Variability of Heat Content in the Central North Pacific in Summer 1987 Determined from Long-Range Acoustic Transmissions

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ABSTRACT

The evolution of the heat content in the central North Pacific Ocean during summer 1987 has been measured using acoustic transmissions between transceivers deployed in a triangle approximately 1000 km on a side. The acoustically determined heat contents of the source—receiver sections agree with heat contents computed from CTD and XBT data obtained during May and September 1987. The accuracy of the acoustical measurements of range-averaged heat content is comparable to estimates from CTD and XBT data. Transmissions at four-day intervals allow the continuous observation of heat content and show that it varies on time scales of weeks or less. The magnitude of these variations is of the same order as that observed from XBT sections, which are only occasionally available. Ocean-atmosphere heat exchange from bulk formulas accounts for only about half of the observed heat content increase from May through September 1987, indicating that advective effects are important in the region. The excess heat change is calculated to be of order 50–150 W m⁻². The advective component of the near-surface heat budget is roughly in phase with the surface flux component.

1. Introduction

There have been numerous measurements of the variability of upper-ocean heat content in the North Pacific Ocean (Bathen 1971; Barnett 1981; Wyrski and Ulrich 1982; Spiesberger et al. 1989; Spiesberger and Metzger 1991; see also Stevenson and Niiler 1983). Primary goals of these efforts have been the identification and understanding of large-scale temperature anomalies that occur in the upper layers of the central North Pacific Ocean and the role of the ocean in the earth's energy balance. Progress on these problems has been hampered by the inaccuracy and infrequency of the directly measured thermal profiles commonly used in the heat storage computations (Wyrski and Ulrich 1982; Hanawa and Yoritaka 1987).

One of the key issues is the relative roles of air–sea heat exchange and advection in the near-surface heat budget. Barnett (1981) examined the variability of 29 approximately monthly AXBT sections taken between 30° and 50°N along 158° and 170°W. He found, in support of the theoretical considerations and calculations of Gill and Niiler (1973), that "the variance associated with the seasonal change in heat storage can be attributed almost entirely to air–sea heat exchange." In contrast, the data along 158°W were used by Wyrski and Ulrich (1982), together with additional data, to conclude that "horizontal advection is a major contributing factor to the annual signal of heat storage and the observed changes in heat storage are larger than can be accounted for by local heat exchange." Wyrski and Ulrich found that the advective effects were in phase with surface fluxes; that is, the upper ocean warmed more during summer and cooled more during winter than could be accounted for by air–sea fluxes alone. In both cases, the calculation of heat content was limited to the top 100 m, since Barnett observed that the seasonal change in heat content is confined to the upper 100 m.

Other investigators have estimated the time-averaged meridional heat transport using the net air–sea heat exchange from bulk formulas (Hastenrath 1982; Lamb and Bunker 1982; Talley 1984). Combining the net air–sea heat exchange with the temporal variability of heat content from temperature profiles, Hsiung et al. (1987) estimated the temporal variability of heat transport. Hsiung et al. conclude that the climatological basinwide meridional heat transport in the North Pacific north of 20°N is mostly northward with a maximum in September. This is generally consistent with Wyrski and Ulrich (1982) but is not directly comparable to their results, which are confined to the central North Pacific Ocean.

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In this experiment, the 1987 Reciprocal Tomography Experiment (RTE87), the evolution of the large-scale heat content during summer 1987 is inferred from acoustic measurements made in the central North Pacific Ocean at 4-day intervals. Dushaw et al. (1993, henceforth DWCH) describe the experiment in detail. A triangular acoustic transceiver array was deployed north of Hawaii between the Subtropical and Subarctic fronts (Fig. 1). The mesoscale activity in this area is relatively low (Emery 1983; Shum et al. 1990) so there is little mesoscale noise in the measurements of 1000-km averages using acoustic techniques. Acoustically determined heat contents are compared with heat contents computed from concurrent conductivity–temperature–depth (CTD) and expendable bathythermograph (XBT) measurements, with other recent data, and with the surface heat exchange estimated using bulk formulas. Estimates of air–sea heat exchange are not large enough to account for the observed evolution of the heat content between 0 and 100 m, suggesting that advection plays a significant role in the large-scale heat content budget.

Section 2 describes the measurements. In section 3, unique problems encountered in the inversion of the acoustic data from this experiment for the sound speed and temperature fields are briefly summarized. Section 4 compares acoustically and CTD/XBT-determined sound speed and temperature fields, providing verification of the acoustic inversions. In section 5, acoustically derived time series of heat content are presented and compared with both concurrent and historical measurements. At short time scales the variability of heat content is shown to be comparable to the accuracy of previous measurements using XBT sections. In section 6 the air–sea heat exchange estimates are differentiated from the time derivative of the heat content to estimate the residual, which is presumably due to advection.

