# SCIENTIFIC COMMITTEE ON OCEANIC RESEARCH



INTERNATIONAL COUNCIL OF SCIENTIFIC UNIONS

# ACOUSTIC THERMOMETRY IN THE ATLANTIC

## A REPORT TO SCOR WG 96

During its June 1993, meeting in Brest, France, the Scientific Committee on Oceanic Research (SCOR) Working Group 96 (Global Acoustic Monitoring of the Ocean) identified as a matter of high priority the need for a feasibility study for an Atlantic Acoustic Thermometry of Ocean Climate (ATOC) programme. The Working Group requested that Dr. John Gould strike a subgroup to investigate an Atlantic ATOC programme under the following terms of reference:

- 1. That it be assumed that two long-life (>10yr) moored 70Hz ATOC source/receiver units will be deployed, one at Bermuda and one in the Azores. In the event that good reasons be found for alternative sites these may be pursued provided first that the Bermuda/Azores sites have been adequately investigated.
- 2. That the measurement of larger scale, lower frequency ocean climate variability be considered as a primary goal.
- 3. That the coupling of such larger scale features to tomographic and other studies of more regional processes be considered.
- 4. That the potential use of US Navy and Air Force facilities be included in this study in addition to the sites for ATOC receivers.
- 5. That the potential links between ocean climate modelling and ATOC measurements be considered.
- 6. That the ATOC Atlantic effort be co-ordinated with other ongoing ocean research efforts. The ATOC effort is to commence in the 1995 time frame.

The subgroup established by Dr. Gould consisted of the members listed in the Appendix. This report summarises the subgroup's activities. It worked by correspondence but Dr. Gould visited APL in October 1993.

#### 1. ATLANTIC OCEAN VARIABILITY

We begin by summarising the evidence for the dominant length and time scales of ocean temperature variability in the area and the physical processes that might be studied with an ATOC network.

Time series of ocean temperatures are available at depths from the ocean surface to 2000m at the Panulirus station near Bermuda. They show thermocline periods of order 10 years whereas at the deepest level there is a warming trend throughout the 60 year period for which observations are available (Fig. 1), (Joyce, 1994; Roemmich 1990). While few other time series of similar length exist below the ocean surface layer, a plot of 600m temperatures at Ocean Weather Station "Alpha" (62°N 33°W) for the 1950s and 60s shows a similar dominant period. (Gould, to be published and reproduced in Dickson and Brander 1993).

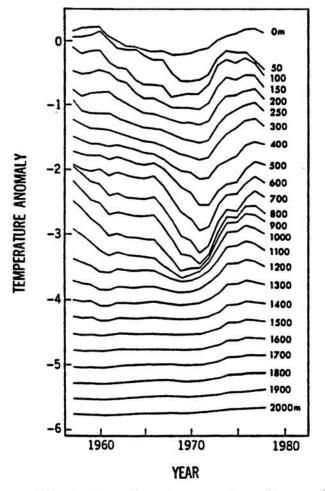


Fig. 1. Panulirus temperature time series

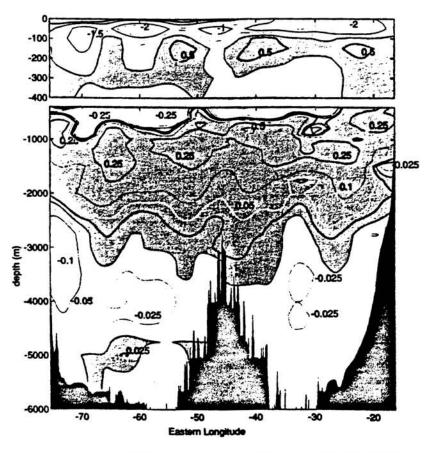


Fig. 2. 24°N temperature difference 1992 - 1957

Repeated hydrographic sections allow the spatial patterns of temperature change to be deduced (Roemmich and Wunsch, 1984; Parrilla, Lavin, Bryden, Garcia and Millard, 1994). These studies indicate a horizontal scale in the subtropical gyre that is approximately equal to the basin size, i.e. the size of the region between the eastern or western basin boundaries and the Mid-Atlantic Ridge. The largest temperature anomalies are confined to the upper 1500m of the water column. There is a tendency for a mode-one baroclinic structure to dominate (Fig. 2). In the subpolar gyre (Read and Gould, 1992), greater horizontal and vertical uniformity is seen and the sign of the temperature trend is opposite to that in the subtropical gyre.

