*DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.*

# Title: 4DVar NCOM in RELO and COAMPS5

PI: Dr. Hans Ngodock
1009 Balch Blvd
Stennis Space Center, MS 39529
Tel: (228) 688 5455 Fax: (228) 688 4759 Email: Hans.Ngodock@nrlssc.navy.mil

Co-PI: Dr. Matthew Carrier
1009 Balch Blvd
Stennis Space Center, MS 39529
Tel: (228) 813 4086 Fax: (228) 688 4759 Email: Matthew.Carrier@nrlssc.navy.mil

Co-PI: Dr. Clark Rowley
1009 Balch Blvd
Stennis Space Center, MS 39529
Tel: (228) 688 5809 Fax: (228) 688 4759 Email: Clark.Rowley@nrlssc.navy.mil

Co-PI: Dr. Scott Smith
1009 Balch Blvd
Stennis Space Center, MS 39529
Tel: (228) 688 4630 Fax: (228) 688 4759 Email: Scott.Smith@nrlssc.navy.mil

Co-PI: Dr. Timothy Campbell
1009 Balch Blvd
Stennis Space Center, MS 39529
Tel: (228) 688 5285 Fax: (228) 688 4759 Email: Scott.Smith@nrlssc.navy.mil

Award number: N0001413WX20550

## LONG TERM GOALS

To improve the accuracy of the ocean data assimilation and forecast by implementing the four-dimensional variational (4DVAR) technique with the Navy coastal ocean model (NCOM)

## OBJECTIVES

This project will implement a 4DVar capability into the relocatable / regional NCOM system and the COAMPS5 system as well as merge the NCODA and NAVDAS-AR frameworks. The tangent linear and adjoint for NCOM will be for the latest version using the generalized vertical coordinate system. All code will be added to the appropriate subversion repositories. The code will be tested on the operational computer systems prior to a validation test report. The results will be validated in one area to be determined in coordination with the operational POC. The area extent of the validation area will be balanced against available computational resources in conjunction with the operational POC. A validation test report for the area relative to available in situ data will be written. The evaluations will

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

| | | |
|---|---|---|
| 1. REPORT DATE<br>**30 SEP 2013** | 2. REPORT TYPE | 3. DATES COVERED<br>**00-00-2013 to 00-00-2013** |
| 4. TITLE AND SUBTITLE<br>**4DVar NCOM in RELO and COAMPS5** | | 5a. CONTRACT NUMBER |
| | | 5b. GRANT NUMBER |
| | | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | | 5d. PROJECT NUMBER |
| | | 5e. TASK NUMBER |
| | | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**Naval Research Laboratory,1009 Balch Blvd,Stennis Space Center,MS,39529** | | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | | 10. SPONSOR/MONITOR'S ACRONYM(S) |
| | | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | **Same as Report (SAR)** | **9** | |

**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18

be for temperature structure, salinity structure and acoustic proxy parameters relative to in situ profile data. In addition, evaluations will be constructed for velocity comparisons to in situ drifter data. All evaluations will be constructed with the new 4DVar system relative to the existing operational 3DVar system. The code will be available to all Navy operational centers to OPTEST.

## APPROACH

The approach is divided into the following tasks

**Integration with Regional NCOM and COAMPS**

At present, the 4DVar uses the output files generated by the NCODA OcnQC data prep. The 4DVar must be integrated with the merged NCODA/NAVDAS-AR code. Initially the 4DVar will be called from NCODA so that tests can proceed on the HPCMP platforms and other work can progress. As the NCODA and NAVDAS-AR are merged, the 4DVar will also be incorporated.

**Parallelization and scalability**

The present parallelization of the 4dvar code leverages the parallelization of the NCOM code itself. It uses the same tiling for the TL and adjoint models as in the parent NCOM code. The conjugate gradient step is performed simultaneously by all processors.

