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ALTIMERTIC AND IN-SITU OBSERVATIONS OF UPPER-OCEAN STRUCTURE AND HEAT CONTENT OFF THE U.S. WEST COAST DURING THE 1998 EL NINO EVENT

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1. INTRODUCTION

During the 1997/1998 El Nino event record warm surface waters were observed off the North American West Coast, which had a profound impact on coastal ecosystems, including fish populations and behavior. Although the development of these warmer waters was readily observed with satellite SST and altimeter measurements, the depth of the warmer coastal water was unknown, as were the physical mechanisms that generated its formation.

As part of the NOAA sponsored California Landfalling Jets Experiment (CALJET), extensive oceanic temperature profiles were taken off California during this El Nino event using Airborne Expendable Bathythermographs (AXBT's). The CALJET program was investigating El Nino associated winter storms that were bringing record precipitation amounts to the U.S. West Coast. The AXBT study was conceived of as an oceanographic component to CALJET that would improve our understanding not only of the El Nino-associated upper ocean structure, but also of the interactions between the warm coastal waters and landfalling storms.

Our analysis of the El Nino coastal event follows two paths. The first evaluates the vertical thermal structure of the upper ocean by comparing the mean AXBT profiles for each of the three observation days to the climatological upper-ocean temperature profile. The second path compares upper-ocean heat contents derived from the AXBT's with several different methods of heat content estimation using satellite altimetry. The satellite methods are then used to derive a 6-year time series of heat content for the same region, thereby placing the 1998 AXBT measurements in an historical context.

2. AXBT MEASUREMENTS

Over 220 AXBT's were dropped from the NOAA P3, covering a large area from approximately 119.5 – 134^{o} W longitude and from 31 – 41^{o} N latitude, and reaching as far as 1100 km offshore. The CALJET data were taken during the period 18 Jan – 24 March, 1998. Although AXBT data were taken on most CALJET flights as the flight plan permitted, the majority of the data were collected on three flights that were dedicated to taking AXBT data.

The three AXBT flights occurred on 20 January, 11 February, and 26 February, spanning a 5 week period. On each of these 3 flights a backward "E" pattern was flown (Fig. 1), with a southern boundary near Pt. Conception and a northern boundary near Cape Mendocino, with the closest near-shore data approximately 50 km from the coast and the furthest data approximately 600 km offshore. AXBT's were dropped approximately every 50 km along the flight path. Separation distances between flight legs were on the order of 150 km, giving an average horizontal resolution of the data of approximately 100 km. Thus the data were taken with the intent of describing the large-scale offshore oceanic structure, and do not well resolve individual eddies associated with the California Current. The AXBT's had a constant fall speed of 1.52 ms^{-1}, and were sampled every 1.0 s, providing 230 measurements to a depth of 350 m. The nominal accuracy of each AXBT measurement was 0.18 ^{O}C. For the three dates, there were 57, 41, and 40 successful AXBT profiles.

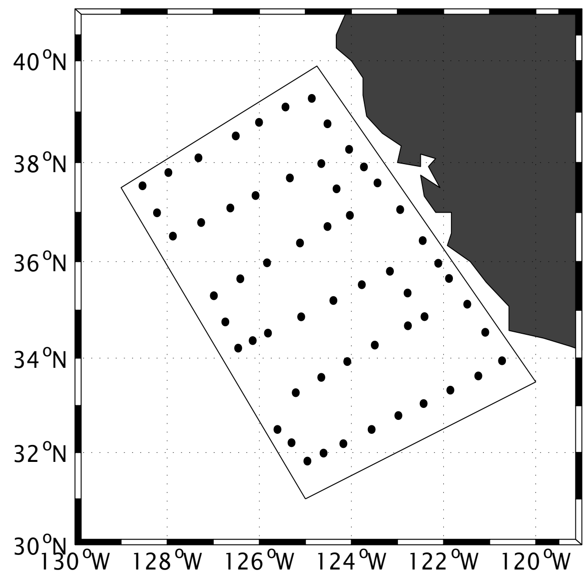

Fig. 1. Locations for AXBT profiles taken on 20 Jan 1998 off central California. A similar pattern was flown on the other two analysis days.

