# IMPACT OF MULTI-VARIATE ASSIMILATION ON ESTIMATES OF THE STATE OF THE TROPICAL PACIFIC OCEAN

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## INTRODUCTION

Most current realistic applications of ocean data assimilation focus on approximations to the error covariance statistics in order to achieve computational viability. For the ocean, even the simpler assimilation techniques such as optimal interpolation suffer from inadequate representation of error statistics because of the paucity of ocean observations. Monte Carlo methods provide one possible way to evolve the forecast error statistics in a realistic manner while limiting the computational burden. The ensemble Kalman filter (EnKF) integrates an ensemble of model states from which the evolving error covariances can be calculated, consistent with the evolving model dynamics and any data assimilated. Evensen and van Leeuwen (1996) showed the viability of this approach for assimilating GEOSAT data into a two-layer quasi-geostrophic model of the Agulhas Current. Keppenne (1999) demonstrated its efficacy for a strongly nonlinear two-layer shallow water model. Keppenne and Rienecker (1999) have demonstrated the viability of using an EnKF even for a multi-layer model of the Pacific basin when implemented on a parallel computing architecture. However, the computational burden is still significant.

An alternative Monte Carlo application is to use the variability of the ensemble as a one-time estimate of the statistics of model forecast error – an optimal interpolation framework, but with anisotropic, inhomogeneous error covariances estimated consistent with model dynamics and the impact of ocean-land boundaries. This is the approach taken here to estimate forecast error statistics for the Poseidon quasi-isopycnal ocean model. The ensemble is generated by forcing the model with an ensemble of air-sea fluxes. These fluxes are obtained from a series of integrations of the Aries atmospheric model (e.g., Suarez and Takacs, 1995) forced by the same interannually varying sea surface temperatures (SST) and differing only in slight perturbations to the initial atmospheric state. Differences between the time series from each ensemble member are due to atmospheric internal variability. The interannual anomalies in surface stress and heat flux components are added to climatological seasonal forcing estimated from the SSM/I wind analyses (e.g., Busalacchi et al., 1993), ERBE shortwave radiation, ISCCP clouds, and air temperatures and specific humidity from the NCEP reanalyses. This approach attributes all of the ocean model forecast error to uncertainties in the longer timescale surface flux anomalies. In all, 96 ensemble runs were conducted.

The Poseidon ocean model is a reduced gravity model with explicit Kraus-Turner bulk mixed layer physics implemented in the uppermost layer of the model (e.g., Schopf and Loughe, 1995). For this application, the ocean model has 20 layers, zonal resolution of 1°, and meridional resolution of 1/3° in the equatorial region, stretching to 1° at 20°N and 20°S. The model domain extends from 120°E to 85°W, from 45°S to 65°N, with a solid northern boundary and a 10°-wide buffer zone at the southern boundary where the temperature and salinity are relaxed to the Levitus climatology.

## ERROR COVARIANCE ESTIMATES

An example of the covariance estimates calculated from the ensemble members in winter is plotted in Figure 1. The covariances have been calculated by interpolating the layer variables to the depths of sensors on the TAO moorings. The covariance along the equator has the anticipated structure of elongated zonal scales compared with meridional scales. There is also a slight tilt with depth of the covariance along the equator, consistent with the influence of the equatorial undercurrent. The meridional structure displays a slight asymmetry in the tilt from south to north across the equator consistent with the slightly deeper thermocline to the south. Covariance estimates between temperature and salinity (not shown) display much shorter horizontal scales and distinct asymmetries. Covariance estimates for velocity (not shown) also display shorter scales. These covariances are used to assimilate the TAO temperature observations in an optimal interpolation framework.