This behaviour suggests that any acoustic thermometry array, even if designed to study the possible basin-wide anthropogenic temperature signal, should have sufficient horizontal resolution to allow the study of the larger amplitude, decadal scale variability already revealed by more conventional observational techniques.

#### 2. BERMUDA-AZORES TRANSMISSIONS

The subgroup was asked to consider, as a first option, transmissions between a cabled transceiver located on the eastern side of Bermuda and one located in the Azores. The Azores is a complex archipelago of some 9 major islands located in an area of shallow relief on the Mid-Atlantic Ridge. The subgroup reviewed a number of possible transceiver locations and concluded that transmissions between Bermuda and the islands of Flores or Faial would be possible.

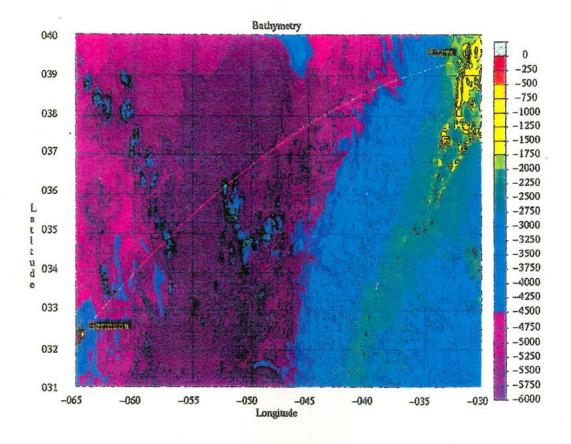


Fig. 3. Unrefracted geodesic Bermuda-Flores showing seamounts.

Both Flores and Faial lie at the westernmost extremity of their local island groups. Faial is the terminus for a number of active and redundant transatlantic cables while Flores was selected because the sound channel axis intersects the ocean bottom relatively close to the shore. A more detailed investigation of local topography (although the sound channel axis intersects the bottom close to the shore the bottom is not steep so there may be strong acoustic interactions) and logistics (e.g. power supply availability) would be required before a final site selection could be made. It should be noted that the Admiralty Pilot book (The Hydrographer of the Navy, 1983) mentions two conspicuous radar antennae on Flores. It may, therefore, reasonably be supposed that some power supply and general logistics support would be available there.

An investigation of the unrefracted geodesic path between Bermuda and Flores suggested possible interference from the New England and Corner Seamount chains (Fig. 3). Scattering of sound by these seamounts can be significant (Koenigs, Browning, LaPlante and Martin, 1981). However, based on path estimates made using refracted rather than unrefracted geodesics, the subgroup concluded that with a judicious selection of transceiver sites, transmissions between Bermuda and the Azores would be possible without significant interference from these seamounts.

The path length of only 3000km between Bermuda and the Azores is such that if that path alone were the subject of interest, a higher-frequency source (~200Hz) could be used rather than those (~70Hz) being designed for the Pacific ATOC array. However, these sources would also be expected to insonify as much as possible of the ocean in order to extend the area in which other ATOC receivers could be located and hence a low frequency source is preferred.

#### 2.1 Insonification from Azores/Bermuda sources

Using software available at the Applied Physics Laboratory, University of Washington, shadow plots were produced for the source sites considered. The plots were based on the Levitus climatology (Levitus, 1982) and a standard US Navy bathymetric data base, etop05. Plots were produced for four horizons: the sound channel axis, and 500, 1000, and 1500m below the axis. Along each ray path traced from the source, a determination is made whether the horizon intersects the bathymetry. If it does, then all points further along the ray path from the point of intersection are considered in the acoustic shadow.

A Bermuda site close to the island that could be heard from the Azores (Fig. 4) would not be able to insonify the entire western part of the subtropical gyre, including much of the Gulf Stream, due to blocking by Bermuda. To the east, transmissions would be blocked by the bulk of the Azores plateau. Only a narrow window of insonification is possible to the north, between the Azores and the Grand Banks and into the Biscay area. Insonification into the South Atlantic is possible, however.

