3.1 RECENT EXPERIENCE WITH PRACTICAL OCEAN DATA ASSIMILATION

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I.

ECCO is a Consortium of scientists at MIT/JPL/SIO under the National Ocean Partnership Program (NOPP) directed at producing three-dimensional time-dependent estimates of the
ocean circulation from all available global and near-global observations. In contrast to some other attempts at global state estimates, ECCO aims to use methods which produce dynamically consistent states and time-evolving transitions between states. Thus the focus has been on using methodologies which become rigorous with increasing resolution full model physics, and accurate a priori covariances, at the expense of a greatly increased computational load. The methods being used are that of Lagrange multipliers (adjoint method) and sequential smoother methods, both of which can produce state estimates without spurious sources/sinks either at one time step or in the transition between time steps (as happens for example, with Kalman filter methods).

The first general results have been documented in manuscripts, reports and animations available on-line at http://ecco-group.org/. They were produced at MIT and SIO using the MIT general circulation model, the WOCE data, including especially altimetry, over the period 1992-1998, and the adjoint method. A nearly fully optimized solution, in which control variables include initial conditions, twice-daily wind-stress, and daily buoyancy fluxes were determined. The resulting solutions, perhaps best appreciated in the animations, show a remarkably energetic time-variable
circulation. Adjustments to the control variables are represented, e.g. in Fig. 1, which shows the modifications made to the heat, freshwater and wind stress components averaged over the 6 year period; these appear to be generally acceptable within the (guessed) error bars of the initial NCEP estimates.

The solution is being analyzed for the physics of the circulation, e.g., for the implied heat and fresh water flux divergences, and for the vertical exchanges within the water column (Fig. 2). The MIT/SIO estimates are being extended through year 2000. Ongoing work is directed at greatly increasing the model resolution (now 2 degrees), comparing the results to those from a method based upon reduced state Kalman Filter/RTS smoother algorithms, with these used to generate error estimates, and beginning production of a near-real-time product with slightly reduced skill.
Ultimately, these state estimates will become the basis of large-scale forecasts and initial states for fully coupled models.

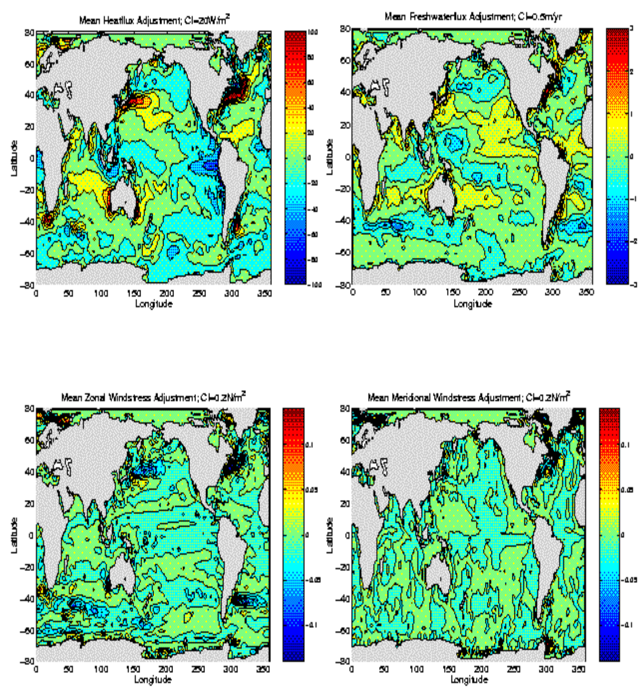

Figure 1
Mean adjustments over the six year assimilation period of the surface flux conditions. Although a few regions are problematic, primarily associated with low resolution in western

boundary currents, these adjustments are not in conflict with estimates of the errors in NCEP fields.

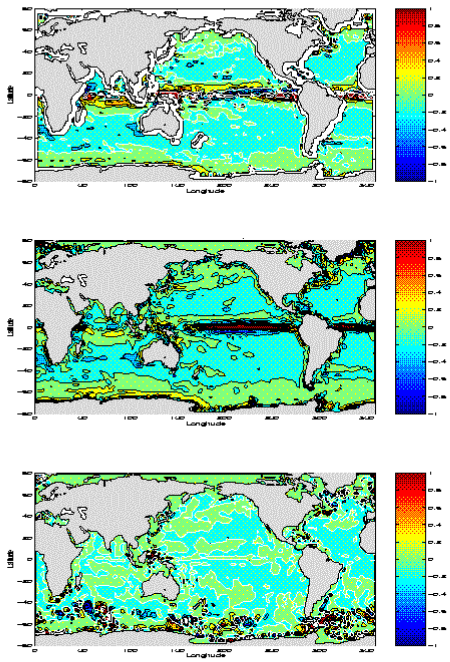

Figure 2.
Ekman pumping velocity and vertical velocity at 37.5 and 1750m (top to bottom) as it results from the estimated ocean state. Contour interval is 0.2x10^(-5) m/s.

