On the impact of TOPEX/Poseidon data in the analyses of the tropical Pacific Ocean

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INTRODUCTION

* There has been substantial progress in forecasting the El Nino/Southern Oscillation (ENSO) since the start of the Tropical Ocean-Global Atmosphere (TOGA) program (e.g., Latif *et al.*, 1998). Numerical models are now able to perform considerably better than persistence in forecasting standard ENSO indices at lead times of 6 to 12 months. Given this progress, operational ENSO prediction systems have been established at weather forecast centers such as NCEP. In such systems, the initial state of the atmosphere is taken from the operational weather analysis while oceanic observations are used to estimate the initial ocean state through data assimilation. Of course, such forecast tools are in constant development, evolving along with our understanding of the physics and our ability to parameterize them and with the availability of observations to determine the initial conditions.

** The mission of the Climate Modeling Branch at NCEP is to develop models to produce an integrated suite of climate forecasts for time periods from weeks to multi-seasons. The forecasts depend in part on an ocean data assimilation system that is used to initialize the forecast model. Recent work has shown that to use sea surface height data properly, an assimilation system must use the information contained in them to correct salinity as well as temperature (Behringer *et al.*, 1998; Ji *et al.*,
1999). Since the TOPEX/Poseidon (T/P) altimeter databe came an integral part of the operational satellite system for monitoring the ocean, several questions arise concerning the use of altimetric sea level data in monitoring and forecasting ENSO.

THE PROBLEM

* There is growing evidence that salinity variability cannot be neglected in such ocean data assimilation systems. The issue is how we can determine the salinity variability, given the present scarcity of direct observations. But first, let us respond to a preliminary, related question:

Is the salinity variability strong enough to generate a detectable signal in sea level?

We show next (Figs. 1-3) the effect of neglecting the salinity variability in the computation of dynamic height anomalies. These plots are based on the indirect method proposed by Maes and Behringer (1999), and/or on direct computation using Conductivity-Temperature-Depth (CTD) observed profiles.

