A Comparison of Acoustic Thermometry, TOPEX, XBT, and HOT Observations of Ocean Temperature in the Northeast Pacific Ocean

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Abstract

Acoustic thermometry offers naturally integrating observations of large-scale temperature with unrivalled accuracy and precision. These temperature measurements have no calibration drift. In a world of a climate signal of order 0.01 C/yr and high wavenumber (mesoscale) noise of order 1 C rms, some spatial low-pass filtering is needed to pull out the climate signatures.

Time series of temperature have been measured using long-range acoustic transmissions in the Northeast Pacific as part of the Acoustic Thermometry of Ocean Climate (ATOC) project (The ATOC Consortium, 1998; Dushaw, et al., 1999; Dushaw 1999; Worcester et al., 1999). In this paper,these timeseries are compared with other available data types.The acoustic timeseries of transmissions from a source off the coast of central California began in early 1996, while the timeseries from a source north of Kauai, Hawaii began in late 1997. As a result of marine mammal protocols, the timeseries are intermittent. The California source was turned off in Fall 1998 after 24 months of operation in accord with permit requirements. Transmissions from the Kauai source ended on October 6, 1999, although we are seeking to extend the timeseries of these transmissions for another 5 years.

Assuming that the variations in sea surface height observed by TOPEX/POSEIDON are caused solely by thermal expansion, the amplitude of the annual cycle of heat content derived from altimetry is larger than that found by the acoustic data, Levitus climatology, and monthly maps of ocean temperature derived from XBT's of opportunity (courtesy of W.White). The "anomalies", or deviations of temperature from the annual cycle, are the essence of the climate problem. The heat content "anomalies" determined by the XBT maps are comparable in size to the differences between the XBT and acoustically derived heat content. These differences may be due to undersampling in space or time by the XBTs, errors in the XBT maps as a result of such things as fall rate errors, aliasing of internal wave or mesoscale variability, or the deeper sampling (below 400 m) of the acoustic data. The 12-year timeseries of temperature derived from the Hawaiian Ocean Timeseries (HOT) data set (monthly CTD casts), highlights the problem of mesoscale noise in sampling at a single point. However, thermal variability at 100-day timescales is observed in the acoustic data obtained between Hawaii and California using the Kauai source with no corresponding variability in the TOPEX data (and certainly not in the heavily-smoothed XBT maps). Acoustic thermometry is complementary to altimetry and hydrography.

Theory

The travel time along a ray path Γ_i is

$$T_i(t) = \int_{\Gamma_i} \frac{ds}{c_0(\mathbf{x},\mathbf{t}) + \delta c(\mathbf{x},\mathbf{t}) + \mathbf{u}(\mathbf{x},\mathbf{t})\cdot\tau}$$

c_0 is a reference sound speed field (Levitus)

δc is the difference between "true" sound speed and reference

ds is an element of the ray path length

$\mathbf{u}\cdot\tau$ is the current effect (neglect)

$$\frac{\delta c(\mathbf{x},\mathbf{t})}{c_0(\mathbf{x},\mathbf{t})} << 1$$

$$T_i(t) \approx T_i^0(t) - \int_{\Gamma_i^0} \frac{\delta c(\mathbf{x},\mathbf{t})}{c_0^2(\mathbf{x},\mathbf{t})}\, ds \quad (\Gamma_i^0 \text{ not } \Gamma_i)$$

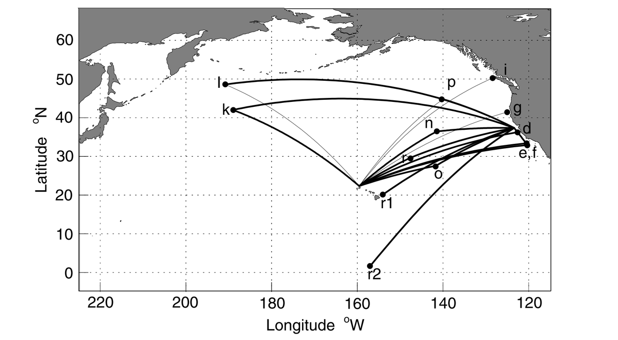
$$T_i^0(t) = \int_{\Gamma_i^0} \frac{ds}{c_0(\mathbf{x},\mathbf{t})} \quad \text{(calculated)}$$

Assuming fixed raypaths, solve for $\delta c(t)$ using travel time data.