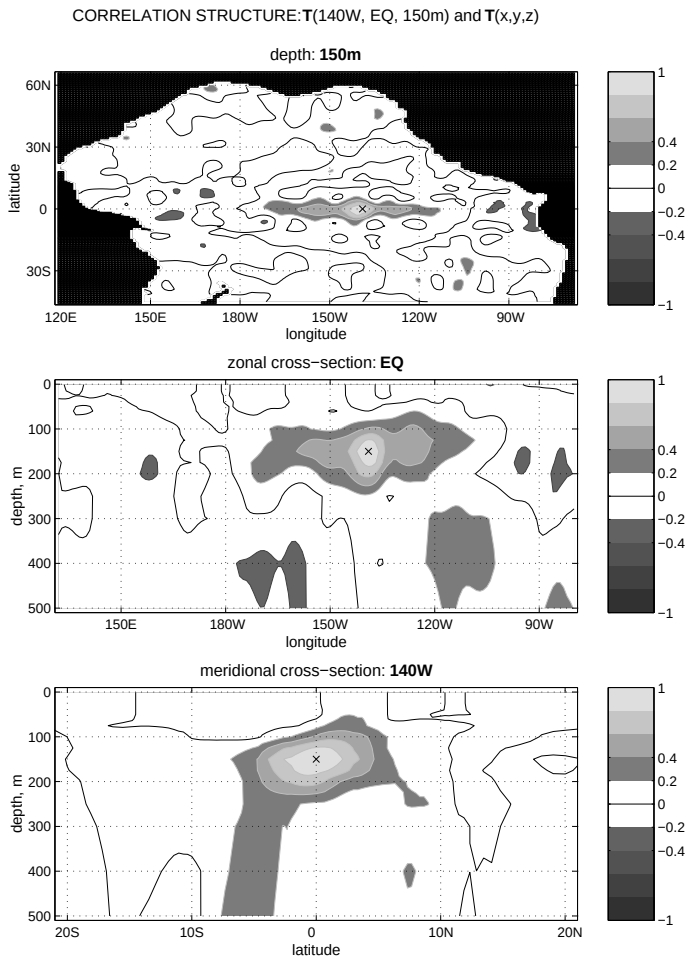


Figure 1. Correlation between 150m temperature errors at 140°W on the equator and temperature errors elsewhere in the Pacific basin, as calculated from an enemble of integrations. The upper panel shows the correlation at 150m, the middle panel the correlation along the equator as a function of depth, the lower panel the correlation at a meridional cross-section at 140°W. Only values estimated as significant at the 95% level are shaded The contour interval is 0.2.

## ASSIMILATION EXPERIMENTS

When assimilating TAO temperature observations, corrections are often made to only the model temperature fields (e.g., Behringer et al., 1998), relying on the model to adjust the remaining fields according to the updated temperature fields and the governing dynamics. However, a multi-variate framework allows the correction of the entire model state vector. Here experiments have been conducted both to assess the efficacy of the Monte Carlo estimated error covariances and of corrections made to the entire state vector. Because of the lack of salinity observations, the assessment is first undertaken through an identical twin experiment.

For the identical twin experiment, the control integration from which synthetic observations are extracted is forced by time-dependent SSMI surface winds and time-dependent surface heat flux estimates. The forecast experiment is forced by FSU surface winds and climatological surface heat flux estimates. The differences between the SSMI and FSU surface winds are enough to produce significant (although not large) differences in model climatologies and model evolution (e.g., Borovikov and Rienecker, 1999). The synthetic observations are assimilated into the FSU forecast. The first assimilation experiment corrects temperature only, the second corrects temperature, salinity and velocity. The accuracy of the model integrations and of the assimilation analysis fields is assessed in relation to the control integration. Note that in this case the differences between the two integrations (control and forecast without assimilation) do not display a significant bias (e.g., Figure 2). These experiments have been conducted for a single 6-month period with assimilation of daily-averaged observations every 5 days.

