

Designing Optimal Sampling Networks, Fixed and Adaptive for Ocean Forecast Modeling

Paola Rizzoli, P.I.
Dept. of Earth, Atmos. & Planetary Sci.,
MIT, 54-1416, 77 Massachusetts Ave. Cambridge, MA 02139
Phone: 617-253-2451 Fax: 617-253-4464 Email: rizzoli@mit.edu

Award Number: NOOO 14-06-1-0290

LONG TERM GOAL

The overall long term goal is to develop innovative, practical and efficient methodologies for the design of fixed and adaptive oceanic platforms, eulerian and lagrangian, such as fixed moorings, profiling moorings, gliders, drifters, AUVs.

OBJECTIVES

The main objective is to develop this methodology for the Gulf of Maine/Georges Bank (GM/GB) region where an integrated model system has been developed at the University of Massachusetts at Dartmouth centered around the Finite- Volume Coastal Ocean circulation Model (FVCOM).

APPROACH

The technical approach will be to test the available data assimilation packages, i.e. Reduced Rank Kalman Filter (RRKF); Ensemble Kalman Filter (EnKF); Ensemble Square Root Kalman Filter (EnSRF) and the Ensemble Transform Kalman Filter (ETKF) in the idealized test-cases outlined in the report. Successively, the filters will be adapted to FVCOM in the GM/GB configuration for coastal circulation prediction and adaptive sampling studies.

WORK COMPLETED

See following pages.

RESULTS

See following pages.

IMPACTS/ APPLICATIONS

The potential future impacts of adaptive sampling in an oceanographic context, where they are still non-existent, will be comparable to the enormous impacts it has had in meteorology.

RELATED PROJECTS

None

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 30 SEP 2007		2. REPORT TYPE		3. DATES COVERED 00-00-2007 to 00-00-2007	
4. TITLE AND SUBTITLE Designing Optimal Sampling Networks, Fixed and Adaptive for Ocean Forecast Modeling				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) Massachusetts Institute of Technology (MIT), Dept. of Earth, Atmos. & Planetary Sci, 77 Massachusetts Ave, Cambridge, MA, 02139				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 unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

REFERENCES

- Bishop, C.H., B.J.Etherton and S.J.Majunder, 2001. Adaptive sampling with the Ensemble Transform Kalman Filter. Part I : theoretical aspects *Mon. Wea.Rev.*, 129,420-439
- Burchard, H., 2002. Applied turbulence modeling in marine waters. *Springer:Berlin-Heidelberg-New York-Barcelona-Hong Kong-London-Milan Paris- Tokyo*, 215pp.
- Chen, C., H. Liu, and R. Beardsley, 2003. An unstructured grid, finite-volume, three-dimensional, primitive equations ocean model: Application to coastal ocean and estuaries. *Journal of Atmospheric and Ocean Technology*, 20 (1), 159-186.
- Chen, C, G. Cowles and R. C. Beardsley, 2006a. An unstructured grid, finite-volume coastal ocean model: FVCOM User Manual. Second edition, SMAST/UMASSD Technical Report-06-0602, pp315
- Chen, C, R. C. Beardsley and G. Cowles, 2006b. An unstructured grid, finite-volume coastal ocean model (FVCOM) system. Special Issue entitled "Advance in Computational Oceanography", *Oceanography*, 19(1), 78-89.
- Chen, C., H. Huang, R. C. Beardsley, H. Liu, Q. XU, and G. Cowles, 2006c. A finite-volume numerical approach for coastal ocean circulation studies: comparisons with finite-difference models. *Journal of Geophysical Research*, in press.
- Chen, c., R. C. Beardsley, Q. XU and R. Limeburner, 2006d. Tidal Dynamics in the Gulf of Maine and New England Shelf: An Application of FVCOM. *Deep Sea Research II: GLOBEC/GB Special Issue*, in revision.
- Galperin, B., L. H. Kantha, S. Hassid, and A. Rosati, 1988. A quasi-equilibrium turbulent energy model for geophysical flows. *Journal of the Atmospheric Sciences*, 45, 55-62.
- Huang, H., C. Chen, G. Cowles, R. C. Beardsley, and K. Hedstrom, 2006a. Sensitivity of the numerical solution to unstructured triangular grids: A validation experiment of FVCOM for the Rossby equatorial soliton. *Journal of Atmospheric and Oceanic Technology*, in revision.:
- Huang, H., C. Chen, R. C. Beardsley, and K. Hedstrom, 2006b. Validation experiments of FVCOM for the wind-driven flow in an elongated rotating basin: A comparison with analytical solution. *Journal of Atmospheric and Oceanic Technology*, to be submitted.
- Mellor, G. L. and T. Yamada, 1982. Development of a turbulence closure model for geophysical fluid problem. *Reviews of Geophysics and Space. Physics*, 20,851-875.
- Smagorinsky, J., 1963. General circulation experiments with the primitive equations, I. The basic experiment. *Monthly Weather Review*, 91, 99-164.