The Flores site, by contrast, insonifies the western subtropical gyre, portions of the Labrador Sea, the Irminger Sea, and the region south of Iceland (Fig. 5).

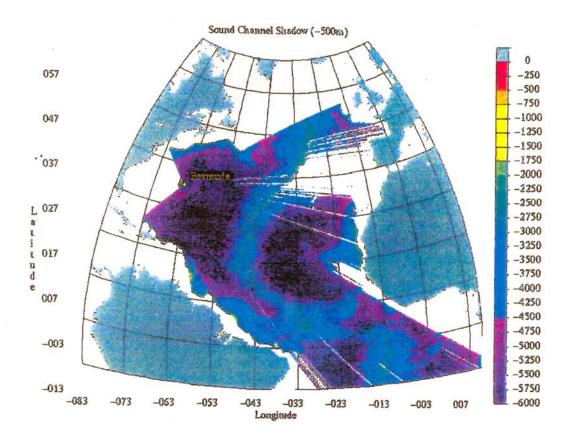
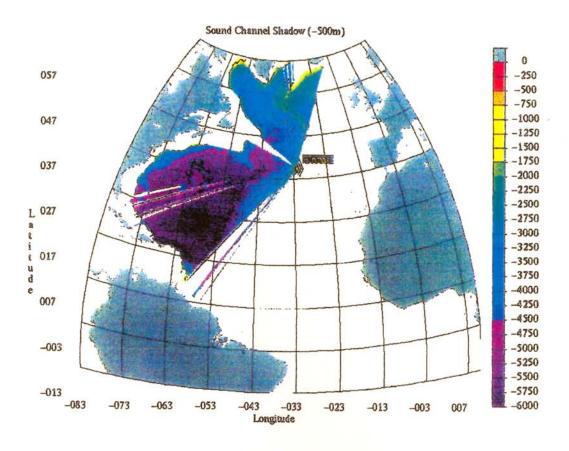


Fig. 4. Shadow plot from Bermuda source



5. Shadow plot from Flores source

The summation of these plots indicates that a Flores-Bermuda transceiver pair would insonify a large part of the North Atlantic but would not insonify the area of influence of the Mediterranean water to the east of the Azores plateau, nor the area immediately west of the UK. We concluded therefore that an Azores-Bermuda pair of transceivers would be insufficient to carry out a satisfactory North Atlantic ATOC study.

# 2.2 Selection of other possible cabled source sites

A search was made for sites in the North Atlantic for which cabled sources might be possible. The primary consideration was that no more than 40 nm of cable would need to be laid. Since sources are to be deployed at the sound channel axis, sites are possible only if the sound channel axis intersects the topography within 40 nm of the shoreline. Candidate sites are listed in Table 1 and indicated in Fig. 6.

Table 1. Candidate Cabled-Source Sites

Site	Lat (N)	Long(W)	Depth of Axis (m) (nominal)
Caribbean			
1 Tortola	18.723	64.130	1000
2 Abaco	26.249	76.915	1000
3 Eleuthera	25.574	76.503	1000
4 Barbuda	17.674	61.570	1000
5 San Salvador	24.136	74.466	1000
South Atlantic			
6 Noronha	3.939	32.357	1000
7 Ascension	-7.822	14.602	1250
Mid-Atlantic Islan	ds		
8 Madeira	32.641	17.254	1000
9 Flores	39.360	31.949	1000
10 Azores	37.295	24.202	1500
11 Bermuda	32.393	64.462	1000
Eastern Atlantic			
12 Canaries	28.680	18.000	1000
13 Cape Verde	17.198	25.598	1000
14 Portugal 1	39.972	9.840	1200
15 Portugal 2	39.022	10.367	1200
16 N Spain	44.152	8.953	1300
17 France	46.834	5.240	1500
Subpolar region			
18 Iceland 1	63.180	18.550	100
19 Iceland 2	63.003	24.379	100
20 Greenland	59.546	42.784	100