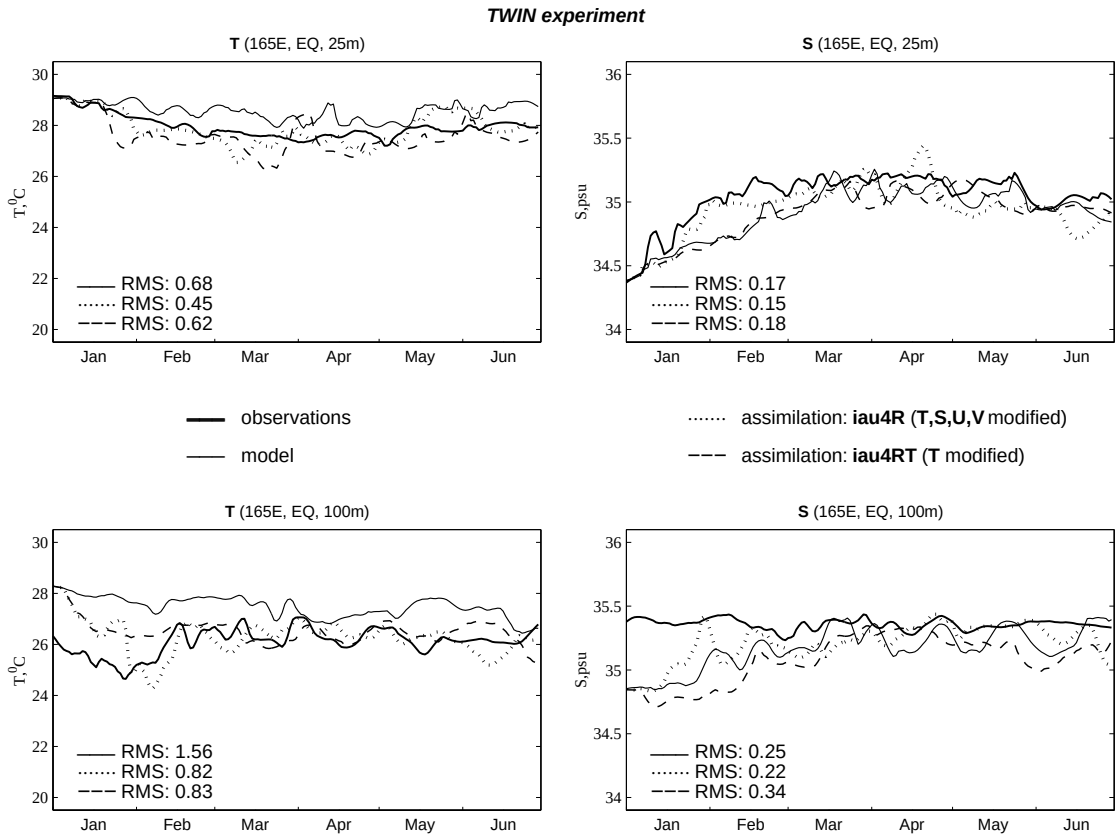


Figure 2. Time series of temperature (left panels) and salinity (right panels) at 165°E on the equator, at 25m (upper panels) and 100m (lower panels). The synthetic observations from the SSMI integration are denoted observations, the FSU integration is denoted model, the assimilation with temperature only corrections is denoted iau4RT, the assimilation with full state vector corrections is denoted iau4R. The RMS (root mean square) values are differences between the model/assimilation time series and control integration.

In the western Pacific, the assimilation which corrects the entire model state tends to produce a more accurate time series of both temperature and salinity in the upper ocean. Both assimilation experiments improve the temperature time series, but when no salinity corrections are made, the salinity errors are slightly worse than the forecast case without assimilation. Below the thermocline the results are mixed. In the eastern Pacific (not shown), both assimilation experiments improve the salinity. Surprisingly, the assimilation which corrects only temperature produces a slightly more accurate temperature time series than the correction to the full state vector. However, much of the discrepancy lies later in the integration period when the winter covariance estimates are probably not appropriate. Assimilation experiments where the covariance estimates are seasonally varying are underway.

