The contribution of the salinity field in sea level variability of the equatorial Pacific Ocean: an overview of results

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Introduction

Despite the success of the Tropical Ocean Global Atmosphere (TOGA) program, the physical processes involved in the El Niño-Southern Oscillation (ENSO) are not definitively understood. Based on the ideas that accurate estimations of the upper ocean state are essential, the TOGA decade demonstrates that forecasting ENSO was indeed possible. Firstly concerned by the thermal state of the ocean, initial forecasting models have only corrected their temperature field but there is now a large body of literature devoted to the salinity counterpart. The consideration of sea level data from altimetry confirms definitively the necessity of separating the thermal and haline contributions from the total variability [Ji et al., 2000]. The permanent presence of salinity barrier layers [Lukas and Lindstrom, 1991] in the western Pacific Ocean also contributes to study in details the role of the salinity field in ENSO dynamics and forecasting [Ballabrera-Poy et al., 2002; Maes et al., 2002a; 2005]. In the tropics, salinity effects have generally been neglected because changes in density due to changes in temperature are several times greater than similar changes in density due to salinity. Moreover, the familiar practice of deriving the salinity at depth from a climatological T-S relationship has provided a substitute way to fill the lack of direct salinity observations. Such an approach is not always satisfactory and it is legitimate to call this method into question when the salinity variability may be detectable by an altimeter. This poster questions about the role of salinity in the forecasts of ENSO and presents the different studies (from A to D) that allow us to claim that salinity contribution of the upper ocean may be critical in climate variability.

A - Signature of salinity variability in dynamic height anomalies from a climatological data set

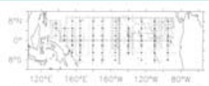
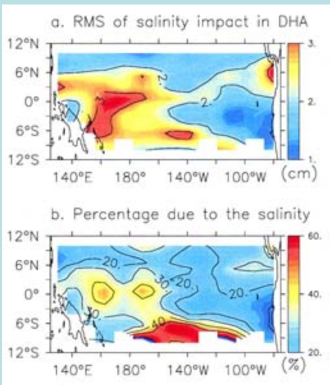


Figure A1: Spatial distributions of CTD casts (gray cross) and TAO mooring sites (square) use in this study. Note that many CTD casts are systematically done close to the TAO sites.

Dynamic height variability represents the vertical integral of the specific volume anomaly, and thus is a function of temperature, salinity and pressure. The effect of salinity variability can be highlighted by comparing two computations of DHA, one in which the observed salinity profiles are used and a second in which these are replaced by the time mean profiles of salinity over the same region. The salinity impact is then defined by the difference between the two computations.

Figure A2 illustrates the impact of salinity variability on sea level on the basin scale of the Pacific Ocean as derived from a compilation of Conductivity-Temperature-Depth (CTD) profiles (**Figure A1**). The profiles were averaged in boxes of 15° in longitude by 2° in latitude as detailed by Maes et al. [2002b]. This analysis confirms first that, in much of the Pacific basin, the standard deviation of DHA due to the salinity variability is larger than 2 dyn cm, and that the importance of the salinity variability varies from 10% in the eastern basin up to 30% in the western Pacific.



In the absence of direct measurements, salinity has been traditionally estimated from a local T-S relation computed from climatological data. The uncertainty caused by using a T-S relation was considered sufficiently small until some evidence based on sea level from altimetry demonstrated otherwise. The standard deviation of the difference between the estimate of DHA and the estimate based on constant profiles of salinity is shown in **Figure A3**. This figure shows that the salinity variability is only partially reproduced when we rely on mean T-S relationships. As expected, a large part of the observed sea level signal due to salinity variability in the upper layers (i.e., the western Pacific warm pool region) cannot be accounted for by a mean T-S relationship.

◄ **Figure A2**: Maps of (a) the salinity impact in DHA (dyn cm reference to 600 db) and of (b) the relative percentage (%) due to the salinity variability compared to the total signal in DHA.

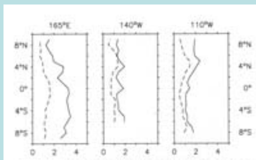
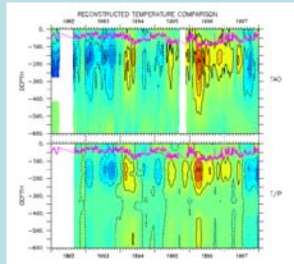


Figure A3: Standard deviations as function of latitude for the salinity impact in DHA and for the salinity impact inferred from a *T-S* relationship (dashed lines) along 165°E, 140°W, and 110°W, respectively. Units are in dyn. cm.