PUBLICATIONS

- Lyu, S.-J., P.Malanotte-Rizzoli, J.A.Hansen, D.McLaughlin and D.Entekhabi, Optimal fixed and adaptive observation arrays in an idealized model of the wind-driven ocean circulation, *J.Atmos.Ocean.Tech.*, 24, 650-665, 2007b

Lyu, S.-J., P.Malanotte-Rizzoli, D.McLaughlin and D.Entekhabi, A comparison of data assimilation results from the deterministic and stochastic ensemble Kalman filters, *J.Atmos.Ocean. Tech.*, 24, 175-187, 2007a

Zang, X. and P. Malanotte-Rizzoli, A comparison of assimilation results from the Ensemble Kalman filter and the Reduced-Rank Extended Kalman filter. *Nonlinear Processes in Geophysics*, **10**, no 6, 477-491, 2003.

Buehner, M. and P. Malanotte-Rizzoli, Reduced-rank Kalman filters applied to an idealized model of the wind-driven ocean circulation. *Journal of Geophysical Research*, 108, no.C6, 3192, 10.1029/2001JC00873, 2003.

Buehner, M., P. Malanotte-Rizzoli, A. J. Busalacchi and T. Inui, Estimation of the tropical Atlantic circulation from altimetry data using a reduced-rank stationary Kalman filter. *Interhemispheric water exchanges in the Atlantic ocean*, Elsevier Oceanographic series, G. Goni and P. Malanotte-Rizzoli eds., **68**, 193–212, 2003.

Changsheng Chen, Paola Malanotte-Rizzoli, Jun Wei, Robert C. Beardsley, Zhigang Lai, Pengfei Xue, Sangjun Lyu, Qichun Xu, Jianhua Qi, and Geoffrey Cowles, *Validation of Kalman Filters for Coastal Ocean Problems: An Experiment with FVCOM*, in preparation.

RESULTS

The P.I. and her Postdoctoral Associate, Dr. Jun Wei, have continued the collaboration with Prof. Chen and his group at the University of Massachusetts at Dartmouth. In the context of this collaboration, Dr. Wei has adapted three Kalman filters packages developed at MIT by the P.I. and her collaborators to the Finite Volume Coastal Ocean Model (FVCOM) developed by Prof. Chen and used to simulate and predict the circulation and properties distributions in the Gulf of Maine. The three packages comprise:

- 1) Reduced Rank Kalman Filter (RRKF) (Buehner and Malanotte-Rizzoli, 2003; Buehner et al., 2003);
- 2) Ensemble Kalman Filter (EnKF) (Zang and malanotte-Rizzoli, 2003);
- 3) Ensemble Square Root Kalman Filter (Lyu et al, 2007a);
- 4) Ensemble Transform Kalman Filter (ETKF) used to design adaptive observations (Lyu et al.,2007b).