**Sigma-z and generalized vertical coordinates**

The 4dvar code was developed with the premise that the generalized vertical coordinate (gvc) of NCOM was going to be the standard operational code. The transition of the gvc NCOM to NAVO is under way presently. Given that NCOM can run in gvc mode with a sigma-z setup and vice versa, we need to ensure that this property is maintained in the 4dvar code, i.e. the gvc-based 4dvar can run with a sigma-z setup.

**Strong or weak constraints**

In an effort to lower the computational cost of the 4dvar, a strong constraint approach can be implemented. A pure strong constraint form will need a steepest descent or quasi-Newton minimization not yet implemented, whereas in the non-pure form we just set the model error term to zero in the system we have now. We will investigate the difference in both approaches and quantify the extra computational cost incurred by the weak constraint approach.

**Cost effectiveness to meet time constraints**

Can the 4dvar analysis be done in a specific amount of time, say 2 hours? This will depend on the region, the preconditioning, and mostly the time window. Balances of these parameters will be constructed to ensure that the system fits within operational constraints.

**Covariance space and relative errors of observations and initial conditions**

The horizontal, vertical and temporal scales of the covariances have to be prescribed carefully according to the prevailing dynamics over the chosen region. The covariance model in place is based on the solution proposed by Egbert et al., (1994) and Weaver and Courtier (2001) using a spatial transformation of a Gaussian function to represent spatial structure dependent on any parameter desired. This was extended to use the diffusion solution (Bennett et al., 1996, 1998, Ngodock 2005) to apply the covariance efficiently (Carrier and Ngodock, 2010, Yaremchuk et al., 2011). At present the vertical structure is uncorrelated, and the vertical correlation structure must be added. Also, as we have found in the Monterey Bay, the correlation scales have a direct impact on the assimilation and forecast skills. This task consists of selecting the correlation scales as well as implementing the vertical correlation model and evaluating them in terms of analysis and forecast skills.

**Assimilation cycle**

The 4dvar system is expected to fit the data within the time range of TLM stability. The latter depends on resolution, dynamical regime and geographic location. Given the computational demands of the system, a short assimilation cycle will most likely fit the time allocated to perform the analysis. There has not been a concise study to determine what the length of the assimilation should be depending on the considerations enumerated. There are several approaches that need to be understood to properly implement this. First, it is possible to use several 1-day cycles in hind cast versus a single multiday hind cast cycle. It is also possible extend the analysis period into the future so that observation could be projected into corrections beyond the final observation time. Evaluations of these alternative implementations will be made, and the operational implementation will be based on the results of the tests.

**Demonstration that the 4DVAR improves the forecast skill of 3DVAR**

There needs to be a robust demonstration that the 4dvar is an improvement to the 3dvar and that it justifies the computational cost. This demonstration has to be done in the area agreed upon with the operational POC. The evaluations relative to present capabilities in 3DVar will be part of the validation test report.

## WORK COMPLETED

During FY13, the 4DVar has been successfully integrated into the relocatable NCOM (RELO). This work involved modifying the RELO scripts to allow for running the 4DVar analysis suite in place of the 3DVar. In addition to this, minor modifications were made to the NCODA OcnQC data prep programs to cycle observations for a time-window. Work to integrate 4DVar into COAMPS-5 is ongoing with expected completion by the end of QTR1 FY14.

The 4DVar has been proven to work for any vertical grid that can be specified for NCOM, including the standard sigma-z and the generalized vertical coordinate. Earlier issues with TLM stability regarding deep sigma layers were resolved in QTR2 FY13 by a minor modification to the linearization of the vertical mixing parameters. The 4DVar is now stable for any NCOM configuration and resolution.

As of FY13, the 4DVar is fully parallelized. Tests of the 4DVar on the DSRC machines (KILRAIN and HAISE) show that the scalability of the 4DVar matches that of NCOM (albeit at a higher computational cost overall). Work is continuing into FY14 to determine the best operational configuration of the 4DVar that is a balance between the quality and computational efficiency of the analysis. This work includes investigating the assimilation cycling (i.e. length of the data window) as well as the errors for the initial condition and/or model fields. All of these aspects affect the quality and efficiency of the analysis, and therefore must be investigated in this light. Expected completion of this work is the middle of QTR1 FY14.

