Project title: Collaborative Proposal: Improving Decadal Prediction of Arctic Climate Variability and Change Using a Regional Arctic System Model (RASM)

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* Each award listed above has varying start/end during the given years

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I. Accomplishments

1. What are the major goals of the project?

This project aims to develop, apply and evaluate a regional Arctic System model (RASM) for enhanced decadal predictions. Its overarching goal is to advance understanding of the past and present states of arctic climate and to facilitate improvements in seasonal to decadal predictions. In particular, it will focus on variability and long-term change of energy and freshwater flows through the arctic climate system. The project will also address modes of natural climate variability as well as extreme and rapid climate change in a region of the Earth that is: (i) a key indicator of the state of global climate through polar amplification and (ii) which is undergoing environmental transitions not seen in instrumental records. RASM will readily allow the addition of other earth system components, such as ecosystem or biochemistry models, thus allowing it to facilitate studies of climate impacts (e.g., droughts and fires) and of ecosystem adaptations to these impacts. As such, RASM is expected to become a foundation for more complete Arctic System models and part of a model hierarchy important for improving climate modeling and predictions.

The project's main rationale is to focus on the pan-Arctic region and to explore spatial and temporal scales of relevance to the operation of the Arctic climate system but not yet achievable in Global Earth System Models (GESMs). RASM will have high spatial resolution (~5-50 times higher than currently practical in global models) to advance modeling of critical physical processes and refine coupling channels among model components as well as to determine the need for their explicit representation in Global Earth System Models (GESMs).

RASM will address societal needs for improved Arctic decadal climate projections. The educational and outreach efforts will provide interactions with scientists, real-world problems for student-directed research, and teacher training. Innovative educational materials for public dissemination, such as curriculum units, lesson plans, simulations, movies, and images, will be produced for use by students and teachers in high school and university classrooms.

This interdisciplinary project builds on successful research by four of the current PIs with support from the DOE Climate Change Prediction Program and it involves expert investigators from the Naval Postgraduate School (NPS), University of Colorado (CU) in Boulder, University of Washington (UW), University of Arizona (UA), Iowa State University (ISU), Los Alamos National Laboratory (LANL), University of California Santa Cruz (UCSC) and University of Texas at El Paso (UTEP).

2. What was accomplished under these goals?

Note: This report covers the whole RASM team, including participants from NPS, CU, UW, UA, ISU, LANL, UCSC and UTEP.

The primary outcome of the project was the development of the Regional Arctic System Model (RASM) and evaluation of its individual model components, coupling among them and fully coupled model results. Overall, we have demonstrated that RASM produces realistic mean and seasonal surface climate as well as its interannual and decadal variability and trends.

The following specific tasks have been completed towards accomplishing the goals of this project.

2.1 ***Evaluation of the Weather Research and Forecasting (WRF) model.*** Extensive testing of the atmospheric model component of RASM (WRF) was completed during this project. These tests included implementation and debugging of WRF within the RASM framework, testing WRF physics options and parameter in both stand-alone WRF and fully-coupled RASM simulations to identify the preferred model configuration(s) for RASM, and evaluation of the RASM simulated climate (Cassano et al. 2011; 2016).

2.2 WRF surface coupling. Improved the WRF surface turbulent flux algorithms over land, ocean, and sea ice to fix the coupling of the atmospheric boundary layer with the surface. We reviewed the various algorithms used in all four components of the model. The original WRF decoupling was reduced when WRF code was modified to use the roughness lengths sent to it from the other components.

2.3 ***A baseline of RASM surface interface performance.*** A comprehensive evaluation of atmosphere-land-ocean-sea ice interface processes in RASM is being completed (Brunke et al. 2016, in preparation). By comparing RASM with global data sets, local observations, reanalyses, and the Community Earth System Model (CESM), we provide a baseline for RASM performance. These evaluations reveal that precipitation is better simulated in RASM than in CESM, since CESM produces an erroneous annual cycle with maximum precipitation in spring rather than summer as observed. Comparing to observations from SHEBA, RASM's sea ice interface is well simulated with surface fluxes and radiation generally falling within observational uncertainty. By comparing with upscaled surface snow observations, we find that snow depth in RASM is better simulated over a flatter landscape than more mountainous terrain. However, there are substantial surface and near-surface temperature biases found to be tied to surface radiation biases that suggest errors in simulating clouds. Another RASM simulation, which included different convection and boundary layer turbulent schemes as well as changes to sea ice physics improves sea surface temperature biases but degrades summer land surface air temperatures. This points to the need for further investigation and improvement of the representation of clouds in RASM.

