from Pioneer Seamount and Kauai are indicated. Red is warm, blue is cold.



7. The Mediterranean and the Polar Seas.

In the meantime some very important results were obtained elsewhere. Acoustic tomography is at its best in an integrating mode, integrating horizontally and integrating vertically. As such it does a good job in estimating the total heat content of a basin. In 1994, the THETIS-2 experiment for measuring the heat content of the western Mediterranean for the first time combined satellite altimetry and acoustic tomography[19] (fig. 11).

In 1994 Mikholevsky et al.[20] conducted a noteworthy 3200 km transmission from a source north of Svalbard across the pole to a receiver near Pt. Barrow (figure 12), An ultra low frequency source (20 Hz) was dictated by the scattering loss from the ice cover. An earlier than expected arrival of acoustic mode 2 (whose wave function favors the depths occupied by North Atlantic Intermediate Water) implies a warming by 0.4°C relatively to a mean climatology. A subsequent 1999 transmission infers a further warming by 0.5°C in the last five years. The results are roughly consistent with independent CTD surveys conducted from submarines.

The polar environment provides three great advantages to acoustic tomography (aside from not being accessible in winter to standard oceanographic techniques): a low background in internal waves (the ultimate limit to precision), a dispersive sound channel favorable to vertical resolution, and remoteness from public attention. The polar work is the most promising application so far of tomography to climate studies. We are pleased that Johannessen and Hasselmann have been planning a major initiative in acoustic monitoring of the Arctic Ocean[21].