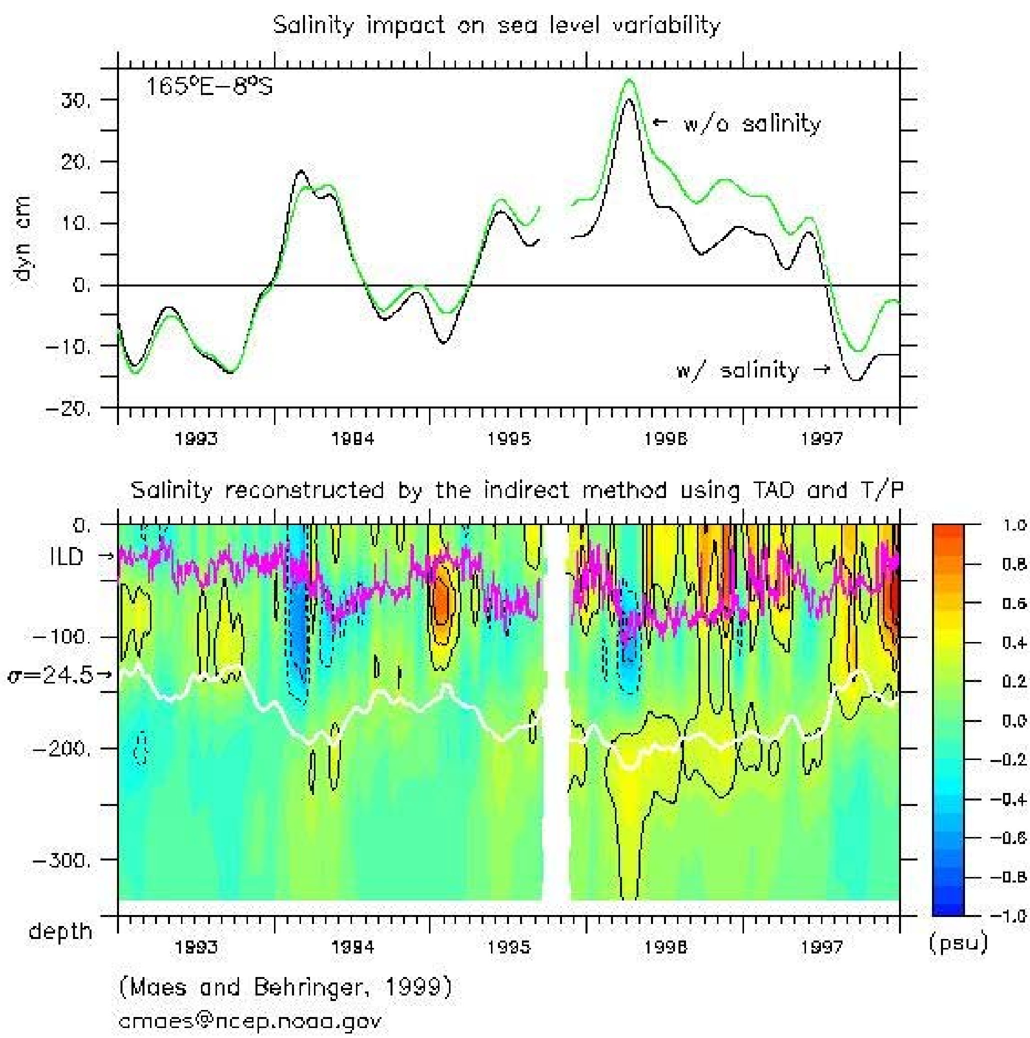

Figure 1: Time plots of the reconstructed dynamic height considering the salinity estimates (black) or the mean salinity field (green). The corresponding depth/time salinity deviations (in psu) for the top 350 m are displayed underneath. The thick white line is the isopycnal 24.5 kg/m3, and the pink line represents the isothermal layer depth (ILD).

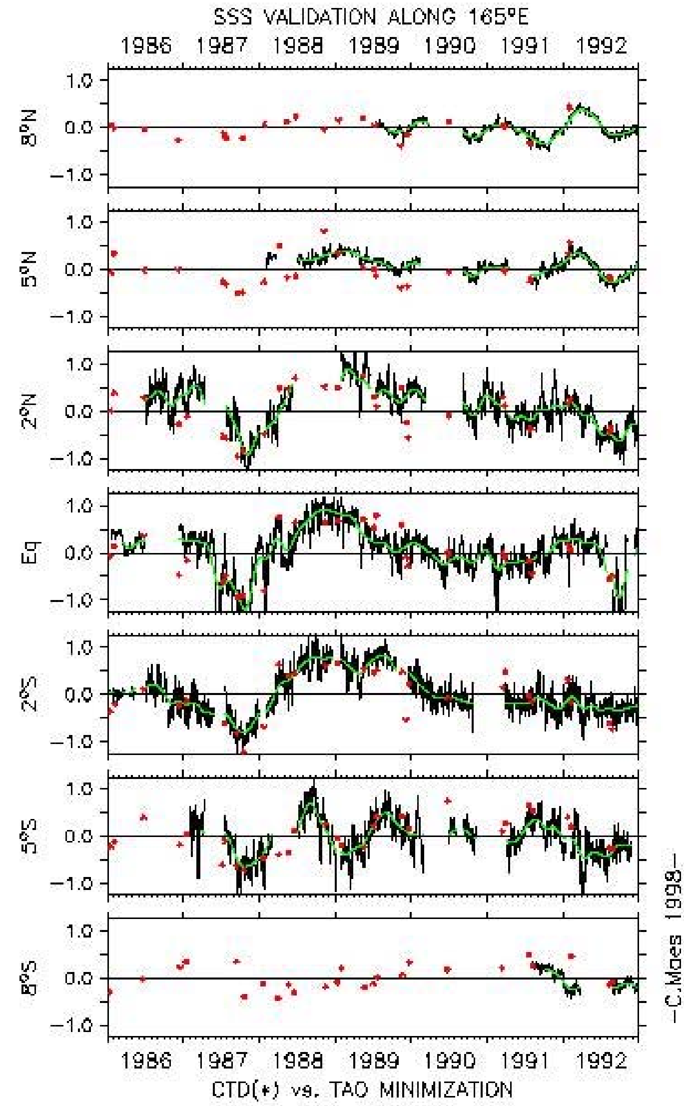

Figure 2: Comparison between the CTD SSS (red stars) and the estimates using the daily TAO temperature profiles (black). The green line represents the low filtered (60 days) of the estimates.

