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

Physically Consistent Eddy-resolving State Estimation and Prediction of the Coupled Pan-Arctic Climate System at Daily to Interannual Time Scales Using the Regional Arctic Climate Model (RACM).

Wieslaw Maslowski
Naval Postgraduate School
Department of Oceanography
833 Dyer Rd.,
Monterey CA 93943
phone: (831) 656-3162 fax: (831) 656-2712 email: maslowsk@nps.edu

Andrew Roberts
Naval Postgraduate School
Department of Oceanography
833 Dyer Rd.,
Monterey CA 93943
phone: (831) 656-3267 fax: (831) 656-2712 email: afrobert@nps.edu

John Cassano
CIRES, University of Colorado at Boulder
216 UCB
Boulder, CO 80309
phone: 303-492-2221 fax: 303-492-1149 email: john.cassano@colorado.edu

Mimi Hughes
CIRES, University of Colorado at Boulder
and NOAA/ESRL/PSD R/PSD2
325 Broadway St.
Boulder, CO 80305
phone: 303-497-4865 fax: 303-497-6020 email: mimi.hughes@noaa.gov

Award Number: N00014-12-1-0419 / N00014-12-WX-21183

LONG-TERM GOALS

The overall science goal of this project is to address the short to long-term US Navy / DOD (Arctic Roadmap, 2009) and national requirements (Roberts et al., 2010) to understand and predict arctic climate change. The proposed research leverages ongoing developments of the state-of-the-art Regional Arctic Climate Model (RACM) through a multi-institutional program supported by the Department of Energy Regional and Global Climate Modeling (DOE/RGCM) program and two ongoing complementary projects. This new project, which started in January 2012, is aimed at

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	2. REPORT TYPE	3. DATES COVERED
30 SEP 2013		**00-00-2013 to 00-00-2013**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Physically Consistent Eddy-resolving State Estimation and Prediction of the Coupled Pan-Arctic Climate System at Daily to Interannual Time Scales Using the Regional Arctic Climate Model (RACM).	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) **Naval Postgraduate School,Department of Oceanography,833 Dyer Rd,Monterey,CA,93943**	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	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**9**	

improved modeling of the atmosphere-ice-ocean interface in the presence of tides and eddies to advance representation of the past and present state of the Arctic Climate System and prediction of its future states at time scales from daily (operational) through seasonal, interannual, and up to decadal (tactical).

OBJECTIVES

Three main objectives are to (i) advance understanding and model representation of critical physical processes and feedbacks of importance to sea ice thickness and area distribution using a combination of forward modeling and state estimation techniques, (ii) investigate the relation between the upper-ocean heat content and sea ice volume change and its potential feedback in amplifying ice melt, (iii) upgrade RACM with the above improvements to advance both operational and tactical prediction of arctic climate using a single model.

APPROACH

This is a collaborative proposal involving the Naval Postgraduate School (W. Maslowski, A. Roberts, J. Clement Kinney) and the University of Colorado in Boulder (J. Cassano and M. Hughes). The core aim of this work is to improve the combined ocean-ice-atmosphere boundary layer state through assimilation, and to test the influence of improved initial conditions on daily, inter-annual and decadal sea ice prediction. First, we will introduce atmospheric assimilation into RACM, testing established and experimental WRF state estimation methods. Next, we will add an innovative coupled sea-ice assimilation scheme that implicitly adjusts CICE sea ice thickness distributions (g(h)) and upper ocean salinity and temperature, while also estimating atmospheric surface temperature. Outcomes from this coupled WRF-CICE state-estimation research will then be used to generate initial conditions for probabilistic RACM hindcasts. These decadal hindcasts will be used to establish timescales of sensitivity of the surface marine state of the arctic on its initial conditions. Throughout, skill and uncertainty of both the RACM analyses and hindcasts will be judged against observations for the data-intensive decade of 2000-2010. Note that interior ocean assimilation has purposefully been omitted from our proposed work due to the relative paucity of real-time under-ice observations available. This approach balances the computational cost of running a 2.3km polar eddy-resolving model with the ability being developed in this project to carefully stipulate Arctic Ocean surface and lateral boundary conditions.

