

## **Mesoscale Ocean Forecast/Assimilation Studies**

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### **LONG-TERM GOALS**

The long-term goal over this three-year project has been to develop computer software needed to optimize initial conditions, internal parameters and external parameters for the Harvard primitive equation (PE) model in order to produce the best forecasts in an arbitrary region. This new tool invokes an inverse technique to fuse all available data types, gathered non-synoptically, with optimized model dynamics. The technique is distinct from (and complementary to) the optimal interpolation and Kalman filter assimilation strategies now being developed and used at Harvard (e.g., Lermusiaux, 1997).

### **OBJECTIVES**

The scientific objectives of this research include answering the following questions. Can forecast skill in a highly unstable region like the Iceland-Faeroe Front be extended to 7 days? Can a diagnostic simulation over a 10-day interval in that region include all the data in an inverse calculation, or is it too nonlinear? What are the relative impacts of the various data types (CTD/XBT/XCTD casts, current meters, surface drifters) on making forecasts in this region? The technical objectives encompass the details of the model fitting process. How nonlinear is the fit? Can the nonlinearity be reduced by optimizing large-scale structure first? How much data can be fit at one time? Is the distribution of the data sufficient to initialize the model? Are the open boundaries causing instabilities in the model?

### **APPROACH**

Real-time ocean forecasting involves assembling an initial state which often requires merging many data types that are usually gathered over non-synoptic intervals. Furthermore, dynamical ocean forecast models still require improvements in their physics (including parameterizations). We are addressing these two issues simultaneously in applying a standard inverse technique to the Harvard PE ocean model in the context of a unique dataset in the Iceland-Faeroe frontal region. The computational strategy that we are developing will be applicable to whatever new regions, updated PE model versions, or varieties, amounts or qualities of data become available. The Harvard ocean modeling group provided expertise in setting up and modifying the model for our purposes.

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## WORK COMPLETED

During the three-year project, we prepared the data, designed the model domain, developed the iterative process for minimizing model-data mismatch and applied the method to both an identical-twin experiment and the data from the 1993 IFF surveys. The results of our research were submitted to the special issue of *Dyn. Atm. Oceans* dedicated to Prof. A. R. Robinson (Miller and Cornuelle, 1998).

## RESULTS

The fitting procedure was tested and applied with the Harvard PE model to non-synoptic hydrographic surveys of unstable current meandering of the Iceland-Faeroe Front. The initial conditions (including the fields outside the data domain) were adjusted with large-scale structure functions to fit the observations, with no additional forcing or adjustment of boundary conditions during the model runs. The technique was first tested with an 'identical twin' predictability experiments that showed the iterative technique can fit the non-synoptic Initialization Survey data, partly correct the initial condition errors and allow the model to move closer to the true evolution (Figure 1). However, the limited non-synoptic verification data was inadequate for providing convincing evidence of forecast skill even for short 2-day forecasts, which are known to have skill in the identical twin framework.

The PE model was then fit to the observed hydrographic data from August 1993 in several scenarios. With only a few iterations, typical temperature and salinity along-track error variance reductions of 70-80% were achieved relative to initializing the model from a time-independent objective analysis. Although hindcast skill increased by applying the method, significant quantitative forecast skill was not achieved probably due to inadequate initialization and verification data (as found in the twin experiments). Qualitative skill assessment proved necessary to distinguish the integrity of the hindcasts and forecasts, especially with respect to the occurrence of a hammerhead baroclinic instability of the IFF (Miller et al., 1995; Robinson et al., 1996). Since the model was successfully fit to the hammerhead instability (Figure 2), the incorrect hammerhead forecasts from fits must be a consequence of (a) inadequate initialization data, (b) high sensitivity to initial conditions, (c) incorrect model physics or (d) insufficient structure functions. The quantitative forecast skill shown by Robinson et al. (1996), who used an optimal interpolation technique in real time, is comparable to what was obtained here for the hammerhead when the model was initialized from or fit to the antecedent (Zig-Zag) survey.

