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PLENARY

A comparison of acoustic thermometry, satellite altimetry, and other observations of ocean temperature in the North Pacific Ocean

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Abstract

Acoustic thermometry gives integral measurements of large-scale ocean temperature, providing the spatial low-pass filtering needed to observe small, gyre-scale signals in the presence of much larger, mesoscale noise. Approximately two-year-long time series of temperature have been measured using long-range acoustic transmissions in the Northeast Pacific by the Acoustic Thermometry of Ocean Climate (ATOC) project. The signals transmitted by two sources, one on Pioneer Seamount off California and one north of Kauai, were received at various times by (i) U. S. Navy SOSUS arrays, (ii) vertical receiving arrays near the island of Hawaii, near Kiritimati (Christmas) Island, and at OWS Papa; (iii) a Russian receiver off Kamchatka; and (iv) a receiver off New Zealand. Temperature data from the Hawaiian Ocean Time-series (HOT) site show substantially more mesoscale noise than the integral acoustic data, as expected, although transmissions between Hawaii and California show a surprising amount of variability at roughly 100-day time scales. Assuming that variations in sea surface height are caused by thermal expansion in the upper 100 m of the ocean, the annual cycle of heat content derived from altimetry is larger than that derived from the acoustic data, from XBTs of opportunity, and from climatology. Consistent results for the seasonal heat storage in the ocean are found when the acoustic and altimetry data are combined with a computer model of the ocean general circulation, however. The conclusion is that acoustic thermometry is complementary to altimetry and hydrography.

1. Introduction

An increasing appreciation of the importance of the ocean and its variability to human activities, together with the advent of new technologies for observing the ocean, have led to increasing efforts during the last decade to develop an integrated global ocean observing system. Until very recently the observational tools needed to make routine measurements in the ocean at a reasonable cost simply did not exist. Ships move too slowly and are too expensive to make up a global ocean observing system. With the advent of new technologies, however, the situation has changed. Satellite altimeter systems now exist that can routinely monitor sea-surface height on a global basis with a precision of about 2 cm rms. Drifting subsurface floats that automatically measure profiles of temperature and salinity in the upper ocean and then transmit the data back to shore via satellite have been developed. Oceanographic moorings that measure a variety of oceanographic parameters, send the data back to shore via satellite, and remain in place for years are under development. Acoustic thermometry has been shown to give accurate integral measurements of large-scale ocean temperature and heat content, providing the spatial low-pass filtering needed to observe small, gyre-scale signals in the presence of much larger, mesoscale noise.

In this paper ocean temperature observations derived from tomographic measurements are compared with those from a number of other data types. The conclusion is that tomography is naturally complementary to other techniques. Altimetry senses the ocean surface (i.e., depth-integrated density), while tomography senses the interior (i.e., depth-integrated sound speed). Profiling floats provide broad spatial coverage and high vertical resolution of the upper ocean, while tomography suppresses internal wave and mesoscale noise and reaches the deep ocean. Eulerian observations provide excellent sampling at one location, while tomography can add the integrals between the Eulerian stations.

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Combining all of these disparate data types in computer models of the ocean circulation will ultimately allow testing and refinement of ocean general circulation and climate models in order to gain a better understanding of ocean variability and the earth's changing climate. In addition, using all of these data types together to constrain ocean models will allow quantitative assessments of the potential contributions of all of the various data types to monitoring the ocean.

2. Acoustic Thermometry of Ocean Climate (ATOC)

The basic idea of acoustic thermometry is simple (Munk *et al.*, 1995). Sound travels faster in warm water than in cold water. The travel time of an acoustic signal from a sound source near Hawaii to a receiver near California, for example, will decrease if the intervening ocean warms up, and will increase if the ocean cools down. Acoustic thermometry is feasible because (i) the ocean is nearly transparent to low-frequency sound, so that relatively weak acoustic signals can be detected over distances of thousands of kilometers using appropriate signal processing techniques; and (ii) the speed at which sound travels in the ocean depends primarily on temperature.

The Acoustic Thermometry of Ocean Climate (ATOC) project was designed to determine the precision with which acoustic methods could be used to measure large-scale changes in ocean temperature and to study the variability of the thermal field in the North Pacific Ocean at the largest scale (The ATOC Consortium, 1998; Dushaw *et al*., 1999; Dushaw, 1999; Worcester *et al*., 1999). Two sound sources were installed for the ATOC feasibility study, one on Pioneer Seamount off central California and one north of Kauai (Fig. 1). The Pioneer Seamount source began transmitting in late 1995 and continued transmissions until it was turned off at the end of 1998, in accord with various regulatory requirements. The Kauai source began transmitting in late 1997 and continued transmissions until it was turned off in early October 1999, again in accord with regulatory requirements. As a result of marine mammal research protocols, the time series are intermittent. The signals transmitted by the sources were received on SOSUS receiving arrays in the North Pacific and, for part of the time, on a vertical receiving array located at Ocean Weather Station Papa (50°N, 145°W). The transmissions from the Pioneer Seamount source were also recorded at various times on vertical receiving arrays located near the Big Island of Hawaii and near Kiritimati (Christmas) Island. A small number of the Pioneer Seamount transmissions were recorded by a temporary receiver (a single hydrophone) located to the east of the North Island of New Zealand at 10-Mm range (Tindle and Bold, 2000). The signals from the Kauai source were also recorded by Russian scientists at a permanent, bottom-mounted receiver located off Kamchatka.

