4.5 THE IMPORTANCE OF SALINITY IN THE ASSIMILATION OF TEMPERATURE OBSERVATIONS IN THE TROPICAL PACIFIC OCEAN

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1. INTRODUCTION

In recent years, the oceanographic data assimilation community has become aware of the deleterious effect of univariate assimilation of temperature on the salinity field and hence on the density field (Cooper, 1988 and Troccoli *et al.*, 2001a, the latter hereafter referred to as TBS01). The equation of state tells us that, for typical temperature (T) and salinity (S) distributions in the tropics, salinity generally has a lower weight in the determination of the sea water density than temperature. This situation has been the main motivation for ignoring salinity adjustments during the assimilation process. However, this consideration is flawed by the fact that it considers the salinity role at isolated grid points rather than as part of 3D mass and flow fields. In practice, the local density gradients, both vertical and horizontal, also have to be taken into account.

A solution to correct the model salinity when temperature observations are assimilated is achieved by using model-derived water mass properties (T and S). Here, the model used is a quasi-isopycnal model. The salinity increments are calculated according to the temperature analysis by preserving the model's local T–S relationships as described in Troccoli and Haines (1999) (hereafter TH99). Thus, this salinity correction scheme (or TH99 scheme) only needs three easily retrievable ingredients: (1) the analyzed temperature profile and (2) the model temperature and (3) model salinity profiles, for each model grid point. The analyzed temperature profile can be the result of any analysis method such as, for example, optimal interpolation. The TH99 scheme does not make any use of statistics for the salinity adjustment.

This paper is organized as follows. In section 2 the ocean model, the data assimilation system and the experiments are briefly described. Comparisons with comprehensive observation analyses recently published by Johnson *et al.* (2000) are presented in section 3. In section 4, results from a simple hindcast experiment is analyzed. Finally, a discussion is presented in section 5.

2. EXPERIMENTAL SET-UP

Ocean Model The ocean model used in this work is the reduced-gravity quasi-isopycnal Poseidon ocean model developed by Schopf and Loughe (1995). This is the same ocean model used in a global configuration for the NASA Seasonal-to-Interannual Prediction Project's (NSIPP) coupled forecast system. However, for this study the domain was restricted to the Pacific Ocean, from 45°S to 60°N. The horizontal resolution was 1° x 1°, plus an equatorial refinement: the meridional resolution changes smoothly from 1/3° at the equator to 1° within ±10°N. There are 20 layers in the vertical.

The model is forced by daily averaged wind stress (Atlas *et al.*, 1991). The same wind product, but monthly averaged, is used to derive the sensible and latent heat components through the atmospheric mixed layer model by Seager *et al.* (1995). The precipitation is given by the monthly averaged analyses of Xie and Arkin (1997). No additional relaxation to observations is applied to either temperature or salinity.

Data Assimilation System The data assimilation system in this study is composed of two parts: a univariate optimal interpolation (OI) to update temperature and the TH99 scheme to update salinity. Note that only TAO (Tropical Atmosphere-Ocean, e.g., McPhaden *et al.*, 1998) sub-surface temperature measurements are employed. The univariate temperature OI (with the model T used as a background) is performed every 2 days. The background temperature error covariance has correlation length scales of about 1200 km zonally and 400 km meridionally.

The TH99 scheme used to update the vertical salinity profiles is in two parts. This procedure is performed on each model grid point. First, a vertical displacement of the model T background profile to match the deepest analyzed T is made. The same displacement is applied to the S profile, too. Second, the scheme computes an S analysis using the T–S pairs and the analyzed T at each grid point. As the T–S preservation assumption generally does not hold near the surface, the salinity is not updated in the surface isothermal layer.

The T and S increments thus calculated are then uniformly added to the model background over a 2-day period, in order to allow the model to gradually adjust to the analyzed density perturbations.

Description of the Experiments Two experiments have been performed: a) only temperature is updated (hereafter *TOI*) and b) both salinity and temperature are updated (hereafter *TOIS*) with salinity increments given by the TH99 scheme. For reference, a third control run with no data assimilation (hereafter *CNT*) is used to check how the data assimilation affects systematic model errors. The three runs all use the same ocean model set-up. The initial conditions were taken from a spun up

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run described in Borovikov *et al.* (2001). The experiments were run for the period July 1996 through December 1998.