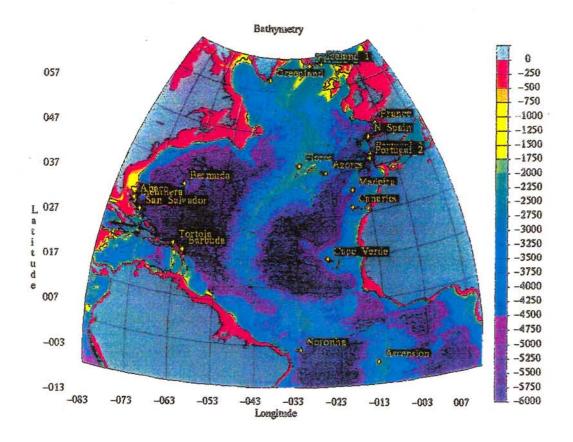


Fig. 6. Candidate source sites

From this list we wished to select a small number of source sites from which maximum insonification could be achieved. We will discuss these candidate source sites in geographical groups:-

#### Caribbean

From many of these sites, insonification of large areas is possible. While Abaco, Eleuthera and San Salvador may be logistically simple, Tortola, Barbuda and Anguilla give the prospect of insonification of the northern North Atlantic via the gap between the Azores plateau and the Grand Banks. It should be noted that Anguilla, the northeasternmost island of the Caribbean arc is not included in the Table.

### South Atlantic

Noronha is remote and logistically problematic. D. Palmer and B. Howe have considered the possibility of Ascension as a cabled-source site and D. Palmer presented the results of their study to the Working Group at the Brest meeting. Summarising the study, Ascension has a reliable source of power, sophisticated timing and communications facilities, and other logistical support. Bottom slopes are large (greater than approximately 9 degrees) and the sound channel axis intersects the ocean bottom within 5nm of the shoreline. Ascension is situated so as to insonify a significant portion of the North and South Atlantic. Specifically, an area of  $2.5 \times 10^7 \, \mathrm{km}^2$  can be insonified using a 70 Hz ATOC source with a signal-tonoise ratio of 20 dB (after processing) using only a single omni-directional hydrophone as a receiver. In addition there are axial hydrophones already located there that could be used to monitor the signals from other sources.

However, a source at Ascension, radiating into the North Atlantic, would not do as well in providing the spatial resolution needed to resolve the North Atlantic climate signal as would sources further to the north. It is likely Ascension will play an important role when the global ATOC network is expanded to include both the North and South Atlantic.

#### Mid-Atlantic Islands

Of these we have already dealt with Bermuda and Flores. The site designated Azores is actually a site off San Miguel which would be significantly shadowed by other Azores islands. Madeira would be shadowed to the west by the Azores Plateau.

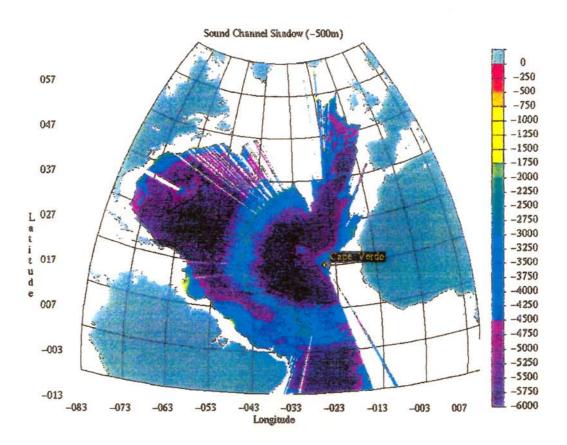


Fig. 7. Shadow plot from Cape Verde source.

#### Eastern Atlantic

Again the Azores plateau limits the potential insonification from many of these sites but a Cape Verde source is of interest in providing potential paths to Barbuda, Bermuda and in insonifying the eastern North Atlantic as far north as the Rockall Plateau. (Fig 7).

# Subpolar Region

Three sites were identified. The site close to Cape Farewell (Greenland) would be logistically difficult and unusable due to possible damage to the cable from iceberg scour beneath the East Greenland current. The two Iceland sites may be possible since a cable already exists to a relatively shallow site on the Mid-Atlantic Ridge. However, we question the utility of northern source sites due to a poorly defined and seasonally very variable sound channel axis structure.