The data obtained during ATOC have shown that acoustic ray arrivals may be resolved and identified to at least 5-Mm range so that these data can be used for acoustic thermometry. The estimated uncertainties in the range- and depth-averaged temperature measurements are about 10 m∞C out to ranges of 3000–5000 km. The time series obtained using the California acoustic source show a clear annual cycle (Fig. 1a) whose amplitude is similar to that derived from climatology (World Ocean Atlas 94: Levitus *et al*., 1994; Levitus and Boyer, 1994). The time series obtained using the Kauai acoustic source is of similar quality in its ability to measure the thermal variability, but it shows greater variability at 100-day timescales (Fig. 1a).

3. Satellite Altimeter and XBT observations

If the variations in sea surface height observed by the TOPEX/POSEIDON satellite altimeter are assumed to be caused solely by thermal expansion in the upper 100 m of the ocean, the amplitude of the annual cycle of heat content derived from altimetry is larger than that derived from the acoustic data obtained using the California source, from climatology, and from XBTs of opportunity (XBT maps courtesy of White, 1999) (Fig. 1a) (The ATOC Consortium, 1998). The altimeter and XBT data are averaged along the acoustic paths for these comparisons. The "anomalies," or deviations of temperature from the annual cycle, are the essence of the climate problem. The heat content "anomalies" determined from the XBT maps are comparable in size to the differences between the XBT and acoustically derived heat contents. These differences may be due to undersampling in space or time by the XBTs, aliasing of internal wave or mesoscale variability, errors in the XBT maps as a result of such things as fall rate errors, or the deeper sampling (below 400 m) of the acoustic data.

Thermal variability on 100-day time scales is observed in the acoustic data obtained on the paths between Hawaii and California. There is no obvious corresponding variability in the across-track averages of the TOPEX/POSEIDON altimeter data (Fig. 1a) (and certainly not in the heavily smoothed XBT maps). However, along-track, rather than across-track, averages of the TOPEX/POSEIDON data do show significant variability on a 100-day time scale similar to that observed in the acoustic data (Fig. 1c); the across-track sampling along the acoustic path is apparently too coarse

