# Importance of salinity measurements in the heat storage estimation from TOPEX/Poseidon

Olga T. Sato, Paulo S. Polito and W. Timothy Liu

Jet Propulsion Laboratory,California Institute of Technology, Pasadena, California

**Abstract.**
Sea surface height anomaly signals from satellite altimeter data are used to estimate heat storage. Since variability in sea surface height is mostly due to expansion and contraction of the water column it can be correlated with variations in the heat and salt content. Therefore, estimation of heat storage from altimeter data requires corrections for the haline effect. Three sites with a nearly continuous time series of temperature and salinity profiles simultaneous with TOPEX/Poseidon data are studied: HOT, CalCOFI and Hydrostation "S". Haline corrections based on *in situ* and climatological salinity measurements are contrasted. For the studied regions, the haline corrections based on climatology provide equivalent or worse results than not applying a correction at all. The use of *in situ* salinity estimates decreased the differences between the heat storage estimates (up to $14 \times 10^7 \, J\, m^{-2}$ ) and significantly improved their correlation (up to 0.19).

## Introduction

The oceanic heat storage (HS) rate together with the surface heat flux and the divergence of oceanic heat transport are essential to understand the oceanic heat balance. Historically, HS was estimated by integrating the temperature profiles from hydrographic cruises or buoy data and therefore was limited by data availability. The accumulation of *in situ* data enabled climatological maps which provide a gain in spatial coverage at the expense of resolution. The use of satellite altimeter data makes it possible to continuously monitor the oceanic HS in a global scale with unprecedented resolution in both space and time.

Heat storage has been derived from altimeter data through the correlation between thermosteric variations in the upper layer and variations in the sea surface height [*White and Tai*, 1995; *Chambers et al.*, 1997; *Wang and Koblinsky*, 1997; *Chambers et al.*, 1998; *Polito et al.*, 1999]. The comparison between *in situ* and satellite derived heat storage estimates shows discrepancies that can be related to haline effects. These effects are relatively strong in coastal regions, decreasing towards the open ocean [*Tabata et al.*, 1986]. In this study, we demonstrate that (a) a haline height correction significantly improves the satellite derived heat storage anomaly signal and (b) this correction should be based on *in situ* salinity measurements rather than climatological estimates.

## Method

The HS of an observed temperature profile is given by:

$$HS = \rho C_p \int_{-h}^{0} T(z) dz, \tag{1}$$

where $\rho$ is the density of seawater, $C_p$ is the specific heat at constant pressure, $T(z)$ is the observed temperature profile, and $h$ is the depth to which the temperature profile is integrated. HS is expressed in units of $J.m^{-2}$.

The heat storage anomaly (HS$'$) can be estimated from the filtered height anomaly ($\eta_s$) according to a linear relation [*Chambers et al.*, 1997]:

$$HS' = \frac{\rho C_p}{\alpha} (\eta_s + \eta_h). \tag{2}$$

where $\alpha$ is the thermal expansion coefficient. In this study, the effects of the haline contraction ($\eta_h$) on the sea height anomaly are investigated.

Mean values of $\rho$ and $C_p$, averaged from the surface to a depth $h$, are calculated from climatological maps of the World Ocean Atlas 1994 (WOA94) [*Levitus and Boyer*, 1994] for a $1^\circ \times 1^\circ$ grid. $\alpha$ is considered constant at each grid point and it is estimated by averaging vertically the climatological $\alpha$ profile weighted by the layer thickness and temperature anomaly between the surface to the depth $h$.

$\eta_h$ is estimated by vertically integrating the product of the haline contraction coefficient, $\bar{\beta}$, and the salinity anomaly (in relation to the annual mean) profiles:

$$\eta_h = \int_{-h}^{0} \bar{\beta} \Delta S dz. \quad (3)$$

The TOPEX/Poseidon (T/P) sea surface height anomaly is decomposed using 2D finite impulse response filtering [*Polito and Cornillon*, 1997; *Polito et al.*, 1999]. This method uses previous knowledge of the spectral composition of the signal (approximate period and zonal wavelength) to separate it into additive components:

$$\eta_s = \eta_t + \eta_w + \eta_r. \quad (4)$$

$\eta_t$ is the basin-wide non-propagating variability, mostly due to seasonal heating and cooling and advection by the broad oceanic currents. $\eta_w$ is the large to meso-scale westward propagating signal composed mainly of first-mode baroclinic Rossby waves. $\eta_r$ includes a variety of signals among them equatorial Kelvin waves and meso-scale eddy variability. The small-scale, non-propagating signals are filtered out.