2. Measurements

Three 250-Hz acoustic transceivers were moored near the sound channel axis (at about 800-m depth) from mid-May to mid-September 1987. They transmitted simultaneously at 2-h intervals every fourth day. A well-defined set of early ray arrivals was observed for all three legs of the triangle. The later part of the arrival pattern was complex and unstable prior to a sharp, well-defined acoustic energy cutoff. The starting and ending sound speed fields between the transceiver moorings were determined from CTD and XBT measurements made about every 40 km during the deployment and recovery of the transceivers (Fig. 2). Using these sound speed fields, the acoustic arrival pat-

![Image](image_url)

**FIG. 1.** Geometry of the 1987 gyre-scale reciprocal acoustic transmission experiment, with acoustic transceivers at locations 1, 2, 3. A current meter mooring with temperature sensors is on the northern leg of the acoustic triangle at location CM. Reproduced from Worcester et al. (1990), as modified from Roden (1975).
May 1987

Yearday 134-138

North

Yearday 261-264

East

Yearday 132-141

West

Yearday 138-141

Yearday 258-261

Fig. 2. Initial and final sound speed fields for all legs computed using the the XBT and CTD data. The CTD data was used to construct $T-S$ relations for each leg, and the $T-S$ relation from the CTD profile nearest each XBT profile was used to assign salinity to the XBT measurements. The tick marks denote the locations of the CTD (long) and XBT (short) casts. Three or four fronts are present on the east and west legs. The summer thermocline has formed by recovery. The days on which the XBT and CTD measurements were made on each leg are indicated. Modified from Dushaw et al. (1993).
terns were calculated and pulse arrivals were identified with specific ray paths. Although calculations suggested that a variety of ray paths with upper turning depths in the main thermocline would be resolved, only rays that turned at or very near the surface were in fact resolved.

Our data consist of time series of the travel times of the resolved ray arrivals and of the final cutoff, defined as the time at which the acoustic energy of the latest arriving pulse falls to the noise level. Averages of the travel times of oppositely traveling pulses were formed to remove the effects of ocean currents (Howe et al. 1987; Fig. 3). The resolved rays cycle through almost the entire water column, averaging over both range and depth (Fig. 4). The final cutoff provides important information about sound speed near the sound channel axis, since its travel time and sampling characteristics approximately correspond to those of the latest predicted ray arrival, with upper and lower turning point depths near the sound channel axis. The failure to resolve rays that turn in the main thermocline is important since it limits the amount of vertical resolution available in this experiment.

The acoustic travel times have been corrected for clock error and mooring motion (DWCH). Absolute mooring positions were initially determined to about 50 m rms using the NAVSTAR Global Positioning System (GPS), giving ranges between the transceivers accurate to about 70 m rms. The measured travel times and calculated travel times for the XBT/CTD-determined initial and final sound speed fields were used to correct these ranges slightly (DWCH). The final ranges are 745.214, 995.466, and 1274.716 ± 0.025 km, giving predicted travel times that agree with measurements within 6–10 msec. An error in range is indistinguishable from a range- and depth-independent sound speed perturbation, giving a small time-independent bias to the estimated temperatures and heat contents. Since the absolute ranges between the transceivers are known to ±25 m, it is possible to determine absolute temperature and heat content from the acoustic measurements, as opposed to only relative changes in temperature and heat content.

The error in the measured travel times is dominated by mooring motion correction error and by internal wave–induced fluctuations, since the signal processing techniques allow the raw travel time to be measured to 1 msec precision. The clock correction and its error cancel in forming the sum travel times (Munk and Wunsch 1982). The high-frequency (>0.5 cpd) travel time variability is mainly due to internal waves and must be added to the travel time measurement error. The measurement error in the one-way travel times is 5–7 msec, and the error in the sum travel times is 7–12 msec. The error in the daily averaged sum travel times is reduced to 2–8 msec, depending on the number of receptions (at most 12) in the average. The error in the travel times does not contribute significantly to the uncertainty in the inverse solution.

All of the travel times decrease with time from May through September (Fig. 3). Decreases in the travel times of the surface-reflected, deep-turning rays are predominantly due to the formation and evolution of the summer mixed layer, since sound speed increases with increasing temperature. On all three legs of the experiment triangle, the travel times of the axial rays, those trapped near the sound channel axis with upper and lower turning depths of about 500 and 900 m, respectively, also decrease with time, indicating increasing temperatures at depths well below those modified by seasonal surface forcing. The 50-msec change for the axial ray on the north leg corresponds roughly to a range-averaged warming of about 40 m °C.