2.4 ***Evaluation of the LANL sea ice model (CICE).*** We identified one cause of biases in RASM sea ice thickness simulations as the representation of the liquid droplet size in the radiation scheme used in the atmospheric model (WRF). We therefore updated the model to include full coupling between the radiation and cloud scheme in WRF. The sea ice sensitivity to this change greatly exceeded other physical aspects of coupling. It suggests that uncoupled ice-ocean models, and fully coupled ice-ocean-atmosphere-land models with simplistic representations of liquid water droplet size in cloud schemes, are subject to compensatory errors or tuning in sea ice albedo. We suggest this is a large source of uncertainty in many existing sea ice simulations.

2.5 ***Development and coupling of the Variable Infiltration Capacity (VIC) model.*** VIC was selected for the land surface component of RASM, because of previous experience with the model in high-latitude environments. However, extensive model modifications were required to couple VIC to RASM, as previous VIC simulations were performed in a stand-alone mode, outside of a coupled model environment. These changes are also available to VIC use outside the RASM modeling infrastructure, thus benefitting the VIC-community at large.

2.6 ***Evaluation of VIC in RASM.*** The RASM version of VIC reproduces the dominant features of the land surface climatology in the Arctic (Hamman et al., 2016), such as the amount and distribution of precipitation, the partitioning of precipitation between runoff and evapotranspiration, the effects of snow on the water and energy balance, and the differences in turbulent fluxes between the tundra and taiga biomes. Surface air temperature biases in RASM, compared to reanalysis datasets ERA-Interim and MERRA, are generally less than 2°C; however, in the cold seasons there are local biases that exceed 6°C. Compared to satellite observations, RASM captures the annual cycle of snow-covered area well, although melt progresses about two weeks faster than observations in the late spring at high latitudes. With respect to derived fluxes, such as latent heat or runoff, RASM is shown to have similar performance statistics as ERA-Interim while differing substantially from MERRA, which consistently overestimates the evaporative flux across the Arctic.

2.7 ***Implemention of a streamflow routing (RVIC) scheme in RASM.*** We implemented a streamflow routing scheme to deliver the freshwater flux from the land surface to all coastal grid cells. This routing scheme is implemented separately from the land model and communicates directly with the CPL-7 coupler, which means that it can be used with multiple land models. The implementation of the streamflow routing model (RVIC) is described in Hamman et al. (2016, in review). As part of this paper we will also make the RASM dataset available to the community-at-large, since it compares well with (limited) streamflow observations and it offers a greater spatial and temporal resolution than other existing data sets.

2.8 ***VIC / C-N coupling.*** The NCAR CESM's version of carbon-nitrogen (C-N) model has initially been incorporated into two versions of the offline VIC (4.1.2.d and 4.1.2.i). The addition of CN was shown to change the VIC simulation. Recently, CN was successfully integrated into the image driver of a development version of VIC5.0.0 and remains to be integrated into this latest version of VIC to be used and evaluated in RASM Phase III.

2.9 ***Evaluation of 'new' parameterizations in CICE.*** We worked in collaboration with the National Center for Atmospheric Research and Los Alamos National Laboratory to jointly implement the latest available sea ice physics in CICE Version 5 in the RASM/CESM fully coupled modeling frameworks. This collaborative work enabled the first coupled simulations of sea ice using the so-called prognostic salinity "Mushy-Layer" thermodynamics, which greatly improved water properties in the ocean model (Hamman et al., 2016 in review; DiMaggio et al;, in preparation).

2.10 **Evaluation of a 'new' sea ice rheology option in CICE.** As part of the implementation of CICE 5, RASM was the first model to test new anisotropic sea ice mechanics in a fully coupled framework. This work is currently in preparation for publication. This advance was much lauded, because it offered the potential to circumvent the problem of representing sea ice, which is a fragmented material, using continuum mechanics. Our results present a mixed story, and suggest that anisotropic mechanics may not be the panacea we expected it to be.

2.11 ***RASM-VIC 'new' parameterizations.*** The vegetation-dependent snow albedo (Barlage et al. 2005) was integrated into RASM-VIC to reduce the persistent surface temperature biases due to high positive albedo biases over forests, which were diagnosed in both the mean annual and diurnal cycles in comparison to surface temperature biases in RASM. This was largely done by comparing with the NASA Modern Era Retrospective Analysis for Research and Applications (MERRA) and in situ observations. Also, the roughness length formulation for sea ice (Brunke et al. 2006) was introduced in RASM to help improve the model simulation of inertial oscillations in the sea ice.

2.12 ***Investigations of strong surface winds in RASM.*** RASM and stand-alone WRF simulations were also used to study strong surface winds in the Arctic by assessing the model resolution necessary to accurately simulate barrier winds along the coast of Greenland (DuVivier and Cassano 2013), assessing the impact of different wind regimes on ocean surface fluxes (DuVivier and Cassano 2015), comparing extreme winds across the Arctic in WRF and multiple reanalyses (Hughes and Cassano 2015), comparison of surface winds around southeastern Greenland in WRF and ERA-Interim (DuVivier and Cassano 2016), and evaluation of the impact of strong surface winds on ocean buoyancy forcing in RASM (DuVivier et al. 2016).