## Data

Three sites were selected for this study (Figure 1): the hydrographic sections from the California Cooperative Oceanic Fisheries Investigations (CalCOFI) cruises at the California coast; the hydrostation ALOHA from the Hawaii Ocean Time series Program (HOT) in Hawaii [*Karl and Lukas*, 1996]; and the hydrographic time series in Bermuda sometimes referred to as the Panulirus Station (Hydrostation "S") in the western Atlantic [*Schroeder and Stommel*, 1969]. Relatively long time series of *in situ* temperature and salinity measurements are available concurrent with T/P data in these three locations.

The general procedure consists of linearly interpolating individual temperature and salinity profiles in the vertical. Stations with gaps larger than one standard depth were discarded. Missing surface data (above 25 m) were extrapolated by repeating the first measured value upwards assuming the presence of a mixed layer. Missing data in the deepest part of the profile (below the main thermocline) were extrapolated using the local mean gradient.

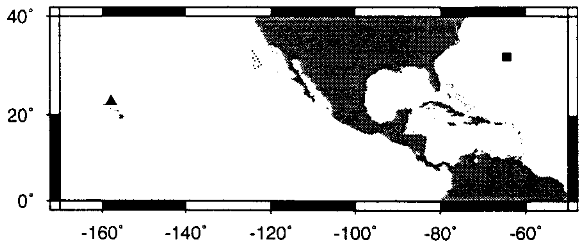


**Figure 1.** Location of the *in situ* data: triangle represents the HOT station, square the Hydrostation "S" and dots the CalCOFI stations.

The *in situ* HS is calculated integrating the temperature profiles from the surface down to a depth below the main thermocline (Equation 1). For each time series the annual mean is computed using the maximum number of complete years of data from which HS′ is estimated by removing this long-term mean.

The heat storage anomaly from T/P is estimated using Equation 2. To evaluate the role of $\eta_h$ in determining HS′, three cases are studied using: (*i*) no salinity; (*ii*) climatological salinity (WOA94, [*Levitus and Boyer*, 1994]); and (*iii*) *in situ* salinity.

## Results

The comparison of the results are based on the root mean square (rms) differences and correlation between the *in situ* and satellite derived HS′ for the three selected sites.

The time series of the Hydrostation "S" spans from 1993 to 1997 (Figure 2) and has on average one measurement every 15 days. For comparison to T/P, HS′ time series from both sources were interpolated to one month resolution. HS′ using *in situ* salinity are in better agreement with the T/P estimates than those obtained using climatological salinities. Both the rms difference and correlation improve for the HS′ estimates (Table 1).

At this location, when the salinity is not used, the differences and correlations are the same as when the climatological salinity is used. The dominant signal in the heat storage spectrum apparently shifts from semi-annual before 1995 to annual after. The results are in better agreement after 1995. Between 1995 and 1997 the rms differences for the *in situ* (climatology) are significantly lower compared to the whole time series, 64 (70) $\times 10^7\, J m^{-2}$ , and the correlation is much higher,

**Table 1.** Summary of the rms differences (in $10^7 J\,m^{-2}$) and correlations between the *in situ* and T/P derived heat storage anomaly with (climatological/*in situ*) or without salinity corrections.

| Source | No sal. | | WOA94 | | *in situ* | |
|---|---|---|---|---|---|---|
| | rms | corr. | rms | corr. | rms | corr. |
| Hyd. "S" | 69 | .75 | 67 | .75 | 61 | .82 |
| HOT | 65 | .63 | 71 | .58 | 57 | .73 |
| CalCOFI | 63 | .48 | 64 | .48 | 53 | .67 |

0.83 (0.76). The location of Hydrostation "S" coincides with a T/P cross-over latitude where the zonal spacing between samples is maximum. This distance is approximately twice the wavelength of the semi-annual Rossby waves. Therefore, T/P cannot properly resolve the semi-annual signal which results in spatial aliasing and degradation of the correlation.

The time series at HOT spans from 1993 to 1999, and has a sampling period of 40 days (Figure 3). Both time series were interpolated to monthly resolution for comparison. Similarly to the previous case, the results when including *in situ* salinity are significantly better than using the climatology. In fact, when the salinity is not used, the rms and the correlation ($65\times10^7 J\,m^{-2}$ and 0.63) are better than using climatology ($71\times10^7 J\,m^{-2}$ and 0.58).