After a first proof-of-concept application to three idealized configurations (Chen et al, 2007, submitted to JGR, here attached), FVCOM has been adapted to the realistic configuration of the Northeast Channel of the Gulf of Maine where three current-meters moorings have been deployed providing one year long hourly data of temperature, salinity and horizontal velocity components. Fig 1 shows the geographic configuration of the Northeast Channel with the location of the three moorings and the depths of the current meters. Fig 2 shows the variable finite-volume domain used in the simulations with the number of observations and the dimension of the state vector.

Northeast Channel Case

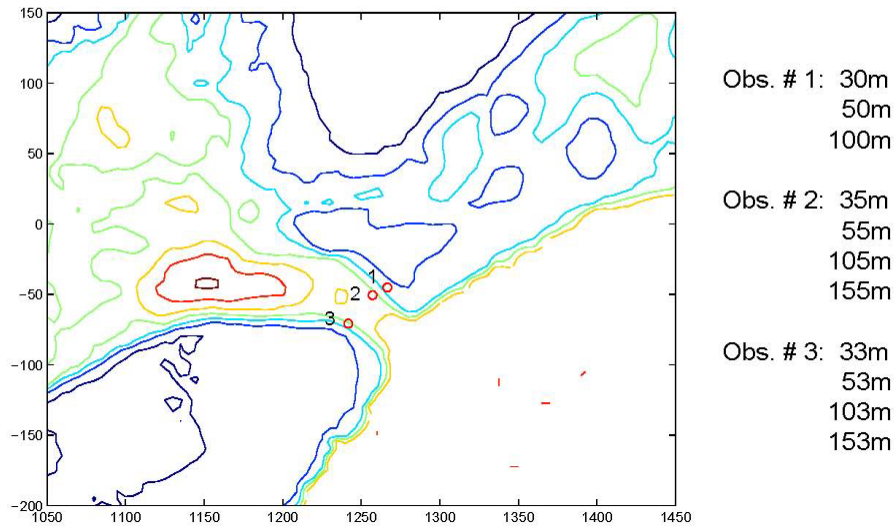
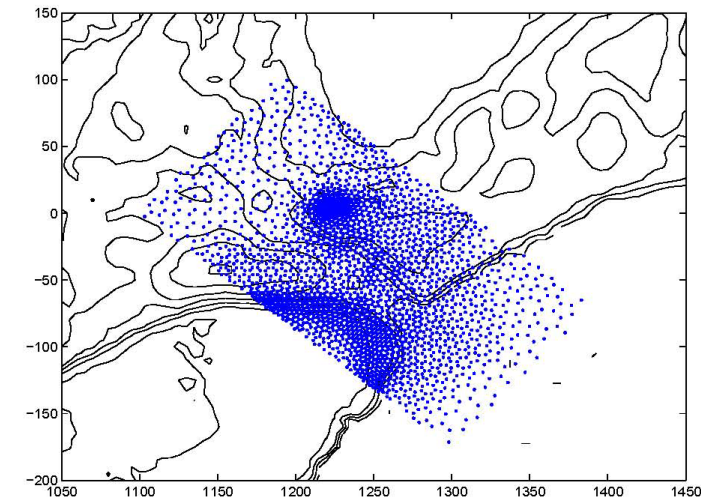


Fig 1. *The geographic configuration of the Northeast Channel with the location of the three moorings and the depths of the current meters.*

Localization



Number of Observations: $(3+4+4) \times 4 = 44$

Number of State vectors : $\sim 10^4$ \longrightarrow $K \sim [10^4 \times 44]$

Fig 2. *The variable finite-volume domain used in the simulations with the number of observations and the dimension of the state vector.*

The Northeast Channel is the major passage connecting the basins of the Gulf of Maine and the slope water of the Northwest Atlantic Ocean. The transport crossing the channel, the deep inflow water on the northeast side of the channel and the outflow on the southwest side, play an important role in controlling the cyclonic circulation in the gulf.