2.13 ***RASM-WRF studies*.** Numerous regional climate model studies over the Arctic, using two domains. While the domains differ in size, they both encompass vital components of the Arctic climate system. Glisan et al. (2013) analyzed how changing the spectral nudging coefficient in a polar-optimized version of the Weather Research and Forecasting (WRF) model affected mean and extreme precipitation and temperature events across four high-latitude analysis region on the standard RASM domain.

2.14 ***RASM-WRF-CORDEX studies*.** Simulations on the smaller Coordinated Regional Climate Downscaling Experiment (CORDEX) Arctic domain, established the physical credibility of WRF simulations for extreme behavior in summer (Glisan and Gutowski, 2014a) and winter (Glisan and Gutowski, 2014b) seasons. They also gave insight into the nature of extremes in select Arctic regions and showed that topography plays an important role in the dynamical processes producing widespread precipitation events in high-latitude North America. The polar-optimized WRF was used to evaluate circulation regimes in the Arctic atmosphere (Fisel and Gutowski, 2011) and their relationship to extremes in daily temperature (Fisel and Gutowski, 2016). Further work is evaluating how the potential for extreme weather will change in the future, projected climate of the Arctic.

2.15 ***The analysis of polar temperature and precipitation extremes.*** Using Self-organizing maps (SOMs) (Cassano et al. 2015a, 2015b, Glisan et al. 2016) show that the polar-optimized WRF simulates well physical processes creating daily widespread events of polar temperature and precipitation in Alaska. Moreover, SOMs are a powerful tool in diagnosing physical characteristics leading to extreme. In a broader sense, we are confident that the SOM technique gives us another method for analyzing changes in present and future climate extremes.

2.16 ***Identification of the physical constraints on modeling ice-ocean inertia in high-resolution models.*** This enabled RASM to be used to model the full drift spectrum of sea ice across timescales ranging from a few hours to many years, which compared favorably with *in situ* observations (Roberts et al. 2015). This result is important for understanding the extent to which RASM can be used to refine processes in Global Earth System Models, and allowed hour-by-hour analysis of momentum exchange with observations. As part of this work, we discovered a significant problem in the way many Earth System Models couple ocean, sea ice and atmospheric components that leads to instability in the ice-ocean boundary layer. We identified an inertial instability belt that can result in either chaotic ice-ocean coupling, or catastrophic non-linear instabilities. We engineered a way to avoid this problem in RASM within the coupling framework, and the result from this work is now being used in ACME and CESM.

2.17 ***Evaluation of the impact of freshwater forcing on ocean model performance.*** Three different model treatments that were evalauted include two cases of standalone ocean-sea-ice components with one case forced by salinity restoring and the other one with CORE2 reanalysis freshwater data. The third case consisted of the fully coupled RASM model with the river routing scheme (RVIC; see below), which prognstically calculates land-ocean freshwater fluxes. Performance of the three cases was evaluated using the Labrador Sea. The Labrador Sea part of the RASM domain was selected as a case study and because of its importance to the global ocean thermohaline circulation, the connection to the Greenland Ice Sheet, the availability of direct observational data and prior modeling studies for this region (e.g. McGeehan and Maslowski, 2011 & 2012). The fully coupled RASM performed generally better than the other two modeling cases in terms of producing more realistic seawater stratification and circulation. However, all three cases still overpredict the occurrence of deep ocean convection in the Labrador Sea basin, which might be in part related to the generation and impact of fresh-top eddies determining shelf-basin interaction in the region. Increased spatial resolution of the ocean model may allay some of these problems by enabling more realistic water column stratification. This work is currently in preparation for publication.

2.18 ***Impact of oceanic forcing on sea ice thickness distribution.*** Maslowski et al. (2014) hypothesize that the northward advection of Pacific Water together with the excess oceanic heat that has accumulated below the subsurface mixed layer in the western Arctic Ocean due to diminishing sea ice cover and subsequent increased solar insulation are critical factors affecting sea ice growth in winter and melt the following year. We argue that process-level understanding and improved model representation of ocean dynamics and ocean-ice-atmosphere interactions in the Pacific-Arctic region are needed to advance knowledge and improve prediction of the accelerated decline of sea ice cover and amplified climate warming in the Arctic. A key ocean contribution is the inflow of Pacific Water from the Bering Sea, through Bering Strait and into the western Arctic, which remains a challenge for ocean models to properly represent its volume and property fluxes, as documented by Clement Kinney et al. (2014). The spatial resolution such as employed in RASM POP and CICE models (~10km) allows realistic simulation of seasonal variability in sea ice cover and its multi-decadal trends (Frey et al. 2014). However, even higher resolution is needed to improve the representation of warm Pacific Water inflow from the Bering Sea, through Bering Strait and into the western Arctic (Clement Kinney et al. 2014) and its impact on sea ice. Several critical processes needing improvements include mesoscale eddies, shelf-break flow and upwelling/downwelling, shelf-basin exchanges of both warm and fresh water in summer and cold and salty water in winter as well as sea ice deformation including polynyas and leads (Williams et al. 2014).