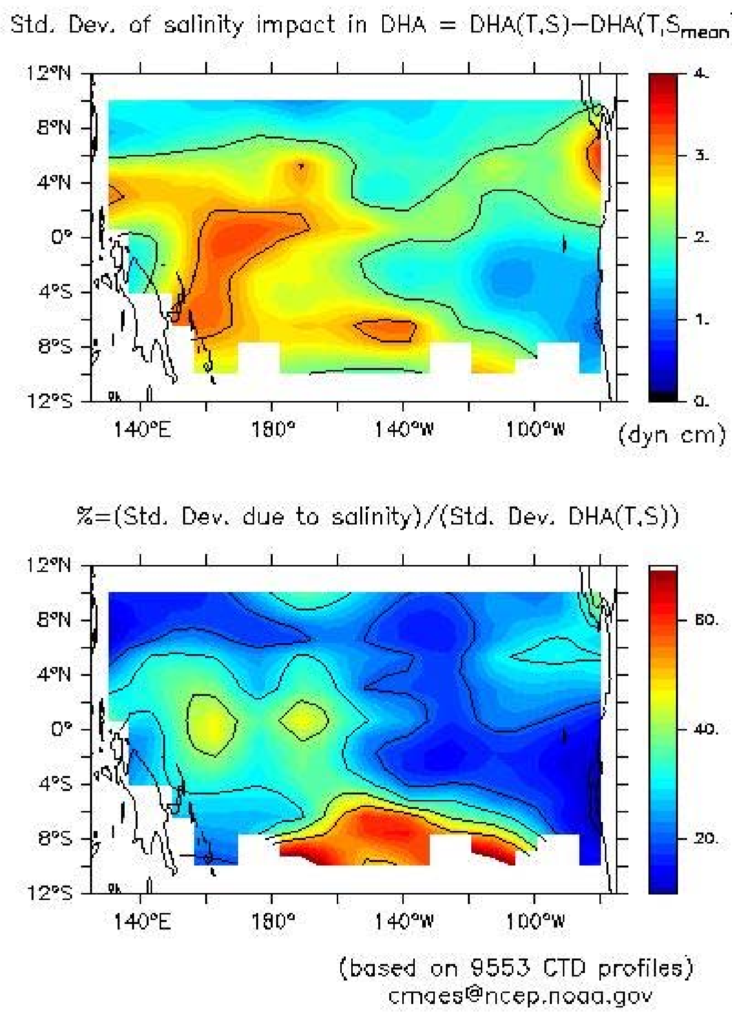

Figure 3: Estimate of the impact of the salinity variability on sea level fluctuations. The computation is based on the CTD data set (1976-1998) provided by PMEL (maintained by Mike McPhaden and Kristy McTaggart, many thanks to them).

The main results may be summarized as follows:
1. The processes involve the salinity variability within the tropical mixed layer and the baroclinic response in the main halocline.

2. Some compensation as well as additional effects between different parts of the water column may be observed. It means that the vertical extrapolation of sea level anomalies into the subsurface mass field must consider the whole column.

3. An important point is that in the western tropical Pacific Ocean the effect of salinity variability on sea level may be equal to the effect of thermal variability. In the context of the Seasonal-to-Interannual (SI) prediction problem, it means that to exploit successfully altimetric observations the salinity field must be considered explicitly and

carefully.

** In the present absence of extensive observations of the salinity field one has to consider indirect methods. The conventional approach is to have recourse to T-S diagrams. We show next (Figs. 4-5) that such an approach is insufficient to represent fully the salinity variability, especially the variability associated with the low frequency ENSO timescales.

Figure 4
shows different T-S diagrams across the tropical Pacific. The casts are plotted with different symbols to highlight the differences between "El Nino" and "La Nina" years which are midentified by anomalous SST in the Nino 3.4 region (Barnston *et al.*, 1997). The thresholds are fixed to an anomaly greater than 1 degC for the "El Nino" conditions (in red) and an anomaly less than 0.8degC for the "La Nina" conditions (in blue). The largest dispersion of salinity is observed for the higher temperatures, i.e., in the surface layer. One exception is represented by the southern diagram of the central Pacific (140W) which shows the largest dispersion of salinity at depth. In the southwestern Pacific, the dispersion of salinity is fairly important regardless of whether the conditions are representative of "El Nino" or "La Nina" conditions. Along the equatorial band a clear distinction between the ENSO extremes can be seen.