3. MEAN VERTICAL PROFILES

Mean vertical AXBT profiles for each of the three flights were calculated by averaging all of the AXBT measurements made at each depth for that flight. These mean profiles were then compared to the World Ocean Atlas 1998 (WOA) climatology. The WOA 1998 climatology, which is heavily weighted towards the last 10 years of observations, consists of monthly mean profiles at a grid resolution of 1 degree, with 13 levels between the surface and 350 m depth. For each month there were 40 WOA 1998 profiles within the AXBT region. These 40 profiles were averaged, and then the monthly mean profiles were interpolated in time to the dates of each of the three AXBT flights.

Figure 2 shows the comparison of the three mean AXBT profiles with the three mean climatological profiles, using the observed values at each of the 13 levels of the WOA 1998 climatology. In each of the three profile intercomparisons, the AXBT profiles are seen to be warmer than the climatology, with the AXBT profiles on average 1.15 ^{O}C warmer at the surface. This temperature anomaly, however, is present almost exclusively in the upper 125m of the profile. Using a definition of the ocean mixed-

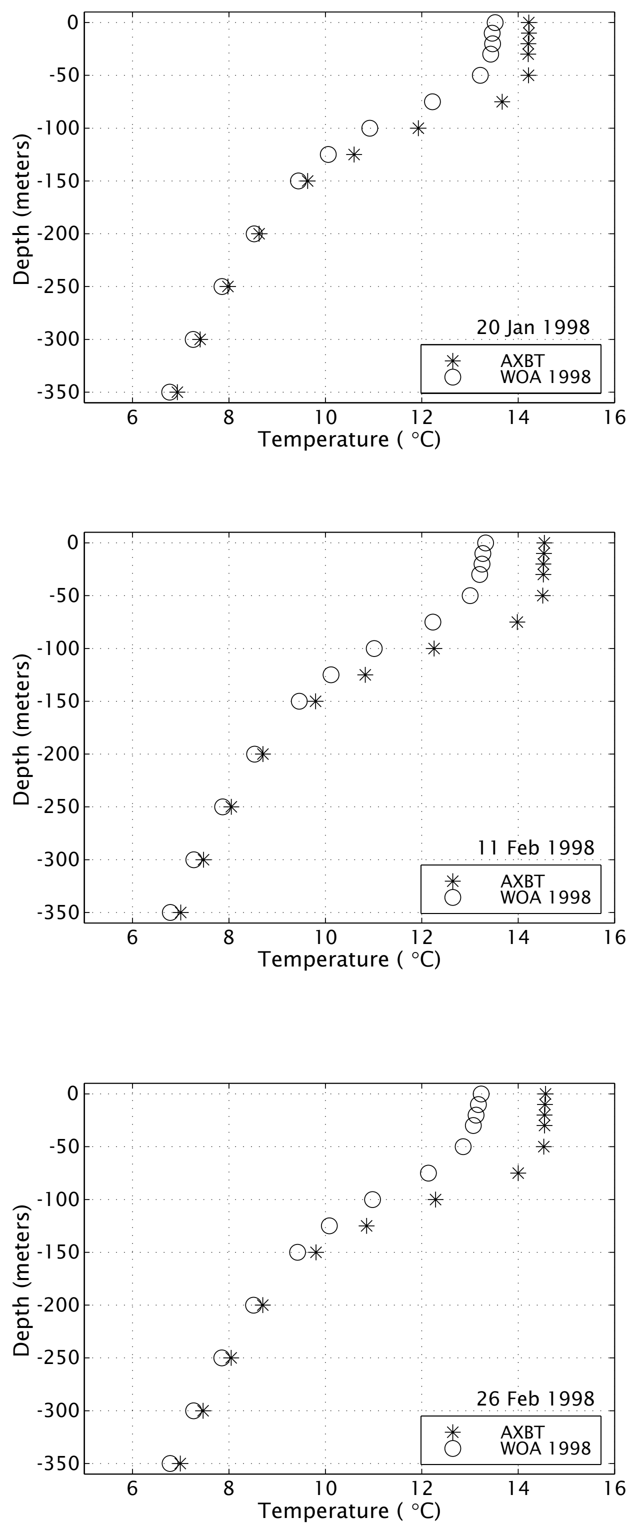

Fig. 2. Mean AXBT and climatological temperature profiles for each of the three analysis days.