# Summary of site selection issues.

The blocking effect of the Azores plateau makes site selection problematical since the Azores acts almost as a mid-ocean continent so far as sound transmission is concerned (Fig. 8).

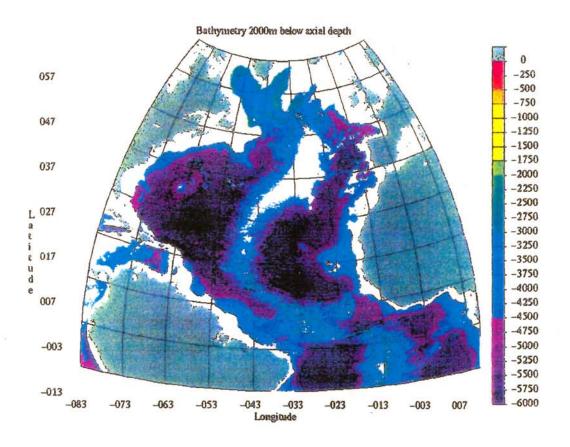


Fig. 8. Blocking effect of Azores Plateau (sound channel +2000m)

A strong case can be made for a network based on 4 sources located at Bermuda, Flores, Cape Verde and Barbuda or Tortola. To some extent Barbuda/Tortola is a possible replacement for Bermuda if only a 3 source array were possible. However, Bermuda is not an alternate to Barbuda/Tortola since it does not permit insonification of the subpolar gyre nor of the western margin around the Gulf Stream. From Cape Verde, Flores and Barbuda/Tortola the entire North Atlantic

basin could be insonified as could much of the South Atlantic. Maximum ranges achievable in the North Atlantic from these sites are, however, no more than approx 7000km. This means that it might be possible to use a higher-frequency, lower-energy source than those that will be used for the ATOC Pacific array but care would have to be taken not to reduce signal to noise ratios. Autonomous sources might even be possible but while positional accuracy and timing problems might well be overcome, power would be a problem for long term deployments.

# 2.3 The receiving network

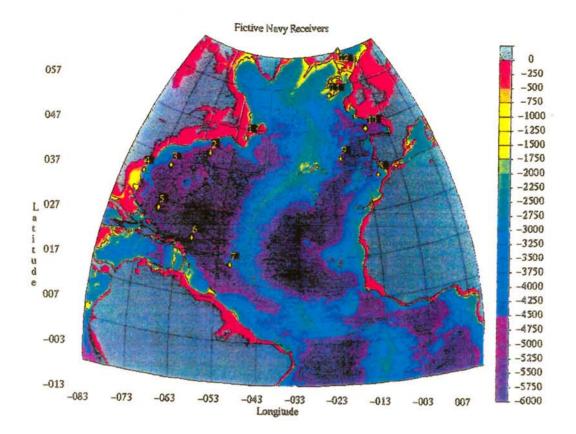
We based our study of the receiving-array network on the following criteria:

- (i) The network should be capable of long-term resolution of possible anthropogenic temperature change.
- (ii) The network should be capable of resolving the dominant horizontal and vertical scales of the decadal temperature variability.
- (iii) The network should exploit the opportunity to use existing US Navy and Air Force receivers, if possible.

Using these criteria and knowledge of the approximate locations of US Navy receivers in the North Atlantic (Fig. 9), we concluded that a transmitting array consisting of three or four sources would require supplementary receivers at the positions shown in Fig. 10. This receiver network would allow the analysis of the changes in temperature anomalies over the entire North Atlantic; particularly into the areas of the subpolar gyre where water mass modification occurs on a seasonal basis and where mode waters of differing temperatures are produced.