In addition to the work done on the cycling and relative error settings, a preconditioner has been added to the minimization software used in the 4DVar. This preconditioner (based on Courtier 1997) has resulted in a significant cost savings by reducing the number of minimization steps needed to achieve convergence (figure 1).

The assimilation of sea surface height (SSH) has proven problematic in shallow water regions. In these locations (depths less than 200m), the assimilation of SSH results in the excitation of gravity waves, which degrade the resulting analysis. We have temporarily addressed this issue by increasing the spatial correlation for the SSH field in the assimilation, thereby smoothing the increment added to the tangent linear model. In the long-run, however, filtering the gravity waves in the solution of the free-surface may be best; this will be incorporated into the tangent linear and adjoint models in QTR1 FY14.

We have had great success in assimilating velocity observations with the 4DVar. Velocity observations, by nature, are highly variable in space and time. This aspect makes them very difficult to assimilate via a 3DVar method, which assumes all the data were taken at one time. For the recent Grand Lagrangian Deployment (GLAD) experiment that took place in the Gulf of Mexico in the summer of 2012, a large number of surface drifters were released. Eulerian velocity values have been derived from the position data. These derived velocity observations are assimilated into the 4DVar (using a 6 km Gulf of Mexico domain, where the observations are assimilated every hour during a 4-day data window). The resulting forecast shows excellent skill in the velocity fields out to 96-hours (when compared to a forecast that did not assimilate the velocity data). Figure 2 shows the comparison between selected modeled (purple) and observed (green) drifter tracks between 15-19 August, 2012 in the northern Gulf of Mexico. The top (bottom) panel of fig. 2 shows the comparison using an NCOM forecast that excluded (included) GLAD velocity observations in the analysis step. The forecast that used the analysis that included the velocity observations matches the actual drifter positions very closely, clearly indicating that the assimilation of velocity observations improves the prediction of the velocity field.

Early comparisons between the 4DVar and 3DVar have been made in the Okinawa trough domain selected for this project. Initial indications are that the 4DVar produces a forecast that is more accurate than the 3DVar, in terms of model-observation differences during the forecast cycle of 1-30 August, 2007. Figure 3 shows the absolute difference between model and observed temperature for no assimilation (top panel), 3DVar assimilation (middle panel), and 4DVar assimilation (bottom panel); figure 4 shows this same comparison for salinity. All the model-observation differences for figs. 3 and 4 are shown for profile observations, where the profiles have been arranged chronologically (not spatially). Fig. 3 shows that the forecast using the 4DVar analysis has lower error in the 100-400 m depth range than its 3DVar counterpart. A similar conclusion can be made for salinity in fig. 4, as the error here is lower for the 4DVar than the 3DVar. It is important to note that these results are preliminary; a more extensive comparison between the 3DVar and 4DVar will be made as part of the validation test report (VTR); experiments for the VTR are on-going with expected completion QTR 2 FY14.

