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

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Abstract. Sea surface height anomalies 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, when compared to in situ estimates, 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 17×10^7 J m^{-2}) and significantly improved their correlation (up to 0.18).

Introduction

The oceanic heat budget is a balance of heat storage (HS) rate, heat flux at the air–sea interface, and horizontal divergence of oceanic heat flux. Historically, HS was obtained from the integral of temperature profiles from limited hydrographic stations or buoy data. 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.

HS has been derived from altimeter data through the relation 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; *Polito et al.*, 2000]. The comparison between in situ and satellite derived HS shows discrepancies that can be related to haline effects. These effects are relatively strong in coastal regions, decreasing toward the open ocean [*Tabata et al.*, 1986]. In this study, we demonstrate that a haline height correction significantly improves the satellite derived HS and that this correction should be based on in situ rather than climatological estimates.

Method

The HS of an observed temperature profile is

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

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

The heat storage anomaly (HS$'$) is estimated from the filtered height anomaly (η) according to the linear relation [*Chambers et al.*, 1997]

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

where α is the thermal expansion coefficient and η_h the height correction for the haline effect.

The product $\rho C_p(x, y, t)$, a function of longitude, latitude and time, is derived from climatological maps of the World Ocean Atlas 1994 (WOA94) [*Levitus and Boyer*, 1994] for a 1°×1° grid and is averaged from the surface to a depth h. $\alpha(x, y, t)$ is estimated by averaging from the surface to a depth h the climatological α profile weighted by layer thickness and temperature anomaly.

$\eta_h(x, y, t)$ is estimated by the integral of the product of the climatological haline contraction coefficient, β, and the salinity anomaly (residual after subtracting the annual mean) profiles from the surface to a depth h

$$\eta_h = \int_{-h}^{0} \beta \Delta S dz. \tag{3}$$

The original TOPEX/POSEIDON (T/P) sea surface height anomaly (η_o) is decomposed using 2D finite impulse response filters [*Polito and Cornillon*, 1997; *Polito et al.*, 2000]. This method uses previous knowledge of the spectral composition of the signal (approximate period and wavelength) to separate it into additive components:

$$\eta_o = \eta_t + \eta_w + \eta_r = \eta + \eta_r. \tag{4}$$

η_t is the basin–wide variability, mostly due to seasonality and advection. η_w is the meso to large–scale propagating sig-

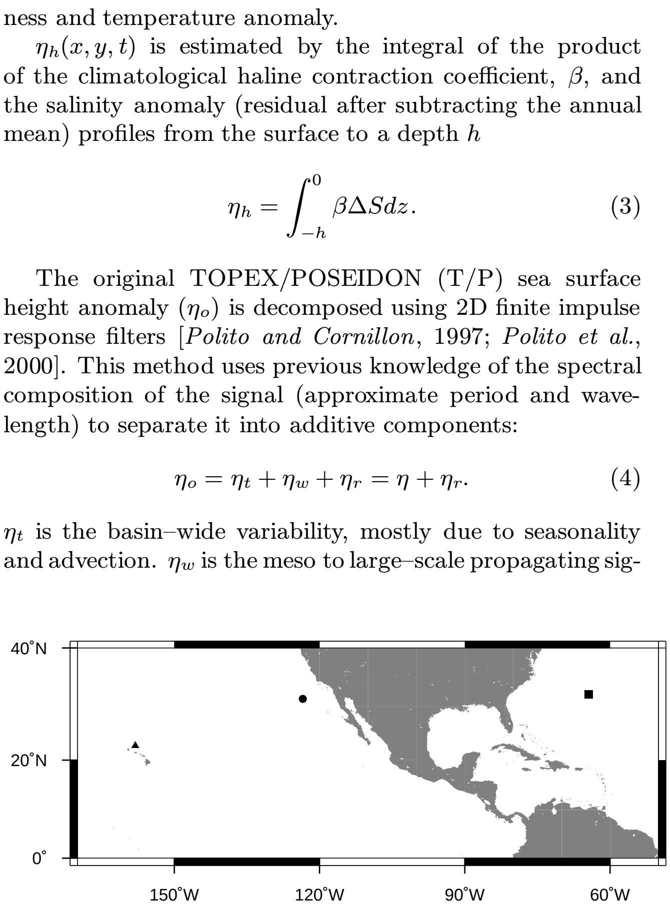

Figure 1. Location of the in situ data: triangle represents the HOT station, square the HyS, and circle the CalCOFI area.