Further specification of a receiver array design requires analysis beyond the scope of this outline study. However, we guess that the existing network of US Navy fixed receivers will need to be supplemented with approximately 10 autonomous receivers. These could be either bottom mounted or free drifting. Candidate sites for these supplementary receivers are:

- 3 receivers on the acoustic path from Cape Verde to SW of Ireland:(at 30N, 40N, and on the slope SW of Ireland)
- 1 receiver on the acoustic path between Cape Verde and Barbuda:(on the axis of the Mid-Atlantic Ridge).
- 4 receivers on the acoustic path from Barbuda to South of Iceland:(at 33N, 43N, in the Charlie-Gibbs Fracture Zone, and south of Iceland)
- 2 receivers on the acoustic path from Flores to the Labrador Sea: (at 53N and in Labrador Sea)



# 9. Fictive US Navy receiver sites

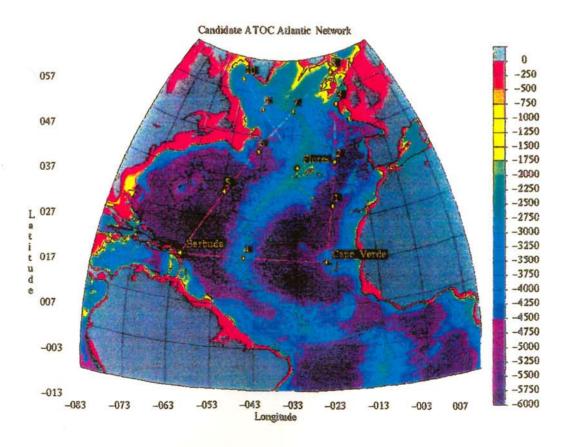


Fig. 10. Proposed outline of the receiver array

This network would enable the eastern and western basin thermal anomalies to be distinguished, as well as the separate responses of the subtropical and subpolar gyres.

Some of the most important transmission paths are those that traverse from the subtropical to the subpolar gyre and require transmission through relatively narrow gaps in the Mid-Atlantic Ridge. One such gap is the Charlie-Gibbs Fracture Zone on the path from Barbuda to south of Iceland.

Confirmation of the feasibility of this path and of that from Cape Verde to the Labrador Sea would be required before deciding on the location and design of a receiving array in the northern area since the Mid-Atlantic Ridge can result in increased propagation losses, (Laplante, Koenigs and Browning 1981). The confirmation should include a study of the modal structure of the signals received in the subpolar gyre. This could be done using the JETI self-contained HLF-6A ship-deployed source near the Barbuda site and towed arrays and VLA receivers located south of Iceland and in the Labrador Sea. However before a JETI trial is started detailed studies will need to be made of candidate JETI source sites (bathymetry, local political sensitivities, bio-acoustical impact) and receiver array design (Vertical Line Arrays and/or towed arrays and their location relative to local topography).

#### 3. RELATIONSHIP TO SMALLER SCALE PROCESS STUDIES

If the ATOC array is to be designed to detect decadal scale temperature anomalies and the generation of these anomalies is to be related to changing surface forcing, two types of measurements will be required:

- (i) High-quality measurements of surface forcing fields
- (ii) Measurements throughout the year in areas of water mass modification of sufficient quality that the process of water mass transformation by deep convection and the subsequent spread of these winter-formed water masses could be observed.

Since the areas in which water mass modification occurs are hostile and remote, this second requirement is unlikely to be accomplished by surface vessels making conventional observations. However, this requirement could be meet using smaller-scale tomographic arrays similar to those used in the Greenland Sea (Jin, Lynch, Pawlowicz and Wadhams, 1993; Lynch, 1987).

Process studies need to be carried out throughout much of the western basin in order to study the anticipated gyre-wide recirculation of water masses generated or modified by deep convection (e.g. Schmitz and McCartney, 1993). Coverage of key areas of the (relatively small) subpolar gyre could be achieved with presently available autonomous transceivers. The motivation for such smaller scale studies goes beyond just looking at local processes since it can address the cause and effect of thermohaline conveyor belt variability. However whereas process studies might be short lived (a year or less), measurement of gyre-scale variability would be a multi-year project.

While the scientific planning of a large-scale Atlantic array and smaller scale tomographic experiments need to be co-ordinated so that simultaneous measurements are made by both techniques, it seems unlikely that the transmission frequency and the number of daily transmissions would be compatible. However, it is thought that there would be considerable advantages in having the tomography receivers capable of recording the arrivals of ATOC transmissions in order to assess the information content of the ATOC data on short length scales.