B - Retrospective analyses of the salinity variability using an indirect minimization approach

In the absence of direct observations, different methods have been recently proposed to improve the estimate of the salinity variability trying to exploit information contained in additional field such as the sea level [Vossepoel et al., 1999; Maes et al., 2000]. The objectives of such approaches are to determine whether the salinity variability can be reconstructed when only temperature profiles and/or sea level are available. The reconstruction is then based on a linear combination of dominant modes coupled in T and S that have been previously determined from a climatological CTD data set. In the Pacific Ocean such a way is particularly well suited in order to exploit the temperature observations collected by the TAO/TRITON array. The reliability of the indirect method proposed by Maes and Behringer [2000] could be evaluated in **Figure B1** that shows a comparison between observed salinity variability from the TRITON mooring and the indirect estimate that considered only temperature observations and the SSS. In such a region the requirement of SSS data is essential for the method to works well, and in its absence, **Figures B2 and B3** show that the contribution of salinity variability in sea level could be usefully inverted. The direct comparison between estimates and observations in the upper depth definitely confirms the potential of exploiting the contribution of salinity in sea level variability (**Figure B4**).



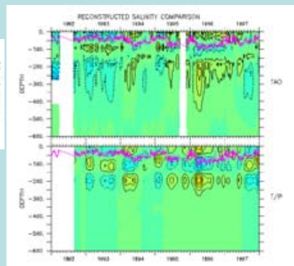
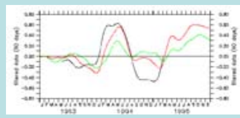
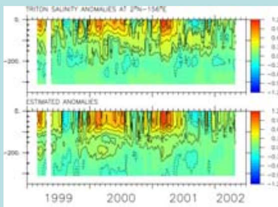


Figure B4 ► : Time series at 2°S-165°E of the salinity variations from in situ observations (black line), the reconstructed variability based on both T/P sea level anomaly data and TAO temperature profiles (red line), and the reconstructed variability using only the TAO temperature profiles (green line).





◄ **Figure B1:** Depth-time series at 2°N-156°E of the salinity variations from in situ observations (top) and from the reconstructed variability based on both T/P sea level anomaly data and temperature profiles (bottom).

Figures B2 & B3: Depth-time evolution of the temperature and salinity variability at 8°S-165°E during the 1993–1998 period: each top figure corresponds to the reconstruction using the TAO temperature profiles only and bottom part the reconstruction using the sea surface fields only (SST or SSS and SLA). The pink line is the depth of the isothermal layer determined from the original TAO data.

Does the salinity may influence the forecasts of ENSO?

The indirect estimation of the salinity variability based on sea level observations and temperature data from the TAO/TRITON array allows to study the integrated contribution of salinity into dynamic height variability at the scale of the Pacific Ocean. A decomposition into EOFs shows that the dominant mode is relevant for the ENSO phenomenon associated with the tilting of the thermocline during its mature phase (top of **Figure 1** and red curve). A similar decomposition for the salinity contribution into sea level variability displays another features with a maximum signal confined within the western Pacific warm pool and a temporal evolution as a mixing of seasonal variations and of interannual signal, mainly associated with the period prior to the 1997-98 El Niño event (middle of **Figure 1** and blue curve). During this period, a negative contribution into sea level variations is due to salinity that counteracts the positive thermal contribution that may be associated with the heat buildup prior to the event onset. These results are consistent with the coupled model analyses reported by Maes et al. [2005] and they represent a first clue to ascertain the role of the salinity variability in the equatorial Pacific warm pool in ENSO forecasts.

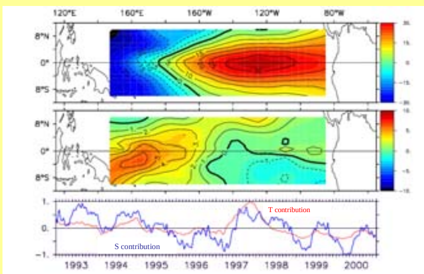


Figure 1: EOF decomposition of the thermal (top) and haline (middle) contribution in dynamic height variability (ref to 600 db); the temporal series being displayed in the bottom panel. Note that the ratio between the amplitudes of the T and S contributions is set to 3.

Conclusions and perspectives

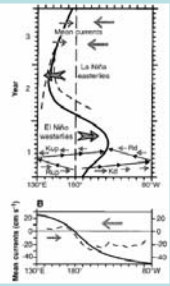
Because the impact of salinity variations on density in the tropical Pacific Ocean is significant, seasonal-to-interannual predictions of ENSO events may benefit from a more accurate representation of the salinity variability. Our different investigations also demonstrate that the accuracy of present altimetry data is sufficient to detect the salinity variations and that a combination of different observations, in situ and from satellite, will provide accurate estimations of the ocean state. Inter-comparisons of model and assimilation technique such as the one involved within GODAE will definitely benefit from these results.

In ocean-atmosphere interactions, the salinity field does not play a direct role as does sea surface temperature. However, the potential exists for salinity variations to feed back indirectly to the atmosphere through their influence on the density stratification of the upper ocean. Further work will be required to explore these findings in detail and to highlight the importance of the upper ocean salinity in climate variability.