3. Inverse procedure

While the ultimate goal is to compute heat content along the source-receiver sections, the travel times are first inverted to give the sound speed fields between the transceivers. These are then converted to temperature and finally range averaged and vertically integrated to obtain heat content. While it is, in
principle, possible to invert directly for heat content, if one does so, it is impossible to check the solution by retracing rays through the estimated sound speed field. Standard linear weighted least-squares inversion techniques are used to compute sound speed perturbations relative to the reference sound speed field from sum travel times. The method used is identical to that described by Howe et al. (1987) except that the reference sound speed field is chosen to be a function of space and time to minimize non-linearities (Mercer and Booker 1983; Spiesberger and Worcester 1983; Spiesberger 1985a,b; Munk and Wunsch 1985, 1987; Malanotte-Rizzoli and Holland 1985; Malanotte-Rizzoli 1985).

The 1000-km scale of this experiment, which extends in latitude from the Subtropical Front to the Subarctic Front, means that the underlying climatological sound speed field contains significant range dependence, especially on the east and west legs of the transceiver triangle. Similarly, large near-surface sound speed changes are associated with the formation and evolution of the summer thermocline from May through September. A time-dependent, smoothly evolving reference ocean was therefore constructed from the Levitus atlas (Levitus 1982) and occasional XBTs of opportunity (called XBTO hereafter, to distinguish them from the XBTs taken during deployment and recovery) collected through the Volunteer Observing Ship Program (Pazan and White 1991). We have rather artificially used only XBTO data to generate the reference state so that the inverse solution is independent of the CTD and XBT data collected during the experiment,
since we will subsequently use the CTD and XBT data to check the solutions.

The relative lack of vertical resolution makes it important to use a parameterization of the sound speed perturbations that minimizes the number of parameters to be determined and varies smoothly in the vertical. A key element in the ocean model used in the inversion procedure is a mixed-layer function that acceptably models the large near-surface sound speed changes. The details of these procedures are summarized in appendix A.

As an alternative to construction of a time and range-dependent reference state, it is possible to iterate the linear inverse until the solution converges. Iterated solutions for the deployment and recovery east leg range-averaged sound speed profiles, starting with the summer Levitus climatology as the reference state, converged to range averages constructed from the CTD/XBT data with the inverse solution uncertainty (not shown). Convergence is not guaranteed when the ray paths do not give depth resolution and is sensitive to the a priori assumptions, such as the vertical functions used to model the perturbation, and the data error. Large data error must be assumed for the first few iterations to include nonlinear effects. It seems to us to be preferable to combine all available information, including climatological and other data, to linearize the inverse problem as much as possible. We have therefore followed the procedure outlined in the previous paragraphs, rather than using iterated inversions.

The conversion from sound speed to temperature contributes little error to the final solution. While it is necessary to take account of the nonlinear relation between temperature and sound speed, due to the large temperature range encountered, it is straightforward to do so (appendix B). Realistic salinity errors cause temperature errors that are smaller than the estimated uncertainties.

Using the temperature estimates, the range-averaged, depth-integrated heat content is

$$H = \rho C_p \int_0^{-D} \bar{T}(z) dz,$$

where $H$ has units of energy per area, $\rho = 1024$ kg m$^{-3}$ and $C_p = 3996$ J/(kg °C) are the density and specific heat of seawater, $\bar{T}(z)$ is the range-averaged temperature profile obtained from the inversions, and 0 to $-D$ is the depth interval of the integral. The approximation that $\rho$ and $C_p$ are constants has been shown by Wyrtki and Uhrich (1982) to give an error of about $1.0 \times 10^7$ J m$^{-2}$ in the range-averaged heat content between 0 and 100 m, which is much less than the inverse solution uncertainty. Heat content is integrated over two layers, 0–100 m and 0–2000 m. The lack of vertical resolution due to the limited number of ray paths resolved in this experiment means that the inverse solution uncertainty is correlated with depth, that is, the inverse solution may be too warm at one depth and correspondingly too cold at another depth, so long as the total travel times are not affected significantly. The uncertainty in the inverse solution at any particular depth may therefore be large, but the uncertainty of the depth integral of the inverse solution is smaller. The lack of vertical resolution therefore contributes little uncertainty to the 0–2000-m heat content estimate, but does contribute to the uncertainty in the 0–100-m heat content estimate.

4. Sound speed and temperature

Prior to presenting the heat content results, the validity of the inverse solutions will be tested by comparing the computed sound speeds and temperatures with other measurements. At the beginning and end of the experiment, the XBT and CTD data obtained on the source-receiver sections provide independent estimates of the sound speed and temperature fields. Throughout the experiment, acoustically derived sea surface temperatures can be compared with other sea surface temperature estimates.