layer depth (MLD) as the depth at which the profile is 0.5 ^{O}C cooler than the surface temperature, the MLD is approximately 25m greater for the mean AXBT profiles than for the climatology. Examination of individual AXBT profiles shows several for each flight that have mixed layer depths reaching 150m, and that the temperatures at this depth are more than 4 ^{O}C warmer than the climatological temperature profiles. Thus, it appears likely that most of the temperature anomaly that exists between 75 and 125m is still associated with warm water within the AXBT mixed layer. At depths below the level of mixed-layer influence (175-350 m) the AXBT temperatures agree more closely with the climatology, but still remain 0.1-0.2 ^{O}C warmer.

4. SATELLITE ALTIMETRY OBSERVATIONS

Altimeter measurements of sea surface height (SSH) from the TOPEX/Poseidon and ERS satellites are used in this study, spanning the time period from January, 1993 to present. The standard corrections applied to the TOPEX data include ionosphere, wet and dry troposphere, sea-state bias, inverted barometer, solid Earth tide, and pole tide (Fu et al., 1994) all of which are available on the T/P Geophysical Data Records. An improved tide correction, which is more accurate in both deep and shallow (Tierney, 1999), has also been applied. Standard corrections were also applied to the ERS data to make it consistent with the TOPEX processing.

Three altimeter-derived data sets were used for comparison with the AXBT measurements. The first altimetric data set was based on TOPEX data alone. The second altimetric data set was obtained by "blending" TOPEX and ERS-2 altimeter data with an emphasis on retaining the longer wavelength oceanographic signals accurately measured by TOPEX, and the mesoscale signal sampled by both the TOPEX and ERS-2 satellites (blended TOPEX/ERS2). The third data set is an operational data set that is produced by heavily filtering, combining TOPEX with ERS-1 and ERS-2 altimetry data with an emphasis on retaining only mesoscale structure (mesoscale TOPEX/ERS) (Lillibridge, 1997). Along-track 10 day repeat TOPEX data were used on a 1 deg-10d space-time grid. For the blended TOPEX/ERS product, the 35 day repeat cycle ERS data was combined with the TOPEX data and interpolated to a 1/4 degree, 7-day space-time grid, while for the mesoscale product the data were available on a 1/4 degree, 3-day space-time grid.

No in situ measurements of salinity were made during the aerial surveys. Since climatology-based salinity corrections do not significantly improve altimetry based heat content estimates, none were applied (Sato, 2000).

For each of the three sets of altimetry-based SSH's, height anomalies (SSHA's) were calculated relative to the 1993-1999 mean. SSHA's were then used to compute the heat content anomalies (HCA's) in the upper 350 meters of the water column. These altimetry-based heat content estimates were made using a linear relationship between changes in the surface height anomaly and the underlying heat content variations using the World Ocean Atlas (WOA 1998) climatology (Hendricks, 1996; Chambers, 1997). The AXBT heat content was computed directly from the temperature profiles, and AXBT HCA's were calculated relative to the observed climatological annual value (WOA 1998) interpolated to each AXBT location.

