Anomalous Temperature and Salinity Variations in the Tropical Atlantic: Possible Causes and Implications for the use of Altimeter Data

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Abstract. Near real time subsurface observations at a PIRATA mooring in the western equatorial Atlantic show a temperature and salinity drop in boreal spring 1999 which is consistent with a 60 m upward shift of the thermocline. At the same time, sea level observations from TOPEX/Poseidon and ERS-1/2 show anomalously low values over a large part of the tropical Atlantic north of the equator. The sea level observations are also used to correct for errors in upper ocean heat content in a global ocean analysis, which is used to initialize seasonal forecasts. It is shown that the ability of altimeter data to reproduce observed temperature changes is limited in the western equatorial Atlantic. This may partly be because large temperature changes occur very rapidly, but is mainly because strong salinity variations compensate up to 10 cm of the sea level signal from temperature.

Introduction

The skill of coupled seasonal climate forecasts relies heavily on realistic oceanic conditions at least in the tropical Pacific. At ECMWF, a global ocean analysis assimilating subsurface temperatures is used to initialize coupled seasonal forecasts. Near real time observations of in-situ temperature for the Pacific have been available since the early nineties from the TAO moorings [*McPhaden*, 1995]. The recently introduced PIRATA network [*Servain et al.*, 1998] provides near real time observations of temperature (T) and, more limited, salinity (S) in the tropical Atlantic. These observations show a most interesting feature in boreal spring 1999: a rapidly developing strong negative subsurface temperature and salinity anomaly at 4° N, 38° W, starting during April 1999 and lasting for many weeks.

Sea level observed by satellite indicates that the observed changes form part of a larger scale anomaly, which may be important in the context of seasonal forecasting (Fig.1). However, the quasi-operational ocean analysis at ECMWF which incorporates the assimilation of in-situ temperatures including the PIRATA data, largely failed to reproduce the observed temperature decrease. The routinely performed comparison of observed and analyzed sea level therefore drew our attention to the problem.

Attempts are underway to efficiently use the information about upper ocean heat content provided by satellite observed sea level anomalies [*Ji et al.*, 2000; *Segschneider et al.*, 1999; *Segschneider et al.*, 2000]. Sea level has been shown to be a good proxy for upper ocean heat content and TOPEX/Poseidon and ERS-1/2 now observe sea level anomalies with high accuracy at dense spatial and temporal coverage in near real time [*Le Traon et al.*, 1998]. However, altimeter data are an integral measure of density, and therefore reflect vertically integrated temperature *and* salinity. Problems for the use of altimeter data arise when salinity variations have a significant impact on sea level (e.g. [*Ji et al.*, 2000]).

In the following we shall first investigate the observed hydrographic variations in more detail. We will then examine the extent to which ocean analyses in which all available in-situ temperature observations or, additionally, altimeter data are assimilated can reproduce the observed temperature and salinity changes. Finally a summarizing discussion is given.

Observed changes and possible causes

A map of near real time altimeter data is shown in Fig.1a for 19 May 1999 to demonstrate the spatial extent of negative sea level. Because no geoid of sufficient accuracy is available and therefore no absolute sea level can be provided, the data are produced by CLS (Centre Localisation Satellite) relative to the 1993 to 1995 mean, using a repeated track analysis. Negative sea level values of more than 20 cm are observed in a large region from 45° W to 25° W and between 2° N and 7° N. Anomalies with respect to the average seasonal cycle are shown in Fig.1b. The seasonal cycle is computed over the years 1993 to 1998 from the CLS-data to give the best possible estimation of the seasonal cycle. Fig.1b shows sea level up to 15 cm lower than the climatological average in a large area of the western Atlantic between the equator and 10° N, suggesting that the observed temperature drop at the PIRATA mooring is part of a larger scale feature, which could be important in the context of seasonal forecast initialization. Time

