# Surface fluxes and ocean state estimates in the Eastern Subtropical North Atlantic

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## Introduction

The goal of ocean state estimation is to obtain a dynamically consistent synthesis of a diverse set of in situ and remote observations through their combination with ocean general circulation models (OGCMs). Early results from a global state estimation effort [1] have indicated that significant corrections (with typical magnitude of specified uncertainties) on surface fluxes of buoyancy and momentum can be obtained in the process, and that the corrected forcing fields might be in closer agreement with independent observations than the uncorrected fields. Global solutions can also provide boundary conditions for regional models. It was demonstrated [2] that the flow field of an Indian Ocean model which incorporated the results of a global model run at its open boundaries improved markedly over a closed boundary solution.

Here we start to investigate these two applications in a small box in the Subtropical North Atlantic between 9° N and 39° N and 43° W and 5° W. This area contains the locations of 5 moorings which were employed during the Subduction Experiment between June 1991 and June 1993 and measured sub-surface temperature and velocity, as well as meteorological variables at the surface [3].

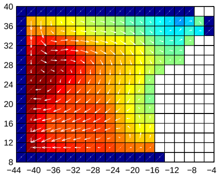

**Fig. 1:** Model configuration with mooring locations. The mean flow at 90m from unconstrained experiment B is shown with the mean SSH.

## Method

NCEP reanalysis products are used to force the model at the surface. Experiments identified below by the letter F use prescribed fluxes of heat, fresh water and momentum (stress), while experiments B use the atmospheric state variables temperature, humidity and wind speed through application of the bulk formulas [4]. Hydrography and velocities as obtained from a global optimization are prescribed at the open boundaries. The model integration period is February 1992 to January 1997.

We use the 'adjoint method' to combine TOPEX/POSEIDON and ERS altimetry, Reynolds SST fields, and Levitus subsurface $T$ and $S$ with the MIT GCM. The time-dependent adjoint of the model is generated automatically with the Tangent-Linear and Adjoint Model Compiler [5]. A quasi-Newton descent algorithm is used to iteratively minimize a cost function consisting of weighted model-data misfits and penalty terms for the controls:

$$\begin{aligned} J = & \sum_{i=1}^{N} (\mathbf{E}\,\mathbf{x}_i - \mathbf{y}_i)^T \mathbf{R}^{-1} (\mathbf{E}\,\mathbf{x}_i - \mathbf{y}_i) \\ & + \sum_{i=0}^{N-1} \mathbf{u}_i^T \mathbf{Q}^{-1} \mathbf{u}_i \\ & + \Delta\mathbf{x}_0^T \mathbf{Q_0}^{-1} \Delta\mathbf{x}_0 \\ & - 2 \sum_{i=0}^{N-1} \boldsymbol{\mu}_i \left(\mathbf{x}_{i+1} - \boldsymbol{\mathcal{F}}(\mathbf{x}_i, \mathbf{L}\,\mathbf{u}_i, \mathbf{B}\,\mathbf{q}_i)\right) \end{aligned} \tag{1}$$

The control vectors $\mathbf{u}_i$ contain corrections to the surface forcing fields and the open boundary values for $T$, $S$, $U$, and $V$. The control term for the initial condition (Levitus $T$ and $S$) has been written out explicitly. The model dynamics are enforced as a strong constraint.

## NCEP versus buoy surface fluxes

Figure 2 displays surface fluxes of total heat and momentum from the NCEP reanalysis and as determined from in-situ measurements at the central (CE) and southeast (SE) moorings.

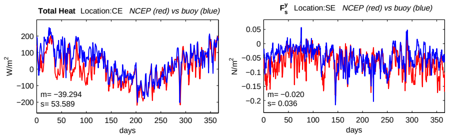

**Fig. 2:** Errors in the reanalysis products can be substantial. For the model region, errors in the total heat flux budget originate primarily in the latent heat flux and from both short- and long-wave radiation contributions. Errors in the sensible heat flux tend to be much smaller.

## Unconstrained runs (no assimilation)

Model SST at the central mooring location from a 5-year run with both flux (F) and bulk formulae (B) forcing are depicted in Fig. 3 and compared with in-situ measurements and with the Reynolds SST.

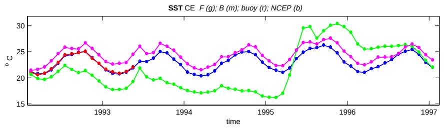

**Fig. 3:** SST is very poorly reproduced in run F, with temperatures underestimated by up to 5°C during the first 3 years and strongly overestimated in year 4 with a return to normal values in the last year. Run B produced fair estimates of the SST, albeit with a nearly constant positive bias over all 5 years. The Reynolds SST is a very good measure of the in-situ SST as measured by the buoys.

The biases between the model runs and the measurements are also present in a comparison of subsurface temperature with Levitus monthly climatology over the model integration period.

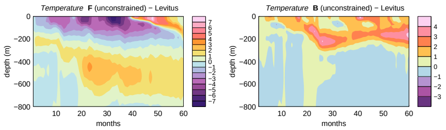

**Fig. 4:** The representation of temperature at depth is significantly better when bulk formulae are used to force the model.