C - Direct observations at the eastern edge of the western Pacific warm pool based on Argo profiles

Picaut et al. [1996] demonstrate that the interannual movements of the warm pool are dominated by zonal advection and that they are in phase with the Southern Oscillation. These results lie at the heart of the modification by Picaut et al. [1997] of the delayed action oscillator theory in favor of an advective-reflective conceptual model (see **Figure C1**) for the ENSO phenomenon. The convergence zone at the eastern edge of the warm pool is characterized by a salinity front that has been detected on several cruises [Eldin et al., 2004], and Maes et al. [2004] have shown that the features of the main parameters involved in the air-sea interactions are nearly constant on each side of the salinity front.

Figure C1: Diagram of the advective-reflective oscillator for ENSO (from Picaut et al., 1997).



Direct observations of temperature and salinity profiles as derived by the Argo floats that have been deployed during the last few years could be used to study the role of the salinity variability. By combining three sources of sea surface salinity observations, Maes et al. [2006] show that the salinity front on the order of 0.4 psu over 1-2° in longitude and a barrier layer on the order of 20 m are permanent features of the equatorial Pacific hydrography during the period 2002-2004. The same profiles are used to estimate the thermal and haline contributions in dynamic height anomalies (reference to 600 db) near the salinity front (**Figure C2**). These results are consistent with our previous results based on the indirect approach (part B) and further work is needed to fully understand them.

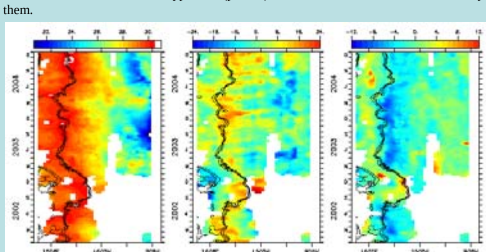


Figure C2: Time/longitude sections of SST (left), thermal contribution (middle) and haline contribution (right) for the 3°N-3°S band during the 2002-2004 period. The black thin lines represents the salinity front as a mark of the eastern edge of the warm pool. Note that these estimates are based on the data collected by the Argo floats and analyzed by Maes et al. [2006].

D - Modeling and assimilation results with the NCEP system

The use of sea level in an assimilation system that corrects only the temperature field neglects the fact that sea level is determined by salinity as well as temperature. Recent experiments with the NCEP assimilation system have revealed large discrepancies between different ocean analyses and between the analyses and the observations depending on whether salinity is corrected as part of the assimilation [Ji et al., 2000; Vossepoel and Behringer, 2000]. An illustration of this can be seen in **Figure D1**, which shows four salinity sections at 165°E in the western Pacific Ocean. At this location there is a strong subsurface tongue of high salinity water directed toward the equator from the southern hemisphere and a much weaker asymmetric tongue in the northern hemisphere. The top section is based on the Levitus climatology and the remaining three are based model analyses that have been averaged over the period 1990-2004. The Control is a quasi-global model (no Arctic Ocean) based on GFDL's MOMv3 and forced by NCEP's Reanalysis 2 and in which no data are assimilated. The overall resolution is 1°x 1°, enhanced to 1/3° in the N-S direction within 10° of the equator. In the Control the surface water is far too fresh in the tropics. The salinity tongue in the southern hemisphere is too salty, while the salinity tongue in the northern hemisphere has all but disappeared. The RA6 analysis is from the original tropical Pacific Ocean data assimilation system in use at NCEP [Ji et al., 1995]. This section shows the weak salinity signal typical of systems that assimilate only temperature. The southern salinity tongue has been prevented from reaching the equator by its encounter there with a false upwelling of fresher water caused by the temperature assimilation. The analysis shown in the bottom panel is from the Global Ocean Data Assimilation System (GODAS) which is the data assimilation system currently in use at NCEP [Behringer and Xue, 2004]. This system is based on the same model configuration as the Control and it assimilates both temperature profiles and synthetic salinity profiles based the temperature profiles and the local climatological T-S correlation. The GODAS analysis restores the average salinity structure at 165°E and, in fact, the average water mass characteristics are maintained throughout the model. This simple method cannot, however, capture salinity variations due to changes in water mass characteristics or variations in the mixed layer where the T-S correlation is weak.

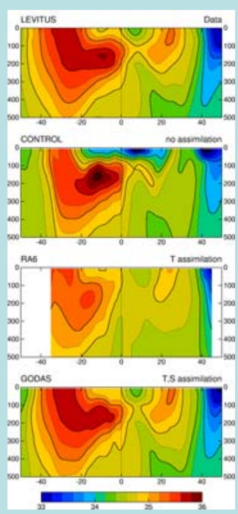


Figure D1: Salinity sections at 165°E in the western Pacific. The data are taken from, top to bottom: the Levitus climatology, a control model run that assimilates no data, RA6, and the current data assimilation system in use at NCEP. The three model sections are averages for the period 1990 to 2004.

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