RACM has used state-of-the art “off-the-shelf” models for the land hydrology, ocean, sea-ice and atmosphere components. The atmospheric model used in RACM is a version of the NCAR Weather Research and Forecasting model (WRF) that has been optimized for the polar regions. Land surface processes and hydrology are represented by the Variable Infiltration Capacity (VIC) model. The ocean and sea ice models are regional adaptations (Maslowski et al., 2004; Maslowski and Lipscomb, 2003) of those currently used in the NCAR CESM, the Parallel Ocean Program (POP) and the Community Ice CodE (CICE). The RACM simulation domain (Figure 1) covers the entire pan-Arctic region and includes all sea-ice-covered regions in the Northern Hemisphere as well as all terrestrial drainage basins that drain to the Arctic Ocean. For the baseline RACM, the ocean and sea ice models use a horizontal grid spacing of 9 km, while the atmosphere and land component models use a horizontal grid spacing of 50 km. The RACM model is being expanded into a Regional Arctic System Model

(RASM; with additional model components for the Greenland Ice Sheet, ice caps, mountain glaciers and dynamic land vegetation) and it will continue through 2015 under the 2nd phase of DOE support.

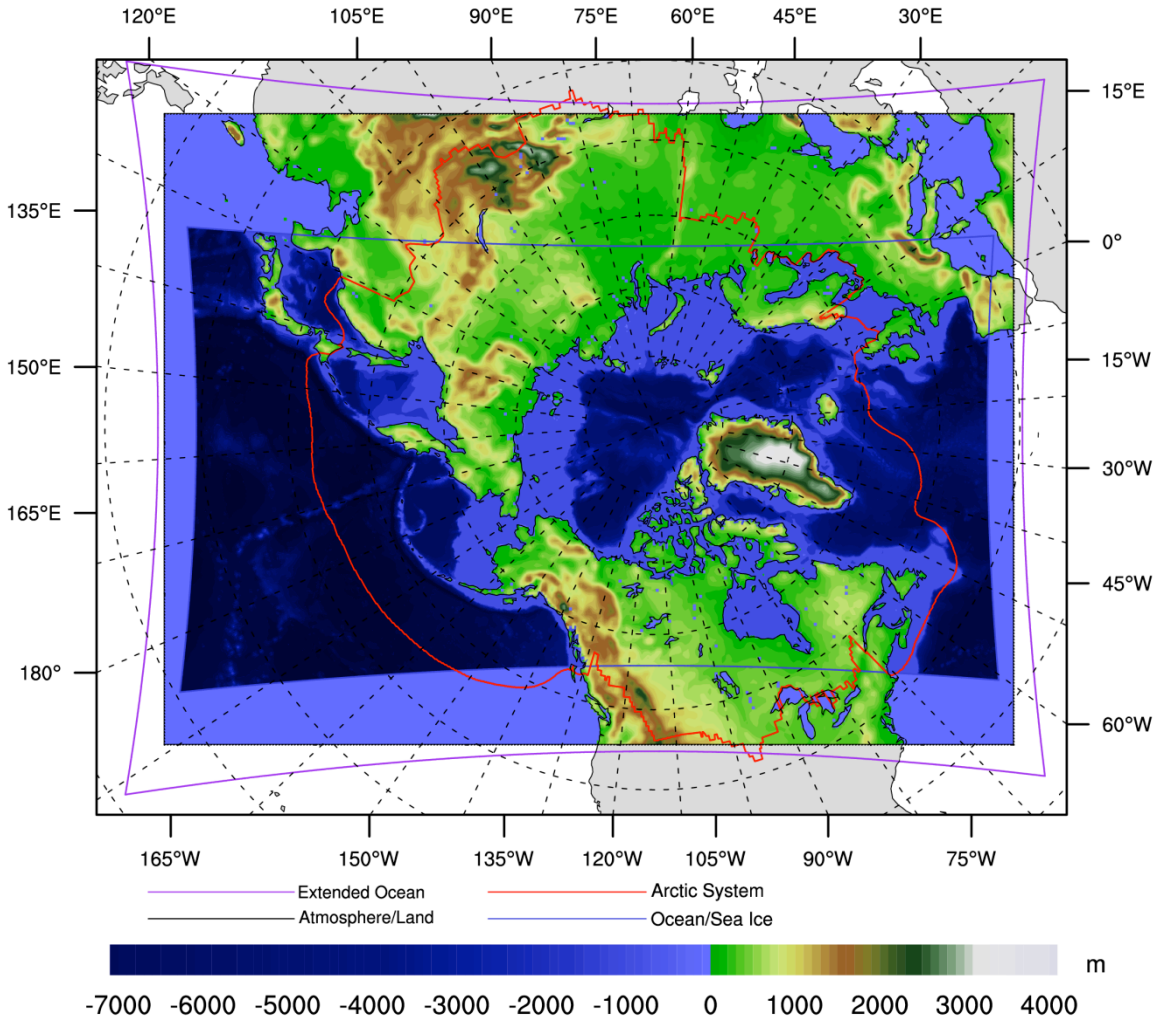

Figure 1. RACM pan-Arctic model domain. WRF and VIC model domains include the entire colored region. POP and CICE domains are bound by the inner blue rectangle. Shading indicates model topobathymetry. The Arctic System domain (red line) is defined in Roberts et al. (2010).

WORK COMPLETED