The CalCOFI cruises are composed of an array of stations near the California coast. Satellite measurements of the sea surface height degrade near the coast due, to a large extent, to local tides that are inadequately modeled in the T/P data and spread westward by the filter. Thus, correlations decrease and rms differences increase towards the coast. A strong gradient in

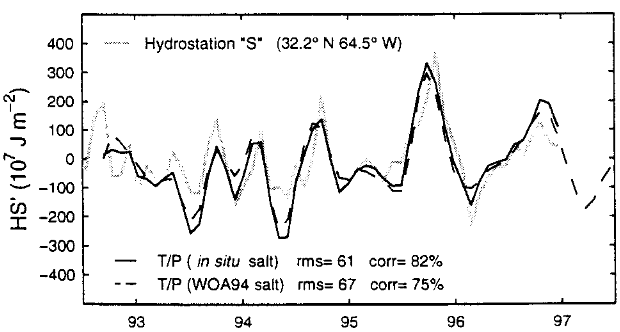


**Figure 2.** Comparison of the heat storage anomaly between Hydrostation "S" (gray) and T/P (black). T/P heat storage includes climatological (WOA94, dash-dotted) and *in situ* salinity (continuous).

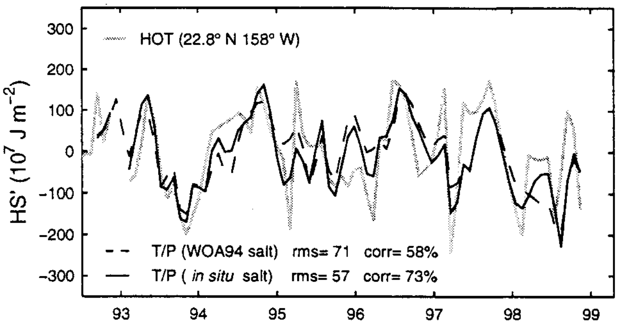


**Figure 3.** Comparison of the heat storage anomaly between HOT and T/P, similar to Figure 2.

both rms and correlation is located in the approximate SE-NW diagonal of Figure 4. Therefore, only eleven stations west of this gradient were considered. Station 90/110 located at 30.75°N, 123.33°W gave results which were de-correlated with all stations in its vicinity and was excluded from the analysis. The CalCOFI stations have lower temporal resolution compared to the other sites, with one sample every 90 days. The T/P time series was interpolated to match this resolution.

In general, away from the influence of the coast the results favor the use of *in situ* salinity. As shown in the two stations in Figure 5 the T/P estimates including salinity effects from *in situ* measurements improved significantly. As observed for other regions the inclusion of a climatological salinity is detrimental to the results.

## Conclusions

Time series of temperature and salinity measurements from three hydrographic sites were used in this study to evaluate the importance of haline effects in the determination of the heat storage anomaly from sea surface height anomaly. In all locations (Hydrostation "S", HOT, and CalCOFI) the haline effects were estimated for three cases: absent, climatological (WOA94), and *in situ* salinity profiles. The results based on climatological salinities are equal or worse than not including haline effects at all. The use of *in situ* salinity estimates significantly augmented the correlations and decreased the rms differences in the HS′ estimates.

For the Hydrostation "S", HS′ decreased from 67 to $61\times10^7 J\,m^{-2}$ and the correlation increased from 0.75 to 0.82 when using *in situ* instead of climatological salinity. Better results were obtained from the other sites. On HOT, the rms difference decreased by $14\times10^7 J\,m^{-2}$ and the correlation improved 0.15

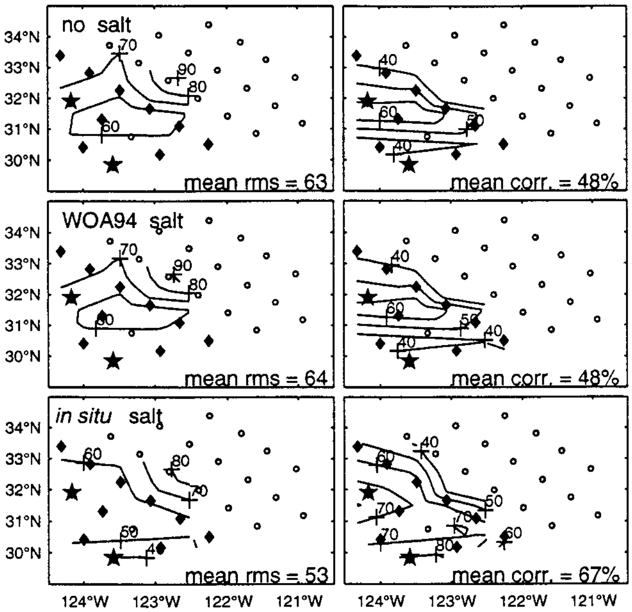


**Figure 4.** Rms differences (left) and correlation coefficients (right) between CalCOFI and T/P estimates of heat storage anomaly in $10^7 J\,m^{-2}$. Diamonds (dots) mark the location of the stations used (discarded) in this study. Stars indicate the stations used in Figure 5.