The main difference between this method and the representer method of Bennett (1992) is our use of the restricted set of basis functions. An adjoint model can give the complete structure of the data sensitivity in the forward problem, but using similar smoothing assumptions (i.e. a covariance matrix for the initialization changes) should lead to similar solutions. The restriction to large-scale perturbations is useful for linearized methods since the small-scale structure of the sensitivity should be less reliable than the large-scale structure, due to nonlinearity. For example, in the identical twin experiment where the error was spanned by 50 structure functions the linearized iteration did not produce the exact initial condition. A similar problem would arise for the linearized derivatives made by an adjoint model.

The model run from the optimized initialization constitutes a possible dynamically consistent scenario explaining some of the variability seen in the IFF observations as a meandering of the front. To the extent that the model is accurate, the observations have been reconstructed into a four-dimensional picture of the flow field in the area. The results here set the stage for diagnostic analyses of the frontal

baroclinic instabilities, e.g., using a primitive equation analogue (under development by Miller, Lermusiaux, Pinardi and Robinson) of the energy and voracity analysis (EVA) system developed by Pinardi and Robinson (1986) for quasigeostrophic dynamics and applied by Miller et al. (1995) to quasigeostrophically modeled IFF variations.

A correct ocean model is a valuable tool for the interpolation and interpretation of data, as well as practical prediction problems, but it is dependent on obtaining adequate data for judging model quality. The techniques tested here could easily accommodate other data types, but the best type of data for constraining the model initializations and for testing forecast skill would appear to be synoptic hydrographic surveys as could be obtained from aerial XBT surveys. For this August 1993 IFF dataset there are drifter observations, current meter observations and a satellite SST image which can be used in future applications of this technique to improve the fits and forecasts. Giving higher vertical resolution to the model is of high priority in improving the details of the model fit, especially the baroclinic structure of the hammerhead instability.

## **IMPACT/APPLICATIONS**

We expect the procedure to prove useful in initializing ocean model forecasts at sea in real time. We also expect the optimized hindcast simulations to be useful in developing a better understanding of ocean physical processes, especially with the use of energetic analysis package. We also will be able to use these techniques in a California Current SCRUM modeling effort, the results of which can be compared to the application of the adjoint, the design of which is to be funded by ONR.

## **TRANSITIONS**

This work is in the development stage and is not being used by others at this time.

## **RELATED PROJECTS**

The ocean modeling group at Harvard is using and developing complementary assimilation techniques. We have begun a project, funded by NASA, to attempt to optimize predictability of the California Current System (using the CalCOFI CTD data with altimetry, ADCP profiles and surface drifters) using SCRUM and these inverse techniques. We will begin the development of the adjoint for SCRUM under ONR support shortly.

## **REFERENCES**

Bennett, A. F., 1992. Inverse Methods in Physical Oceanography, Monographs on Mechanics and Applied Mathematics, Cambridge University Press, New York, 346 pp.

Lermusiaux, P. F. J., 1997. Error Subspace Data Assimilation Methods for Ocean Field Estimation: Theory, Validation and Applications. Ph.D. dissertation, Harvard University, Cambridge, Massachusetts, 402 pp.

Miller, A. J., Poulain, P.-M., Robinson, A. R., Arango, Leslie, W. G. and Warn-Varnas, A., 1995b. Quantitative skill of quasigeostrophic forecasts of a baroclinically unstable Iceland-Faroe Front. J. Geophys. Res., 100:10,833-10,849.

Miller, A. J. and B. D. Cornuelle, 1998: Forecasts from fits of frontal fluctuations. *Dyn. Atmos. Oceans*, sub judice.