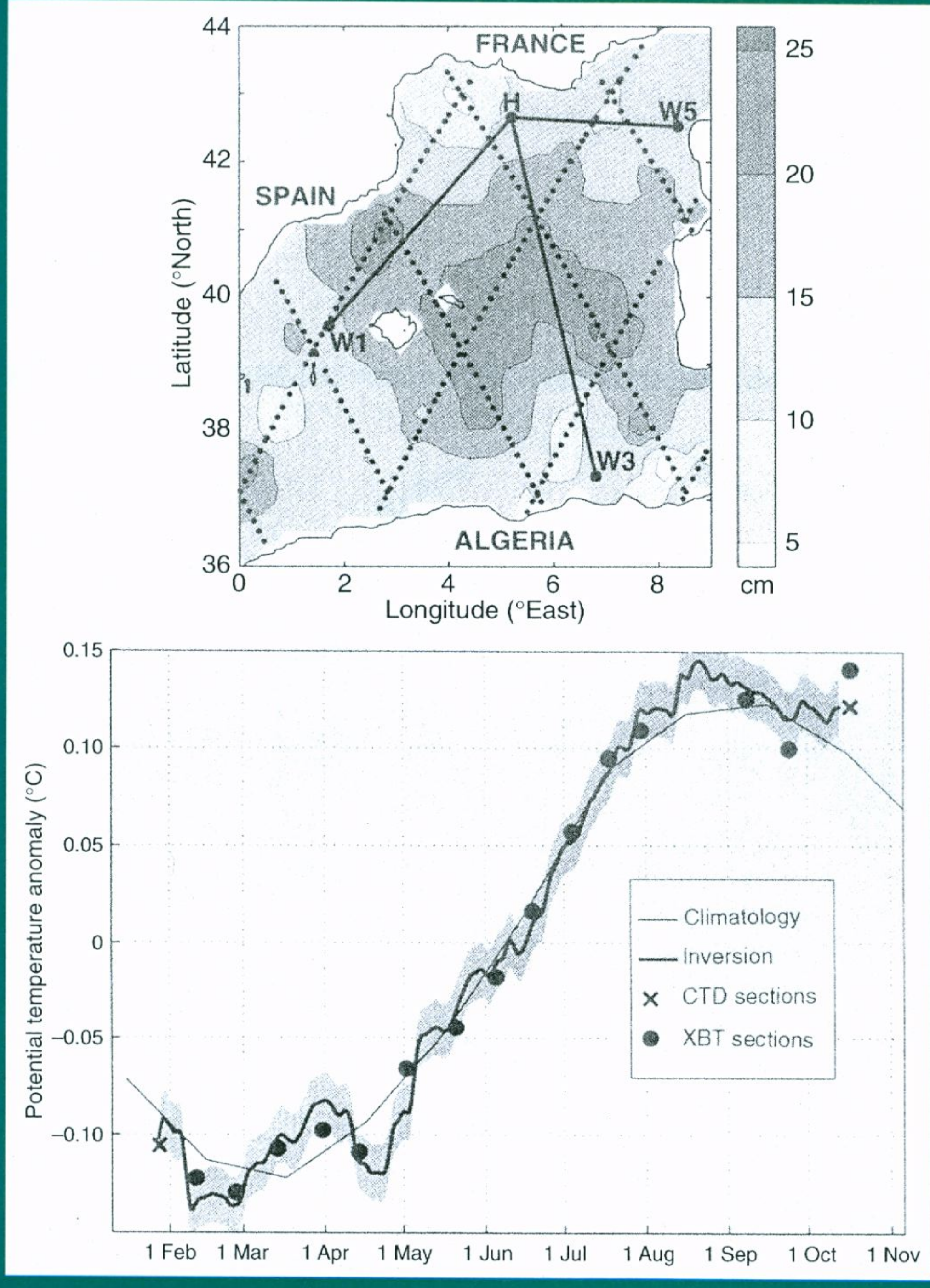
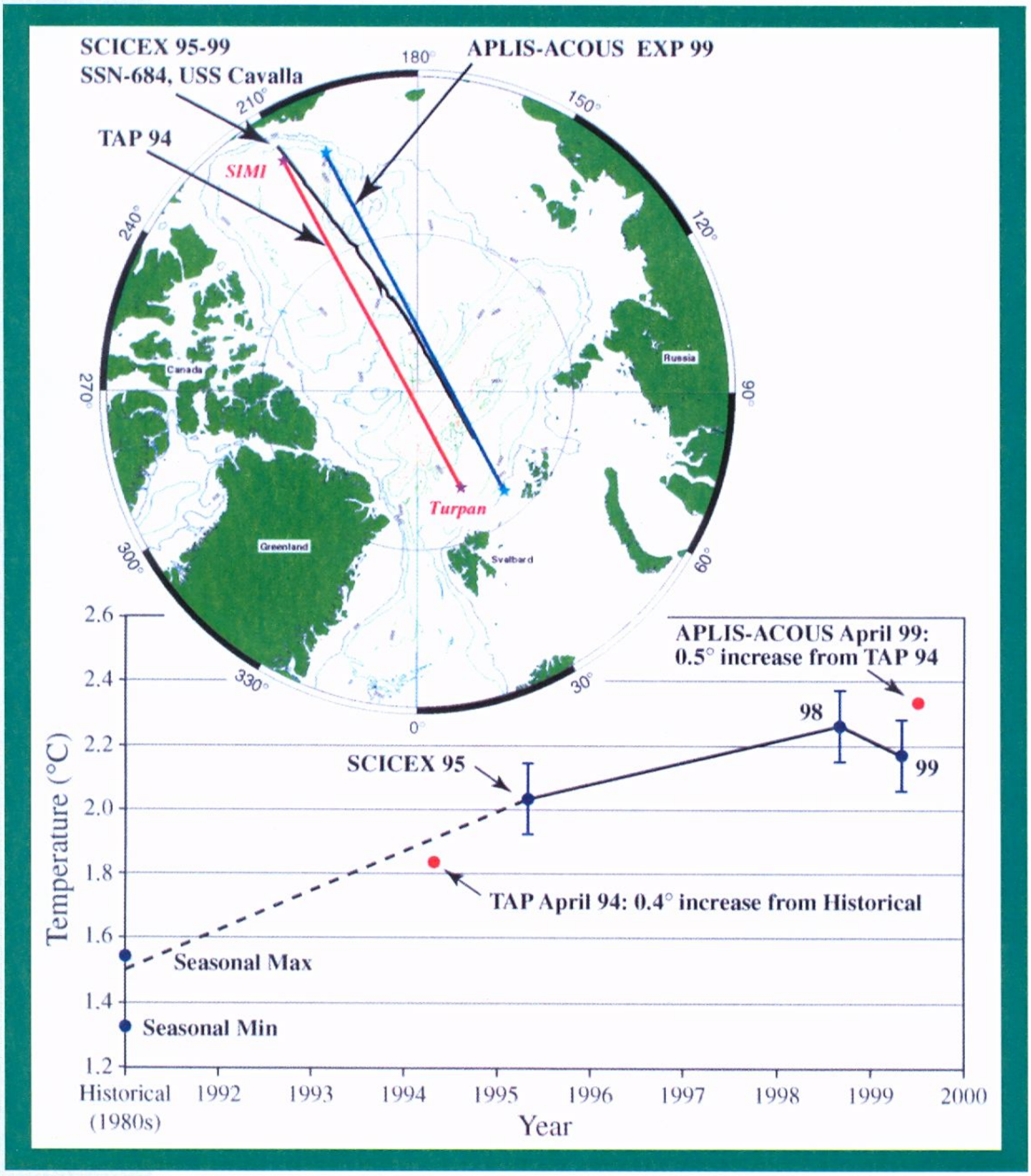


