REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
13-09-2011	Final Technical Report	1 April 08 - 31 Mar 11

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
The ROMS IAS Data Assimilation and Prediction System: Quantifying Uncertainty	
	5b. GRANT NUMBER
	N00014-08-1-0556
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)	5d. PROJECT NUMBER
Andrew M. Moore and Brian S. Powell	08PR05812-00
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
The Regents of the University of California University of California at Santa Cruz 1156 High Street, Santa Cruz CA 95064	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
Office of Naval Research 875 North Randolph Street Arlington VA 22203-1995	ONR
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for Public Release; distribution is Unlimited.

20110919022

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The main objectives of this project were: (i) to assess the impact of observations on ocean state estimates and the ensuing forecasts; (ii) to quantify the expected errors in 4-dimensional variational (4D-Var) ocean circulation estimates; and (iii) to develop multimodel ensemble and superensemble methods for ocean models. The primary tool used in this project was the Regional Ocean Modeling System (ROMS). To address the aforementioned goals and objectives, we used a recently developed suite of tools that utilize the tangent linear , adjoint, and finite-amplitude tangent linear versions of the ROMS code. Three 4D-Var data assimilation systems have been developed for ROMS, one based on the primal formulation and two based on the dual formulation. During the project we completed the following tasks: (1) observation impact, (2) observation sensitivity, (3) Analysis and forecast error estimates based on adjoint 4D-Var, (4) Graduate student and post-doc training and mentoring, (5) a 4D-Var training workshop, and (6) preparation and publication of five manuscripts.

15. SUBJECT TERMS

Ocean modeling, data assimilation, 4D-Var, ocean prediction, predictability

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Anrew M. Moore
			UU	3	19b. TELEPHONE NUMBER (Include area code)
					831-459-4632

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The ROMS IAS Data Assimilation and Prediction System: Quantifying Uncertainty

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LONG-TERM GOALS

The long-term scientific goals of this research project were:

1. To develop a state-of-the-art ocean 4-dimensional variational (4D-Var) data assimilation and ocean forecasting system for the Regional Ocean Modeling System (ROMS);
2. To develop a state-of-the-art suite of post-processing and diagnostic tools in support of ROMS 4D-Var;
3. To gain the necessary experience using the ROMS 4D-Var systems in complex circulation environments;
4. To train the next generation of users of the ROMS 4D-Var system.

OBJECTIVES

The main objectives of this project were: (i) to assess the impact of observations on ocean state estimates and the ensuing forecasts; (ii) to quantify the expected errors in 4D-Var ocean circulation estimates; and (iii) to develop multimodel ensemble and superensemble methods for ocean models.

APPROACH

The primary tool used in this project was the Regional Ocean Modeling System (ROMS). To address the aforementioned goals and objectives, we used a recently developed suite of tools that utilize the tangent linear (TL), adjoint (AD), and finite-amplitude tangent linear (RP) versions of the ROMS code. ROMS, TLROMS and ADROMS were developed under the support of previous ONR funding, while the development of RPROMS was supported by NSF. Three 4D-

Var data assimilation systems have been developed for ROMS (Moore et al., 2011a,b,c), one based on the primal formulation and two based on the dual formulation.

WORK COMPLETED

During the project we completed the following tasks:

1. **Observation impact:** The transpose of the gain matrix derived from each 4D-Var assimilation cycle provides information about the impact of each observation on the circulation estimate. A separate driver was developed for ROMS for computing observation impacts, and was applied to explore the impact of observations in two different ROMS configurations: the Intra-Americas Sea (IAS) and the California Current System (CCS). The results of this work are described in Moore et al (2011c) and Powell et al (2011).
2. **Observation sensitivity:** The adjoint of the entire 4D-Var system can be used to assess the impact of changes in the observations or the observation network for a single 4D-Var assimilation cycle without the need to recompute the 4D-Var analysis. This is a very efficient tool for performing Observing System Experiments (OSEs), and a separate driver was developed for ROMS for computing observation sensitivities, and has been applied to ROMS CCS. The results of this work are described in Moore et al (2011c).
3. **Analysis and forecast error estimates based on adjoint 4D-Var:** Using the adjoint of the 4D-Var system, we have developed a new method for efficiently computing background, analysis and forecast error variances without the need to explicitly generate the 4D-Var ensemble members. At the present time, we are restricted to computing covariance information for linear functions of the state-vector (e.g. space-time averages, transport, heat content, etc), but the method holds promise for extracting more detailed information. The results of this work are described in Moore et al (2011d).
4. **Graduate student and post-doc training and mentoring:** During this project one graduate student at UC Santa and one technician at U Hawaii were trained and mentored. The graduate student at UC Santa Cruz worked on developing superensemble methods for ROMS IAS, while personnel at U Hawaii focussed attention on 4D-Var in the North Atlantic and IAS regions.
5. **4D-Var Workshop:** A one week, hands-on, ROMS 4D-Var workshop was held at UC Santa Cruz 12-16 July, 2010, attended by 37 scientists and students from seven different countries. The aim of the workshop was to provide help and training for expert ROMS users in running the ROMS 4D-Var drivers. The workshop was comprised of a combination of formal lectures, tutorials, and hands-on exercises based on ROMS CCS. Lecture notes are available at http://myroms.org/index.php?page=4DVAR_2010_agenda, while https://www.myroms.org/wiki/index.php/4DVar_Tutorial_Introduction provides detailed information about the hands-on exercises.
6. **Manuscripts published:** A series of three manuscripts describing the entire ROMS 4D-Var system were prepared and published in *Progress in Oceanography* during this project. Moore et al, 2011a (Part I) describes the mathematical and technical aspects of ROMS 4D-Var and supporting diagnostic algorithms, while Moore et al, 2011b (Part II) and Moore et al, 2011c (Part III) demonstrate the performance of the systems, and present examples of calculations from all of the 4D-Var system components. A fourth

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manuscript describing the use of the adjoint of 4D-Var for computing error covariance information was also submitted to *Monthly Weather Review* and is currently under review (Moore et al, 2011d). A manuscript describing the impact of various observing platforms on the Yucatan Channel transport and the inter-island passage transports of the Caribbean Sea is in preparation (Powell et al, 2011).

PUBLICATIONS

Moore, A.M., H.G. Arango, G. Broquet, B.S. Powell, J. Zavala-Garay and A.T. Weaver, 2011a: The Regional Ocean Modeling System (ROMS) 4-dimensional variational data assimilation systems. Part I: System overview and formulation. *Progress in Oceanography*, doi:10.1016/j.pocean.2011.05.004.

Moore, A.M., H.G. Arango, G. Broquet, C. Edwards, M. Veneziani, B. Powell. D. Foley, J. Doyle, D. Costa and P. Robinson, 2011b: The Regional Ocean Modeling System (ROMS) 4-dimensional variational data assimilation systems. Part II: Performance and application to the California Current System. *Progress in Oceanography*, doi:10.1016/j.pocean.2011.05.003.

Moore, A.M., H.G. Arango, G. Broquet, C. Edwards, M. Veneziani, B. Powell. D. Foley, J. Doyle, D. Costa and P. Robinson, 2011c: The Regional Ocean Modeling System (ROMS) 4-dimensional variational data assimilation systems. Part III: Observation impact and observation sensitivity in the California Current System. *Progress Oceanography*, doi:10.1016/j.pocean.2011.05.005.

Moore, A.M., H.G. Arango and G. Broquet, 2011: Analysis and forecast error estimates derived from the adjoint of 4D-Var. *Monthly Weather Review*, Submitted and under review.

Powell, B., A.M. Moore, M. Hsu, and J. Fiechter: Observational Contribution to Estimates of Caribbean Transport. *J. Physical Oceanography*, in prep.