2.19 ***Greenland Ice Sheet initial conditions and sensitivity studies.*** Initial work on coupled climate/ice-sheet models focused on the development of validation tools and procedures. Using Latin hypercube sampling, LANL scientists generated a large ensemble of initial ice sheet conditions for the Community Ice Sheet Model (CISM), all forced with coupled climate model output but varying in internal ice sheet parameters. The resulting preindustrial Greenland ice sheet states were objectively and automatically ranked according to a suite of diagnostics to arrive at a parameter set that best recreates the observed ice sheet. This work was published in Lipscomb et al. (2013), which provided century-scale projections of Greenland mass loss in a high-emissions warming scenario and showed that ice dynamics provide a large negative feedback to surface-melt-driven sea-level rise. Related work was aimed at improved spin-up techniques for the Greenland Ice Sheet. Since ice sheets have a long memory of past climates (since before the Last Glacial Maximum), spin-ups that incorporate realistic Ice Age forcing can improve estimates of future sea-level rise. To obtain a more realistic initial state of CISM, the model was spun up for 122,000 years using climate forcing from multiple CESM paleoclimate simulations. The resulting preindustrial initial condition was found to match the observed internal ice state better than an equivalent "constant preindustrial" spin-up. This work was described in a paper by Fyke et al. (2014) in *Geoscientific Model Development*.

2.20 ***Development of a distributed global glacier model (GDDM).*** LANL scientists created and evaluated the DGGM. Using new global datasets of glacier hypsometry, the DGGM was used to simultaneously track the evolution of all Arctic glaciers in a statistical model, converting surface mass balance (SMB) changes to volume and area changes. SMB biases were reduced by adapting a subgrid downscaling scheme previously applied to ice sheets and by improving the treatment of incoming shortwave and longwave radiation, snow thickness, and subgrid rain/snow partitioning. The overall statistical approach proved to be practical, but was limited in usefulness because of remaining large SMB biases in regions of complex mountain topography. In future work, these biases could be reduced by higher-resolution atmosphere models and/or downscaling schemes that include orographic effects on precipitation.

2.21 ***Evaluation of Greenland's surface mass balance (SMB).*** In the later part of the project, work focused on evaluating Greenland's present-day and future SMB in coupled climate simulations. Originally, the SMB was to be computed in the VIC land model, coupled interactively to the WRF atmosphere model. For technical reasons, however, it was not possible to use VIC for this purpose during RASM Phase II. (This work will be pursued in RASM Phase III.) Instead, LANL scientists analyzed output from the Community Land Model in CESM, the first complex global climate model to generate a realistic SMB for Greenland. Fyke et al. (2014) published the results of this analysis in two papers in *Geophysical Research Letters*. The first study showed that Greenland SMB variability will likely increase over the next several decades as the total SMB becomes less positive. This increase, which is a robust consequence of anthropogenic warming, can be attributed primarily to a growing ablation area and secondarily to greater variability of specific SMB within the ablation area. Long-term changes to SMB variability will affect GrIS dynamics, freshwater fluxes, and regional oceanography. The second study used a signal-to-noise approach to identify the time of emergence of an anthropogenic SMB signal. There is a bimodal pattern of signal emergence, with early emergence around the ice sheet margins (where a large signal of increased melting emerges from a background of high variability) and in the cold interior (where a smaller signal of increased snowfall emerges from a background of lower variability). Counterintuitively, signal detection may occur soonest in the cold interior near the Greenland summit.

2.22 ***Development of land data for RASM evaluation.*** Land data for use in the RASM and for the evaluation of the dynamic vegetation model simulation have been developed. The interannual variability and trends have been explored in annual maximum green vegetation fraction (MGVF) derived from Advanced Very High Resolution Radiometer (AVHRR) normalized difference vegetation index (NDVI) data in the NASA Global Inventory Modeling and Mapping Studies (GIMMS) first generation product from 1982 to 2008. We are comparing this to MGVFs derived from NDVIs in NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) land products (from 2001 to 2008) and from another AVHRR-derived product produced the NOAA Center for Satellite Applications and Research (STAR) from 1982 to 2008. In addition, the LAI derived from the NASA's MODIS measurements, are directly comparable to RASM simulated LAI. Summer LAIs simulated by VIC-CN are found to be consistent with MODIS values, and they also perform better than those from VIC alone. Also, a new global 0.5-degree hourly land surface air temperature dataset from 1948 to present has been developed (Wang and Zeng 2014) under a separate project and allows data-model comparison of the monthly mean diurnal temperature range (MDTR) and the range of monthly averaged diurnal cycle of temperature (RMDT) in pan-Arctic region. Finally, a climatology of specific humidity inversions based on intercomparing five reanalyses [NCEP-2, ERA-40, MERRA, ERA-Interim, and CFSR] was established in Brunke et al. (2015). The use of reanalyses allows investigation of the critical processes behind humidity inversion formation, including dynamics, turbulence, and moist physics. Initial analyses of the RASM simulated specific humidity profiles at nine Arctic locations in January compares better to observed profiles derived from radiosondes and the reanalyses than CESM.

