

Expanding the ATOC/NPAL North Pacific Array using the TPC-4 Submarine Cable

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Abstract — Large-scale, depth-averaged temperatures have been measured by long-range acoustic transmissions in the North Pacific Ocean for the past nine years as part of the Acoustic Thermometry of Ocean Climate (ATOC) project and the North Pacific Acoustic Laboratory (NPAL) project; a six-year time series has been obtained so far. Comparison between upper-ocean Argo profiling float temperatures and the acoustically measured temperature along one path illustrates the strength of the integral acoustic measurements, with substantially lower uncertainty. It is now time to begin planning the evolution of this acoustic array to obtain sustained time series with more spatial coverage. In the context of ocean observatories; the TPC-4 trans-Pacific cable figures significantly in this regard.

I. INTRODUCTION

Ocean acoustic tomography was introduced by Munk and Wunsch in 1979 as a tool for observing the energetic ocean mesoscale. This was extended to basin scales, complemented by satellite altimetry, and was made specific to measuring basin-scale climate change signals, leading to the Acoustic Thermometry of Ocean Climate (ATOC) project [1, 2]. Thermometry may be thought of as a subset of tomography. With the latter, multiple crossing paths are used to obtain spatial resolution, whereas with the former, a sparse set of paths are used to obtain a good measure of the mean temperature, with the mesoscale “noise” largely averaged out by the path integral properties of the measurement. Given the realities associated with instrument placement, there are elements of both in the present North Pacific Acoustic Laboratory (NPAL) array (Fig. 1).

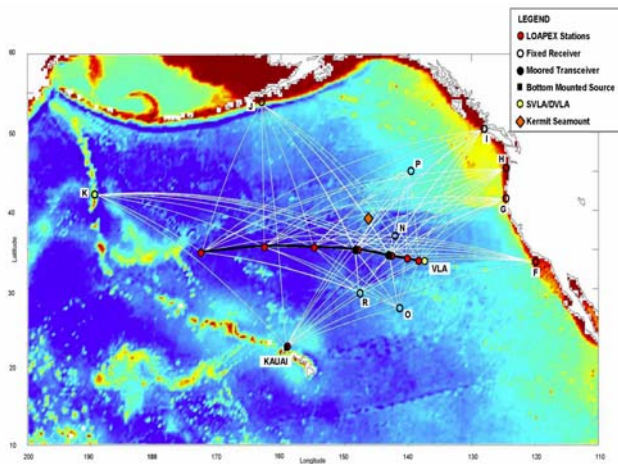


Fig. 1. The present NPAL array augmented in 2004–2005 by the vertical line array (VLA) and transceivers S1 and S2.

A major goal of basin-scale acoustic thermometry is to obtain high precision estimates of average heat content and temperature. The motivation is that the oceans are by far the largest reservoir of heat in the global climate system; as has been oft said, they are the flywheel of climate. As pressures on the environment grow, it will be necessary to monitor this reservoir with increasing accuracy and precision. A worthy goal would be to measure the ocean annual cycle and longer term variation of equivalent heat flux to a fraction of 0.3 W m^{-2} over a year ($\sim 0.4 \times 10^{22} \text{ J}$, the 50 year trend averaged over the area of the whole Earth).

Levitus et al. [3] examined the temperature variations in the ocean basins over the past 50 years using all available historical hydrographic data (5 million profiles, on average 100,000 per year). Time series of temperature variations in the ocean basins were obtained by averaging temperature over entire ocean basins, and then calculating 5-year running means of the time series (Fig. 2). The estimated uncertainty in 0–1000-m average temperature obtained for the North Pacific was about $\pm 0.01^\circ\text{C}$, comparable to the formal uncertainty in temperature derived acoustically on a single day on a single acoustic path. More recently Argo floats are being deployed and roughly the same number of profiles is expected per year, albeit more uniformly distributed.

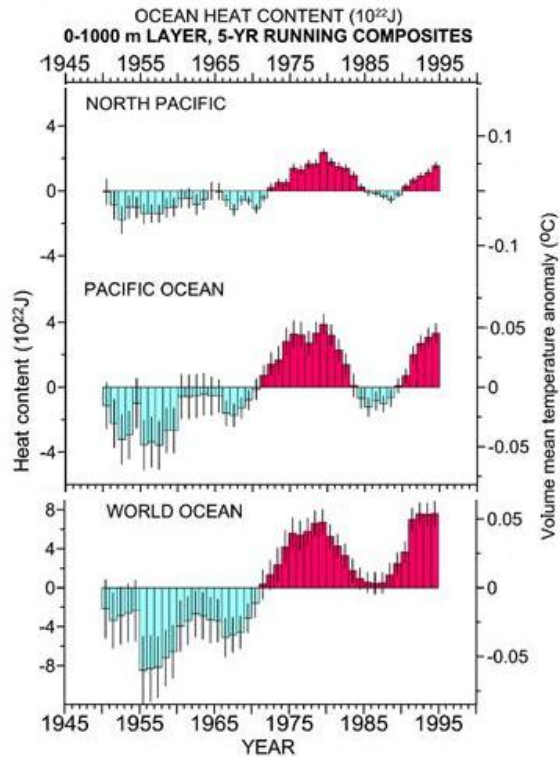


Fig. 2. Changes in heat content and temperature, adapted from Levitus et al., 1999. Vertical lines are standard errors. Note scale changes.