II.

The ocean data assimilation system at NCEP is used to provide the initial ocean conditions for coupled ocean-atmosphere forecasts of the Pacific Ocean sea surface temperature. The present operational system is confined to the Pacific basin and is based on GFDL's MOM. It has a nominal 1o resolution with increased resolution in the tropics and it has 28 levels in the vertical. A new global version of the system based on MOM 3.0 is also running in prototype. The global model has similar horizontal resolution as the Pacific model, but with 40 levels in the vertical aimed at better resolving the upper ocean and a full suite of improved model physics. The assimilation system is a 3D variational scheme that has evolved from the work of Derber and Rosati (1989). Over the past 10 years the original system which assimilated only temperature observations has been extended to assimilate sea surface height (SSH) and salinity data as well. Because of our interest in ENSO forecasting the focus of these changes has been the improvement of the representation of the tropical ocean.

Assimilating SSH

Only the variable part of the observed sea surface height (SSH) is assimilated which avoids the problem of having to establish an accurate geoid. The SSH observations represent an integral constraint on the model field of mass. Because variations in ocean density are largely determined by variations in temperature, the assimilation of SSH was originally designed to correct only temperature. In such a system a mismatch between observed SSH and model SSH implies a correction to the model temperature field that must be distributed down through the water column. How that correction is apportioned at each depth is determined by the specification of the first guess or background error covariance. By assimilating SSH the amount of data available to constrain the model is greatly increased over what was possible when only temperature data were assimilated.

Assimilating salinity

In a univariate system that assimilates SSH, but corrects only temperature, a situation can arise where errors in the model SSH are caused to salinity errors and, in that case, the response to that error can be wrongly folded into the temperature correction. Also, if only temperature is corrected in an ocean model it will result in the corruption of the salinity structure in the tropics. The reason for this is that the correction of temperature alters the mass field and leads to a change in the setup of the zonal pressure gradient on the equator. This, in turn, alters the zonal currents associated with the pressure gradient. However, the assimilation has no effect on the currents that are driven directly by the winds. The net result is an imbalance that produces a false zonal circulation cell with deep upwelling in the west and downwelling in the east. The upwelling brings up low salinity water that is then distributed eastward by the equatorial undercurrent, degrading the salinity maximum in the upper layers of the equatorial zone.

Assimilating and correcting salinity has two effects. First, the model salinity field is maintained and the water mass characteristics remain correct. Second, the imbalance between the zonal gradient currents and the directly wind driven currents is lessened and the false zonal circulation cell is greatly reduced in magnitude. The reason is that if only temperature is corrected in the NCEP model the zonal pressure gradient is strengthened leading to the imbalance described above; however, if salinity is also corrected the net change in the pressure gradient is greatly reduced and the imbalance between gradient and wind currents is reduced as well.

At present there are too few in situ salinity profiles to be of practical use in a data assimilation system and instead we use synthetic profiles computed via a statistical method developed by Maes et al. (2000). As the Argo array is deployed in situ profiles of salinity will replace the synthetic profiles.

Although the assimilation of temperature data had a clear, positive impact on ENSO forecasting at NCEP, the additional assimilation of SSH and salinity has not resulted in a significant further improvement. It may be that we will not see the effect of these data on ENSO forecasting until we have the next generation ocean-atmosphere model based on a global ocean with improved physics.