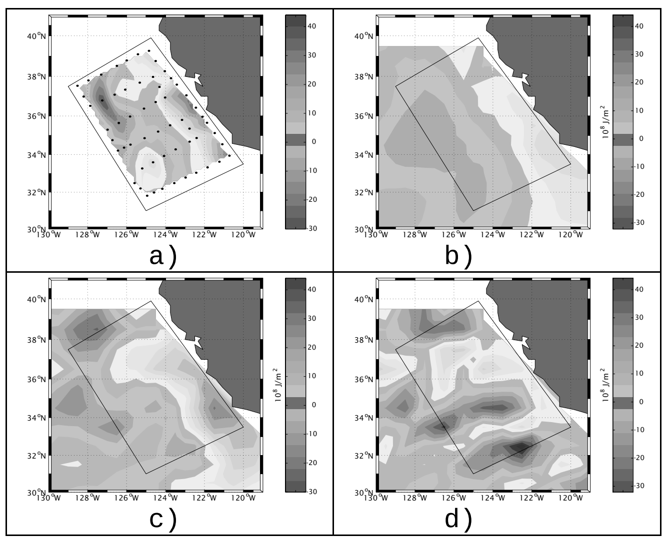

Fig. 3. Heat content anomaly maps for 20 Jan 1998. (a) AXBT, (b) TOPEX, (c) blended TOPEX/ERS, and (d) mesoscale TOPEX/ERS.

Figures 3-5 show maps of HCA estimates for each analysis date, comparing the altimetry-based estimates with the AXBT heat content anomalies for the upper 350 meters of the ocean. Here the altimetery-derived HCA's were interpolated in time to each of the three AXBT dates. Visual inspection of the heat content anomaly maps reveals the very good correlation between the blended TOEPX/ERS and AXBT heat content anomalies.

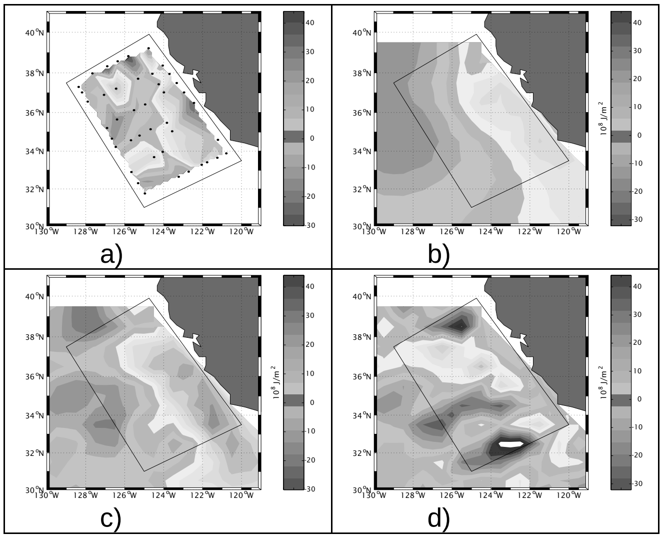

Fig. 4. Heat content anomaly maps for 11 Feb 1998. (a) AXBT, (b) TOPEX, (c) blended TOPEX/ERS, and (d) mesoscale TOPEX/ERS.

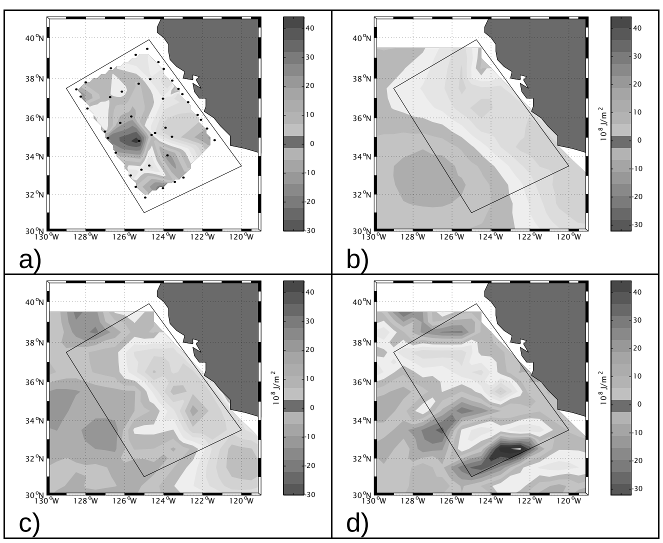

Fig. 5. Heat content anomaly maps for 26 Feb 1998. (a) AXBT, (b) TOPEX, (c) blended TOPEX/ERS, and (d) mesoscale TOPEX/ERS.