Since the inverse solutions do not resolve horizontal variability, range averages of the sound speed maps constructed from the CTD and XBT data have been computed for comparison with the acoustic results. Figure 5 shows the range average of the Levitus atlas (Levitus 1982) summertime mean sound speed profile, the reference sound speed profile used in the acoustic inversions, and the inverse solutions for the sound speed fields that correspond to the north leg deployment and recovery sound speed fields of Fig. 2. The acoustic estimates agree much better with the CTD and XBT estimates than either Levitus or the reference profile used.

Plotting the differences, after converting to temperature, displays the discrepancies between the XBT/CTD and acoustically derived fields more clearly (Fig. 6). Six comparisons are available since XBT/CTD measurements were made on each of the experiment triangle legs during both deployment and recovery. The differences are less than 0.5°C below about 200 m, increasing to about 1°C at the surface, roughly consistent with the expected uncertainty of the inverse. The near-surface error is less during September than during May, since ray paths with upper turning depths at the base of the summer mixed layer are present in September, but absent in May, giving increased depth resolution at that time. The rough balance between the negative temperature differences near the surface and positive temperature differences at 200–400 m in Fig. 6 is due to the limited vertical resolution available in this experiment, as discussed above. The differences cancel when temperature is vertically integrated to depths greater than about 400 m to obtain heat content.

Errors other than the formal uncertainty of the inverse solution, caused by data error and lack of reso-
lution, are in part responsible for the discrepancies observed in Fig. 6. The XBT/CTD and acoustic measurements were not coincident in time. Typically, the XBT and CTD casts were taken several days before or after the first or last transmission day, respectively. The variability in the travel times (Fig. 3) shows that significant changes in the sound speed field can take place over several days. In addition, the range averages computed from the CTD and XBT data are not perfect. For example, baroclinic tides displace isotherms, and will affect the temperature (and sound speed) field as it is sampled. Since the XBT casts were taken about every two hours as the ship steamed between mooring locations, the internal tide variability could have been aliased into the XBT/CTD-determined sound speed field. The sound speed variability at 300 m, as observed by a temperature sensor on a mooring located midway between the northern moorings, is mainly tidal and varies by about 2 m s\(^{-1}\) peak to peak. This temporal variability is similar to the variability observed by the XBTs at 300 m.

The acoustic solution for temperature allows a rough estimate of sea surface temperature (SST), although the uncertainty of the acoustic estimates is relatively large near the surface due to a lack of resolution. Figure 7 compares the acoustically derived SST with values from the XBTs and the monthly National Meteorological Center/Climate Analysis Center (NMC/CAC) range-averaged SST. The acoustically derived SSTs are within about 1 °C of the NMC/CAC SSTs and the SSTs derived from the deployment and recovery XBTs. The estimate of SST is possible only because we have used the mixed-layer function, and the summertime SST is generally the same temperature as the top 20 m of the mixed layer. For example, in September the difference between the NMC/CAC sea surface temperature and the XBT and XBTO temperatures at the surface is \(-0.3 \pm 0.8{\circ}\)C, while at a depth of 20 m the difference is \(-0.1 \pm 0.7{\circ}\)C.

From the comparisons given above we conclude that the inverse procedure is yielding results consistent with the expected uncertainty. The vertical resolution available is limited, as expected.

5. Heat content

Heat contents derived from the acoustic data are more accurate than the estimates of the sound speed and temperature profiles given above, since the depth integration to some extent removes the vertical resolution problem in the inverse solutions, depending on the vertical range for which heat content is calculated. Figures 8 and 9 show the range-averaged, depth-integrated heat contents computed from the acoustic and the CTD/XBT data for 0–2000-m and 0–100-m depth intervals. The error bars on the acoustic estimates of heat content, calculated as \(W_1^E W\), where \(W\) is the integrating operator used to convert the estimated
temperature profiles to heat content and $E$ is the error covariance of the temperature profile estimates, are predominantly due to a lack of resolution. Only about 15% (40%) of the variance of the 0–2000-m (0–100-m) heat content estimates is due to travel time measurement error. Travel time measurement error does not contribute significantly to the uncertainty in the heat content estimates. The heat content of the reference state is fortuitously close to that actually observed on all three legs of the array for 0–100 m and on the east leg for 0–2000 m. The acoustically derived 0–2000-m heat content differs significantly from that of the reference state for the north and west legs, however.