Fig. 3 shows the experimental set-up of the Ensemble Kalman filter with the objectives, i.e. to assess the Filter performance changing the assimilation frequency, the time scale and the ensemble size. These preliminary simulations were carried out with 20 members in the ensemble generated from previous model fields.

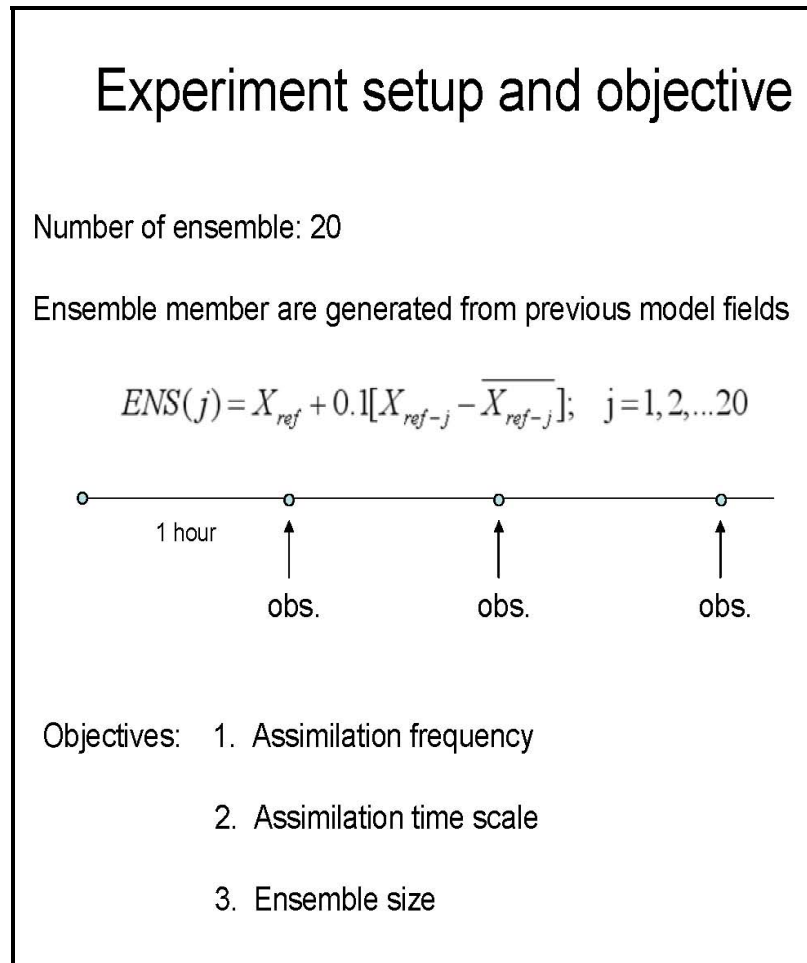


Fig. 3. The experimental set-up of the Ensemble Kalman filter with the objectives