For statistical comparison, the altimetry HCA's were then also were interpolated to the geographic locations of the AXBT data. Scatter plots of each of the 3 altimeter data sets compared to the AXBT data are shown in Figure 6. The best agreement is found with the blended TOEPX/ERS product (Fig. 6b), with a correlation of 0.72, inferring that 51% of the variance in the AXBT heat content is represented by the blended TOPEX/ERS heat content estimate. In contrast, the correlation coefficient for the TOPEX and mesoscale products are 0.56 and 0.35. We note the positive bias to the heat content anomalies in Fig. 6a,b associated with the El Nino event.

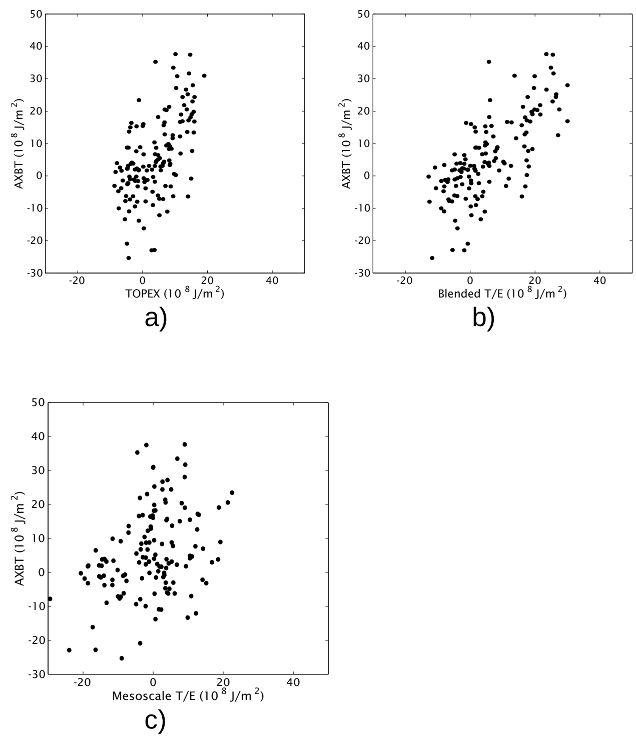

Table 1 shows the correlation coefficients for the three analysis dates taken separately. In each case, the blended TOPEX/ERS heat content estimate has the best correlation to the AXBT heat content, highlighting the importance of resolving the mesoscale circulation when estimating heat content.

Table 1. Correlation coefficients of altimeter and AXBT heat content anomalies, for TOPEX, blended TOPEX/ERS and mesoscale TOPEX/ERS products.

	TOPEX	BTE	MTE
20 Jan	0.77	0.78	0.40
11 Feb	0.58	0.69	0.37
26 Feb	0.52	0.68	0.29
All	0.56	0.72	0.35

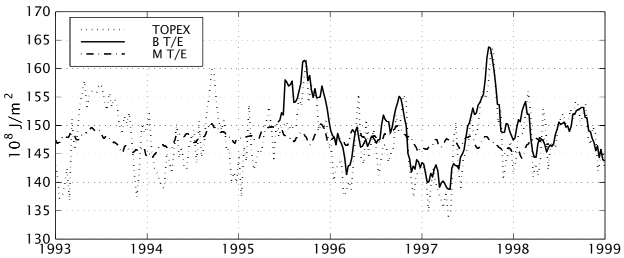

Fig. 7. Time series of the spatial mean heat content in the analysis region for the three altimeter products for the period 1993-1999.