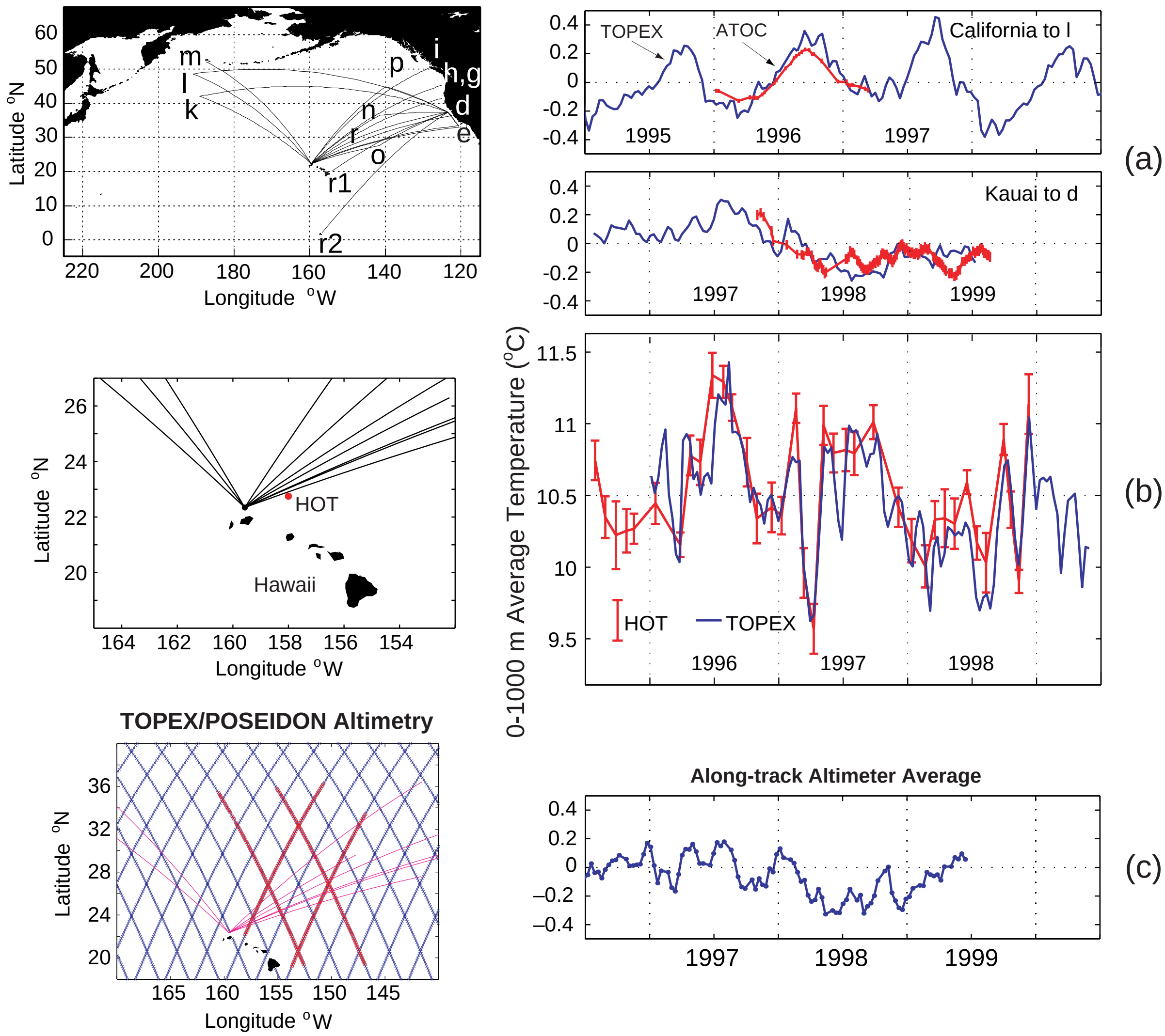

Fig. 1. A comparison of line-integral and point data. (a) The ATOC array. Acoustic thermometry (red) compared to TOPEX/POSEIDON altimetry (blue) for two acoustic paths as indicated. The error bars on the acoustical results are small. The annual cycle was removed from the TOPEX/POSEIDON data for the acoustic path from Kauai to d; the acoustic data on this path sample below the seasonally varying surface layer so that the annual cycle is not observed. (b) The HOT site. A similar comparison of 0–1000 m averaged temperature derived from HOT hydrographic data (each point of this time series shows the average and rms of 10–20 CTD casts obtained during each HOT cruise) and from TOPEX/POSEIDON. All panels have the same scaling of both axes. A nearly identical result is found when comparing dynamic height and altimetry. The differences between the temperature inferred from TOPEX/POSEIDON and the direct measurement at HOT (a point measurement) are comparable to the temperature signal observed in the line-integral data. The error bars of the hydrographic data are comparable in magnitude to the signal observed in the line-integral data, and the hydrographic times series is dominated by mesoscale variability. (c) A time series of along-track averages of TOPEX/POSEIDON data; this time series has variability on a 100–day timescale that is similar to that observed in the acoustic time series. (Reproduced from Dushaw et al., 2000.)

to resolve the coherent features of the mesoscale variability. The comparison is complicated by the presence of rapid barotropic variability in the altimeter data, however.

4. Hawaiian Ocean Time (HOT) observations

The 12-year time series of temperature derived from the Hawaiian Ocean Time series (HOT) data set (monthly sets of CTD casts) illustrates the problem of mesoscale noise in sampling at a single point (Fig. 1b). Each point of the time series in Fig. 1b is calculated by averaging the depth-integrated temperature profiles from the 10–20 CTD casts obtained during each HOT cruise. The time series is dominated by mesoscale variability; its variance is roughly 30 times the value obtained acoustically for the average temperature between Kauai and California. To achieve a similar reduction in variance using point measurements would require samples at 100-km intervals along acoustic paths between Hawaii and California. This sampling density is difficult to achieve by random point sampling; the ARGO program, for example, plans for an average spacing between the floats of around 300 km (ARGO

Science Team, 1998). These crude numbers suggest that the areal density of ARGO floats will be nine times less than is necessary to match the signal-to-noise capability of the acoustics for detecting large-scale temperature variations. Two offsetting caveats to this calculation are (i) the acoustic sampling near Hawaii misses the upper 200 m or so of ocean and so it does not detect the variability there, and (ii) each point in the HOT time series used for these calculations is the average of 10-20 CTD casts, while most often broadcast-mode point measurements offer only one hydrographic profile (note the error bars in Fig. 1b).

5. Discussion

Acoustic thermometry holds promise of becoming a cost-effective method to make rapid and repeated gyre-scale temperature and heat content observations on a long-term basis (Dushaw *et al.*, 2000). Temperature measurements from tomography are robust, Eulerian measurements of the large-scale variability with no calibration drift. Tomographic measurements directly probe the existence and nature of signals at the lowest wave numbers. These data are also sensitive to variability almost to the ocean bottom, and thus can detect changes below the depths at which XBT and float data are obtained. The theme here is not that acoustic thermometry is a substitute for the point measurements, but that acoustic thermometry is complementary to altimetry and hydrography.

The impact of the integral measurements on the quality of ocean estimation using numerical models remains an open question, however. This impact is best assessed when all data types, tomography, subsurface drifters, XBTs, satellite altimetry, etc., are used. Permits are being sought from appropriate governmental agencies to continue acoustic transmissions from the Kauai source for another five years. The goals of these observations include studying the spatial structure of the thermal variability of the Northeast Pacific at the largest scales and determining the extent to which the acoustic data and other data types, such as satellite altimetry, can best be combined for optimal estimation of the ocean state.

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