Use $\delta c(\mathbf{x},\mathbf{t}) = \sum A_i(\mathbf{t})F_i(\mathbf{x})$, and solve for the $A_i(t)$.

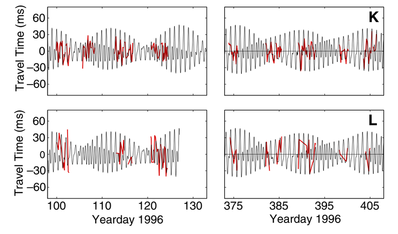
Are data equal to ray travel times in $c_0(\mathbf{x},\mathbf{t}) + \delta c(\mathbf{x},\mathbf{t})$? (YES)

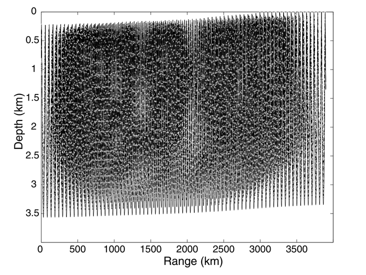
ATOC



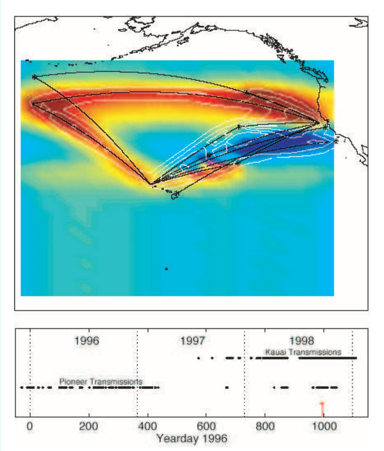
The Acoustic Thermometry of Ocean Climate (ATOC) array. The array spans most of the Northeast Pacific Ocean. Acoustic paths to the various SOSUS and vertical-line array receivers from the Kauai and Pioneer Seamount acoustic sources are shown. Paths noted by heavy lines are those for which ray travel time data have been derived. Paths noted by light lines have weaker or noisier receptions in which clear ray arrivals are not evident, but travel time data may eventually be derived for these paths.

The acoustic data are of high quality. Tidal variations of order 10 ms in travel time are observed in the data obtained at 5-Mm range on acoustic paths from California to receivers K and L (below). These tidal variations are caused by tidal currents, and they match the tidal variations predicted using a TOPEX/POSEIDON tidal model (TPXO.2) fairly well. This is one of many aspects of these acoustic data that give us confidence in the measurement of oceanic temperature.



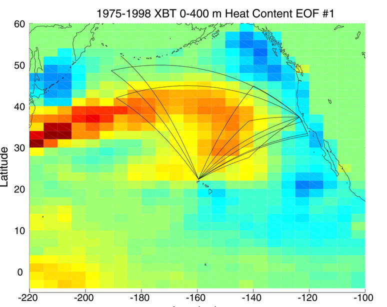


The acoustical sampling must be considered in the interpretation of the temperature measurements. The ray paths associated with resolved ray arrivals for acoustic transmissions from Kauai to receiver D located near Central California are shown above. Near Hawaii the ray paths do not sample the upper 100-200 m of the ocean, while near California the rays are surface reflecting, or near-surface refracting. These raypaths were derived using the annual mean Levitus ocean atlas. Ray paths for the transmissions from California to the central North Pacific are generally surface reflecting for the entire path, and so the entire water column is sampled.