The following tasks have been addressed by the PIs at the Naval Postgraduate School.

Sea ice assimilation in RASM

As part of this project, we are developing a new sea ice assimilation method that utilizes passive microwave brightness temperatures to assimilate sea ice surface snow- and ice-temperature within CICE. This approach provides a mechanism for, first, indirectly assimilating turbulent fluxes in WRF by better specifying the surface temperature in the atmosphere, and, second, assimilating sea ice

thickness by indirectly adjusting the heat conducted through the vertical sea ice column. Early research relevant to this approach has been undertaken by Roberts (2005) and Scott et al. (2012), and the goal of this project is to bring this work to fruition in a large scale, fully coupled polar model because it has significant advantages over existing methods of sea ice assimilation.

Development of the TBSASSIM procedure

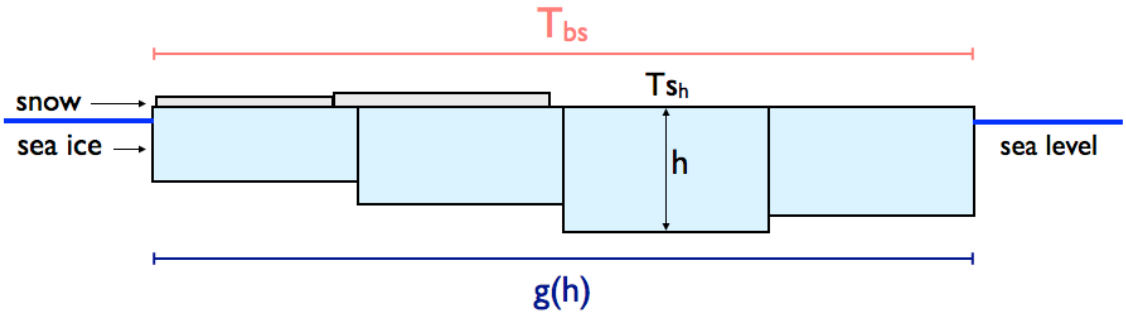

Figure 2. Schematic of surface brightness temperature, *Tbs*, and its relationship to individual sea ice thickness categories' surface temperatures, *Tsh,* or *Ts(h),* for the modeled thickness distribution *g(h)* in the Regional Arctic System Model.

Figure 2 explains the approach being utilized for TBSASSIM. Passive microwave retrievals provide a mean surface brightness temperature for a given channel, *Tbs*, for an area of sea ice with many different sea ice thicknesses, *h*, which has a thickness distribution *g(h)*. A snow thickness distribution also exists in this area, although, for brevity, we will not address this in the following discussion.

