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Transition regions and their role in the relationship between sea surface height and subsurface temperature structure in the Atlantic Ocean

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Abstract.
Expendable bathythermograph (XBT) profiles and TOPEX/Poseidon altimeter data (T/P) are compared for the years 1993 through 1997 to determine how much can be understood about water column variability from XBT's given only sea height anomalies (SHA) from T/P. Our focus is on the annual cycle along two well sampled XBT sections in the Atlantic Ocean from 10°S to 40°N. Regions of transition are identified that separate the mid-latitudes where surface buoyancy fluxes dominate the forcing of sea level, from those in the equatorial region where thermocline effects dominate. Zones of transition occur in the vicinity of troughs where small fluctuations in SHA belie the true nature of water column variability. Here, surface and thermocline variability tend to cancel each other. Thus, the character of SHA in transition regions emphasizes how important direct observations can be in interpreting satellite altimetric observations correctly when both surface and thermocline variability are important but are compensating in nature.

Introduction

The relationship between sea surface height anomalies (SHA) and subsurface density structure has been studied using both models and observations. The objective was to develop models for interpreting observations of SHA from satellite altimeters (e.g., TOPEX/Poseidon, T/P) in terms of subsurface temperature and salinity variability. For example, *Stammer* [1997] used 3-years of T/P data and sea surface energy flux observations to study their effects on SHA. He found that in mid-latitudes, buoyancy fluxes dominate the generation of SHA, whereas in the tropics, a thermocline depth process caused mostly by changing winds and near-surface currents dominate SHA variability. Using a numerical model, *Fukumori et al.* [1998] found similar results, as did *Ferry et al.* [2000], hereinafter FRO, using a combination of in situ data and model fields. These findings are consistent with earlier studies of the oceanic thermal structure. For example, *Gill and Niiler* [1973] described the importance of seasonal variability of surface buoyancy fluxes and their effects on the mid-latitude temperature structure of the upper ocean. In contrast, *Merle and Arnault* [1985] discussed the importance of thermocline variability in forcing temperature changes in the tropics by virtue of anomalous surface winds and ocean dynamics.

As will emerge below, both processes are important for the annual cycle in certain areas where both impact SHA variability. Moreover, from the studies cited above, or from any others of which we are aware, none have considered the regions between the tropics and subtropics, where neither surface fluxes nor wind-driven processes dominate and, in particular, where these processes mutually interfere. Herein, we describe such transition regions of the tropical Atlantic for the annual cycle. First, the data and analyses used are described followed by our findings in a succinct summary.

Data

To describe the subsurface temperature field we used expendable bathythermograph (XBT) data. The XBT temperature profiles were collected along two western and eastern regions of the Atlantic Ocean where data are most plentiful (Figure 1). Along the two transects in our domain, 8,012 profiles were collected during the five years of available T/P data, 1993-1997. Quality control procedures for the XBT data are given in *Molinari et al.* [1997].

Data were binned by 2 degrees of latitude by 4 degrees of longitude (2 x 4) quadrangles (bins) and then averaged by month for the 52 positions, or grid points shown in Figure 1. A more detailed discussion of the rationale for this resolution is given in *Molinari et al.* [1997] and *Mayer et al.* [1998]. At each position temperature anomalies (TA) were computed with respect to the 5 yr mean. The annual cycle was computed from 12 monthly means over the 5 yr of observations.

Dynamic height anomalies (DHA) were also computed for direct comparison with the SHA data. To derive the DHA, seasonal temperature and salinity-relationships from the *Levitus* [1982] climatology were used. The XBT temperature data were matched to the nearest position and month from this climatology to obtain the inferred salinity values. Using these tem-

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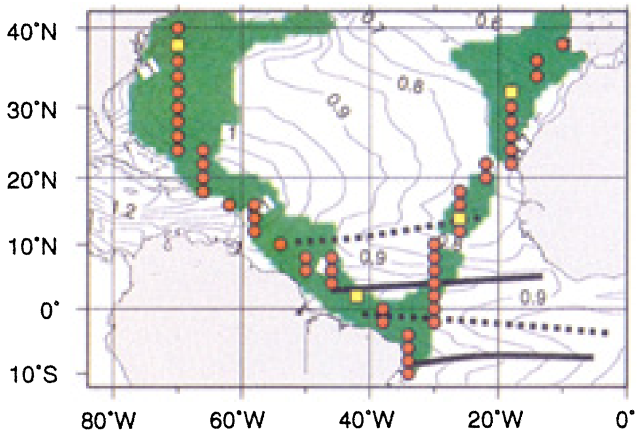

Figure 1. Western and eastern regions in the analysis domain for XBT data. Red dots and yellow boxes are positioned at the center of 2° of latitude by 4° of longitude boxes. Dark shading indicates areas of highest data density of profiles near major shipping routes where 30 months or more out of a possible maximum 60 months are available for the five years (1993-1997). The 4 yellow boxes selected for detailed analysis have at least 41 months of data. Contour interval for dynamic height with respect to 500m is 0.05 dynamic meters. The tropical ridges (heavy dark lines) and troughs (heavy dashed lines) are also indicated.

perature and salinity profiles, inferred DHA were then computed down to 500m.