The assimilation of TAO observations requires the assimilation to compensate for model bias as well as temporal error. This it does effectively (e.g., Figure 3). These integrations are conducted with daily SSMI surface wind forcing and climatological surface heat flux forcing. Again in the upper ocean the correction of the full state vector improves the accuracy of the temperature time series, however in the mid-thermocline and below, the assimilation which corrects temperature only seems to be more accurate. In the eastern basin, the two assimilation experiments are of comparable accuracy.

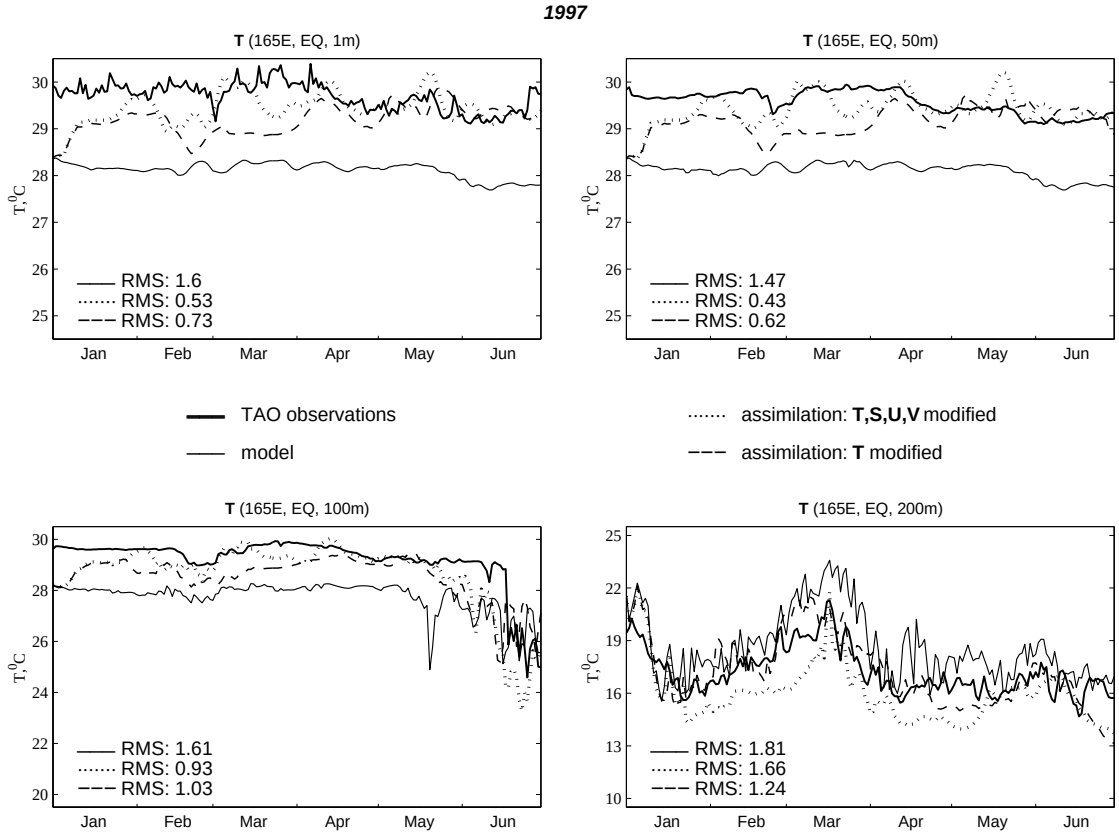


Figure 3. Time series of temperature at 165°E on the equator, at selected depths. The TAO observations are shown with the model integration without assimilation and with the two assimilation experiments. The RMS (root mean square) values are differences between the model/assimilation time series and the TAO observations.

## CONCLUSIONS

The Monte Carlo estimates of forecast error covariance have proven effective for multi-variate upper ocean assimilation, however it appears that at least seasonally varying estimates will improve the results. Some problems were encountered in the inversion of the representer matrix because of ill-conditioning. This is likely associated with erroneous covariance at large spatial lags and will be addressed by tapering the estimated covariances.

## ACKNOWLEDGMENTS

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