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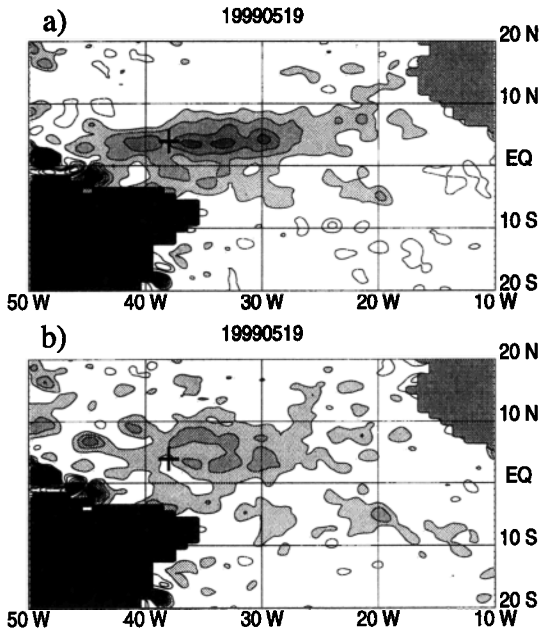

Figure 1. (a) Sea level relative to the 1993 to 1995 3-year mean observed by TOPEX/Poseidon and ERS-2 on 19 May 1999. (b) Sea level anomaly relative to the average seasonal cycle, computed from altimeter data for 1/1993 to 4/1998. The contour interval is 5 cm, negative values are shaded and the zero contour is not shown. The position of the PIRATA mooring at 4° N, 38° W is marked by a cross.

series of the sea level imply that the variations observed in spring 1999 are an about twofold amplification of the seasonal cycle.

The PIRATA mooring at 4° N, 38° W (marked by the plus sign in Fig.1) measured a temperature decrease of up to 10° C at 80 - 120 m depth in April 1999 (Fig.2a). Subsurface salinity was observed at 40 m and at 120 m depth, the latter being the depth of a subsurface salinity maximum. Salinity decreased by 0.75 psu at 120 m depth, but increased slightly at 40 m (Fig.2b). A time depth section of the temperature (not shown, but see http://www.pmel.noaa.gov/pirata/gif/buoy_4n38w.gif) suggests that the observed changes were caused by an upward shift of the temperature and salinity profiles of almost 60 m.

The corresponding time series of sea level at 4° N, 38° W is shown in Fig.2c (solid line) together with dynamic heights (crosses). The latter were computed at the NOAA/PMEL project office using in-situ temperatures down to 500 m, but annual mean salinity (McClurg, 1999, pers.comm.). Therefore any compensating effect on density from salinity is not taken into account in calculating dynamic height. The dynamic height can therefore be used to estimate the impact of the salinity variations on sea level. For most of the time, the agreement between sea level and dynamic height is reasonably good, but differences are as large as 10 cm during May 1999, indicating that the in-situ salinity has a significant impact on sea level. For the assimilation of altimeter data, this means that the sea level is not an accurate proxy for temperature in this special case. The density change caused by variations of S is roughly equivalent to that of a 3° C change of T. The impact of S on the in-situ density thus amounts to almost one third of the impact of T.

The physical processes that cause the temperature and salinity anomalies are not fully known yet. Several explanations are possible, outlined in the following. Significant changes in T at 75 m in the equatorial western Atlantic have been noted before at a similar time of year (April 1983), but they were smaller and at somewhat different location (0°, 28° W; [*Weingartner and Weisberg*, 1991]). The authors argue that the change in T is related to local wind changes. Instability waves do occur in the Atlantic, but appear to originate later in the season and further east than 38° W [*Steger and Carton*, 1991; *Weingartner and Weisberg*, 1991].