Figure 11. THETIS-2 experiment in the western Mediterranean[15]. TOP: Acoustic tracks (solid lines) and altimetry tracks (dashed) are combined to estimate September 1994 minus March 1994 changes in heat content (as represented by sea level). BOTTOM: Comparison of acoustically inferred heat content (plotted as mean temperature 0-2000 m) with direct observations and climatological estimates.

Figure 12. Red: Trans-polar acoustic transmissions (TAP)[16]. The earlier than 1994 computed arrivals (relative to the 1980 "historical mean") indicate a warming by 0.4°C, subsequently confirmed by the SCICEX measurements from a submarine (black). The 1999 APLIS-ACOUS measurements (blue) indicate further warming by 0.5°C between 1994 and 1999, roughly consistent with the 98 and 99 submarine CTD sections.



8. Where do we stand?

I will summarize the pros and cons of ATOC. The long spatial integrations are a great help in detecting any climate signals above an intensive (but relatively small-scale) mesoscale "noise". We have detected 0.005°C changes at 5000 km ranges. The method is at its best in measuring vertically integrated temperature, e.g. heat content, a fundamental climate parameter. There is no calibration drift (as might be the case for slowly varying satellite orbits); all that is needed is an easily available millisecond time standard. In a multiple array of transceivers the information increases factorially with the number of moorings.

Vertical resolution is good in an arctic profile, but needs improvement at temperate latitudes, especially in range-dependent environments. A remaining key issue is the sensitive dependence of the coefficient of thermal expansion on temperature, hence depth. The analysis is limited by internal wave fluctuations. Lower frequencies, with source and vertical receiving arrays off the bottom will help.

From the earliest days of tomography, we had to make a choice between battery-powered autonomous moorings or moorings cabled to shore. We took the autonomous route for its greater flexibility of location. For the climate-oriented tomography of the 90's we chose to go the cable route. This introduced a host of unimaginable permitting problems, and might have been a mistake.

Acoustic tomography is expensive. It suffers especially from high start-up costs. This is associated with the high cost of deploying and maintaining deep-sea moorings, of providing power and of transmitting data. It is inevitable that some form of global mooring system (TOGA TAO, DEOS) will become the weather ships of the 2000's, providing for power and satellite data transmission. Acoustic tomography can be an economic "value-added" component of such a system.

It has been ten stormy years since the snowy peaks of Heard Island came in sight. This audience must forgive me if I have talked too much about the storms. We are encouraged by the German, French and Japanese efforts, and the ongoing and proposed Arctic work.

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