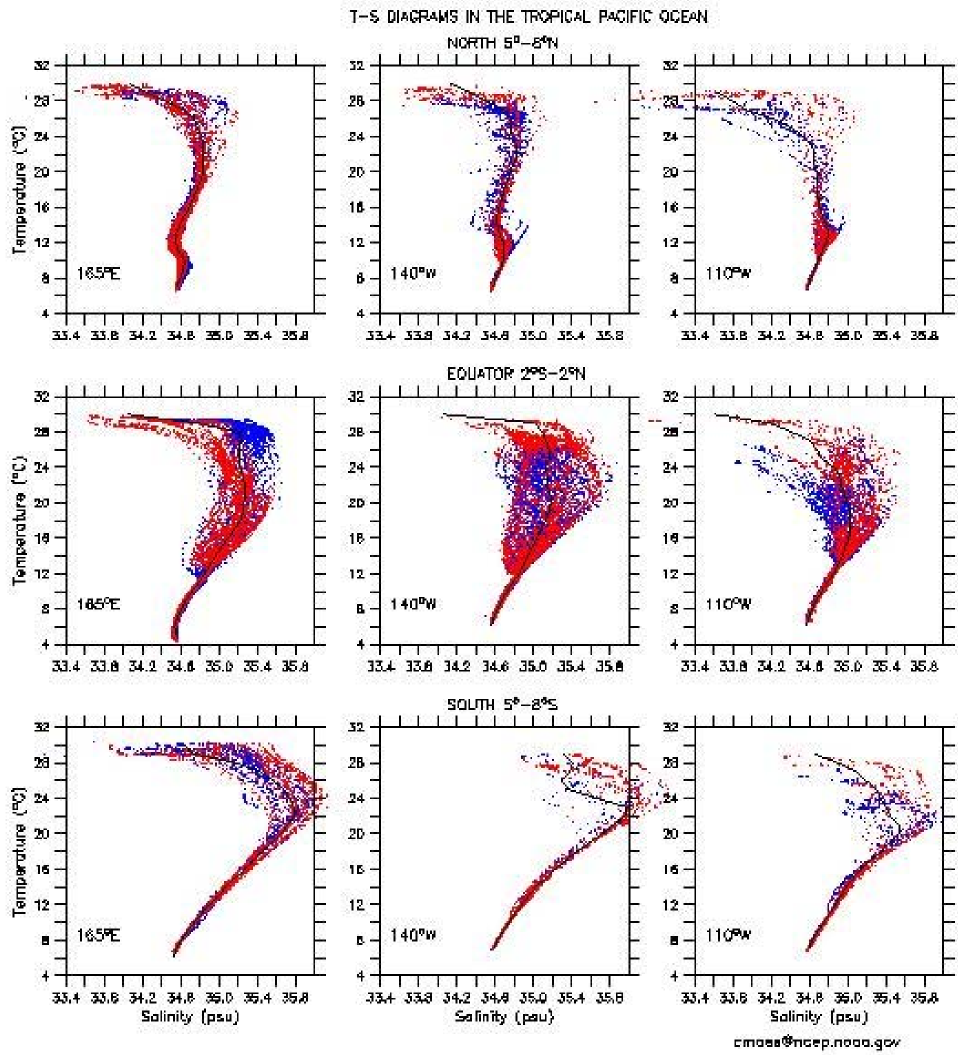

Figure 4

Figure 5
shows the respective impact of neglecting the salinity variability in dynamic height anomalies along 165E, 140W, and 110W (see also Fig. 3). The standard deviations as a function of latitude are shown on the right. Using the climatological T-S curves (see Fig. 4) a similar computation shows that the salinity variability is reproduced only partially, and that the respective signal in DHA is weaker compared to the observed effect across the entire basin. Moreover, it may be demonstrated that such an approach fails to reproduce the low frequency variability associated with ENSO events.