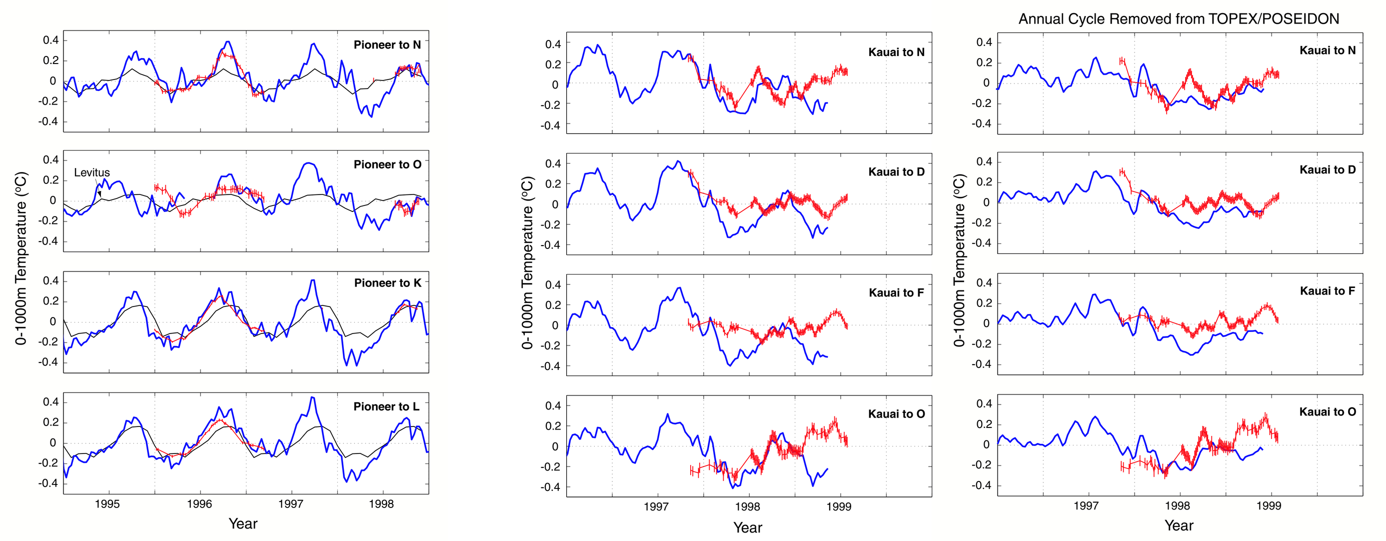


At left, an objective map of ocean sound speed variability averaged over the top 1000 m of the ocean calculated using data obtained from both the Pioneer Seamount and Kauai acoustic sources. The error map (the diagonal of the error covariance) is shown by the white contour lines; the assumed correlation length scale (1000 km) is evident in the width of the contour lines across an acoustic path. The uncertainty at any one point is only slightly reduced from the *a priori* uncertainty, but the uncertainty of the average along an acoustic path is much smaller. Because the ray paths do not sample to the ocean surface in the subtropical Pacific like they do in northern and eastern Pacific, these maps must be interpreted with care.

Acoustical arrays such as these may be used to detect spatial patterns of climate variability. The panel to the right shows the first empirical orthogonal function (EOF) of 0-400 m heat content derived from XBT's of opportunity (XBT data courtesy of Warren White). This EOF shows the "classic" pattern of the Pacific Decadal Oscillation, with the Central Pacific variability out of phase with the variability in the Gulf of Alaska and along the California Coast. Other spatial patterns, such as those of anthropogenic climate change, may not be so easy to detect by conventional means.



ATOC and TOPEX/POSEIDON



Conversion of Sea-Surface Height to 0-1000 m Average Temperature

a) Interpolate SSH onto the acoustic path and average along path.

b)

$$\alpha = -\frac{1}{\rho}\left(\frac{\partial\rho}{\partial T}\right)_{P,S} \qquad \left[\beta = \frac{1}{\rho}\left(\frac{\partial\rho}{\partial S}\right)_{P,T} \text{ IS IGNORED}\right]$$

$$\Delta\rho \approx -\rho\alpha\Delta T$$

$$\Delta v \approx \frac{\alpha}{\rho}\Delta T$$

c) Consider a 100 m X 1 m X 1 m column of water; $\alpha = 2230\times10^{-7}\ ^\circ C^{-1}$

$$\Delta h_{100} = 2.23\,\frac{cm}{^\circ C}\,\Delta T \text{ , or}$$

$$\Delta T = 0.48\,\frac{^\circ C}{cm}\,\Delta h_{100} \quad (\text{or } 2\times{}^\circ C \approx \text{height in cm})$$

