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 \cite{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 \cite{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\textdegree} N and 39\textdegree} N and 43\textdegree} W and 5\textdegree} 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 \cite{3}.

Method

NCEP reanalysis products are used to force the model at the surface. Experiments identically as those in 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 \cite{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 TOPEXPOSEIDON and ERS altimetry, Reynolds SST fields, and Levitus subsurface \textsuperscript{7} S and \textsuperscript{8} S with the MIT GCM. The time-dependent adjoint of the model is generated automatically with the Tangent-Linear and Adjoint Model Compiler \cite{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{equation}
\frac{1}{2} \sum_{m=1}^{M} (e_m - y_m)'^2 + \sum_{n=1}^{N} \lambda (\sigma_n - \sigma_n)^2 + \sum_{s=1}^{S} \lambda (\sigma_s - \sigma_s)^2
\end{equation}

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.

The control vectors \textbf{u} contain corrections to the surface forcing fields and the open boundary values for \textsuperscript{7} S, \textsuperscript{8} S, and \textsuperscript{9} S. The control term for the initial condition \textbf{u} was not used 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.

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 \textsuperscript{7} S and \textsuperscript{8} S, boundary conditions for \textsuperscript{9} S and \textsuperscript{10} S. The change of the control function contributions are shown below as a function of iteration number.

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. 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\textdegree} 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 ... positive bias over all 5 years. The Reynolds SST is a very good measure of the in-situ SST as measured by the buoys.

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

Conclusions (preliminary)

The above results suggest that an unconstrained model in an open boundary configuration will produce more realistic results when forced by bulk formulae 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 brings 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 appears to ensure significant corrections to all controls. However, many questions remain to be addressed:

- Why has it been necessary to adjust the controls 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