Results

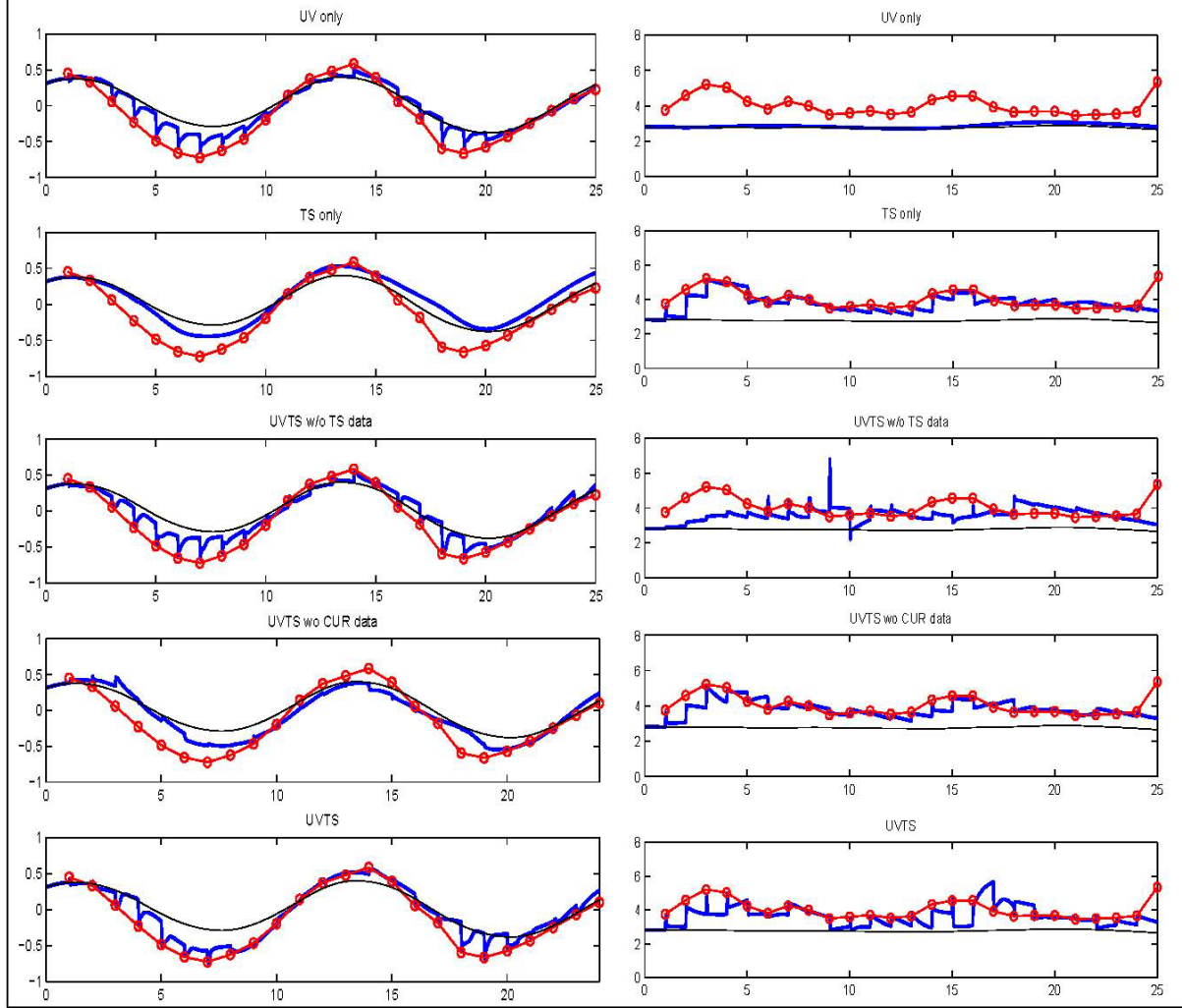


Fig. 4 An example of these preliminary results.

The left columns show the v -velocity component at 30 m. depth and at observation site 1 (Fig.1). The right columns show the temperature again at 30 m. depth at site 1. The Black lines indicate the model simulations without assimilation. The red lines are the observations with hourly data shown as circles. The blue lines are the results of the ensemble assimilations at hourly interval. The titles of the various panels indicate the type of assimilation. In the upper panels only (U,V) velocity components were assimilated and updated; in the second panel from the top only (T,S) observations; in the third panel all (U,V,T, S) were updated using only (T,S) data; in the fourth panel again all variables were updated using only velocity data; finally, in the bottom panel all the variables were assimilated and updated. It is evident that velocity data only are quite ineffective in reproducing the temperature evolution and the assimilation is identical to the control model run (upper right panel). Similarly (T, S) data are ineffective in reproducing the V-component evolution (left panel, second from the top). As expected, the best results are obtained when assimilating and updating all the variables, bottom panels. Further experimentation is in progress and we envision the submission of a second paper by the end of the year.