while on CalCOFI, the average rms difference decreased by $11 \times 10^7 J\,m^{-2}$ and correlations increased by 0.19. These results stress the importance of having salinity measurements concurrent with satellite altimeter measurements to study sub-surface processes. Although *in situ* salinity measurements are sparse the lack of a relatively small haline correction does not preclude the use of altimeter data for oceanic heat storage estimation.

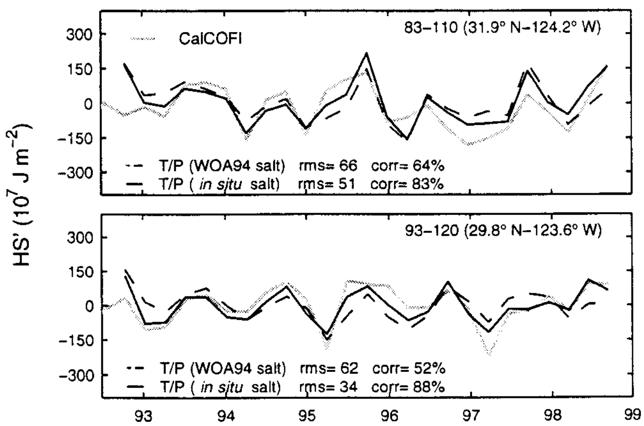


**Figure 5.** Comparison of the heat storage anomaly between CalCOFI and T/P at selected stations, similar to Figure 2.

**Acknowledgments.** This study was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA). The study is jointly supported by the Physical Oceanography and Earth Observing System Interdisciplinary Sciences Programs of NASA. The authors wish to express their gratitude to the reviewers whose comments and suggestions were of immense help.

## References

Chambers, D. P., B. D. Tapley, and R. H. Stewart, Long-period ocean heat storage rates and basin-scale heat fluxes from TOPEX, *J. Geophys. Res.*, *102(C5)*, 10,525–10,533, 1997.

Chambers, D. P., B. D. Tapley, and R. H. Stewart, Measuring heat storage changes in the equatorial Pacific: A comparison between TOPEX altimetry and tropical atmosphere-ocean buoys, *J. Geophys. Res.*, *103(C9)*, 18,591–18,597, 1998.

Karl, D. M., and R. Lukas, The Hawaii Ocean Time-series (HOT) Program: Background, rationale and field implementation, *Deep Sea Research II*, *43*, 129–156, 1996.

Levitus, S., and T. P. Boyer, World ocean atlas 1994, *Tech. Rep. Vol. 4*, National Oceanographic Data Center, Ocean Climate Laboratory, 1994, 117 pp.

Polito, P. S., and P. Cornillon, Long baroclinic Rossby waves detected by TOPEX/POSEIDON, *J. Geophys. Res.*, *102*, 3215–3235, 1997.

Polito, P. S., O. Sato, and W. T. Liu, Characterization of the heat storage variability from TOPEX/POSEIDON at four oceanographic sites, *J. Geophys. Res.*, 1999.

Schroeder, E., and H. Stommel, How representative is the series of Panulirus stations of monthly mean conditions off Bermuda?, *Prog. Oceanogr.*, *5*, 31–40, 1969.

Tabata, S., B. Thomas, and D. Ramsden, Annual and interannual variability of steric sea level along line P in the northeast Pacific ocean, *Journal of Physical Oceanography*, *16*, 1378–1398, 1986.

Wang, L., and C. Koblinsky, Can the Topex/Poseidon altimetry data be used to estimate air-sea heat flux in the North Atlantic?, *Geophysical Research Letters*, *24(2)*, 139–142, 1997.

White, W. B., and C. K. Tai, Inferring interannual changes in global upper ocean heat storage from TOPEX altimetry, *J. Geophys. Res.*, *100*, 24,943–24,954, 1995.

O. T. Sato, P. S. Polito and W. Timothy Liu, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., MS 300-323, Pasadena CA 91109. (e-mail: sato@pacific.jpl.nasa.gov; polito@pacific.jpl.nasa.gov; liu@pacific.jpl.nasa.gov)