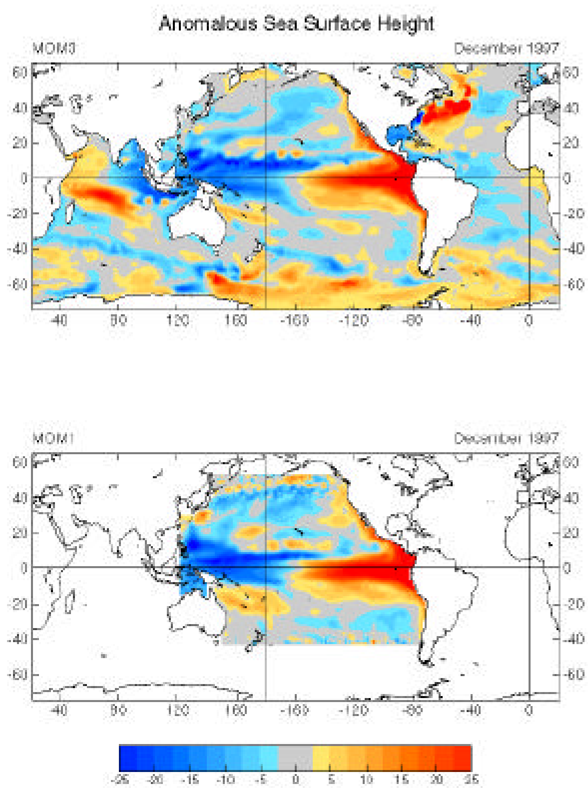

Figure 3. Anomalous sea surface height for December, 1997, in the prototype global ocean data assimilation system (Top) and in current operational Pacific basin system (Bottom). The point is simply to illustrate the domains of the two systems.

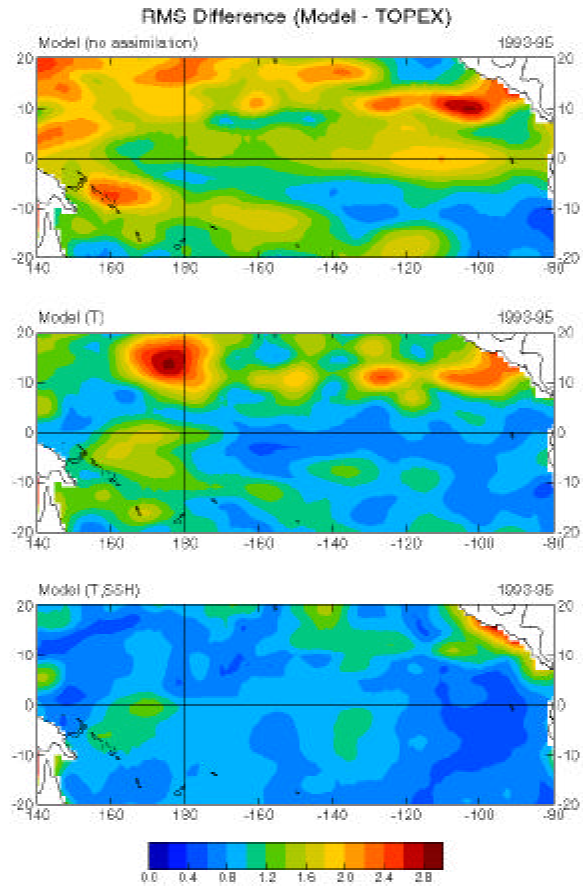

Figure 4. RMS difference in SSH between three model runs and TOPEX. These are based on monthly average time-series, each with its mean removed. TOPEX has been interpolated to the model grid. Top: This is for a simulation, no data have been assimilated. Middle: In this case temperature profiles from XBTs and TAO moorings have been assimilated. The TAO mooring array spans the basin at about 15O degree intervals and the equatorial zone between 8S and 8N at 2-4O intervals. They provide daily profiles of temperature and their ability to reduce the model - TOPEX difference in the equatorial zone is apparent. Bottom: In this case TOPEX itself has been assimilated as well as the XBTs and TAO profiles. This last is not a validation, but it illustrates the effectiveness of assimilating TOPEX.

III.

The data assimilation effect ongoing at Goddard Space Flight, NASA Research Center under the leadership of Michele Rienecker is now discussed:

Because of its thermal inertia, the initialization of the ocean state plays a key role in the ability to forecast El Nino with coupled models. Such forecast systems (e.g., Ji et al., 1994) usually produce ocean initial conditions by assimilating subsurface temperature data to compensate for model and forcing errors. The assimilation of sea surface height (SSH) observations from satellite altimeters can also potentially improve the model representation of temperature and SSH, especially where subsurface temperature observations are sparse. Historically, both subsurface
temperature and SSH assimilation have been conducted in a univariate assimilation system where only temperature corrections have been made. The model then has had the burden of modifying the salinity and flow fields in accordance with the new temperature analysis. In recent years, the oceanographic assimilation community has become aware of the deleterious effects of univariate assimilation on the salinity field and hence on the density field (e.g., Ji et al., 2000; Troccoli et al., 2001) and ultimately on the forecast. In many cases, not only the salinity field is degraded but also the temperature field because the modification of water masses (see Figure 5). The degradation of the mass field then leads to poor flow fields. Corrections can be made through multivariate assimilation if the forecast error statistics are estimated reliably. An alternative technique adjusts the model¹s local salinity profiles such as to conserve the model
water masses. This simple technique appears effective in maintaining both temperature and salinity structures in the model (figure 5).