Using a radiative transfer model, such as has been utilized by Scott et al. (2012), a mean surface temperature, *Ts*, for the given area represented by *g(h)* can be derived from *Tbs*. For the sea ice thickness distribution, there exists a surface temperature distribution *Ts(h)*, so that $Ts = \int_0^{\infty} Ts(h)g(h)dh$. Assuming that the radiative transfer model that generates *Ts* from *Tbs* is not significantly skewed toward against areas of large heat fluxes or cold surfaces, we may assimilate the surface temperature using:

$$Ts(h)_t^a = Ts(h)_t^f + K_t \Phi_t(h)$$

where superscripts *f* and *a* provide the model forecast (*f*) and assimilation analysis (*a*) values of Ts(*h*) at model step *t*, K_t is the analysis gain $P_t^f/(P_t^f + \sigma^2)$ for error covariance *P*, and $\Phi_t(h)$ is the surface temperature innovation function. We intend to evaluate *P* in a manner consistent with the WRF assimilation also mentioned in this report.

The challenge here is in developing a model for $\Phi_t(h)$ that sufficiently represents the change in surface temperature of individual thicknesses relative to the change in *Ts* that represents the entire swath area encapsulated in *Tbs.* We are initially testing the model

$$\Phi_t(h) = (Ts(Tbs)_t - Ts_t^f)\frac{g(h)k(h)}{\int_0^{\infty} g(h)k(h)dh}$$

given $k(h) = k_s k_i/(k_s h + k_i h_{snow})$ for the ice and snow thermal conductivity k_i and k_s, given ice and snow thickness *h* and h_{snow}. This may be considered a "bulk innovation function" for sea ice, given the observed surface temperature at time *t* derived from passive microwave brightness temperature $Ts(Tbs)_t$, and a model forecast surface temperature Ts_t^f. More sophisticated models for

the bulk innovation function may be needed, however a similar approach as already been adopted by Roberts (2005) for Southern Ocean concentration assimilation (not brightness temperatures assimilation), and was found to be relatively robust.

A second problem we are working to solve is in best approximating $Ts(Tbs)_i$ using Special Sensor Microwave/Imaged (SSM/I) retrievals in a radiative transfer model. Scott et al. (2012) utilized a different sensor for their work (AMSR-E), but we see several advantages in using SSM/I due to its continuity of service. It should be noted that Scott et al. (2012) have only used *Tbs* to assimilate sea ice concentration *not g(h)*, so their work is not entirely compatible with research we are undertaking. Notwithstanding, we are currently working to understand the most effective way to utilize various SSM/I channels available to us, including 19, 22, 37, 85, and, more recently, 91 GHz, both in horizontal and vertical polarization, and how to use a radiative transfer model that takes into account clouds in the assimilated WRF model.

Issues related to different radiative transfer models are relatively well understood in the research community, but not without problems, as evidenced in approximations of sea ice concentration approximations using the NASA TEAM SSM/I algorithm as against the combined TEAM and Bootstrap Climate Data Record (Meier et al., 2011). We have detected a significant trending difference between the two approaches, especially in the Marginal Ice Zone, as summarized in Fig. 3.