2.23 ***Toward modeling of future Arctic climate using RASM.*** We implemented in RASM the optional reading in of time-varying GHGs into WRF's radiation schemes, and time-varying ocean temperature and salinity lateral boundary conditions. These new features allow RASM to simulate future Arctic climate using output from GESMs, which will advance understanding of future climate change.

2.24 ***Expanding on research findings resulting from this project.*** During the implementation of form-drag in RASM, we inadvertently happened upon a result that shed light on an Achilles heel of sea ice models – the representation of frictional loss during ridging and rafting. Within the sea ice momentum balance, sea ice friction has been represented as a simple linear function without guidance from any physical principle on energy dissipation in non-conservative systems. This limitation affects sea ice drift and thickness strongly, because frictional loss typically accounts for 95% of energy consumed during ridge building. With further investigation, we found a way to explicitly model frictional loss in the pack using continuum mechanics models, and to produce spectra of ridge shapes to calculate form drag on sea ice founded on fundamental physics principles. This result was made possible by using advances by astrophysicists working on non-conservative systems in an unrelated field, and we have applied the results of their work to sea ice models. While much of the work on this problem is now part of a sister project to DOE's RASM project, the development was seeded by this project. Aside from improving the fundamental physics of sea ice models, it will allow much better comparison with ICESat-2 freeboard observations of sea ice and RASM when that satellite is launched late next year or in early 2018, thus laying the groundwork for developments planned within the new phase (III) of DOE funding for RASM.

2.25 ***RASM education and outreach.*** Finally, as part of the RASM education and outreach efforts the UTEP team used RASM as a platform to develop products for public dissemination, such as curriculum units, lesson plans and other materials (simulations, movies, and images) for use by students and teachers in high school and university classrooms. By the use of problem-based learning (PBL, a student-centered, inquiry-based approach in which students work in teams to solve challenging, open-ended problems) approaches, we have provided real-world scenarios and problems enabling students to do research and develop position papers or presentations on topics related to RASM. We also developed teacher-training materials that will be developed within the curriculum in order to aid teachers in understanding how to use RASM content in the classroom. Overall, we have provided a broad, and long-term program for RASM infused education and outreach.

3. What opportunities for training and professional development has the project provided?

Support from this project has contributed to the professional development of the nine graduate students, three postdoctoral research fellows, and four junior scientists, as listed below.

Graduate Students: A. Barbosa (UTEP; M.Ed.), A. DuVivier (CU; Ph.D.), J. Glisan (ISU; Ph.D.), B. Fisel (ISU; M.S. and Ph.D.), J. Hamman (UW; Ph.D.), S. Hossainzadeh (UCSC; Ph.D.), M. Murnane (NPS, M.S.), T. Mills (NPS, M.S.), D. DiMaggio (NPS, M.S. and Ph.D.).

Postdoctoral Research Fellows: M. Higgins (CU), J. Glisan (ISU), J. Fyke (LANL).

Junior Scientists: M. Hughes (CU), M. Seefeldt (CU), J. Clement Kinney (NPS), A. Roberts (NPS).

All of these project participants gained experience in model development, use of high performance supercomputers, analysis of climate model simulations, and presentation of research results at national and international conferences and in the peer reviewed literature. They also learned how to collaborate within a multi-institutional research team, pursue interdisciplinary science questions and use research results from this project in support of education and outreach.

RASM research results and findings have contributed to the development of Polar Meteorology and Oceanography education at the Naval Postgraduate School. Also, as part of the RASM educational components a curriculum for high school and undergraduate students on "Confronting Global Climate Change" has been developed by Dr. W. Robertson and A.C. Barbosa at the University of Texas at El Paso. Finally, Dr. B. Nijssen started on this project as a research scientist and later took over as PI after he became faculty and when Dr. D. Lettenmaier (the original RASM PI) moved from the University of Washington to the University of California in Los Angeles.

4. How have the results been disseminated to communities of interest?

The RASM team members have so far been the lead authors on 30 peer reviewed publications, with at least partial support from this project. Several additional papers are in final stages of preparation for submission to relevant peer reviewed scientific journals. In addition, the RASM team co-authored over 150 invited and contributed presentations at international and national scientific conferences related to climate change and develivered a number of RASM-related presentations to the general public, including at K-12 schools, colleges, and other institutions.

