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:

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

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 ($\eta_h$) according to a linear relation [Chambers et al., 1997]:

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

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° × 1° grid. α is considered constant at each grid point and it is estimated by averaging vertically the climatological α profile weighted by the layer thickness and temperature anomaly between the surface to the depth h.

\[ \eta_h = \int_{-h}^{0} \beta \Delta S dz. \]  

(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:

\[ \eta_s = \eta_w + \eta_e. \]  

(4)

\( \eta_s \) 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. \( \eta_e \) 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 [Schoeder 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

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

the main thermocline) were extrapolated using the local mean gradient.

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 \( \eta_s \) 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, \( 64 \times 10^7 \ J m^{-2} \), 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.

<table>
<thead>
<tr>
<th>Source</th>
<th>No sal.</th>
<th>WOA94</th>
<th>in situ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>rms</td>
<td>corr.</td>
<td>rms</td>
</tr>
<tr>
<td>Hyd. &quot;S&quot;</td>
<td>69</td>
<td>.75</td>
<td>67</td>
</tr>
<tr>
<td>HOT</td>
<td>65</td>
<td>.63</td>
<td>71</td>
</tr>
<tr>
<td>CalCOFI</td>
<td>63</td>
<td>.48</td>
<td>64</td>
</tr>
</tbody>
</table>

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 ($65 \times 10^7 J m^{-2}$ and 0.63) are better than using climatology ($71 \times 10^7 J m^{-2}$ 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

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 $61 \times 10^7 J m^{-2}$ 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 $14 \times 10^7 J m^{-2}$ and the correlation improved 0.15
while on CalCOFI, the average rms difference decreased by $11 \times 10^7 \text{J m}^{-2}$ 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.

**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**


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)