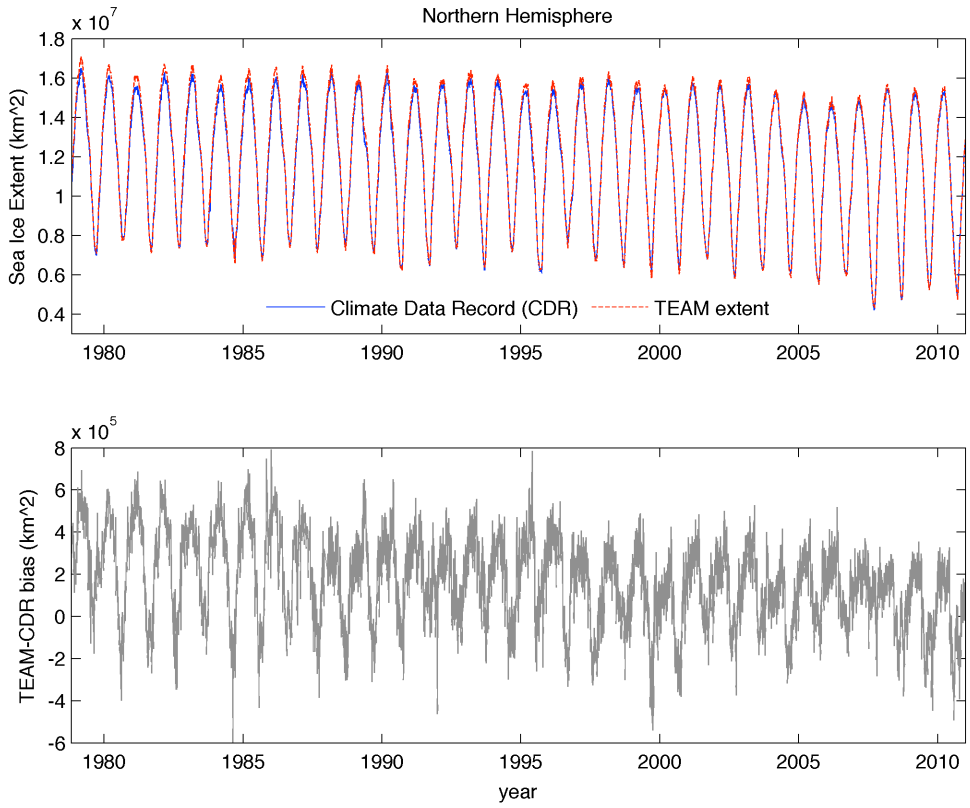

Figure 3. Comparison of sea ice extent estimates for the northern hemisphere using the NSIDC Climate Data Record Algorithm, and the NASA TEAM algorithm, which is partly included in the CDR record.

This can lead to a bias that may sometimes exceed 500,000 km^2 in extent at some times of the year. While the difference between the TEAM and Bootstrap algorithms is well understood, the climatic trend in the bias is perhaps less understood. This is of sufficient concern for assimilating a climate model as to carefully understand why this bias occurs, and to avert it where possible, in RACM. To that end, we are still giving consideration as to how to accommodate the presence of melt ponds in approximating $Ts(Tbs)_i$.

Development of software infrastructure for RASM

We have established a number of tools in MATLAB to carefully analyze SSM/I retrievals and experiment with prototype radiative transfer models before applying then to RACM. Initially, we intend to ingest daily brightness temperature maps into RACM, although this will not be without error, since these are calculated from individual swaths measured at different times of the day. Figure 4 illustrates an example where daily brightness temperatures are sharply delineated along swath boundaries. Therefore, in parallel with this effort, we are migrating the coupling framework in RACM from the Community Climate System Model infrastructure, to the Community Earth System Model coupler. Included in this new bundle of software is a tool for sampling model variables along satellite swath lines, and we intend to employ this to evaluate $\Phi_i(h)$ at the time *Tbs* is measured, rather than at the time at uniform time across the model grid. Development of this software base has occupied the majority of our time in this project.

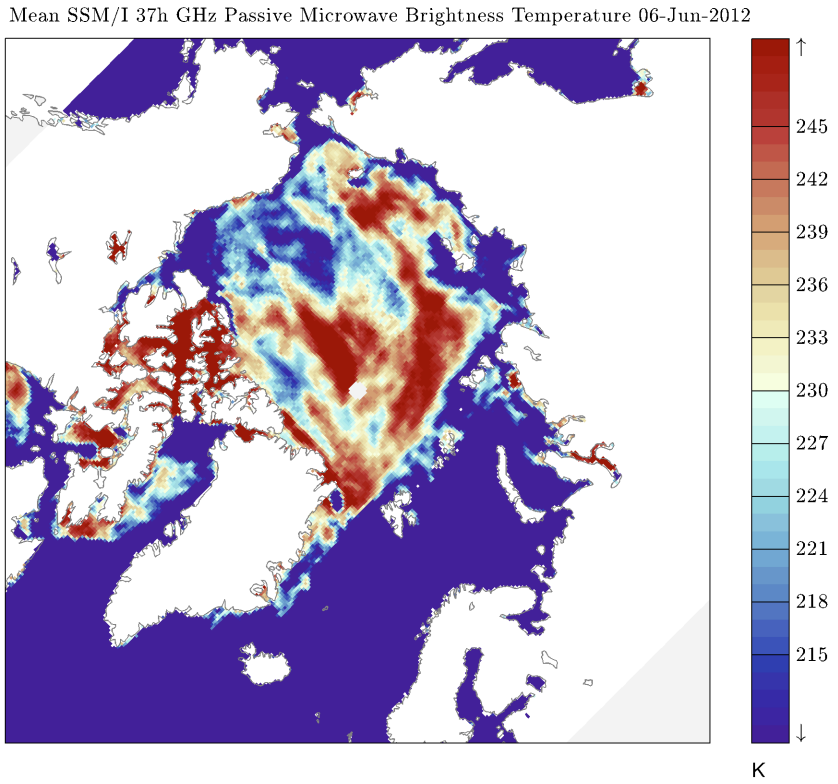

Figure 4. An example of a daily brightness temperature composite from the SSM/I sensor. Share lines of delineation mark the edge of swaths, rather than any physical features in the pack.