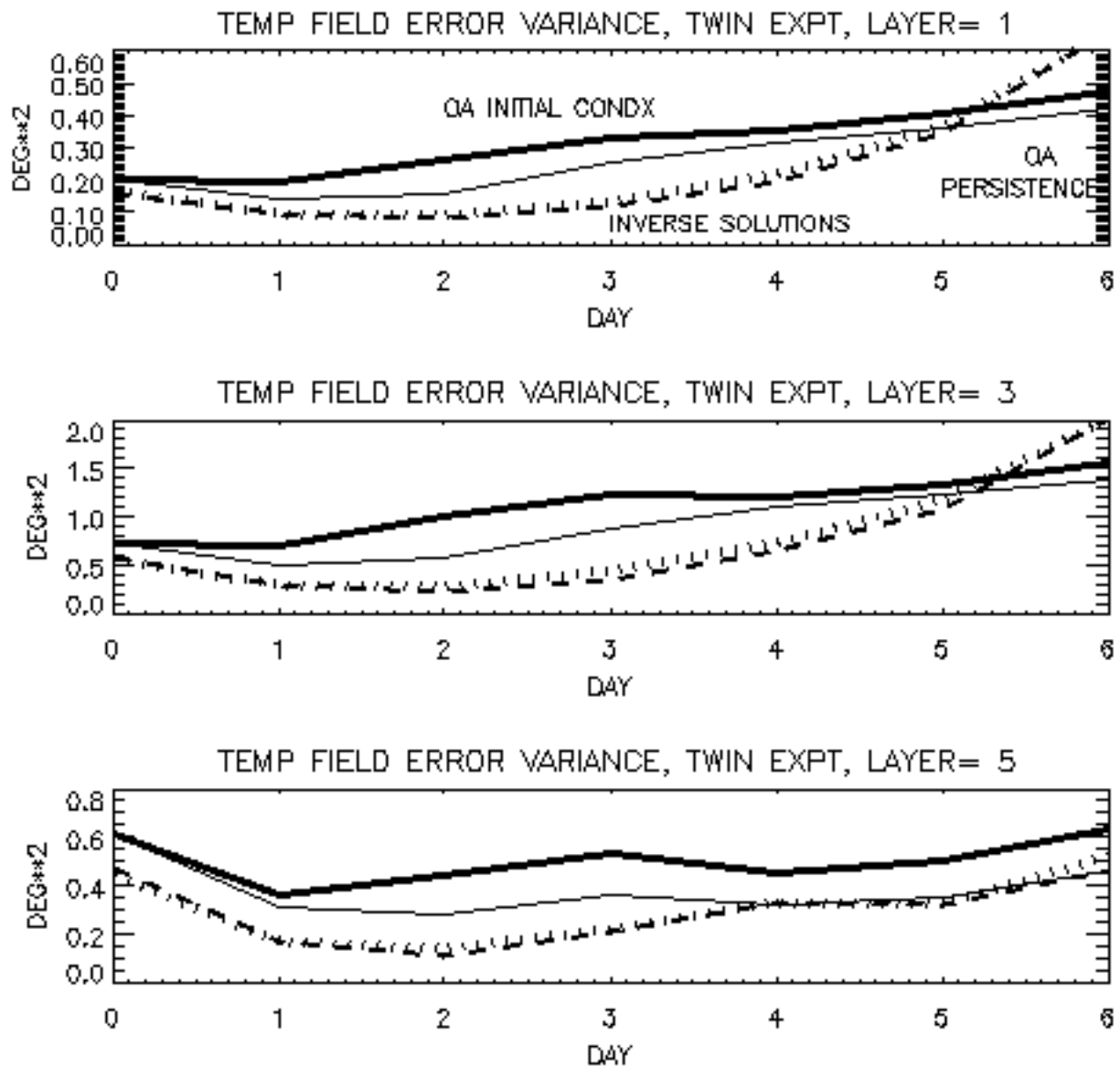
Pinardi, N. and Robinson, A. R., 1986. Quasigeostrophic energetics of open ocean regions. *Dyn. Atmos. Oceans*, 10:185-219.

Robinson, A. R., Arango, H. G., Miller, A. J., Poulain, P.-M., Warn-Varnas, A. and Leslie, W. G., 1996. Real time operational forecasting on shipboard of the Iceland-Faroe frontal variability. *Bull. Am. Meteorol. Soc.*, 77:243-259.