The problem of univariate assimilation is exacerbated in the assimilation of SSH. Errors in the mass field that may be due to salinity errors can be wrongly folded into the temperature correction. Indeed, there are significant salinity variations in upper ocean salinity on interannual time scales (e.g., Ji et al., 2000; Maes and Behringer, 2000), and this precludes the use of climatological T-S relations when using SSH data (figure 6). In a bivariate system that corrects both salinity and temperature, SSH assimilation produces corrections that are apportioned between temperature and salinity. Several techniques have been devised for this. One (Maes and Behringer, 2000) uses vertical modes of T and S to reconstruct salinity profiles by a weighted least squares procedure. The technique preserves some of the temporal variability in the local T-S relationship.

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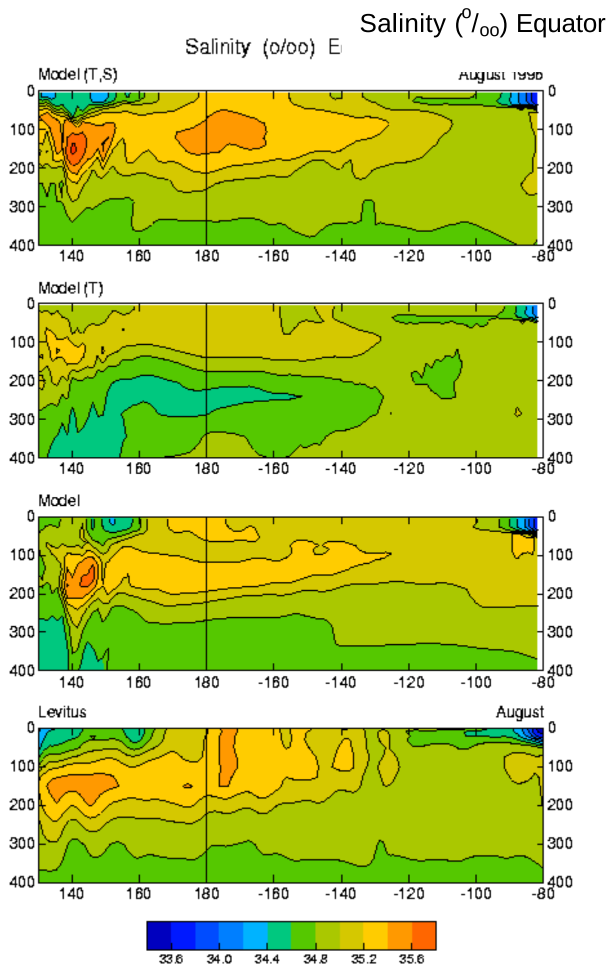

Figure 5

A comparison of analyses of equatorial sections of salinity. The first three are from model analyses that assimilate both temperature and salinity (Model(T,S)), temperature alone (Model(T)) and no data at all (Model) and the last is from Levitus. They illustrate the degradation of the model salinity field in the tropics that occurs when only temperature is assimilated. It demonstrates the importance of assimilating salinity as well as temperature if water mass characteristics are to be conserved.

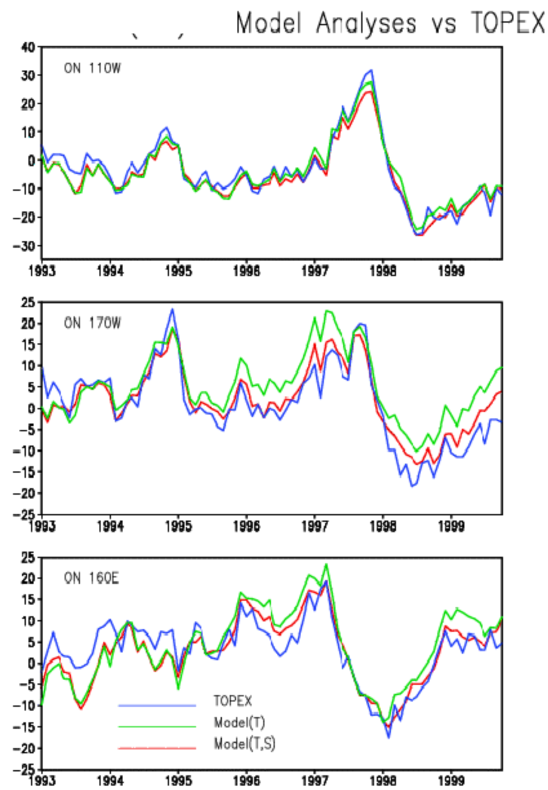

FIGURE 6

An illustration of the improvement in the model representation of sea level for the case where both temperature and salinity are assimilated as compared to the case where only temperature is assimilated. The model runs are compared to TOPEX altimetry, which is independent data for these two runs.