## RESULTS

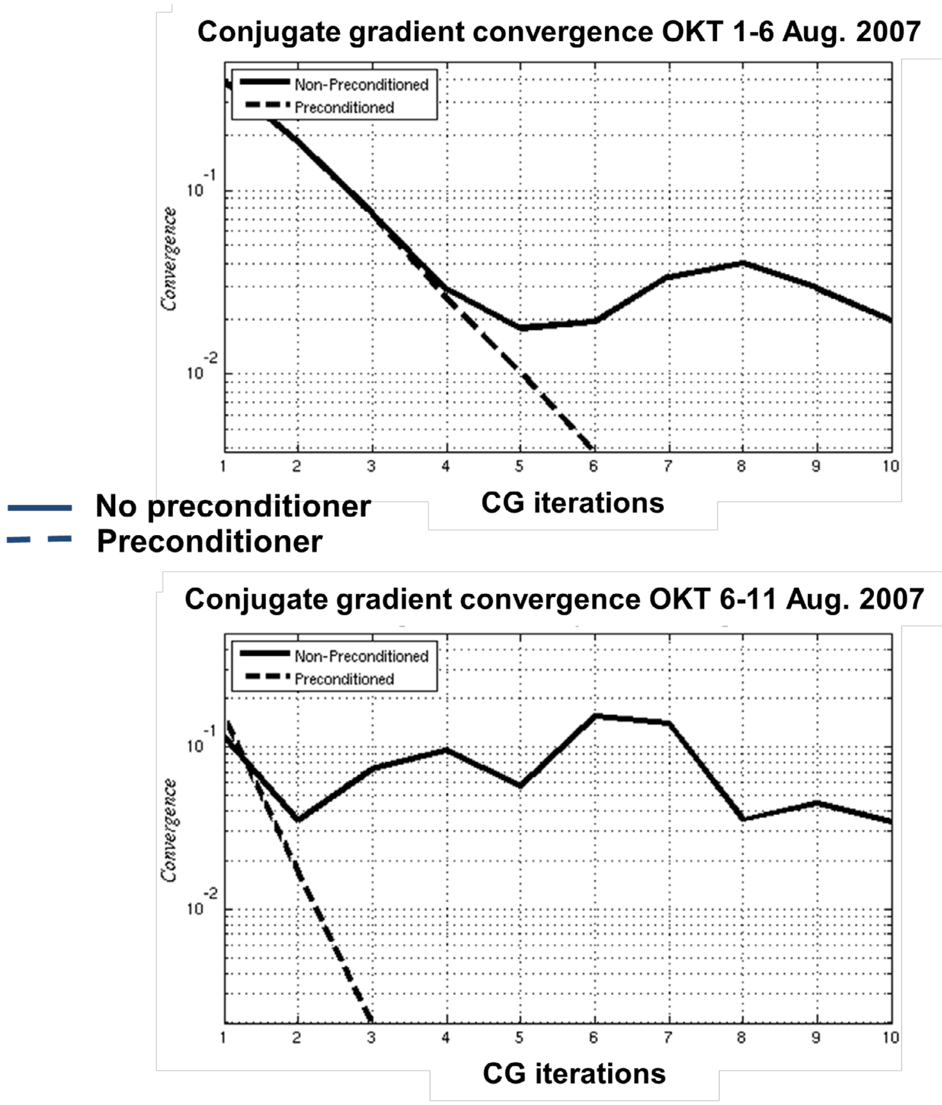


***Figure 1: Conjugate gradient convergence comparison between the non-preconditioned (solid line) and preconditioned (dashed line) NCOM-4DVAR for 5-day assimilation window between 1-6 August, 2007 (top panel) and 6-11 August, 2007 (bottom panel).***