Development of products to service the observational community

We believe an important role of the modeling being undertaken in this project is to providing statistics and forecasts to help improve field measurements and deployments in the ONR Marginal Ice Zone program. To that end, we have developed a number of post-processing tools to provide guidance for the upcoming 2013 deployments in the Beaufort Gyre. An example of this guidance is provided in Figure 5, which shows modeled drift tracks of sea ice. These results are from hourly positions traced from interpolated daily sea ice drift fields in one ensemble member of RACM. Therefore, no track should be considered the most probable realization for that particular year. Rather, the suite of trajectories, taken as a whole, are an indication of variability associated with drift in the Beaufort Sea. Atmospheric conditions within RACM are predicted by a limited area configuration of WRF, forced with lateral boundary conditions and nudging to the first two wave numbers (for the global circulation) in the upper half of the atmosphere from the ERA-Interim reanalysis.

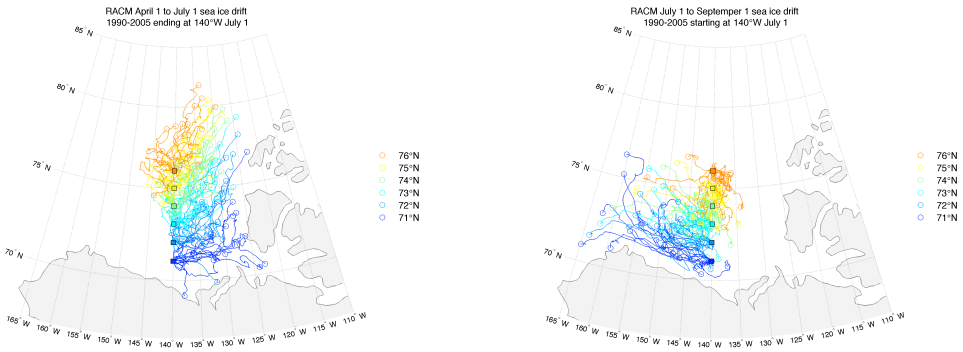

Figure 5. Sea ice drift estimates from a single ensemble member of RASM indicating start and finish of drift tracks crossing 140W in the Beaufort Sea on July 1.

University of Colorado PIs are currently comparing background error covariance matrices for the WRF Data Assimilation (WRFDA) control variables in the RACM WRF domain generated by an NMC approach with the default background error matrices provided by WRFDA. Surface, ship, and upper air data are also being downloaded for the period 2000-present from the CISL Research Data Archive. Once these data are downloaded, they will be converted to LITTLE_R format for direct ingestion into WRFDA. A meeting with Zhiquan Liu, the lead of the assimilation team for the Arctic System Reanalysis, has been scheduled for mid-October, 2012, to discuss lessons learned about Arctic data assimilation in WRF for their project.

WRFDA has been compiled on the Cray XE6 (raptor) at the DOD AFRL and the infrastructure necessary to generate background error matrices (i.e., RACM WRF output from multiple simulations organized in a WRFDA-specific format) has been partially developed.

RESULTS

Most notably, sea ice mass and velocity are never directly adjusted in the RACM model, as occurs in many existing concentration and velocity assimilation schemes employed in stand-alone ice-ocean models. Instead, using passive microwave brightness temperature assimilation, herein referred to as

TBSASSIM, the surface boundary layer state is adjusted via the physics of the atmospheric and sea ice models and their coupling. Our work so far has focused on developing the assimilation theory to apply to RACM and preparing data and software infrastructure for utilizing passive microwave brightness temperatures in RACM. We have also begun to provide model output from RACM to assist in the deployment of instruments as part of the ONR 2013 MIZ field campaign.