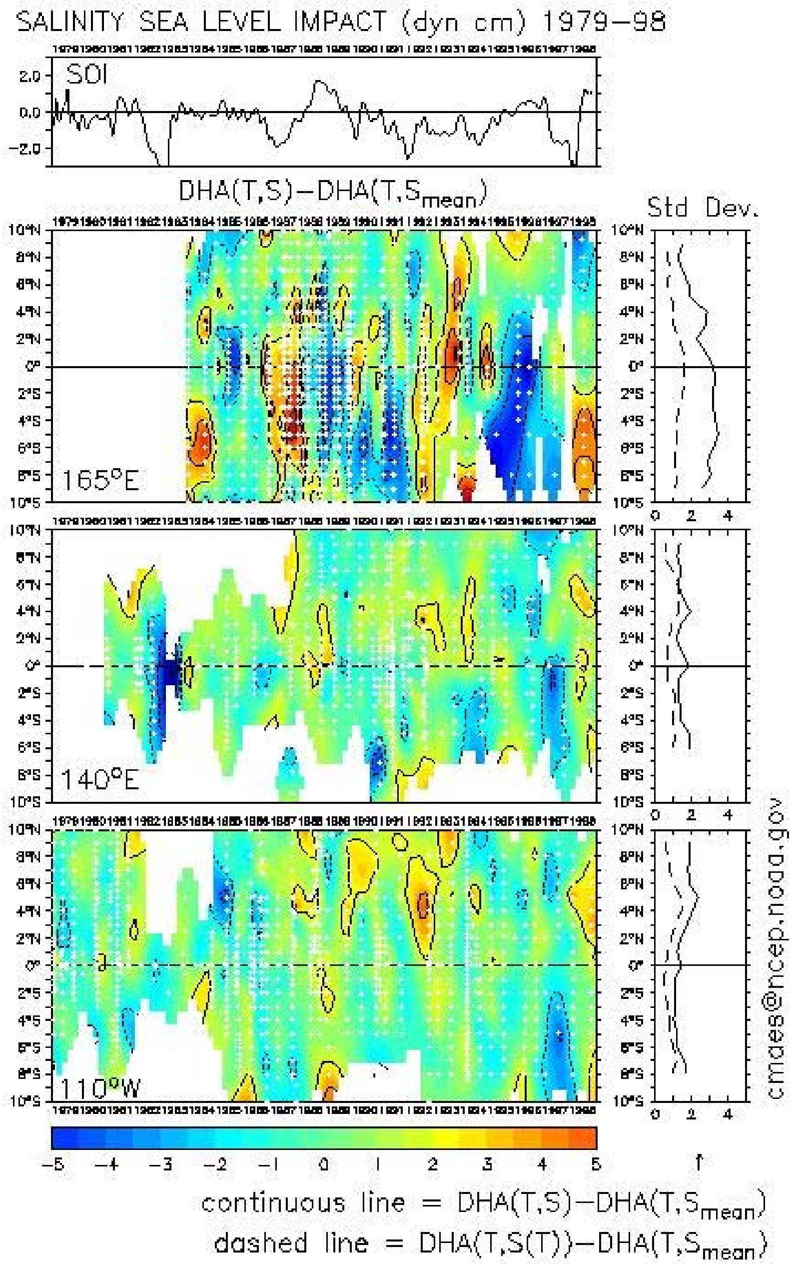

Figure 5

A NEW METHOD TO ESTIMATE SALINITY PROFILES

* The present method is similar to ocean data assimilation where the goal is to achieve a "vertical extrapolation" of surface data into the subsurface ocean (De Mey, 1997). The method uses Empirical Orthogonal Functions of the combined temperature and salinity fields (Maes, 1999) as basis functions in a weighted least squares procedure to reconstruct the internal ocean variability from surface observations.

** The method has two stages:
1.COMPUTATION OF THE BASIS FUNCTIONS
1.1. Determine the deviations of available temperature and salinity profiles relative to a mean period
1.2. Compute the combined EOFs from T'(z) and S'(z)

2.WEIGHTED LEAST SQUARES FIT TO OBSERVATIONS

2.1. Determine the number of EOFs to be used in the reconstruction
2.2. Minimize the difference between the reconstruction and the surface data subject to the prescribed weights

More details are given in Maes *et al.* (1999) and by Maes and Behringer (1999).