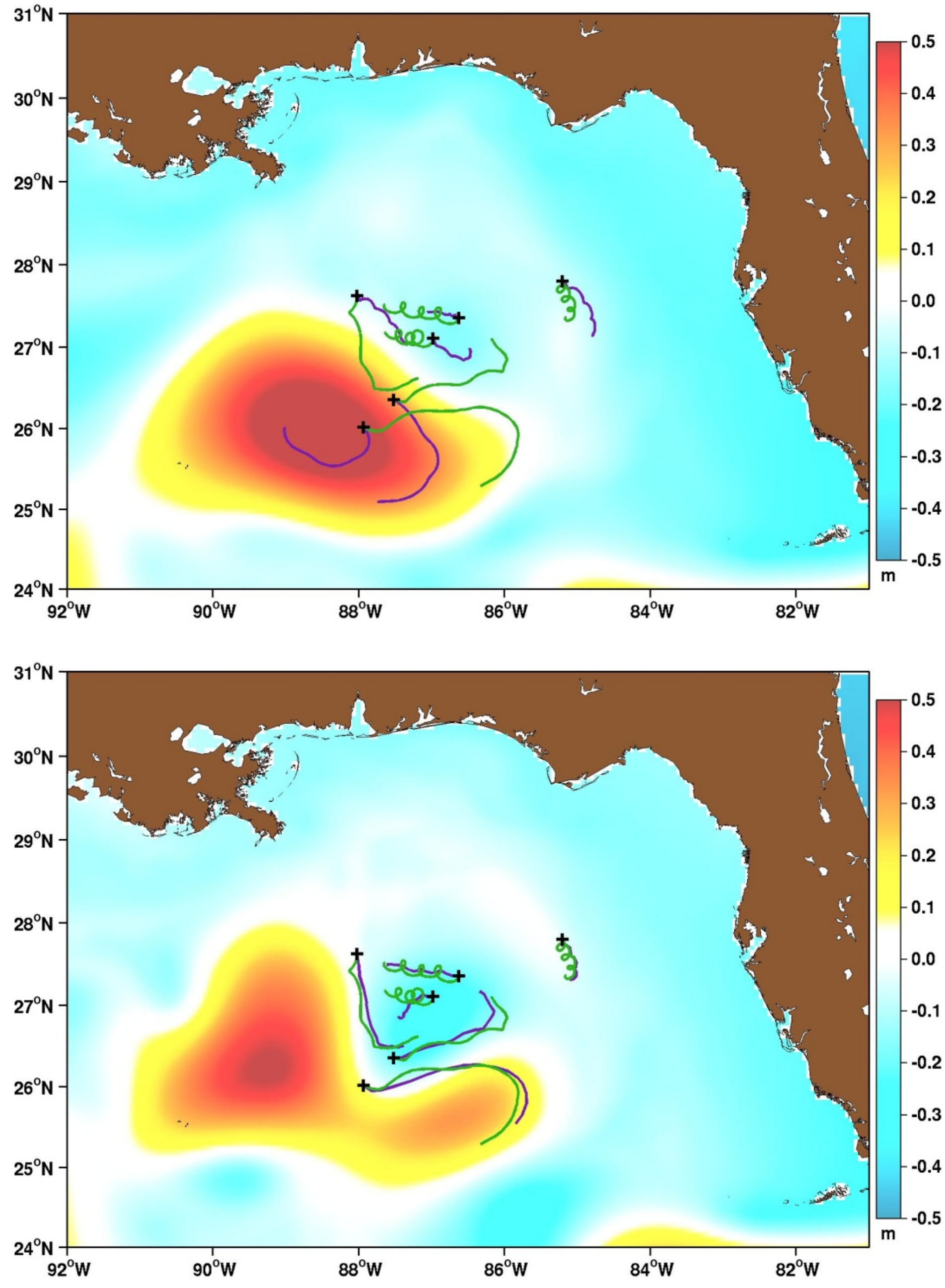


***Figure 2: Comparison of modeled (purple) and observed (green) drifter tracks in the northern Gulf of Mexico between 15-19 August, 2012. The top (bottom) panel shows this comparison for modeled drifters using NCOM forecast velocity that excluded (included) velocity measurements in the analysis step. Each plot is overlaid on the respective SSH field for each forecast.***