Midway along northerly acoustic paths, $\Delta T_{seasonal}$ ranges from 8–15°C,

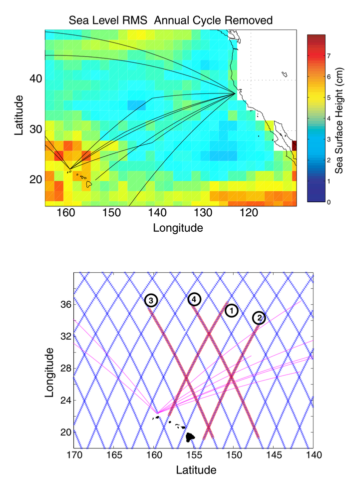
so that the conversion factor ranges from 0.58–0.48 °C/cm !!

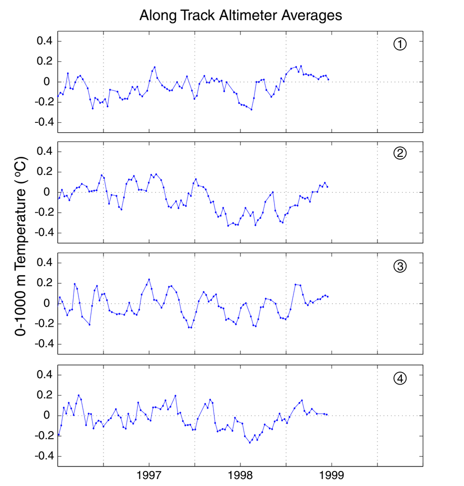
d) A factor of 48 °C/m is used, and 0–100 m ΔT is scaled to 0–1000 m ΔT.

With a variety of assumptions (see left), sea-surface height variations may be used to estimate oceanic thermal variations. The thermal variations derived from TOPEX/POSEIDON altimeter data are compared to the ATOC temperature measurements in the panels above. The data obtained on the paths emanating from California show an annual cycle, and the amplitude of the annual cycle calculated from the TOPEX/POSEIDON data is larger than the *in situ* measurement. The acoustic timeseries are quite smooth, reflecting the inherent averaging of this data type, while high-frequency barotropic motions are apparent in the altimeter data.

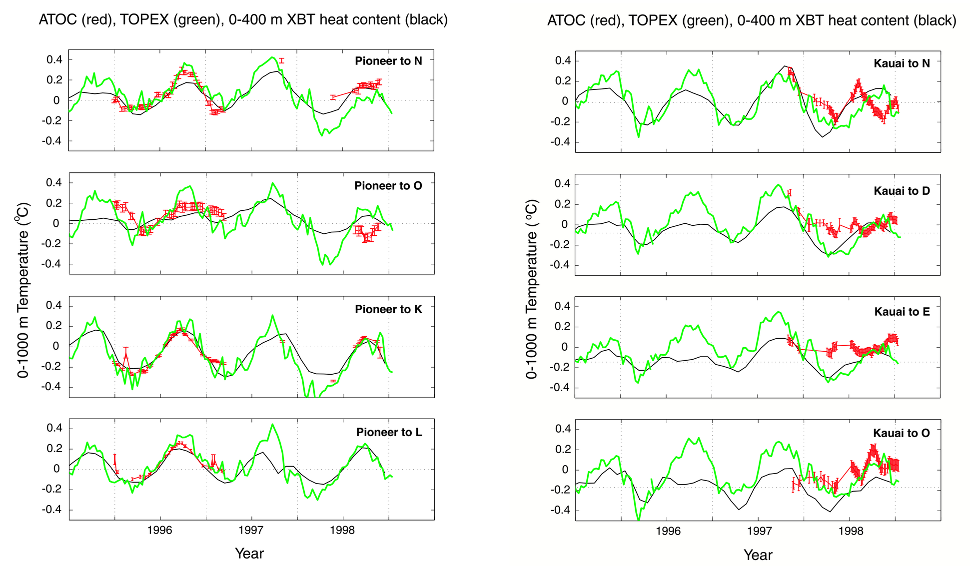
The temperature timeseries derived acoustically from paths emanating from Kauai do not show an annual cycle because of the sampling of the raypaths. Thus, the acoustic and altimeter timeseries are best compared with the annual cycle removed from the altimeter timeseries (above right). In this region, the acoustic data show greater "mesoscale," or 100-day timescale, variability than the altimeter data, while much of the high-frequency variability observed in the altimeter data is caused by large-scale barotropic motions. A variety of data sets (Acoustics, TOPEX (below left), quarterly XBT sections, CalCOFI data, HOT data) show that the area north of Hawaii has greater thermal variability than the California Current does.