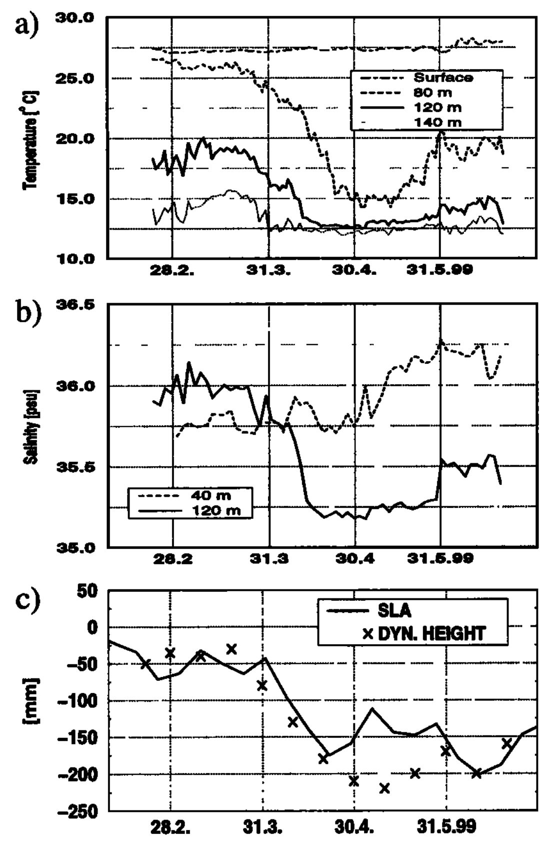

Figure 2. Time series of (a) temperature as observed from the PIRATA mooring at 4° N, 38° W for the surface (dash-dotted), at 80 m depth (dashed), at 120 m (solid), and at 140 m (dotted). (b) time series of salinity at 40 m (dashed) and at 120 m (solid). (c) SLA relative to 1993 to 1995 3-year mean observed by TOPEX/Poseidon and ERS-2 (solid line), and dynamic height anomalies from PIRATA temperatures (crosses). Dynamic height is from in-situ T but annual mean S. The offset between SLA and dynamic height in February 1999 is subtracted.

The observed variations of T and S at 4° N, 38° W could also be associated with lateral shifts of the North Brazilian Current (NBC) which transports warm and haline water north-westward along the Brazilian coast and across the equator. A section through the NBC is given by [*Pailler et al.,* 1999] who show a core of high salinity water close to the Brazilian coast at around 100 m depth and strong horizontal salinity gradients further off-shore. Although our mooring is located outside the main axis of the NBC, we can not rule out a lateral displacement or meander of this current. However, the front between cold and fresh North Atlantic Central Water (NACW) and warm and salty South Atlantic Central Water (SACW) is usually found at 10° N in the western Atlantic [it Tomczak and Godfrey, 1994], which is well to the north of our mooring.

The only depth at which T and S are observed simultaneously is 120 m. At this depth, the observed T-S properties before (T=19° C, S=36psu) and after (T=12.5° C, S=35.2 psu) the cooling coincide with the T-S characteristics of SACW (Fig.15.9 in [it Tomczak and Godfrey, 1994]) This further suggests that SACW has been moved in the vertical. Such a vertical shift could be associated with an anomalously strong southward meridional component of the wind as observed at the location of the mooring, during March to May 1999. To investigate this, we computed the curl of the windstress from the wind fields analyzed at ECMWF. Assuming that a 60 m shift occurred over 30 days, the required Ekman velocity would be 2.3 x $10^{-5} ms^{-1}$, which at 4° N corresponds to a curl of roughly 2 x $10^{-7} Nm^{-3}$. We found that the wind stress curl can explain much of the observed large scale feature of Fig.1a, but only 20% of the required Ekman pumping is explained at the location of the mooring.

A vertical shift could also have been caused by a cyclonic eddy, or have propagated from the east, as a Rossby wave. To investigate this, anomaly maps of sea level were produced from the altimeter data for February to June 1999. Temperature and sea level fields from the high resolution OCCAM model (Ocean Circulation and Climate Advanced Modelling project) were also analyzed (available at http://www.soc.soton.ac.uk/JRD/OCCAM/NAEQ).