Adjacent T/P satellite groundtracks are separated by approximately 3 degrees of longitude and repeated every 10 days [*Cheney et al.*, 1994]. The altimeter data contain the standard corrections for wet and dry troposphere, earth and ocean tides [*Cartwright and Ray*, 1991], inverse barometer, and sea state bias. The SHA data were matched in both time and space to individual XBT profiles and then binned as described above.

Results from the numerical modeling effort of FRO were used to determine the processes responsible for observed Atlantic SHA. FRO employed an oceanic general circulation model to consider the annual cycle in five years of T/P data. The model is forced with daily winds generated by a reanalysis of atmospheric observations.

Results

The importance of the annual cycle is reflected by the annual cycle fraction (variance of annual cycle/total variance). Generally, this ratio is greater than 0.5 for both SHA and DHA except in the tropics near trough regions. These are the North Equatorial Countercurrent trough and the equatorial trough just south of the equator in Figure 1. The root mean square (rms) of the annual cycle from the FRO model and from our estimates of SHA and the differences between SHA and DHA with respect to 500m (SHA minus DHA) are given in Figure 2. Along the western section, the rms of the differences between SHA and DHA are typically of order 2 cm. However, between 6 and 16°N and north of 34°N (Figure 2a) and in the eastern section between 8 and 26°N and north of 36°N (Figure 2b), the differences are larger. The large dots indicate where DHA can account for half or more of the SHA variance and are thus, places where most of the annual cycle can be captured using only inferred DHA.

The rms of the FRO model are akin to those from the observations suggesting that the model is simulating the processes that cause SHA. However, the model underestimates the rms of the observations because only the annual harmonic is considered. The contributions to the annual cycle by the simulated (modeled) buoyancy and wind forcing are also given in Figures 2c and 2d. As discussed in FRO and others cited in the introduction, surface buoyancy flux forcing dominates along both sections north of about 15°N, but south of this latitude wind forcing of SHA increases. Between 12°N and 16°N along the eastern section, the rms of the annual cycle of SHA is of order 2 cm (Figure 2b), and the rms of the model buoyancy and wind forcing components are also each of order 1-2 cm or more at these latitudes (Figure 2d). If the two components (buoyancy and wind) are in phase and both amplitudes are similar in magnitude, then their contributions to SHA would result in an rms that would be about 1.5 times that for just one component. If they are out of phase their contributions would approximately cancel resulting in small values of SHA. The model results show that the minimum in SHA is near 15°N and is consistent with the small values of observed SHA.

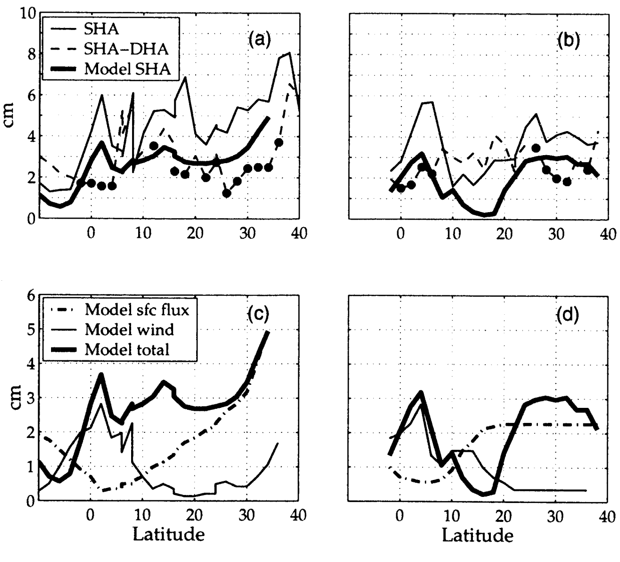

Figure 2. The root mean square (rms) deviation of sea height anomaly (SHA, solid), the differences between SHA and DHA with respect to 500m (dashed) for the annual cycle and model results (thick) from *Ferry et al.* [2000] for the annual harmonic only (a) in the western section and (b) the eastern section. The large dots on the differenced curves show where DHA with respect to 500m can account for half or more of the SHA variance. c) Model rms of SHA from heating/cooling and wind-driven components shown separately and their sum for the western section and d) the eastern section.