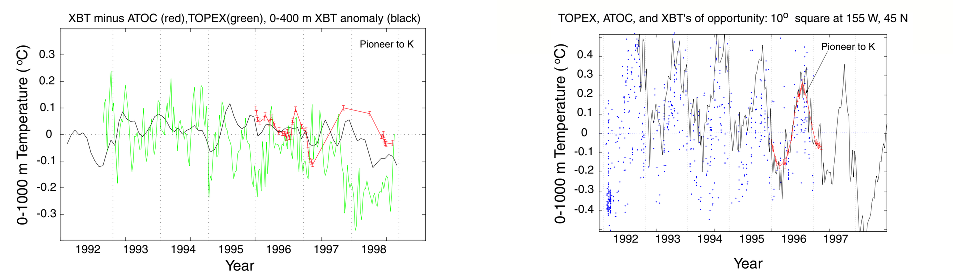
Averages of high-resolution, along-track altimeter data (below) over distances comparable to the acoustic path lengths do show some similarity to the acoustic timeseries, but these averages presumably include both barotropic and mesoscale effects. Reconciliation of the acoustic and altimetric data on these Hawaiian paths is not obvious, e.g. some of the thermal variability observed acoustically may be density compensated by salinity such that the altimeter does not detect it.





ATOC and XBT's of Opportunity



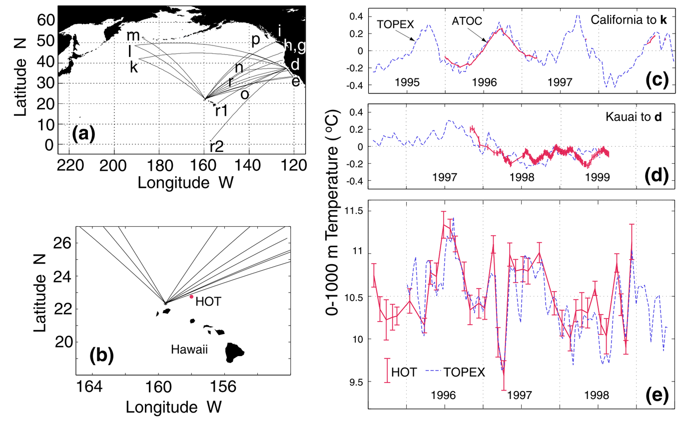


Warren White has made available (http://jedac.ucsd.edu) objective maps of 0–400 m ocean heat content derived from XBT's of opportunity. These maps were used to calculate line-averages of temperature for comparison to the ATOC and TOPEX/POSEIDON timeseries (left, top).

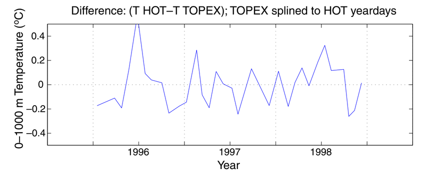
In most cases the amplitudes of the annual cycle derived from the XBT data are similar to that from the acoustic timeseries, but less than that from the altimeter data. The XBT data do not show the "mesoscale", or 100-day timescale variability observed in the acoustic data, of course.

While the XBT and acoustic data have similar amplitude of annual cycles, the differences between the two timeseries (lower left) are comparable to the estimate of the thermal "anomaly" derived from the XBT data. This suggests that the "anomaly" derived from the XBT data has order 100% error. This error may result from inadequate spatial and temporal sampling of the XBT data, from the aliasing of mesoscale or internal wave motions, from the limited depth sampling (to 400 m in this case), or from fall-rate or other instrumental errors (the broadcast XBT's have a 0.2 °C nominal uncertainty). Such problems are illustrated in a comparison of temperature measurements from individual XBT's obtained in a 10°×10° square in the central North Pacific (1998 NODC World Ocean Data Base) to the ATOC and altimeter timeseries (below right). For all of these figures the XBT data have been scaled to obtain a 0–1000 m depth average.