II. PRODUCTS

1. Publications

a. Journal publications (peer reviewed)

Brunke, M., S. Stegall, and X. Zeng, 2015: A climatology of tropospheric humidity inversions in five reanalyses. Atmos. Res., 153, 165-187. doi: 10.1016/j.atmosres.2014.08.005.

Brunke, M. A., J. J. Cassano, N. Dawson, A. K. DuVivier, W. J. Gutowski, Jr., J. Hamman, W. Maslowski, B. Nijssen, A. Roberts, J. Renteria, and X. Zeng, 2016: Evaluation of atmosphere-land-ocean-sea ice interface processes in the Regional Arctic System Model version 1.0 (RASM1.0), in preparation (to be submitted by the end of October).

Cassano, J.J., M.E. Higgins, and M.W. Seefeldt, 2011: Performance of the Weather Research and Forecasting (WRF) Model for Month-long pan-Arctic Simulations. *Mon. Weather Rev.,* 139, doi:10.1175/MWR-D-10-05065.1.

Cassano, J.J., A. DuVivier, A. Roberts, M. Hughes, M. Seefeldt, M. Brunke, A. Craig, B. Fisel, W. Gutowski, J. Hamman, M. Higgins, W. Maslowski, B. Nijssen, R. Osinski, and X. Zeng, TBD: Development of the Regional Arctic System Model (RASM: Near surface atmospheric climate sensitivity. *J. Clim., accepted pending revisions.*

Clement Kinney J., Maslowski W., Aksenov Y., de Cuevas B., Jakacki J., Nguyen A., Osinski R., Steele M., Woodgate R.A., Zhang J., 2014: On the Flow Through Bering Strait: A Synthesis of Model Results and Observations, in The Pacific Arctic Region: Ecosystem Status and Trends in A Rapidly Changing Environment, eds. J. Grebmeier and W. Maslowski, Springer.

Deal, C.J., N. Steiner, J. Christian, J.Clement-Kinney, K. Denman, S. Elliott, G. Gibson, M. Jin, D. Lavoie, S. Lee, W. Lee, W. Maslowski, J. Wang, E. Watanabe, 2014: Progress and Challenges In Biogeochemical Modeling Of The Pacific Arctic Region, in The Pacific Arctic Region: Ecosystem Status and Trends in A Rapidly Changing Environment, eds. J. Grebmeier and W. Maslowski, Springer.

DuVivier, A.K. and J.J. Cassano, 2013: Evaluation of WRF model resolution on simulated mesoscale winds and surface fluxes near Greenland. *Mon. Weather Rev.,* 141, DOI:10.1175/MWR-D-12-00091.1.

DuVivier, A.K. and J.J. Cassano, 2015: Exploration of turbulent heat fluxes and wind stress curl in WRF and ERA-Interim during wintertime mesoscale wind events around southeastern Greenland. *J. Geophys. Res.,* 120, doi:10.1002/2014JD022991.

DuVivier, A.K., J.J. Cassano, A. Craig, J. Hamman, W. Maslowski, B. Nijssen, R. Osinski, and A. Roberts, 2016: Winter atmospheric buoyancy forcing and oceanic response during strong wind events around southeastern Greenland in the Regional Arctic System Model (RASM) for 1990-2010. *J. Climate,* 29, DOI:10.1175/JCLI-D-15-0592.1.

DuVivier, A.K. and J.J. Cassano, 2016: Comparison of wintertime mesoscale winds over the ocean around southeastern Greenland in WRF and ERA-Interim. *Clim. Dyn.,* 46, DOI 10.1007/s00382-015-2697-8.

Fisel, B. J., W. J. Gutowski, Jr., J. M. Hobbs, and J. J. Cassano, 2011: Multiregime states of Arctic atmospheric circulation. *J. Geophys. Res.,* 116, doi: 10.1029/2011JD015790.

Fisel, B. J., and W. J. Gutowski, TBD: Arctic Model Dynamical Regimes and Temperature Extremes. *J. Geophys. Res., In review.*

Frey, K.E., J. A. Maslanik, J. Clement Kinney, W. Maslowski, 2014: Long-Term Trends and Recent Interannual Variability of Sea Ice Cover in the Pacific Arctic Region, in The Pacific Arctic Region: Ecosystem Status and Trends in A Rapidly Changing Environment, eds. J. Grebmeier and W. Maslowski, Springer.

Fyke, J.G., W. J. Sacks, and W. H. Lipscomb, 2014: A technique for generating consistent ice sheet initial conditions for coupled ice-sheet/climate models. *Geoscientific Model Dev.,* 7, doi:10.5194/gmd-7-1183-2014.

Fyke, J.G., M. Vizcaíno, W. Lipscomb, and S. Price, 2014: Future climate warming increases Greenland Ice Sheet surface mass balance variability. *Geophys. Res. Lett.,* 41, doi:10.1002/2013GL058172.