Acoustic transmissions at 4-day intervals allow continuous observation of heat content, while the CTD/XBT data only give heat content during the mooring deployment and recovery cruises in May and September 1987. (Table 1 lists the 0–100-m range-averaged, depth-integrated heat content for each leg of the experiment triangle as a function of yearday.) The heat contents derived from the acoustic measurements and from the CTD/XBT data agree within the expected uncertainties in all cases. The uncertainty of the acoustically determined heat content in the top 2000 m is generally smaller than the uncertainty in the CTD/XBT estimates of the same quantity. By integrating over the top 2000 m, the anticorrelated uncertainties in the acoustic estimates cancel. A lack of resolution near the surface causes the uncertainty of acoustically derived 0–100-m heat content to be significantly larger than the uncertainty in the 0–2000-m heat content. (Note that the vertical axes in Figs. 8 and 9 are identical, except for an offset.) The uncertainty in the 0–100-m heat content derived acoustically is also larger than the uncertainty in the 0–100-m heat content computed from the CTD/XBT data and early in the time series is nearly as large as the a priori uncertainty. When some rays become near-surface refracting toward the end of the experiment, the increased depth resolution makes the error bars smaller and roughly comparable to those computed for the CTD/XBT data (particularly on the north leg).

The acoustically derived time series of 0–100-m heat content are approximately consistent with the average annual 0–100-m heat content cycle computed by Wyrtki and Uhrich (1982, henceforth WU) using 55 XBT temperature sections along 158°W between 1971 and 1977 (Fig. 10). The total change in heat content on the north leg between May and September is close to the average change of WU, while the east and west legs show slightly larger changes than given by WU.

The variability of the inversion estimates for 0–100 m is comparable to the variability of heat content determined by WU (even though our error estimates indicate that the acoustically derived variability is not well resolved). Wyrtki and Uhrich found the standard
point depths, it is difficult to understand the difference in the estimated uncertainties. The smoothness of their heat content time series suggests that the results have been low-pass filtered by the persistence assumptions made in the Kalman filtering operation performed to combine data from different days. Our results assume statistical independence for each inversion.

6. Air–sea heat exchange and advection

In the notation of WU, the difference between the air–sea heat exchange \((Q)\) and the time derivative of the measured heat content \((\partial H/\partial t)\) gives the residual heat content change \((R)\)

\[
R = \frac{\partial H}{\partial t} - Q. \tag{2}
\]

This equation has been discussed in detail (and in more expanded form) by a number of people (WU; Lamb and Bunker 1982; Stevenson and Niler 1983; Talley 1984; Hsung et al. 1987). Figures 8 and 9 show the time integral of the net air–sea heat exchange, aligned to the start of the 0–100- and 0–2000-m heat content

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265 XBT/CTD 5.15 (08) 6.64 (09) 6.77 (10)

Fig. 7. Tomographic determination of sea surface temperature. The SST is taken as the mean of the inversion 0–20-m temperature. The dotted line shows the temperature reference, that is, the results being no ray path travel time. Squares indicate range-averaged, monthly values of the NMC/CAC SST. Dots at the beginning and end of the time series indicate range-averaged XBT/CTD-determined SST.

deviation of the individual XBT values from the mean annual cycle to be \(17.5 \times 10^7\) J m\(^{-2}\). The standard deviation of the acoustically determined heat content from an acoustically derived annual cycle (discussed in the next section) is \(16 \times 10^7\) J m\(^{-2}\) for the north leg and \(11 \times 10^7\) J m\(^{-2}\) for both east and west legs. The acoustics corroborate the assessment of WU that the variability of heat content occurs on time scales of weeks or less.

Finally, the results presented here can also be compared with simultaneous acoustic measurements by Spiesberger and Metzger (1991), who used transmissions from our northwest mooring to a receiver located 3000 km to the southeast to determine changes in heat content. They report little change in 0–100-m heat content during August and September 1987 (Fig. 10). The symbols used in Fig. 10 to plot their results include the estimated uncertainties. While the results presented here suggest a greater change in heat content during this period than obtained by Spiesberger and Metzger, the two results are formally consistent, due to the larger size of our estimated uncertainties. Since the two measurements rely on similar data from ray paths that reflect off the surface or have near-surface upper turning
term mean net heat exchange between 30°N and 50°N at 158°W, gives a residual in agreement with WU’s results, indicating the net heat exchange estimates of Cayan and those used by WU (Clark et al. 1974) are in rough agreement (Fig. 11a). Figures 11b–d show the smoothed time derivative of heat content during 1987, the Cayan net air–sea heat exchange for 1987, and residuals for north, east, and west legs, respectively. A 20 W m⁻² error in the air–sea heat exchange is negligible compared to the errors in the time derivative of heat content. The residuals for the east and west legs agree, but are large. The north leg residual is somewhat smaller. The excess heat content change is 50–150 W m⁻², though the short record length, the data uncertainty and variability, and the uncertainty in the air–sea heat exchange make the calculation quantitatively unreliable. Both our results and those of WU are at least roughly consistent with the results of Hsiung et al. (1987) that the climatological basinwide meridional heat transport is northward north of 20°N and peaks in August or September.