Here we compare the acoustic measurements in the North Pacific with Argo float measurements.

II. THERMOMETRY AND ARGO FLOAT DATA

Argo profiling float data have become available in the past few years for comparison with acoustic time series. The Kauai to k acoustic path (Fig. 1) is used to directly compare ATOC and Argo hydrographic line averages of temperature. All float profiles within 300 km of the acoustic path were first extracted. Figs. 3 and 4 show the horizontal and vertical sampling in a 10-day snapshot. The annual mean World Ocean Atlas temperatures were then subtracted to remove most of the geographical variations in temperature and to focus on the “anomalies”. The resulting temperature profile anomalies were depth-averaged, and these in turn were averaged together on 10-day intervals—insofar as this was possible (many of the floats early in the time series are shallow). The acoustic travel measurements were inverted using a simple statistical ocean model consisting of six modes including a mixed layer to represent vertical variability and a red spectrum with 20 wave numbers to represent horizontal variability; the variance in the main thermocline was $\sim 1^\circ\text{C}$.

The direct comparison between the float “path averaged” temperatures and the ATOC derived temperature measurement is shown in Fig. 5. Here, the thin vertical magenta bar gives the standard deviation of the vertical averages of the float profile data within the area in a 10-day interval, $\pm 0.6^\circ\text{C}$. An estimated uncertainty for the Argo volume mean is this standard deviation divided by the square root of the number of samples in the 10-day interval (~ 20); this is shown by the heavy magenta bar, $\pm 0.15^\circ\text{C}$. The corresponding uncertainty in the ATOC derived temperature from the inversion process is $\pm 0.02^\circ\text{C}$. This substantially lower uncertainty is a direct result of the path averaging inherent in the acoustic measurement (Fig. 5). The difference between the Argo and ATOC determined average temperatures is $\sim 30\text{--}50$ percent of the annual cycle, within the uncertainty estimates and consistent with both measurements.

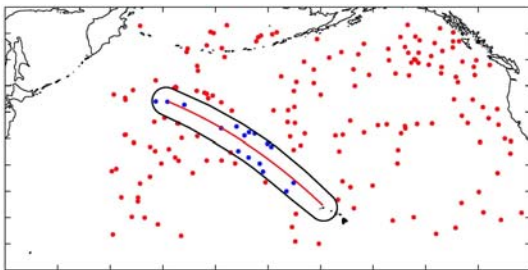


Fig. 3. Acoustic path from Kauai to receiver k with positions of the available Argo floats during a 10-day period in fall 2003.

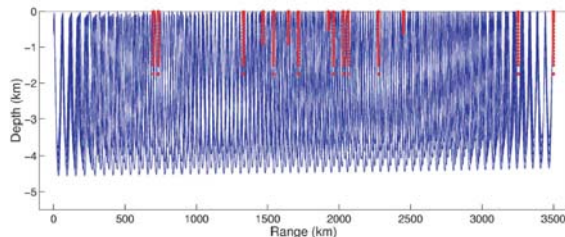


Fig. 4. Sampling for path Kauai-k ray (propagation time ~ 2000 s, six times every fourth day) and 16 Argo float profiles (10 days).

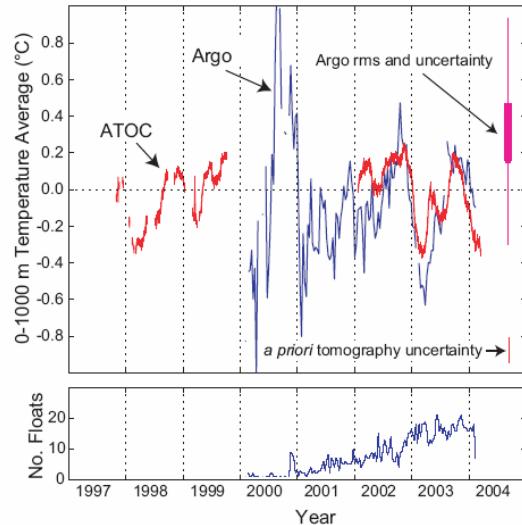


Fig. 5. Timeseries of range- and depth-averaged temperature derived from acoustic thermometry and from Argo float data.

The Argo profiles of temperature show great variability, reflecting the internal wave and mesoscale variability of order 1°C . This variability can make detection of oceanic climate change with point measurements difficult. Quoting S. Levitus [4], “Thus Argo will provide a “Minimum Ocean Observing System” (MOOS).” The acoustic time series are smoothed only by forming a daily average of travel time. Acoustic estimates are based on path averages, with rays cycling every ~ 50 km (60 times in 3000 km). If simple \sqrt{N} arguments are applied, many more float profiles would be needed to yield uncertainties as small as those associated with the acoustic measurements.