3. COMPARISON WITH OBSERVATIONS

Subsurface salinity observations are rather scarce and so it is generally difficult to validate model and/or assimilation results in terms of the salinity field. A recent paper by Johnson *et al.* (2000) (hereafter JMRM) provided a thorough data analysis of salinity (CTD observations), as well as zonal velocity (ADCP observations), for the equatorial Pacific for the period from September 1996 to November 1998. We shall compare JMRM's analysis with our data assimilation runs (a more thorough investigation is carried out in Troccoli *et al.*, 2001b). Note that the period considered covers the strong 1997-1998 El Niño event and the subsequent La Niña event, hence it encompasses a marked range of ocean variability for both salinity and zonal velocity, as discussed by JMRM.

Model vs. observations rms difference An analysis which uses all available JMRM observations is presented in this section. First, the model fields are mapped onto the same grid used by JMRM, which is 1/5° zonally and 10 m vertically. Then, the 35 transects presented by JMRM are grouped into two sets, according to their longitude: Niño4, consisting of transects 165°E, 180°, 170°W and 155°W, and Niño3, consisting of transects 140°W, 125°W, 110°W and 95°W. Further, for each of the two sets, only the depth dependence is retained with the aim of studying how the assimilation affects the vertical structure. The variables considered are temperature (from the same CTD casts as for salinity), salinity and zonal velocity. The RMS difference (RMSD) for the three runs with respect to the observations is then calculated and shown in Figure 1. Note that, because only TAO temperature observations have been assimilated, this analysis represents an independent validation.

As expected, the temperature RMSD is notably reduced in the two assimilation runs with respect to the *CNT* run (Figs. 1a-b). This reduction is more accentuated in Niño3, where the RMSD in *CNT* is about 1°C larger than in either *TOI* or *TOIS* in most of the thermocline, that is from 50 m to 250 m. Important differences between *TOI* and *TOIS*, for both Niño4 and Niño3, are present below 250 m. These differences are about 0.2°C all the way down to 900 m, reaching 0.35°C between 500 m and 600 m in Niño3. The larger RMSD for *TOI* reflects the worsening of the thermal structure below the thermocline as a consequence of gravitationally unstable conditions induced by the univariate T assimilation (see Troccoli *et al.*, 2001b). Therefore, it is a positive feature of the TH99 scheme that by changing the salinity field even the thermal structure is improved.

With Figures. 1c-d we analyze the salinity RMSD. In the upper 110 m of Niño4, the *TOIS* RMSD is the largest of the three runs. However, in the main thermocline, that is from below the mixed layer to a depth of about 250 m, the salinity RMSD in *TOIS* is always smaller than in *TOI* in both Niño4 and Niño3 and their difference reaches a peak of 0.17 at 165 m in Niño4. Below 250 m, the salinity RMSD trend is similar to that for the temperature RMSD, even though now the magnitude of the improvement of *TOIS* is relatively larger: an average of 32% for temperature against 57% for salinity. In absolute terms, the RMSD for *TOIS* is smaller than that of *TOI* by at least 0.02, but often the difference is considerably larger, with a maximum of 0.16 at 410 m in Niño3. It is worth noting that the RMSD for *CNT* is comparable to that of *TOIS*, again indicating that the ocean model alone is able to simulate the salinity field well.

The RMSD for the zonal velocity field in Figures 1e-f indicate an improvement yielded by *TOIS* over *TOI* throughout the whole 450 m, consistent with the density field being better represented by *TOIS* (not shown). The differences between the RMSD of *TOI* and *TOIS* range from 0.01 m s^{-1} to 0.06 m s^{-1}, with an average improvement of about 17.5% over the 450 m. The zonal velocity RMSD for *CNT* is overall better than both assimilation runs, although very similar to that for *TOIS*.

4. HINDCAST EXPERIMENT

In order to investigate the impact of the different subsurface assimilation in *TOI* and *TOIS* on the evolution of the ocean simulation, we have performed two hindcast experiments. These are conducted by simply running the model without assimilation, as in *CNT*, but starting it from two different initial conditions: *TOI* April 1997 and *TOIS* April 1997 (the hindcast are H *TOI* and H *TOIS*, respectively). Note that Spring 1997 coincides with the start of the incoming strong 1997-98 El Niño, as can be seen for instance by the deepening of the 20°C isotherm between March and November 1997 in Niño3 (Figure 2d), and hence April 1997 represents a challenging initial condition.