Fyke, J. G., M. Vizcaíno, W. Lipscomb, and S. Price, 2014: The pattern of anthropogenic signal emergence in Greenland Ice Sheet surface mass balance. *Geophys. Res. Lett.,* 41, doi:10.1002/2014GL060735.

Glisan, J.M., W. J. Gutowski, J. J. Cassano and M E. Higgins, 2013: Effects of Spectral Nudging in WRF on Arctic Temperature and Precipitation Simulations. *J. Clim.,* 26, doi: 10.1175/JCLI-D-12-00318.1.

Glisan, J.M., and W. J. Gutowski, 2014a: WRF Summer Extreme Daily Precipitation over the CORDEX Arctic. *J. Geophys. Res.,* 119, doi: 10.1002/2013JD020697.

Glisan, J.M., and W. J. Gutowski, 2014b: WRF Winter Extreme Daily Precipitation over the CORDEX Arctic. *J. Geophys. Res.,* 119, doi: 10.1002/2014JD021676.

Glisan, J.M., W. J. Gutowski Jr., J. J. Cassano, E. N. Cassano, and M. W. Seefeldt, 2016: Analysis of WRF extreme daily precipitation over Alaska using self-organizing maps. *J. Geophys. Res.,* 121, doi: 10.1002/2016JD024822.

Hamman, J., B. Nijssen, M. Brunke, J. Cassano, A. Craig, A. DuVivier, M. Hughes, D. P. Lettenmaier, W. Maslowski, R. Osinski, A. Roberts, and X. Zeng, 2016: The land surface climate in the Regional Arctic System Model. *J. Clim.,* 29(18), 6543-6562, doi:10.1175/JCLI-D-15-0415.1.

Hamman, J., B. Nijssen, A. Roberts, A. Craig, W. Maslowski, and R. Osinski, TBD: The coastal streamflow flux in the Regional Arctic System Model simulations. *J. Geophys. Res.,* i*n review.*

Hamman, J., B. Nijssen, A. Roberts, and J. Cassano, TBD: On the relationship between Arctic winter precipitation and minimum sea ice extent. *Geophys. Res. Lett., In preparation.*

Hughes, M. and J.J. Cassano, 2015: The climatological distribution of extreme Arctic winds and implications for ocean and sea ice processes. *J. Geophys. Res.,* 120, doi:10.1002/2015JD023189.

Lipscomb, W.H., J. G. Fyke, M. Vizcaíno, W. J. Sacks, J. Wolfe, M. Vertenstein, A. Craig, E. Kluzek, and D. M. Lawrence, 2013: Implementation and initial evaluation of the Glimmer Community Ice Sheet Model in the Community Earth System Model. *J. Clim.,* 26, doi:10.1175/ JCLI-D-12-00557.1.

Maslowski, W., J. Clement Kinney, M. Higgins, A. Roberts, 2012: The Future of Arctic Sea Ice, Annual Review of Earth and Planetary Sciences, Vol. 40: 625-654, doi: 10.1146/annurev-earth-042711-105345.

Maslowski, W., J. Clement Kinney, S. Okkonen, R. Osinski, A. Roberts, W. Williams, 2014: The Large Scale Ocean Circulation and Physical Processes Controlling Pacific-Arctic Interaction, in The Pacific Arctic Region: Ecosystem Status and Trends in A Rapidly Changing Environment, eds. J. Grebmeier and W. Maslowski, Springer.

McGeehan, T., and W. Maslowski, 2012: Evaluation and control mechanisms of volume and freshwater export through the Canadian Arctic Archipelago in a high-resolution pan-Arctic ice-ocean model, J. Geophys. Res., 117, C00D14, doi:10.1029/2011JC007261.

Roberts, A.F., A. Craig, W. Maslowski, R. Osinski, A. Duvivier, M. Hughes, B. Nijssen, J. Cassano, M. Brunke, 2015: Simulating transient ice – ocean Ekman transport in the Regional Arctic System Model and Community Earth System Model. *Ann. Glaciol,* 56, doi:10.3189/2015AoG69A760.

Williams, W.J., E. Shroyer, J. Clement Kinney, M. Itoh, W. Maslowski, 2014: Shelf-break Exchange in the Bering, Chukchi and Beaufort Seas, in The Pacific Arctic Region: Ecosystem Status and Trends in A Rapidly Changing Environment, eds. J. Grebmeier and W. Maslowski, Springer.

b. **Books or other non-periodical, one-time publications**

Grebmeier, J. and W. Maslowski, 2014: The Pacific Arctic Region: Ecosystem Status and Trends in A Rapidly Changing Environment, eds. J. Grebmeier and W. Maslowski, Springer.