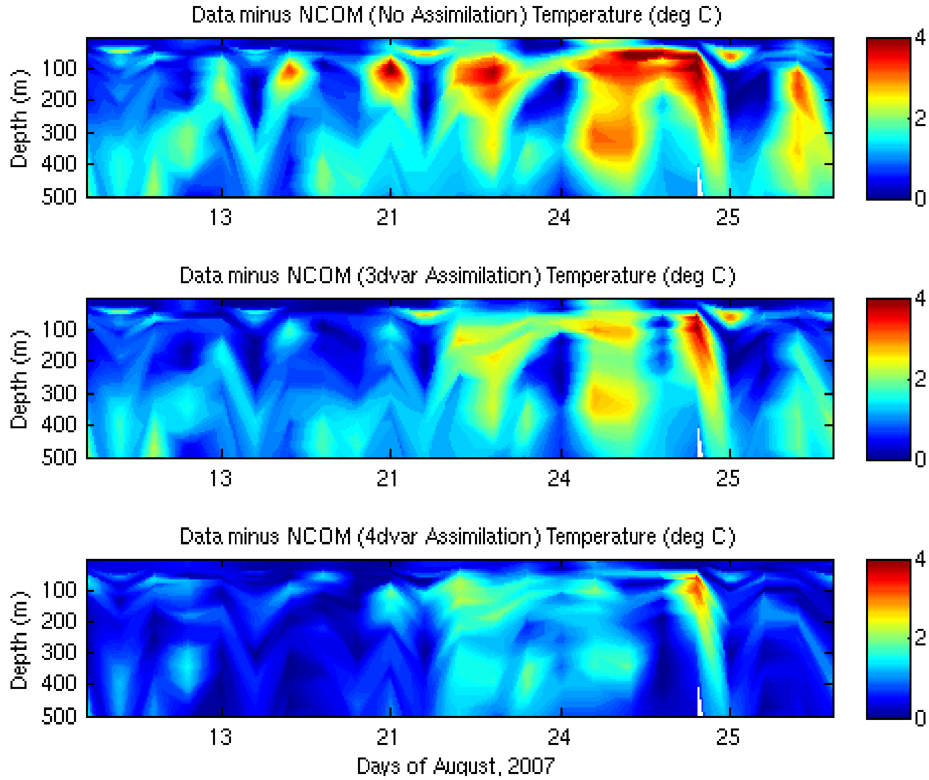


***Figure 3: Absolute difference between NCOM and observed temperature profiles in the Okinawa Trough domain. Observed minus NCOM with (1) no assimilation (top), (2) 3DVar assimilation (middle), and (3) 4DVar assimilation (bottom) is shown. All profiles are plotted chronologically (not spatially) from 1-30 August, 2007.***

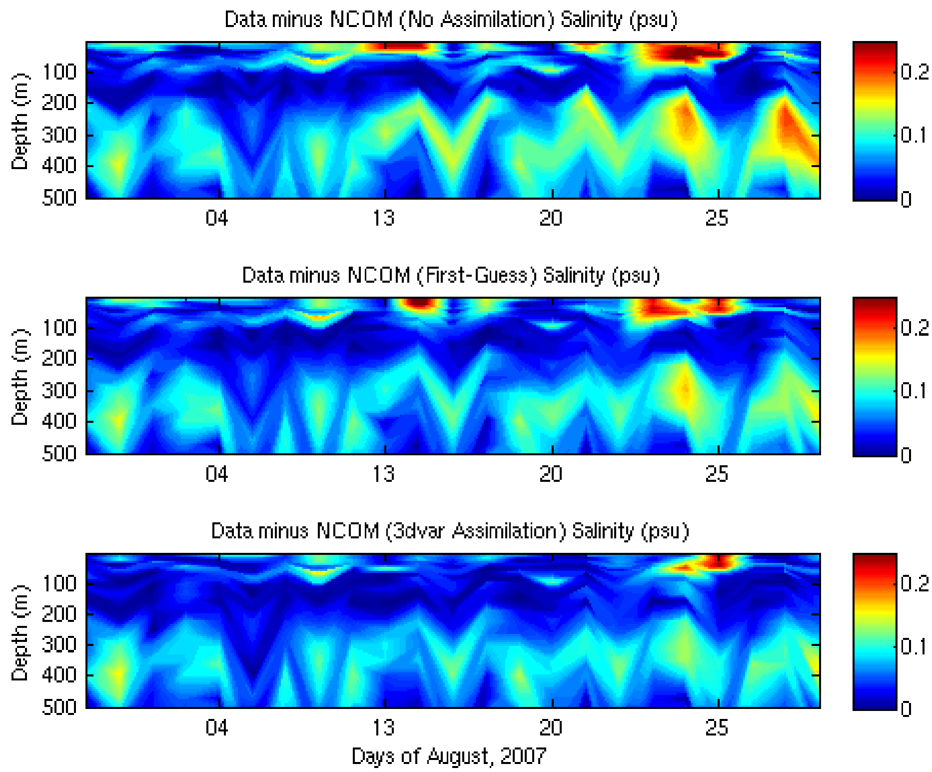


***Figure 4: Same as in fig. 3, but for salinity.***

## IMPACT/APPLICATIONS

## TRANSITIONS

## RELATED PROJECTS

None

## REFERENCES

Smith S. R.; Ngodock H. E., 2008: Cycling the Representer Method for 4D-variational data assimilation with the Navy Coastal Ocean Model. OCEAN MODELLING Volume: 24 Issue: 3-4 Pages: 92-107.