NOTE 1: The present method is a weighted least-squares procedure which minimizes the misfit between the reconstructed and observed temperature profiles. The underlying assumption is that the coefficients of the modes determined by fitting only to temperature observations can be used with the salinity part of the modes to reconstruct the salinity profiles. This assumption is equivalent to that made when applying the traditional technique of using a T-S relationship to associate a salinity value with an observed temperature value, namely that the established statistical relationship between temperature and salinity remains valid for new observations of temperature. For the traditional case the statistical relationship is represented by a single T-S profile, while for the present method it is represented by the set of combined T-S modes, each with a common coefficient for its temperature and salinity parts. The advantage of using several modes is the possibility of representing variations over time in the T-S relationship. This representation seems particularly well suited to low frequency variability associated with ENSO as shown by Maes *et al.* (1999) (see also fig. 2).

NOTE 2 (present status): The ability of the method has been mainly demonstrated in the western Pacific (Maes *et al.*, 1999) where the salinity impact is suspected to be more important. Evidence shows that reasonable salinity signals at low frequency can be reconstructed by the present method. Also, the statistical computation of the vertical modes has been extended throughout the entire tropical band covered by the TAO array (137E95W; 8N8S) in order to benefit from available temperature profiles. Finally, the generalized method which considers temperature profiles and T/P sea level anomalies (Maes and Behringer, 1999) has been implemented for each mooring.

Can we extract from the altimetric sea level some useful information on the salinity variability at depth?

A clear response to this question is hampered by the scarceness of independent data for validation.
Independent validation: The SEACAT data offer however a limited opportunity at 165E-2S for the 1993-1995 period. To get the longest possible records (to compute stable deviations), data from 30m, 37m, 51m, and 62m have been patched together. The timeseries shows large deviations in 1994 related to low frequency variability in the western Pacific Ocean (black lines on Fig. 6). Two reconstructions of the salinity variability by the present method have been attempted without using any salinity observations in the fits. The reconstruction of salinity in the 30-60 m layer, based on both altimetry and temperature profiles (red line on Fig. 6), shows similar amplitude and a coherent phase with the observations, particularly at low frequency. To estimate the impact of the altimetry, the second reconstruction was done based only on the temperature profiles (green line on Fig. 6). At this particular location, including altimetry in the fit, leads to an improved reconstruction of salinity.