## **PUBLICATIONS**

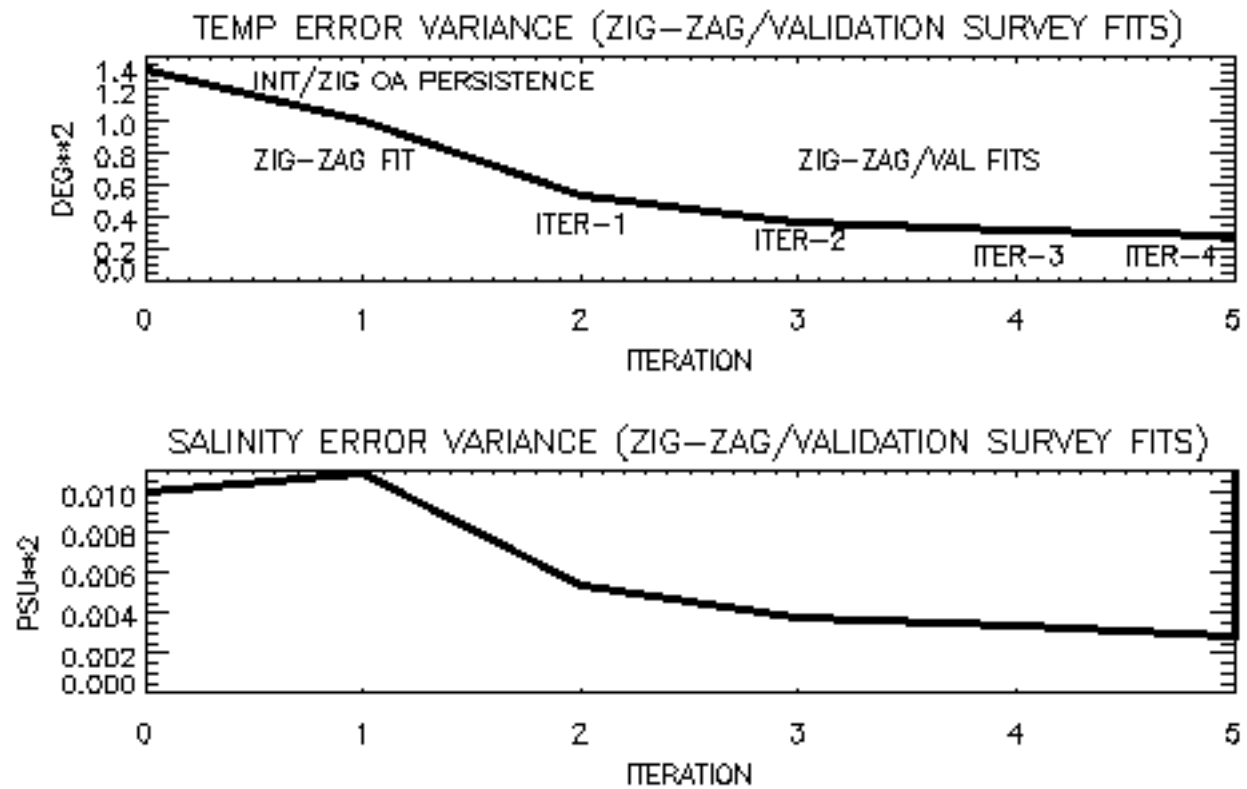
Miller, A. J., Lermusiaux, P. F. G. and Poulain, P.-M., 1996. A topographic-Rossby mode resonance over the Iceland-Faeroe Ridge. *J. Phys. Oceanogr.*, 26:2735-2747.

Miller, A. J. and B. D. Cornuelle, 1998: Forecasts from fits of frontal fluctuations. *Dyn. Atmos. Oceans*, sub judice.



**Figure 1. Twin Experiment: Temperature field error variance in the entire data domain for (thin line) persistence of the Initialization Survey OA, (thick line) model run initialized from the Initialization Survey OA, (dotted line) first iteration model run initialized with the inverse solution and (dashed line) second iteration model run initialized with the inverse solution for (top to bottom) layers 1, 3 and 5. Note the differing scales on the abscissas.**

The time interval from 0-3 days corresponds to the fitting interval. The time interval from 3-6 days is independent forecast data.



**Figure 2. Data from Aug 1993 IFF cruise. (Top) Temperature and (bottom) Salinity error variance of fits of the Zig-Zag and Validation Survey hydrographic data. The first point corresponds to persistence of the Zig-Zag/Initialization Surveys OA. The second point corresponds to the second iteration of the Case 6 model fit using the zig-zag data alone. The third through sixth points correspond to the first through fourth iterations of the Case 8 model fits.**