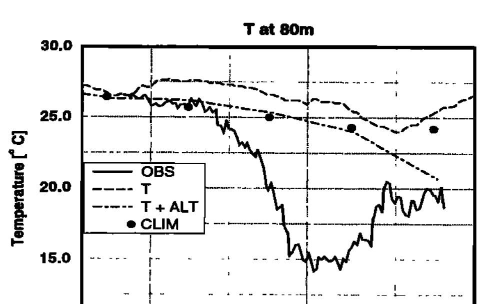

Figure 3. Time series of observed and simulated temperature at 4° N, 38° W. Observed value (solid) is at 80 m depth, model results and climatological data are averages over a 2° x 2° box centered at 4° N, 38° W and 75 m depth. Shown are the the in-situ temperature quasi-operational analysis (long-dashed), the combined assimilation (dot-dashed), and the climatological average from Levitus data (filled circles).

The observed sea level maps show eddy activity embedded in larger scale changes, but no evidence of an eddy at the location of the mooring or a propagation of a Rossby wave at the relevant time. However, the sea surface signal of any cyclonic eddy might have been disguised by the compensating salinity effect. The results from the OCCAM model show strong eddy activity in the region of the mooring, though these are mostly active from September to March. Overall, it does not seem possible to give a definite explanation as yet.

Results from the ocean analyses

The ocean analysis using altimeter data is based on the method of [*Cooper and Haines,* 1996] and described in [*Segschneider et al.,* 1999; *Segschneider et al.,* 2000]. The only difference here is that altimeter data are first used to create pseudo temperature observations, which are then assimilated in combination with the in-situ temperatures using an optimum interpolation scheme. The altimeter derived temperatures are rejected in a 2° x 2° box surrounding each in-situ observation. The remaining pseudo-temperatures have the same weight as the in-situ temperatures. Fig.3 shows time series of observed (solid line) and simulated temperatures as well as monthly climatological data (circles) at 4° N, 38° W at 75 m depth. The quasi-operational analysis at ECMWF, assimilating only in-situ temperatures (dashed line), fails to reproduce the observed temperature decrease. Some of the PIRATA data are rejected by the quality control, and some time delay can be explained by the 10-day interval over which the increment is spread.

The combined analysis of altimeter sea level and insitu temperature (dot-dashed line), reproduces the observed temperature in June 1999 much better than the OI, but temperatures in April and May are still far too high. Fig.2c implies that the compensating effect of salinity on the observed sea level signal reduces the ability of altimetry to correct for temperature and salinity errors in April 1999. The analyzed temperature field at 75 m depth has the strongest anomalies to the east of the PIRATA mooring (not shown), where salinity impact on sea level is most likely less important because the intermediate salinity maximum is less pronounced. Unfortunately, there are no PIRATA moorings in this region to confirm the model results.

Discussion

Rapid changes in both temperature and salinity at a depth of 80 to 120 m lasting several weeks have been observed in the western equatorial Atlantic. Near real time altimeter data show that the anomalies form part of a large scale pattern that extends almost across the whole width of the Atlantic.

The observed changes are only partly reproduced by the analyses that are currently used at ECMWF to initialize seasonal forecasts on a quasi-operational basis. Experimental configurations of the assimilation system, using altimeter data only, or in combination with T data also fail to reproduce the rapid changes. This is partly due to the time scale over which the changes occur: some of the in-situ observations are simply rejected by the quality control because they depart too far from the background. More advanced assimilation schemes are under development to make better use of the available observations.

Assimilation of altimeter data has been shown to improve ocean analyses by correcting misplacements of the thermocline over large parts of the tropical Pacific [*Segschneider et al.,* 2000]. In regions where strong salinity variations impact significantly on sea level, this is less straightforward. Additional observations of subsurface temperature and salinity are required.

Finally, we have not investigated yet, the extent to which the observed anomalies are important in the context of seasonal forecasting. A correct analysis of the thermocline in the Pacific is necessary to obtain good seasonal forecasts, because anomalies in subsurface layers propagate along the thermocline and affect the surface with a time delay. This is likely to be the case for the Atlantic also, although it has not yet been demonstrated.

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