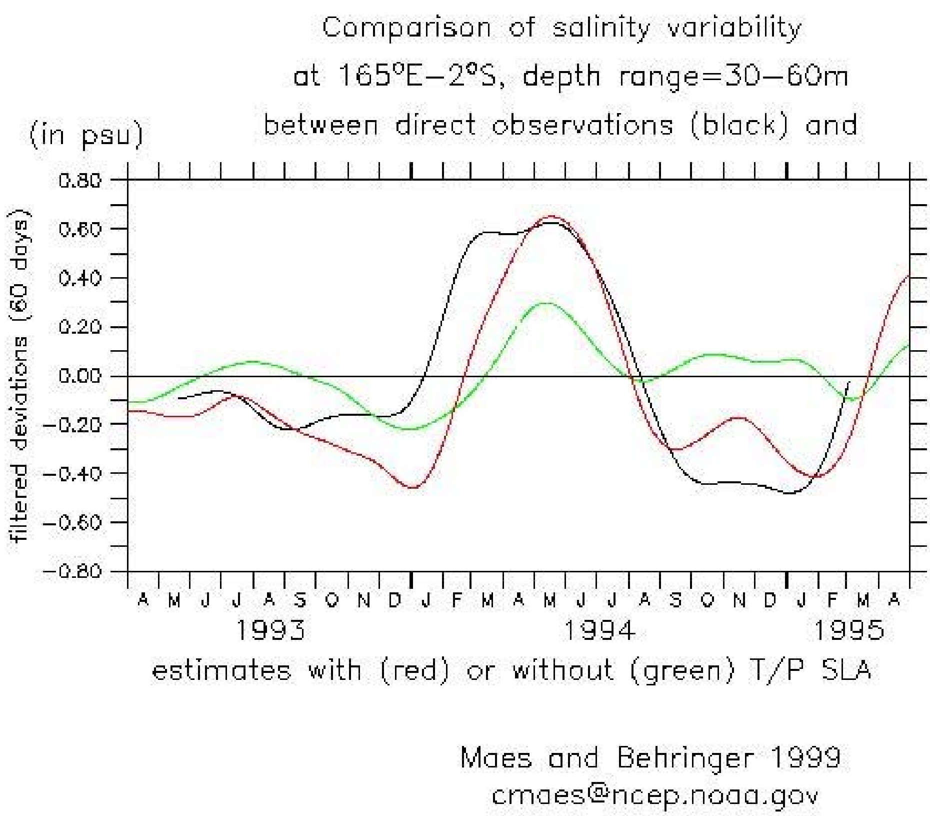

Figure 6

Large scale estimate: A similar computation at the scale of the basin is of course impossible, but an estimate of the potential use of the altimetric data may be addressed by comparing the surface height variability between the temperature fits and the T/P data across the TAO array (Fig. 7). It confirms that T/P data may have a potential and complementary impact in determining accurate analyses of the western Pacific fresh-warm pool.

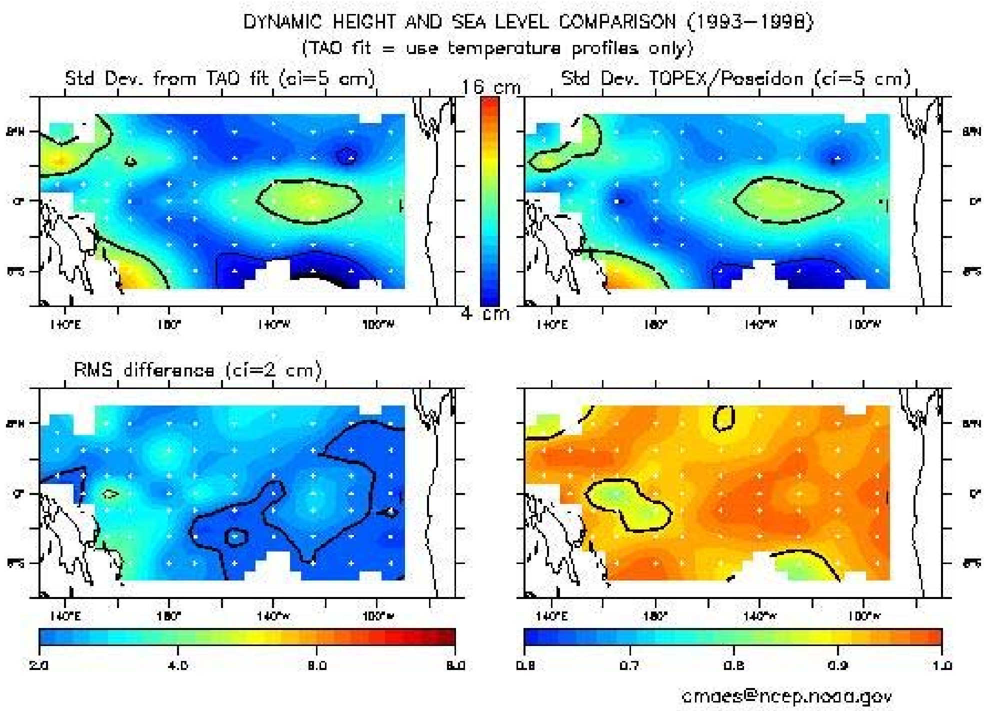

Figure 7

CONCLUSIONS & PERSPECTIVES

The variability of the salinity field is sufficiently large to influence the sea level variability, at a level which is detectable by an altimeter.

The 10 cm signal found in 1996 in the southwestern Pacific Ocean is really due to the salinity variability. The salinity of the surface layers and the stratification in the main halocline region are implicated in this "anomaly".

The sea level such as given by TOPEX/Poseidon offers a complementary source of data with which to estimate the variability of the salinity field. It shows that the present accuracy in altimetric observations is good enough to consider the salinity signal contained in them.

In order to determine the salinity variability along the water column, a novel method based on a minimization over pre-determined vertical EOF structures has been developed. Its advantages are that it avoids the limitations of a constant T-S relationship, and it can treat consistently different kind of observations (temperature, salinity, and sea level).

In order to improve the salinity variability in the NCEP ocean analysis, a new prototype of the ocean data assimilation system has been built (mainly based on the work of Vossepoel and Behringer, 1999). Preliminary assimilation runs have been conducted and they show that the model dynamics may benefit from the assimilation of salinity. Our next goal will be to study the impact of the salinity on the future ENSO forecasts.

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