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Table 1. Rms difference (in $10^7 J\,m^{-2}$) and correlation between in situ and T/P derived HS′ with (climatological/in situ) or without haline correction.

Source	No sal.		WOA94		in situ	
	rms	corr.	rms	corr.	rms	corr.
HyS	71	.77	69	.76	64	.86
HOT	65	.63	73	.57	56	.75
CalCOFI	67	.49	68	.49	56	.67

nal composed mainly of baroclinic Rossby, Kelvin and instability waves. η_r is the small to meso–scale non–propagating eddy variability.

Data

The three selected sites are the sections from the California Cooperative Oceanic Fisheries Investigations (CalCOFI) cruises [*Lynn and Simpson*, 1987], the station ALOHA from the Hawaii Ocean Time series Program (HOT) [*Karl and Lukas*, 1996], and the station "S" in Bermuda (HyS) [*Schroeder and Stommel*, 1969] (Figure 1). Relatively long time series of temperature and salinity measurements are available concurrent with T/P data in these 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 upward assuming that the data were within the mixed layer. Missing data in the deepest part of the profile (below the main thermocline) were extrapolated using the local mean gradient.

The integral in Equation 1 is calculated to a depth h below the main thermocline. For each time series the long–term mean is computed with the maximum number of complete years of data. The in situ HS′ is estimated by removing this mean. The T/P HS′ comes from Equation 2. To evaluate the role of η_h in determining the T/P HS′, three cases are studied: no salinity, climatological (WOA94), and in situ salinity.

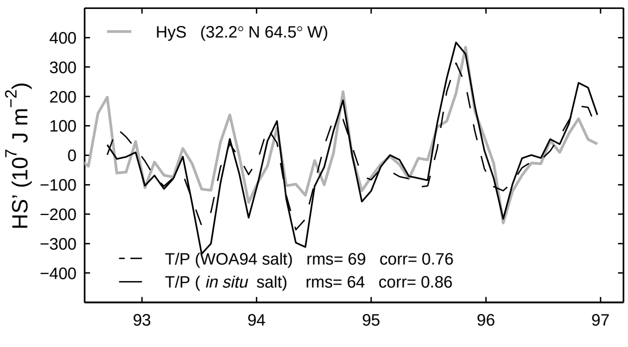

Figure 2. Comparison of the HS′ between HyS (gray) and T/P with climatological (dashed) and in situ (solid) haline correction.

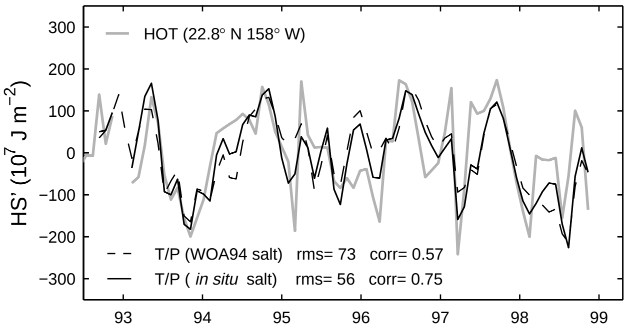

Figure 3. Same as Figure 2 but at HOT.

Results

The comparison of results is based on the root mean square (rms) difference and correlation between the in situ and T/P HS′ for the three sites (Table 1).

The portion of the HyS time series used in this study spans from 1993 to 1997 (Figure 2) and has on average one measurement every 15 days. The HS′ time series from both sources were interpolated to one month resolution. The T/P HS′ are in better agreement (lower rms difference and higher correlation) with in situ HS′ when the haline correction is based on in situ rather than climatological salinity. When the salinity is not used, the rms difference and correlation are about the same as when the climatological salinity is used.