The results of the hindcasts are shown in Figure 2 in terms of sea surface temperature (SST) and depth of the 20°C isotherm averaged over Niño4 and Niño3. Since temperature is assimilated in *TOIS*, these two runs will be taken as the "truth". The *CNT* run, on the other hand, varies significantly from the two assimilation runs. Differences in SST are as large as 1.2°C (June 1997) in Niño4 and 1.1°C (April 1997) in Niño3. Analogously, differences of the depth of the 20°C isotherm are as large as 17 m (June 1998) in Niño4 and 25 m in (July 1998) in Niño3.

In terms of SST, H *TOI* and H *TOIS* show little deviation from one another. Indeed, this similarity was expected as surface forcings and initial conditions are essentially the same for both H *TOI* and H *TOIS*. Further, they gradually reach convergence towards the *CNT* solution after several months: about 7 mn for Niño4 and 9 mn for Niño3. These timescales are, therefore, indicative of the predictability range of a hypothetical coupled model experiment, and in our case do not depend on the type of subsurface assimilation employed.

Somewhat different from SST is the behaviour of the depth of the 20°C isotherm. For this index, in fact, differences between H *TOI* and H *TOIS* are more accentuated and reach a peak of 6 m (September 1997) in Niño4 and 4 m (August 1997) in Niño3. In particular, H *TOIS* is closer than H *TOI* to the assimilation runs for the first seven months, i.e. to December 1997, showing that the correction of subsurface salinity impacts the dynamics for times comparable to those of interest to seasonal forecasting. After the 1997 Summer, however, the two hindcast experiments become basically indistinguishable, except between March and June 1998 when H *TOI* is closer to the assimilation runs than H *TOIS*.

5. SUMMARY AND DISCUSSION

In this study, the salinity scheme proposed by TH99 has been applied to the Poseidon quasi-isopycnal model used at the NASA Seasonal-to-Interannual Prediction Project (NSIPP) with the aim of implementing it in the data assimilation system employed for routine forecasts. The results of two assimilation experiments, one with temperature OI only, *TOI*, and the other like *TOI* but with the addition of the salinity scheme, *TOIS*, have been compared with several observations that were available in the period July 1996-December 1998. The RMS differences between salinity, zonal velocity, as well as temperature, model and observations taken along 35 equatorial meridional transects, from Johnson *et al.* (2000), offer a very encouraging assessment of the salinity scheme when compared to a conventional OI procedure that does not update salinity.

Further, a simple hindcast experiment has shown that, when salinity is corrected, subsurface temperature remains closer to the truth for about 6-7 months, in Niño4 and Niño3 regions. Of course, one should not rely on a hindcast experiment thus formulated since real coupled model simulations might be affected by other surface forcings errors than the pre-assigned forcings used in the present case. Also, one single experiment is not statistically significant and should be regarded with care. However, because to run coupled model simulations is computationally expensive, inexpensive experiments like this are useful to give some indication of the possible behaviour of the ocean model in a forecast setting.

Whether the TH99 salinity scheme performs better than other approaches such as multivariate OI, based on observation or model EOF correlations, or the ensemble Kalman filter is a matter that is under investigation. Given its simplicity, the TH99 scheme is easily implementable to any ocean model and it is computationally efficient. Also, it does not need any observation or model climatology that can limit the variation spread, and no pre-compiled configuration-dependent statistics, such as EOFs, have to be computed. However, the TH99 scheme strongly relies on the model dynamics and realistic forcing to get a good salinity field reconstruction and therefore it can only be applied to ocean models that simulate the distribution of water masses reasonably well. It has been shown in this study, as well as in TBS01, that the two primitive equation models in question, Poseidon and HOPE, satisfy this requirement well.