The spatial mean heat content in the region over six years, 1993 through 1998, is shown in Figure 7. The TOPEX heat content varies the most, a result of under-sampling mesoscale features. The TOPEX and the blended TOPEX/ERS series capture seasonal changes well, including the 1997-1998 El Nino. The greatest heat contents are observed in September, 1997. In Figure 8, the altimetry-based mean heat content is shown for the span of time where all three altimetry data sets are available.

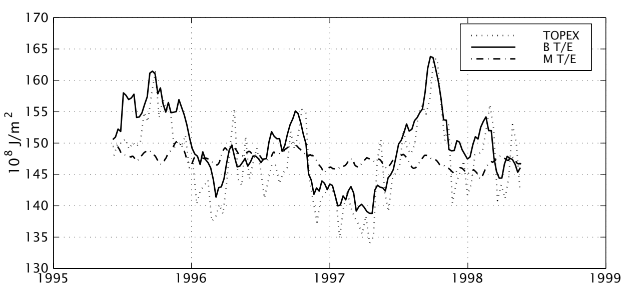

Fig. 8. Time series of the spatial mean heat content of the analysis region for three altimeter products, for the 2.5 year span in which all three were available.

Figure 9 is a zoomed-in view of the mean heat content time series, with the addition of the AXBT mean heat content for the three analysis dates. The AXBT points are shown with error bars, which form a 95% confidence interval about the mean heat content for each date. The mean heat content for the AXBT and blended TOPEX/ERS data correspond favorably.

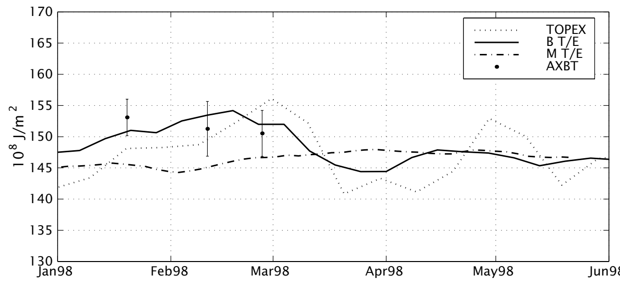

Fig. 9. Time series of the spatial mean heat content for the analysis region for 1998. The error bars on the AXBT points form the 95% confidence interval about the mean heat content.

5. Summary and Discussion

During the 1997/1998 El Nino event, record breaking near surface ocean temperatures were recorded off the U.S West Coast. Although the peak temperature anomalies occurred during the summer and autumn of 1997, by Jan-Feb 1998 warmer temperatures were still present, as seen by the mean AXBT profiles and the satellite-derived HCA's. The mean AXBT profiles demonstrate that the greatest temperature anomaly (larger than 1.1 ^{O}C) existed in the upper 125m, and was due to warmer temperatures within the mixed layer. Below the mixed layer the temperature profiles were still warmer than climatology, but with temperature anomalies an order of magnitude smaller than within the mixed layer. Mixed layer depths observed with the AXBT profiles were approximately 25m greater than the climatology.

The confinement of the strong temperature anomaly to the mixed-layer suggests that a likely mechanism for the warmer coastal SST's observed off California during the 1997/1998 El Nino event was local air-sea interaction. During a normal year strong low-level northwesterly winds are present along the coast during the summer months, driving upwelling that cools the temperature of the near-surface water and reduces the ocean mixed layer depth. During an El Nino event the summertime northwesterly winds relax, interrupting the upwelling process, leading to warmer surface waters and deeper mixed layers.

Altimetry-based heat content estimates were computed using TOPEX and ERS satellite data. The heat content estimates were computed for the upper 350 meters of ocean and were compared with the in situ AXBT data. The altimetry-based heat content estimates were well correlated with the AXBT data, and in particular the blended TOPEX/ERS data performed the best. This is due to the fact that the blended product contains not only the high accuracy SSH's provided by the TOPEX satellite, but also includes higher spatial resolution mesoscale data provided by the ERS satellite.

Time series of upper-ocean heat content provided by the satellite altimetry data for the AXBT analysis region indicates that the greatest values for the 1993-1999 period occurred in September, 1997.

6. References

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