The time series of acoustically derived heat content for 0–2000 m indicates that the depth structure of the heat transport is not simple, however. Figures 8 and 9 indicate that the heat content increases slightly more in the 0–100-m layer than in the 0–2000-m layer over the summer, which requires a decrease in heat content below 100-m depth. At the same time, the decrease in
travel time for the axial rays (Fig. 3) indicates warming at depths well below those for which surface flux effects can be expected to be important. The implication is that cooling must be occurring at intermediate depths in the main thermocline. This result can be checked using the CTD/XBT data collected on the source-receiver sections during May and September (Fig. 12). Near-surface sound speeds and temperatures increase substantially, as expected. Below about 600 m the range-averaged sound speeds derived from the CTD/XBT data increase by a few tenths of a meter per second (or the temperature increases by about 40 m °C), as is observed in the axial ray travel times. Sound speeds and temperatures decrease at 200–400 m, however, as required by the heat content difference between 0–100 m and 0–2000 m derived acoustically. A decrease in heat content of about 0.22 × 10⁹ J m⁻² occurred at 200–400 m. The heat content changes occurring at depth are presumably advective in origin. Particularly dramatic is a sudden increase in the 0–2000-m heat content observed near yearday 200 on the north leg. This change is apparent in the axial travel time data.

7. Discussion

We have shown that depth-integrated, range-averaged heat content can be determined acoustically more frequently and almost as accurately as by XBT sections. We have found that the large-scale heat content varies significantly on time scales of weeks or less. This variability limits the accuracy of heat content determined from XBT sections. When the acoustically determined heat content is compared with air–sea heat exchange, advection of heat is seen to play a role equal to air–sea fluxes in the large-scale heat budget. These results corroborate the main conclusions of Wyrtki and Uhrich (1987), who used seven years of monthly XBT sections. (The 120-day record length here precludes conclusions about interannual variability.)

Our results for excess heat content can be compared with the results of Hsiung et al. (1987) for meridional heat transport in the Pacific. Differentiating their heat transport at 40°N from that at 32°N gives a contribution to the heat budget of 30–70 W m⁻² due to advection, peaking in August/September. While this is an average for the entire North Pacific Ocean, it is encouraging that the magnitude and phase of the excess heat change are comparable to the 50–150 W m⁻² that we obtained.

Finally, the recent paper by Yuan and Talley (1992) on shallow salinity minima may help to explain the cooling we observed between 200–400 m. That paper describes salinity minima in the region of our experiment at roughly 100-, 200-, and 500-m depths. Yuan and Talley argue that these minima are formed when cold, low-salinity surface water in the subarctic frontal zone is "subducted by Ekman pumping and then advected by geostrophic flow along isopycnals." Thus,
the cooling at depth 200–400 m that we observed may be due to the injection of low-salinity, cool water associated with the salinity minima. No direct evidence for this hypothesis exists, however.

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APPENDIX A

Inverse Procedure

To first order, the sum of the travel times of oppositely traveling acoustic pulses for ray path $i$ is

$$T_i^+ (t) + T_i^- (t) = 2T_0(t) - 2 \int_{r_i^0} \frac{\Delta c(x, t)}{c_0^2(x, t)} ds, \quad (A1)$$

where $\Delta c(x, t)$ is the sound speed perturbation relative to the reference sound speed field $c_0(x, t)$, which in general can be chosen to depend on time, range, and depth, and the $T_0(t)$ are the travel times for the reference sound speed field. This equation is approximate because the path $r_i^0$ is determined by $c_0(x, t)$, not the
true sound speed. The data, $d_i$, used for the inversions are then

$$d_i = \frac{1}{2} (T_i^+ + T_i^-) - T_{bi} + \epsilon,$$

(A2)

where $\epsilon$ represents both data and model error. Standard linear weighted least-squares inverse techniques (stochastic inverse) are used to solve for $\Delta c(x,t)$ given the $d_i$ (Cornuelle et al. 1987; Howe et al. 1987), with the perturbation sound speed field expressed as a linear combination of functions of range and depth whose amplitudes are functions of time

$$\Delta c(x,t) = \sum_{j=1}^{N} A_j(t) F_j(x),$$

(A3)

where $A_j(t)$ are the amplitudes of the $N$ two-dimensional basis functions, $F_j(x)$. To proceed requires that ocean variability relative to a specified reference state be parameterized in a model with known statistical properties. After giving a broad description of sound speed variability in the North Pacific, the parameterization and the time-dependent reference sound speed field used here are described.

a. Summertime temperature variability in the northeast Pacific

Both the Levitus atlas (Levitus 1982) and XBT/CTD measurements taken during summer 1987 suggest that summertime warming in the experiment region is limited to a shallow surface layer and is largely geographically invariant. This description is valid because atmospheric forcing is weak during summer.