We have been granted a 3-year computational award by the DOD High Performance Computing Modernization Program to complete all the necessary model simulations planned as part of this project. We have resource allocations on machines at the US Army Engineering and Research Development Center (ERDC), US Air Force Research Laboratory (AFRL) and at the Navy Supercomputing Resource Center (NAVY). Use of multiple systems will help promote model portability.

IMPACT/APPLICATIONS

RACM is extensible, and will benefit from the addition of further components, such as a wave model. However, for this project, significant progress can be made using the well-tested and working RACM in its current form. RACM's computational demand, as determined by the proposed model configurations and integrations, is manageable for the purposes of this project, whereas new model components and their integration are beyond current computational limits. However, complementary efforts using a variable or unstructured global grid approach (Ringler et al., 2010; Skamarock et al., 2011) is under way and shows great promise for bridging the gap and enabling high-resolution regional Arctic climate change exploration and prediction within the context of global climate system model framework (Maslowski et al., 2012). This approach would be also most suitable for inclusion of a global wave model (e.g. Wave prediction Model, WAM) as a follow-up phase to this project.

At least four NPS graduate students sponsored by the U.S. Navy are expected to participate in this project under Maslowski's supervision at no cost to this project. Their thesis projects will address the science questions in the proposal. One student, LCDR Mark Murnane, completed research on Evaluation of Sea Ice Kinematics and their Impact on Ice Thickness Distribution in the Arctic. Another student, LT Thomas Mills, is currently completing his M.S. research thesis (expected graduation in Dec. 2012), which focuses on sea ice deformations and their impact on air-sea coupling. Both projects have used high-resolution and/or high-frequency RACM output.

RELATED PROJECTS

Three complementary projects are of relevance to this project. One, funded by the DOE/RGCM, involves further expansion of RACM into a regional Arctic Climate System model (RASM) with additional model components for the Greenland Ice Sheet, ice caps, mountain glaciers and dynamic land vegetation). Second project, funded by NSF Office of Polar Programs (NSF/OPP), focuses on improved coupling of ice-ocean interface and mixed layer dynamics and their contribution to decadal prediction of sea ice state and climate change in the Arctic. Third project, funded by DOE/SciDAC program, investigate the role of tides and mesoscale eddies on ocean circulation and dynamics as well as their contribution of oceanic forcing of sea ice.

REFERENCES

Maslowski, W., and W. H. Lipscomb, 2003: High resolution simulations of Arctic sea ice, 1979-1993. Polar Research, 22(1), 67-74.

Maslowski, W., D. Marble, W. Walczowski, U. Schauer, J. L. Clement, and A. J. Semtner, 2004), On climatological mass, heat, and salt transports through the Barents Sea and Fram Strait from a pan-Arctic coupled ice-ocean model simulation, J. Geophys. Res., 109, C03032, doi:10.1029/2001JC001039.

Maslowski, W., J. C. Kinney, M. Higgins, and A. Roberts, 2012. The future of arctic sea ice. Annual Review of Earth and Planetary Sciences, 40:625–654.

Meier, W. N., M. Savoie, and S. Mallory. 2011. CDR Climate Algorithm and Theoretical Basis Document: Passive Microwave Sea Ice Concentration. NOAA NCDC CDR Program.

Ringler, T., J. Thuburn, J. Klemp, W. Skamarock, 2010. A unified approach to energy conservation and potential vorticity dynamics on arbitrarily structured C-grids. J. Comput. Phys. 3065–90.

Roberts, A., 2005: Medium-range numerical prediction of Antarctic sea ice. Ph.D. Thesis, Antarctic Climate and Ecosystems Cooperative Research Centre and University of Tasmania, 209 pp.

Scott, K. A., M. Buehner, A. Caya, and T. Carrieres, 2012: Direct Assimilation of AMSR-E Brightness Temperatures for Estimating Sea Ice Concentration. *Mon. Wea. Rev.*, **140,** 997-1013.

Skamarock, W. C., J. B. Klemp, M. G. Duda, L. Fowler, S-H Park, and T. D. Ringler, 2012: A Multi-scale Nonhydrostatic Atmospheric Model Using Centroidal Voronoi Tesselations and C-Grid Staggering. Monthly Weather Review, accepted for publication.