ATOC and the Hawaiian Ocean Timeseries



A comparison of line-integral and point data. (a): The ATOC array. (b): The HOT site. (c) and (d): Acoustic thermometry (solid line) compared to TOPEX altimetry (dashed line) for two acoustic paths as indicated. The error bars on the acoustical results in (c) are small. The annual cycle was removed from the TOPEX data in (d); the acoustic data on this path sample below the seasonally-varying surface layers and hence do not observe the annual cycle. (e): A similar comparison of 0-1000 m averaged temperature derived from HOT hydrographic data (error bars are RMS of 10–20 CTD casts) and TOPEX. All timeseries have the same scale for both axes. In (e), a nearly identical result is found when comparing dynamic height and altimetry. The differences between the temperature inferred from TOPEX and the direct measurement at HOT (below) are comparable to the temperature signal observed in the line-integrating data. The error bars of the hydrographic data are comparable in magnitude to the signal observed in the line-integral data, and the hydrographic timeseries is dominated by mesoscale variability.



Conclusions

1. The acoustical coherence at 75 Hz in the ocean is such that the resolved ray arrivals at greater than 5000-km range give precise measurements of ocean temperature.
From sound speed equation to tides, acoustical measurements have demonstrated high precision.

2. The combination of line averaging and naturally reduced mesoscale in the North Pacific results in timeseries that are remarkably smooth (California source).

3. The area 1000-km north of Hawaii has significantly more mesoscale (thermal) variability than the California Current.
(Acoustics, TOPEX, XBT sections, CalCOFI, HOT....)
(What is the origin of the Hawaiian mesoscale?)

4. More work is needed to reconcile the acoustic and altimeter data; high resolution altimeter data is not the answer. The Hawaiian mesoscale observed acoustically is not readily reconciled with TOPEX data.

5. A suggestion that, given a variety of questionable assumptions, TOPEX overestimates the amplitude of the annual cycle.
Something besides steric expansion may contribute to the annual cycle of sea surface height.

6. Any and all data types are needed to resolve the ocean climate variability; one measurement type does not stand alone.

Recent ATOC publications

A Test of Basin-Scale Acoustic Thermometry using a Large-Aperture Vertical Array at 3250-km Range in the Eastern North Pacific
P. Worcester, B. Cornuelle, M. Dzieciuch, W. Munk, B. Howe, J. Mercer, R. Spindel, J. Colosi, K. Metzger, T. Birdsall, and A. Baggeroer, *Journal of the Acoustical Society of America*, **105**, pp. 3185-3201, June 1999.

Comparisons of Measured and Predicted Acoustic Fluctuations for a 3250-km Propagation Experiment in the Eastern North Pacific Ocean
J. Colosi, E. Scheer, S. Flatte, B. Cornuelle, M. Dzieciuch, W. Munk, P. Worcester, B. Howe, J. Mercer, R. Spindel, J. Colosi, K. Metzger, T. Birdsall, and A. Baggeroer, *Journal of the AcousticalSociety of America*, **105**, pp. 3202-3218, June 1999.

Multimegameter-Range Acoustic Data Obtained by Bottom-Mounted Hydrophone Arrays for Measurement of OceanTemperature
B. Dushaw, B. Howe, J. Mercer, R. Spindel and the ATOC Group, *IEEE Journal of Oceanic Engineering*, **24**, pp. 202-214,April 1999.

Inversion of Multimegameter-Range Acoustic Data for Ocean Temperature
B. Dushaw, *IEEE Journal of Oceanic Engineering*, **24**, pp. 215-223, April 1999.

Ocean Climate Change: Comparison of Acoustic Tomography, Satellite Altimetry, and Modeling
The ATOC Consortium, *Science*, **281**, pp. 1327-1332, August 1998.