Sound speed profiles for the area were computed using the Levitus monthly average temperature profiles and Levitus summertime mean salinity profiles. The summertime changes in the range-averaged Levitus sound speed profiles with respect to the May profiles are shown in Fig. A1. Warming is mainly confined to the upper 50 m. The evolution of the sound speed profile can be represented by scaling a simple vertical function, which will be called a mixed-layer function. The Levitus atlas shows the sound speed at 30-m depth increases by 17–19 m sec$^{-1}$ from May to September, but the geographical variability of the change is only 1–2 m sec$^{-1}$ over 1000-km scales.

XBT data obtained at 40-km intervals on each leg of the triangle during deployment and recovery and

![Figure A1](image_url)

**Fig. A1.** Difference between the range-averaged, summertime monthly Levitus sound speed profiles and the May Levitus sound speed profiles (a), and difference between colocated recovery and deployment XBTs (b). Near-surface mixed-layer changes can be represented by scaling a simple function of depth.
Fig. A2. The a priori variance (solid), XBTO variance with respect to the time-dependent reference (dash), and subinertial variance determined by moored temperature sensors at 73, 173, 296, and 675-m depth (dot). The XBTO variance includes internal wave variability.

\[ C(z_1, z_2) = 4 \exp\left( \frac{(z_1 + z_2)/2}{350} \right) \times \exp\left( \frac{(z_1 - z_2)^2}{100(z_1 + z_2)} \right) (\text{m s}^{-1})^2, \]  

(A4)

where \( z = 0 \) at the surface and \( z \) is in meters (positive up). This analytic covariance function was chosen such that (1) the variance profile is roughly consistent with the variances determined from the XBTOs and moored temperature sensors (Fig. A2) and (ii) the vertical covariances are similar to, but smoother than, those computed from the XBTOs. Figure A3 shows the assumed rms sound speed perturbation and vertical correlation length as a function of depth, as well as the mixed-layer function and first four EOFs of the covariance. The first four EOFs account for 95% of the variance in (A4).

For each vertical function there are sine and cosine functions for each wavenumber plus the constant for zero wavenumber. The wavenumbers are \( k_n = 2\pi n / (L + 250) \) (rad km\(^{-1}\)), where \( n = 1, 2, \ldots, 6 \) and \( L \) is the range between moorings. Since there is little mesoscale variability, higher wavenumber Fourier components do not need to be included. Figure A3 gives the horizontal correlation function. With \( N_\nu \) vertical functions and \( N_H \) wavenumbers in the horizontal, the number of \( F_j(x) \) is \( N = N_\nu \times (N_H \times 2 + 1) \). Here \( N_\nu = 5 \) and \( N_H = 6 \), so \( N = 65 \). This inverse model ade-

XBTO profiles taken during summer 1987 show a thermocline that is similar to, but sharper than, that found in the Levitus atlas (Fig. A1). The XBTO data show an increasing mixed-layer amplitude as summer progresses.

Phenomenologically, the summertime upper-ocean sound speed field can be described as a geographically varying, time-independent sound speed field plus a time-dependent scaling of the mixed-layer function.

b. Ocean parameterization

The \( F_j(x) \) are assumed to be separable into a product of functions that depend only on depth and only on range, respectively (Howe et al. 1987). The vertical functions consist of a mixed-layer function and the EOFs of the vertical covariance matrix. A truncated Fourier series is chosen to represent the horizontal structure. While no horizontal variability is required to fit the travel time data, its inclusion in the ocean model is important to accurately assess the solution uncertainty.

Excluding the summer mixed-layer variability, the vertical covariance of the sound speed perturbations (relative to the reference state to be described next) is taken to be

Fig. A3. Vertical functions (a), depth dependent a priori rms sound speed (b), vertical correlation length (c), and horizontal covariance (d) used in the stochastic inverse. The mixed-layer function is the first vertical function, and is evident in the depth-dependent sound speed rms. The vertical correlation length is the approximate depth increment required for the correlation to fall by a factor of e. The horizontal covariance does not fall to zero because the zero wavenumber accounts for most of the variance.
quately fits the CTD/XBT data taken in May and September.

c. Reference ocean

A time-dependent reference sound speed field can be constructed from the Levitus atlas. However, this reference state is inadequate because of the large differences between Levitus and the ocean during summer 1987. The Levitus sound speed at 100–200-m depth is faster by 5–10 m s\(^{-1}\) (i.e., warmer by 1.5°–3°C) than the measured profiles (Fig. 5). Inversions relative to the Levitus ocean are nonlinear because of the great difference between the Levitus reference and the “true” ocean.