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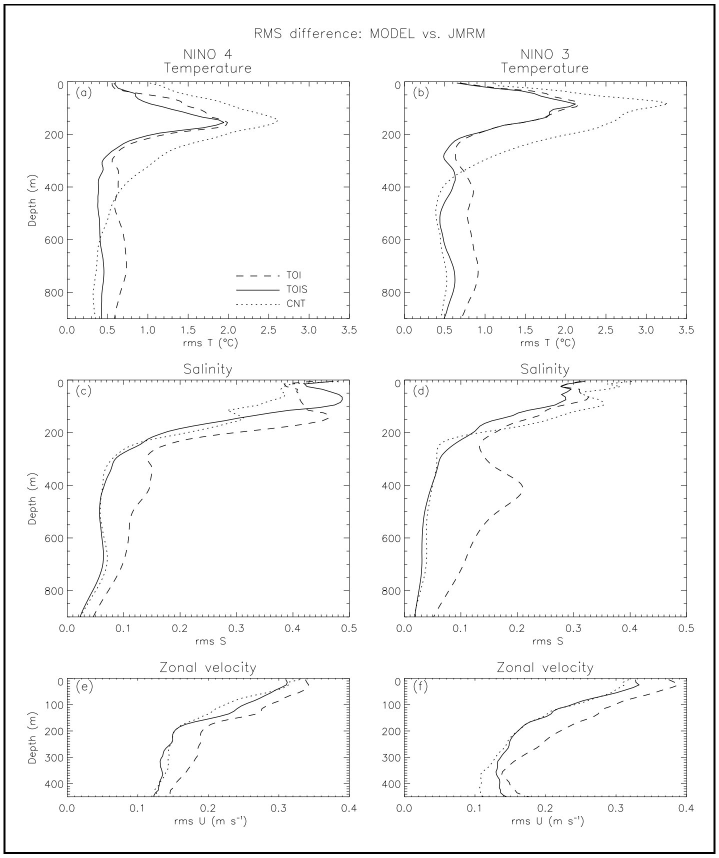

Figure 1: RMSD between the three model runs (*TOI*, *TOIS* and *CNT*) and the JMRM's observations as a function of depth for the 35 transects analyzed by JMRM grouped in Niño4 (a,c,e) and Niño3 (b,d,f). Temperature RMSD (a-b), salinity RMSD (c-d) and zonal velocity RMSD (e-f). Note that temperature and salinity extend to 900 m, whereas zonal velocity to 450 m. Note that salinity is unitless, as defined by the 1978 Practical Salinity Scale, but can be thought of roughly as a ratio of masses multiplied by 1000.

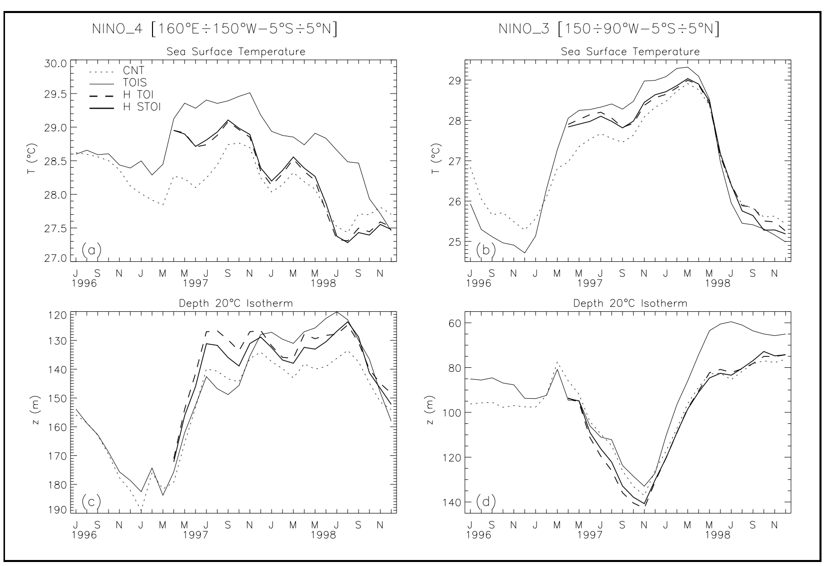

Figure 2: Monthly averages of model derived variables for the *TOIS* and *CNT* plus two hindcasts (H TOI and H STOI) started in April 1997 from *TOI* and *TOIS*, respectively, for Niño4 (a,c) and Niño3 (b,d). Sea surface temperature (a-b) and depth of the 20°C isotherm (c-d).