III. TPC-4 CABLE

The present Kauai source permit expires at the end of 2006; it is not clear whether a renewal is possible. The present geometry is non-ideal for tomographic purposes, e.g., for detecting the PDO mode of variability. New sources and receivers with better spatial coverage are needed. These instruments should be in the water column to avoid bottom interaction. Finally, longevity and time series continuity are needed.

The TPC-4 submarine telecommunications cable (or any other similar one available) could greatly facilitate the implementation of the necessary array, Fig. 6. The power necessary to operate the sources is available, as is the communications for data return and precise timing. The sources and receivers, working on basin and smaller scale can be used for many purposes (see [5], [6]):

- Tomography – temperature/heat content and velocity (including vorticity and fluxes)
- Ambient sound – wind, rain, mammals, seismics, shipping, ...
- Navigation – mobile platforms (floats, gliders, deep vehicles, tagged animals, ...)
- Communications, acoustic spectrum
- Part of integrated acoustic systems for ocean observatories

Such a system would clearly be constructed in close collaboration with other on-going programs: ARENA in Japan, ORION in the USA (with regional NEPTUNE, VENUS, and MARS, as well as the global buoy and coastal observatory components in the area), and OceanSites, Argo

(next generation with acoustic receivers), and GOOS, so the result is a larger, more dense, coherent observing system

IV. CONCLUDING REMARKS

The ATOC/NPAL data is showing signals with clear large-scale, multiyear content with high signal-to-noise ratio relative to Argo. The optimal way to compare and combine the Argo and ATOC data is to use an objective mapping approach, similar to the inversion method mentioned above, but including more resolution in the vertical, horizontal, and (in a simple way) time. This will permit a rigorous treatment of internal waves “noise” and mesoscale and larger-scale variability. This work is in progress.

The use of the TPC-4 cable, as well as telecommunications cables, provides the potential to attain

the ATOC vision of basin scale acoustic monitoring. By Implement integrated acoustics systems for ocean observatories the same infrastructure can be used for tomography as for acoustic navigation and communication. Combined with other point and mobile platform measurements, a truly integrated and coherent ocean observing system can be realized.

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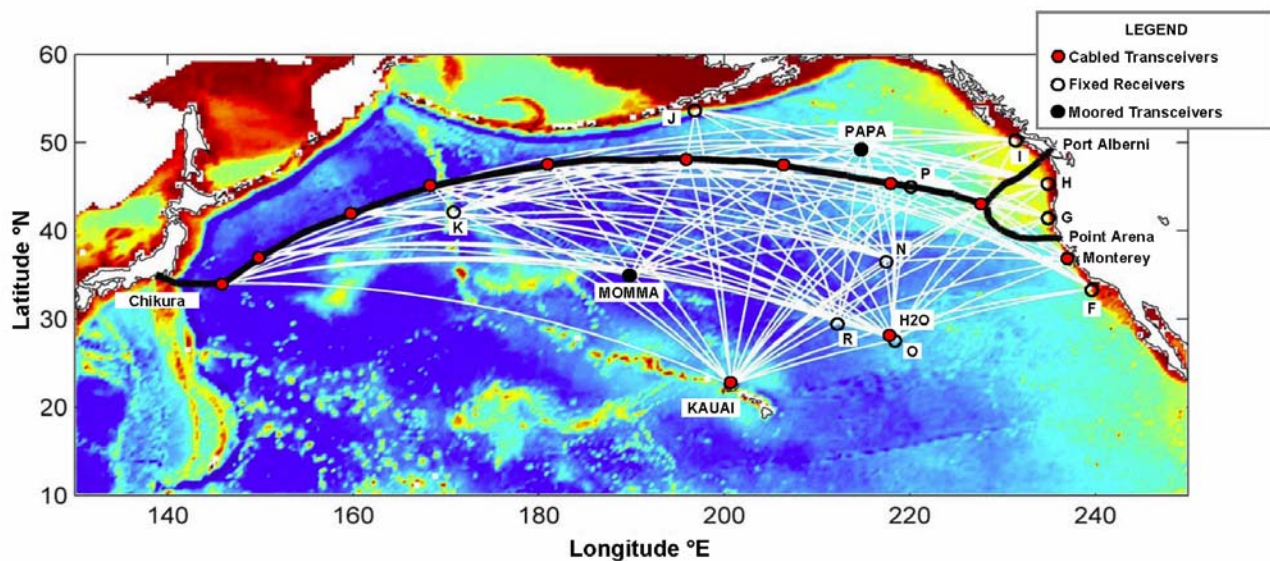


Fig. 6. The TPC-4 cable, with nodes supporting acoustic sources and receivers. Acoustic paths between these and other sources and receivers are shown. Such a system would form a major component of the North Pacific observing system.

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