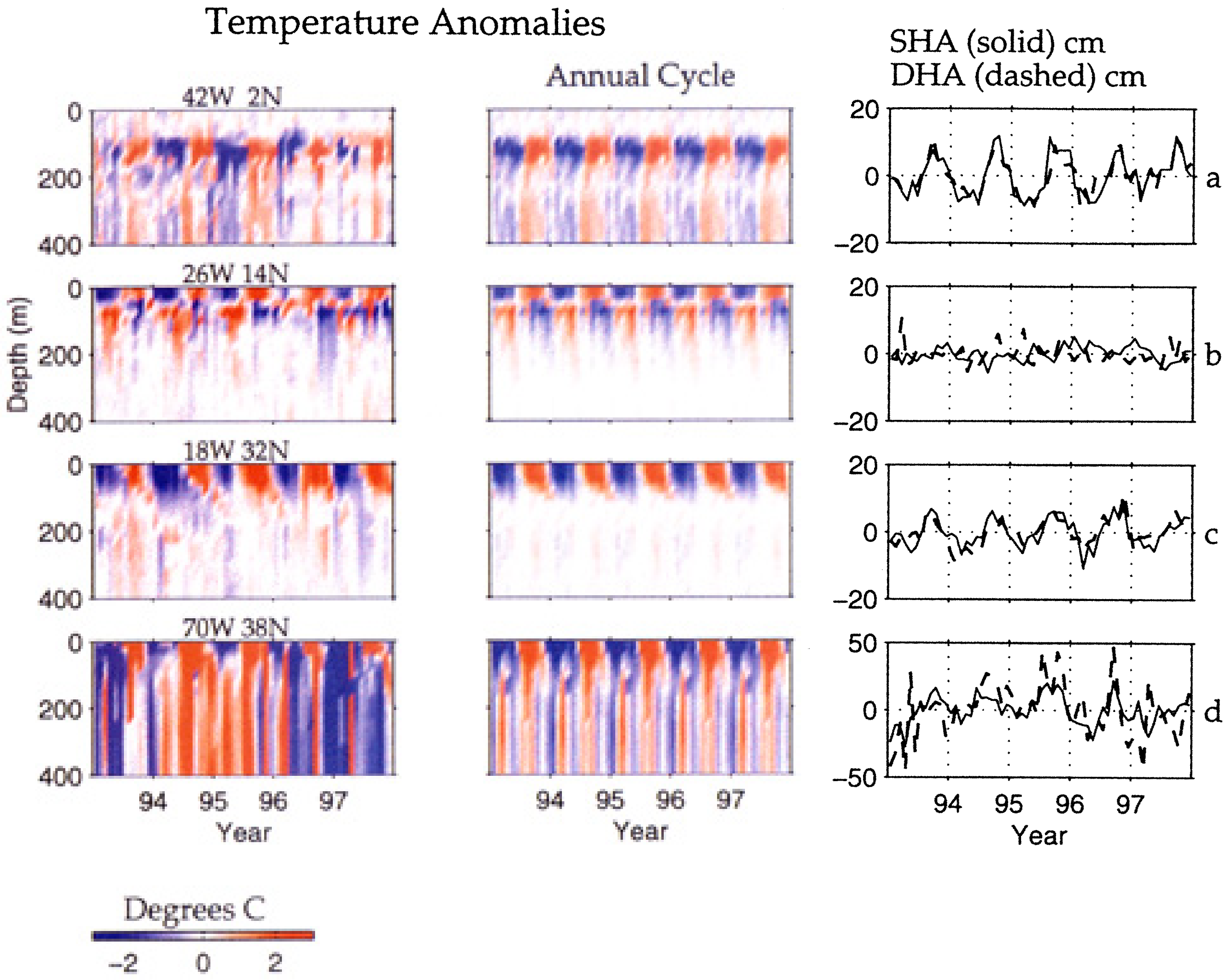

Figure 3. Depth dependence of temperature anomalies for the 4 positions in Figure 1 for the 5 yr period 1993 through 1995 (left panels), for the annual cycle only repeated for 5 yr (middle panels), and time series of SHA and DHA with respect to 500m (right panels). Anomalies are negative (blue) positive (red).