Results at HyS are in better agreement after 1995 as the dominant signal in the heat storage spectrum shifts from semiannual to annual [*Polito et al.*, 2000]. Lower rms difference and higher correlation (52×10^7 J m^{-2} and 0.90) are obtained for the 1995–97 period compared to 1993–95

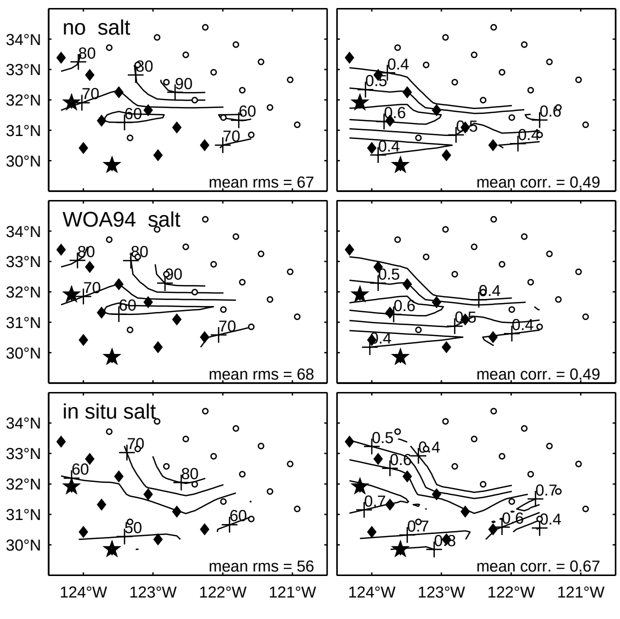

Figure 4. Rms difference (left) and correlation coefficient between CalCOFI and T/P estimates of HS′ in $10^7 J\,m^{-2}$. Diamonds (circles) mark the stations used (discarded). Stars indicate the stations used in Figure 5.

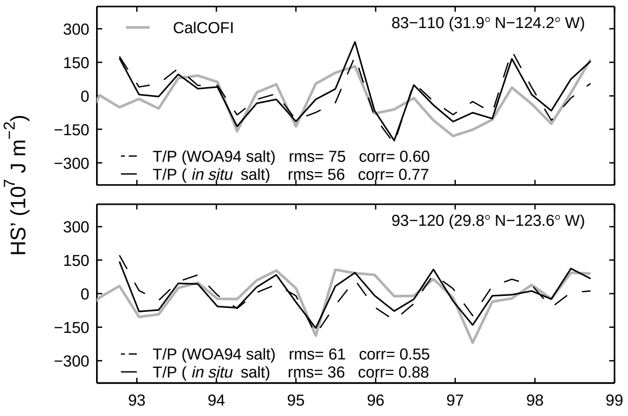

Figure 5. Same as Figure 2 but at CalCOFI.

(75×10^7 J m^{-2} and 0.80). As HyS nearly coincides with a T/P cross-over latitude the zonal spacing between samples is maximum. This distance is approximately twice the wavelength of the local semiannual Rossby waves. Therefore, T/P cannot properly resolve the early semiannual signal which results in spatial aliasing [*Parke et al.*, 1998] and degradation of the correlation.

The time series used at HOT spans from 1993 to 1998, 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 are better than using climatology.

The CalCOFI cruises are composed of an array of stations near the California coast and the used time series coincides with T/P between 1993 and 1998. 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 toward 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 decorrelated 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 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 to evaluate the importance of haline effects in the determination of the heat storage anomaly from sea surface height anomaly. In all locations (HyS, 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.

At HyS the rms difference decreased by 5×10^7 J m^{-2} and the correlation increased by 0.1 when using in situ instead of climatological salinity. Better results were obtained from the other sites. At HOT, the rms decreased by 17×10^7 J m^{-2} and the correlation improved by 0.18 while at CalCOFI, the average rms decreased by 12×10^7 J m^{-2} and correlations increased by 0.18. These results stress the importance of 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.

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