## Constrained runs (with assimilation)

Initially, all controls were corrected simultaneously in both the F and B experiments. It was found that the cost function descent was very slow with most controls receiving only very small corrections. Therefore, a second approach was adopted in which controls were corrected one by one, keeping all others fixed, in the following order: surface fluxes of heat and fresh water, wind stress (air temp, humidity and wind speed for experiment B), boundary conditions for $T$ and $S$, boundary conditions for $U$ and $V$. The change of the control function contributions are shown below as a function of iteration number.

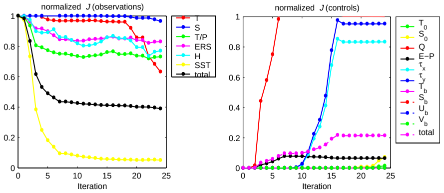

**Fig. 5:** As can be seen in the right panels, controls were adjusted successively, starting with the surface heat and fresh water fluxes during the first 8 iterations (top row). This had a strong effect on the model-Reynolds SST misfits, which were reduced dramatically (left panel). The subsequent adjustment of the wind stress further reduced the model-data misfit but at a much slower pace. More significant changes in the misfits resulted from adding the initial and boundary conditions on the hydrography in iteration 18 which led to a significantly better agreement with Levitus monthly climatology. At this point only the boundary conditions on $U$ and $V$ have not yet been adjusted in experiment F.

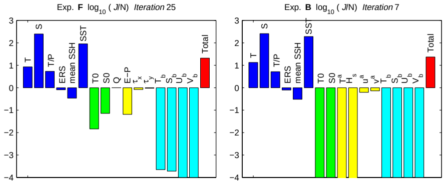

**Fig. 6:** The above histograms show the logarithm of the normalized data-misfit and control contributions to the cost function after a finite number of iterations. In the optimized state, all terms are expected to be close to 1. Most misfits are currently still too large, while the controls are still too small. This could point towards misspecification of uncertainties or inefficiency of the gradient search.

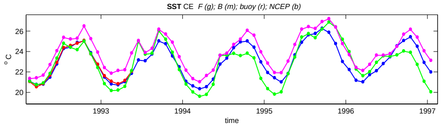

**Fig. 7:** A comparison of SST at the central mooring location similar to Fig. 3 after 25 (F) and 7 (B) iterations respectively. Most noticable is the enormous improvement in the SST obtained for the F runs.

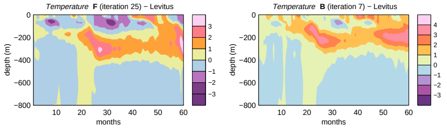

**Fig. 8:** The data-assimilation has also improved the temperature and salinity at depth. The two solutions iterate to the same state which is close to the solution of the unconstrained run with bulk formulae forcing.

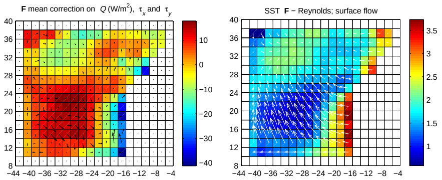

**Fig. 9:** The average corrections on the net surface heat flux and wind stress components over the integration period for runs F show large spatial coherence (left). An area of strongly increased heat loss through the surface corresponds to a region of upwelling along the west African coast. While some upwelling is reproduced by the model, SST remains far too high here (right) and the assimilation attempts to reduce the misfit by increasing the heat loss through the surface. It is known however that also the NCEP reanalysis has problems in this region with the representation of clouds (leading to incorrect radiation budgets, see also the remarks with Fig. 2). Positive heat flux corrections are produced in an area where SST is only slightly overestimated by the unconstrained model (around 32° W, 20° N). At the same time large wind stress adjustments are produced here that counteract the surface flow.

## Conclusions (preliminary)

The above results suggest that an unconstrained model in an open boundary configuration will produce more realistic results when forced by bulk formulas connecting the atmospheric state variables with the model SST. When observed SST is assimilated large improvements can be obtained for a flux-forced model that bring it into closer agreement with the bulk-formula forced model. A condition for a successful optimization in the current application was that the controls are adjusted one by one rather than simultaneously. The order of adjustment as used here appeares to ensure significant corrections to all controls. However, many questions remain to be addressed:

- Why has it been neccesary to adjust the contols one by one? And why are air temperature and humidity not properly corrected?
- How do the box results compare to the global and closed box solutions?
- Is the final solution dependent on the order of control adjustment?
- Does the method improve the surface forcing?
- Can the mooring measurements further constrain the solution?
- What are the estimated mixed-layer depth, subduction rate, etc.?

## References

[1] **Stammer et al.**, 2000: Global sea surface flux estimates obtained through ocean data assimilation, *The ECCO Report Series*, 13, 31 pp. [2] **Zhang and Marotzke**, 1999: The importance of open-bounary estimation for an Indian Ocean GCM-data sy nthesis, *J. Marine Res.*, 57, 305–334. [3] **Brink et al.**, 1995: The Subduction Experiment: Mooring field program and data summary. *Tech. Rep. WHOI-95-08*, 113 pp. [4] **Large and Pond**, 1982: Sensible and latent heat flux measurements over the ocean, *J. Phys. Ocea nogr.*, 12, 464–482. [5] **Giering and Kaminsky**, 1998: Recipes for adjoint code construction, *Trans. Math. Software*, 24, 437–474.