The subsurface temperature data provide an explanation for this apparent discrepancy between the variability of SHA and the contributions provided by different parts of the water column. Temperature depth dependence for the 5 yr period 1993-1995 from the tropics to the northwestern Atlantic (Figures 3a-3d), as well as time series of DHA with respect to 500m and SHA are shown for 4 positions that represent variability typically encountered in our domain (yellow boxes in Figure 1). As expected, north of 20°N the annual cycle in temperature is consistent with surface buoyancy flux forcing (Figure 3c) with the addition of Gulf Stream variability at 38°N (Figure 3d). From 2°N to 8°N, the annual cycle is largest at thermocline depths (Figure 3a) and is consistent with wind forced ocean dynamics described in the references cited previously. However, at 14°N (Figure 3b), there are large annual cycles at both the surface and thermocline depths that are out of phase, where maximum positive surface temperature anomalies are observed in October but maximum subsurface anomalies are observed during April and May. At this position the DHA and SHA are considerably smaller than they are farther north or south. A similar structure is observed south of the equator near 4°S, 34°W

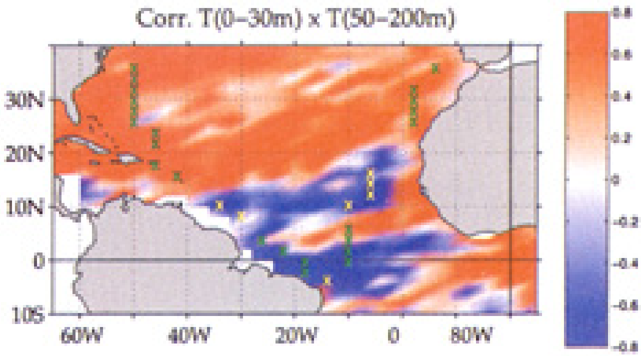

Figure 4. Correlations between indices of temperature, near the surface (0-30m) and for the seasonal thermocline (50-200m). Correlations are negative (blue) positive (red). Green crosses indicate areas where DHA with respect to 500m can account for half or more of the SHA variance. Yellow crosses denote transition regions.

(not shown). We consider these positions as representative of a transition region between the tropics and the subtropics, where TA in different parts of the water column are offsetting causing SHA variability that is small.

Because there are insufficient XBT data for the 5 yr period outside the two sections to define time series similar to those in Figure 3, another approach is needed to estimate the area encompassed by the transition regions. To appreciate how temperature changes of the annual cycle are related to each other over depth throughout the analysis domain, unlagged correlations (Figure 4) between indices of near surface temperature over the upper 30m or so and the seasonal thermocline (50-200m) were computed from a 12 month climatology that was derived in *Mayer et al.* [1998] and which encompasses our whole Atlantic domain.

The green crosses in Figure 4 indicate places where DHA can account for half or more of the SHA variance as in Figure 2. The yellow crosses indicate positions where correlations between indices of the temperature near the surface and the seasonal thermocline are large and negative with large seasonal fluctuations (as in Figure 3b). They are located in quasi-zonal bands in the vicinity of the countercurrent trough near 10°N and the equatorial trough just south of the equator (Figure 1) and hence, are in regions where seasonal fluctuations of SHA are small. In contrast near the countercurrent ridge, fluctuations of SHA are much larger despite the negative correlations, because thermocline variability dominates that near the surface. Thus, two of the areas of negative correlations in the tropics represent zones of transition between the mid-latitudes and the tropics in the vicinity of trough regions. Directly on the equator, correlations are negative in the west and positive in the east but there is not a simple relationship between SST and the thermocline as explained in *Weingartner and Weisberg* [1991].

Summary

In summary, transition regions are characterized by an annual cycle of temperature near the surface and the temperature of the seasonal thermocline that are out of phase and combine to cause relatively small SHA in the vicinity of the equatorial and countercurrent troughs. Equatorward of these transition zones, variability of the seasonal thermocline is dominant and contributes to the large fluctuations of SHA in the vicinity of the countercurrent ridge. Thus, zones of transition separate mid-latitude regions where surface buoyancy fluxes dominate the forcing of sea level from those in the equatorial region where thermocline effects dominate.

The nature of SHA in transition regions emphasizes how important subsurface data can be in interpreting satellite altimetric observations correctly. Specifically, small fluctuations in SHA (e.g., Figure 3b) do not reflect the large seasonal fluctuations in surface and subsurface temperatures because of their compensating nature. Thus, it cannot be assumed that fluctuations of SHA are related primarily to surface fluxes as they are in mid-latitudes, or related to thermocline fluctuations as they are equatorward of the transition zones. Consequently, direct observations are needed in these transition regions to properly identify the processes that relate to both surface and thermocline variability.

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