Ngodock H. E.; Smith S. R.; Jacobs G. A., 2007: Cycling the representer algorithm for variational data assimilation with the Lorenz attractor. MONTHLY WEATHER REVIEW Volume: 135 Issue: 2 Pages: 373-386.

Ngodock Hans E.; Smith Scott R.; Jacobs Gregg A., 2007: Cycling the representer algorithm for variational data assimilation with a nonlinear reduced gravity ocean model. OCEAN MODELLING Volume: 19 Issue: 3-4 Pages: 101-111.

Carrier Matthew J.; Ngodock Hans, 2010: Background-error correlation model based on the implicit solution of a diffusion equation. OCEAN MODELLING Volume: 35 Issue: 1-2 Pages: 45-53.

Yaremchuk, M., M. Carrier, H. Ngodock, S. Smith, and I. Shulman, 2011: Forecast skill and computational cost of the covariance models in 3dVar data assimilation, *Advances in Geosciences*, (submitted).

EGBERT GD; BENNETT AF; FOREMAN MGG, 1994: TOPEX/POSEIDON TIDES ESTIMATED USING A GLOBAL INVERSE MODEL. JOURNAL OF GEOPHYSICAL RESEARCH-OCEANS Volume: 99 Issue: C12 Pages: 24821-24852.

Weaver A; Courtier P,. 2001: Correlation modelling on the sphere using a generalized diffusion equation. QUARTERLY JOURNAL OF THE ROYAL METEOROLOGICAL SOCIETY Volume: 127 Issue: 575 Special Issue: A Pages: 1815-1846.

Ngodock, HE, 2005: Efficient implementation of covariance multiplication for data assimilation with the representer. OCEAN MODELLING Volume: 8 Issue: 3 Pages: 237-251.

Ngodock HE and Carrier M., 2011: 4D-Var assimilation of real and synthetic observations in the Monterey Bay using the Navy coastal ocean model. Submitted to Ocean Modelling.

Ngodock HE and Carrier M., 2011: 4D-Variational assimilation of in-situ observations in the Monterey Bay using the Navy coastal ocean model (NCOM). Submitted to Ocean Modelling.

**PUBLICATIONS**

1. Ngodock, H. E., and M. J. Carrier, 2013: A weak constraint 4D-Var Assimilation system for the Navy coastal ocean model using the representer method. *Data Assimilation for Atmospheric, Oceanic and Hydrologic applications, Vol II*, S. K. Park and L. Xu, Eds., Springer-Verlag Berlin Heidelberg, doi:10.1007/978-3-642-35088-7_15.
2. Ngodock, H.E., and M. J. Carrier, 2013: A 4D-Var system for the Navy Coastal Ocean Model Part I: system description and assimilation of synthetic observations in the Monterey Bay (submitted to Monthly Weather Review; currently in revision).
3. Ngodock, H.E., and M. J. Carrier, 2013: A 4D-Var system for the Navy Coastal Ocean Model Part II: strong and weak constraints assimilation experiments with real observations in the Monterey Bay (submitted to Monthly Weather Review; currently in revision).
4. Carrier, M. J., H. E. Ngodock, S. Smith, P. Muscarella, G. Jacobs, T. Ozgokmen, B. Lipphardt, and B. Haus, 2013: Impact of ocean velocity observations inferred from Lagrangian drifter data using the NCOM-4DVAR (submitted to Monthly Weather Review; currently in revision).

**PATENTS**

None