The Levitus summertime mean sound speed field is “corrected” in a simple time-dependent way using the XBT sound speed profiles. The “corrected” Levitus sound speed profiles are a time-dependent reference state adequate to linearize the inverse problem. The perturbations of the XBT data from the Levitus summertime mean are fit to the mixed-layer function, to account for the time-dependent mixed-layer evolution, and the first EOF of the a priori covariance matrix to account for the deeper bias in the Levitus profiles. Figure A4 shows that the amplitude of the mixed-layer function varies in a smooth way, while the amplitude of the first EOF is maintained for the time independent. The behavior of these amplitudes is expected to be expected from the phenomenological description of variability. Third-degree polynomials in yearday were fit to these two amplitudes (solid and dashed curves in Fig. A4). Our time-dependent ocean reference state consists of the Levitus summertime mean sound speed field corrected and made time dependent by the mixed-layer function and first EOF whose time-dependent amplitudes are given by their respective polynomials.

APPENDIX B

Conversion of Sound Speed to Temperature

The sound speed perturbation \( \Delta c(z) \) found by inverting the acoustic travel time data can be converted to a temperature perturbation \( \Delta T(z) \) by

\[
\Delta T = \int T_0 \frac{\partial T}{\partial c} dc, \quad (B1)
\]

where \( c_0(z) \) is a reference sound speed profile. The absolute temperature \( T(z) \) is then simply

\[
T(z) = T_0(z) + \Delta T(z), \quad (B2)
\]

where \( T_0(z) \) is the reference temperature profile corresponding to the reference sound speed profile. (The reference sound speed profile is normally computed from temperature and salinity data, so a reference temperature profile is readily available.) While salinity also affects sound speed, neglecting salinity perturbations introduces little error, unless the salinity perturbations are unusually large.

The reference profile used in this calculation is not critical, as the answer is not sensitive to the reference selected. The same reference used for the inverse calculation could be used. Alternatively, any reference profile close to the conditions at the time of the experiment could be used (with \( \Delta c(z) \) computed relative to the reference used for the conversion). For this experiment, the reference profiles for the conversion to temperature were constructed using the May CTD/XBT data.

A simple nine-term equation for sound speed (Mackenzie 1981) is used for these calculations:

\[
c(T, S, D) = 1448.96 + 4.591T - 5.304 \times 10^{-2}T^2 + 2.374 \times 10^{-4}T^3 + 1.340(S - 35) + 1.630 \times 10^{-2}D + 1.675 \times 10^{-2}D^2 - 1.025 \times 10^{-2}T(S - 35) - 7.139 \times 10^{-13}TD^3, \quad (B3)
\]

where \( T \) is temperature in degrees Celsius, \( S \) is the salinity in parts per thousand, and \( D \) is the absolute value of the depth in meters. This equation agrees with Del Grosso’s equation (Del Grosso 1974) to within 0.1 m sec\(^{-1}\) to 4000-m depth for the ocean conditions considered here. Using (B3),

\[
\frac{\partial c}{\partial T} = 4.59 - 0.106T + 7.12 \times 10^{-4}T^2 - 1.03 \times 10^{-2}(S - 35), \quad (B4)
\]

\[
\frac{\partial c}{\partial S} = 1.34 - 1.03 \times 10^{-2}T. \quad (B5)
\]

A slight depth dependence has been dropped in (B4). Note that \( \delta T/\delta c \), which is \( 1/(\partial c/\partial T) \), is shown as a

![Fig. A4. Amplitudes of the summer mixed-layer function (dot) and the first covariance EOF (×) from fits to 121 XBT data profiles with the geographically nearest Levitus summertime mean profile removed. The curves are polynomial fits to the amplitudes of the mixed layer (solid) and first EOF (dashed). The increasing intensity of the mixed layer is evident, as is the mainly time-independent bias of the Levitus sound speed.](image-url)
function of temperature in Fig. B1. Although $\partial T/\partial c$ is a function of temperature, not sound speed, the integral in (B1) can be accurately calculated using a series of integrals over small sound speed increments.

The salinity change from deployment to recovery from CTD data can be used to estimate the error incurred by ignoring salinity changes. Salinity changed by up to 0.2 psu in the mixed layer and less than 0.1 psu below. Neglecting these salinity changes gives an error in temperature of about 0.1°C in the mixed layer and less than 0.05°C below. The uncertainty of our inversion sound speed estimate is much larger than the error due to neglecting salinity changes.

REFERENCES