## 4. RELATIONSHIP TO CLIMATE MODELLING.

Recent experiments with climate models of the ocean suggest that the North Atlantic Ocean is a particularly important region for interaction with the atmosphere, and may well actually control much of the natural climate variability, (Gordon, Zebiak and Bryan 1992). Although one must be extremely cautious in accepting specific results of the models as more than purely suggestive, it appears that the thermohaline circulation of the North Atlantic is capable of undergoing rapid transitions between at least two states. Such shifts have apparently taken place in the past - if one accepts the simplest interpretation of some of the recent ice core records. (Greenland Ice-Core Project (GRIP) Members, 1993). (Whether anthropogenic effects can stimulate such transitions, or change the governing physics is unknown). The models also show direct effects of CO<sub>2</sub> and other greenhouse gas-induced changes somewhat similar to the observed changes in the hydrography. (Mikolajewicz, Santer, Maier-Reimer, 1990).

ATOC measurements are one of the very few ways known to us that could be used to test the climate models, either oceanic, or coupled to the atmosphere. For example, we do not know from present conventional measurements whether the ocean is in equilibrium or undergoing major fluctuations.

Ocean modelling capability has expanded recently to the point where we expect that full eddy resolving models of the North Atlantic, such as those being run at present (Böning and Budich,1992; New, Bleck, Jia, Marsh, Huddelston and Barnard 1994), will be driven by wind and thermodynamic forcing fields obtained from twice-daily meteorological analyses during the Atlantic ATOC period. Of equal importance is the availability of very high quality altimetric data from the Topex/ Poseidon mission. The combination of the modelling power with the continuing altimetric data sets, as well as the WOCE deep floats and other observations, means that for the first time, oceanographers will be able to make estimates of the North Atlantic Ocean circulation on a near-daily (probably weekly) basis. In turn, this means that the Atlantic ATOC programme would have forecasts of the measured acoustic travel times at the same interval. The ATOC tomography then becomes a rigid test of the accuracy and precision of the models, and to the extent that one observes differences between predicted and measured acoustics, the two are then combined ("assimilated") to provide estimates of the oceanic state.

An Atlantic ATOC modelling effort would thus produce detailed estimates of the state of the ocean on a nearly continuous basis which would then become the means by which we could finally come to understand the large scale fluctuations and secular trends indicative of climate change.

## 5. CO-ORDINATION WITH OTHER RESEARCH EFFORTS

A major activity in the immediate future will be the focus by WOCE on the North Atlantic in 1996-7, (Gould 1993). The exact observational strategy will be formulated by March 1994. It appears at present that one observational element will be a single occupation of sections previously made during the IGY cruises of the late fifties and early sixties. This will enable the picture of thermal anomalies between that time and the present over the whole North Atlantic to be assessed and a new baseline temperature and salinity field be established against which future trends may be detected. There is an obvious synergy between the WOCE plans and the implementation of an ATOC Atlantic array both in the possibility of making future resurveys of the North Atlantic to compare with ATOC results and the possible use of WOCE ship time to carry out CTD surveys along ATOC transmission paths. In both of these regards the need for an ATOC array to be in the water and operating before mid-1996 is high.

#### 6. CONCLUSIONS

- o A North Atlantic ATOC array will require 3 or 4 cabled sources to insonify all oceanographically important areas of that ocean.
- o An array of approximately 10 autonomous receivers in addition to any fixed USN/USAF receivers that may be available will be needed to resolve the known spatial scales of decadal thermal anomalies in the area.
- o Access to US Navy and Air Force fixed receiver arrays will need to be negotiated and, if more detailed feasibility studies indicate the use of these facilities is essential, an effort made to ensure that they will not be deactivated.
- o Trial surveys with the JETI ship-mounted source are needed to confirm the feasibility of transmission through Mid-Atlantic Ridge fracture zones.
- o The Atlantic ATOC network should be operational before mid-1996 to benefit from the WOCE North Atlantic survey planned for 1996-7.
- o The multiplicity of modelling efforts in the North Atlantic provides ample opportunities to (a) simulate acoustic propagation for ATOC network design studies and (b) ultimately to verify model responses to changing surface fluxes.
- o Smaller scale regional studies in areas of deep winter convection should be carried out to provide evidence of the coupling between this process and the generation of wide area thermal anomalies.
- o All regional experiment tomography transceivers should be modified so that they can record ATOC transmissions.

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