Maslowski W., 2013. Understanding the Arctic Climate System. International Innovation, pp 70-72, February 2013, Research Media, UK, ISSN 2051-8528 www.oc.nps.edu/NAME/ResearchMedia.EU_Maslowski_highres.pdf.

Four M.S. theses and six Ph.D. dissertations by graduate students listed under I.3.

c. **Other publications, conference papers and presentations**

A complete list of conference papers and presentations is too long (150+) to include here and can be made available upon request.

d. **Website(s) or other Internet site(s)**

RASM project website:	http://www.oc.nps.edu/NAME/RASM.htm
RASM repository:	https://svn.nps.edu/repos/racm/rasm
VIC repository:	https://github.com/UW-Hydro/VIC
RVIC repository:	https://github.com/UW-Hydro/RVIC
RASM email list:	https://lists.nps.edu/mailman/listinfo/rasm
Sea ice collaboration website:	http://www.oc.nps.edu/~afrobert

2. **Technologies and techniques**

An improved ice-ocean-atmosphere coupling technique was developed and instituted in the community flux coupling software, CPL, which eradicated a fundamental problem with the way interfacial stresses were calculated and communicated within RASM and the Community Earth System Model (CESM). It also highlighted a potential problem in several other earth system models. Previously in RASM and CESM, coupling software had disregarded timestep lags in communicating state variables and fluxes between the sea ice, the atmosphere and the ocean models. This allowed high frequency inertial oscillations (period of ~12 hours near the North Pole) to become chaotic and numerically unstable. A theoretical understanding of the problem was developed, and hence the practical problem of instabilities was fixed in CPL. The changes were passed to both Los Alamos National Laboratory for development of the Accelerated Climate Model for Energy (ACME) and also to the National Center for Atmospheric Research for CESM. A paper was published showing success of the coupling technique both in RASM and CESM.

3. Other products detail

a. A MATLAB processing software package named "Icepack" was developed at NPS for analysis of high resolution fully coupled sea ice components of Earth System Model and made available in the RASM repository and at http://www.oc.nps.edu/~afrobert.

b. All source code improvements to stand-alone versions of VIC and RVIC are available to the community-at-large via the online source code repositories for the two models (https://github.com/UW-Hydro/VIC and https://github.com/UW-Hydro/RVIC, respectively).

c. As part of the Hamman et al. (2016, in review) paper we will also make the RASM-RVIC dataset available to the community-at-large, since it compares well with (limited) streamflow observations and it offers a greater spatial and temporal resolution than other existing data sets.

d. As part of the RASM education and outreach efforts, the UTEP team used RASM as a platform to develop products for public dissemination, such as curriculum units, lesson plans and other materials (simulations, movies, and images) for use by students and teachers in high school and university classrooms. By the use of problem-based learning (PBL, a student-centered, inquiry-based approach in which students work in teams to solve challenging, open-ended problems) approaches, we have provided real-world scenarios and problems enabling students to do research and develop position papers or presentations on topics related to RASM. We also developed teacher-training materials that will be developed within the curriculum in order to aid teachers in understanding how to use RASM content in the classroom.

III. IMPACT

1. What is the impact on the development of the principle discipline(s) of the project?

This project has led to the development of the Regional Arctic System Model (RASM). RASM is a high resolution regional model that couples atmosphere, ocean, sea ice, and land model components. To our knowledge, RASM represents the first fully coupled, high resolution regional system model for focused studies of Arctic climate and climate change. Experiences gained from RASM have also benefited the development of (global) earth system models.

2 What is the impact on other disciplines?

By focusing on coupled Arctic climate, this project implicitly addresses multiple disciplines, including oceanography, sea ice, atmosphere, and land hydrology as well as multi-connections among those disciplines. RASM could be also integrated with socioeconomic models for the regional assessment and climate impact studies over the Arctic.

3. What is the impact on the development of human resources?

A total of sixteen junior scientists, including graduate students, postdoctoral fellows and early carrier scientists, were supported, at least in part, through funds from this project at the participating RASM project institutions.

4. What is the impact on physical, institutional, and information resources that form infrastructure?

5. What is the impact on technology transfer?

6. What is the impact on society beyond science and technology?

Outcomes from this work aid Arctic stewardship and U.S. interests in line with the National Strategy for the Arctic Region (Office of the President, 2013) and the need for practical tools to better understand and predict Arctic climate for commercial, operational, defense and policy making purposes.

7. Other impacts

Partly due to this project, a number of the RASM PIs (J. Cassano, W. Gutowski, W. Maslowski, A. Roberts, and X. Zeng) have been heavily involved in DOE and other climate modeling cummunity activities. Those include serving on the Science Advisory Board of the DOE/PNNL Earth & Biological Sciences Directorate (X. Zeng) , on two Science Focus Area (SFA) and several proposal review panels for the DOE Office of Science Biological and Environmental Research (BER) Program, planning for the DOE Exascale computing capability, on Advancing X-cutting Ideas for Computational Climate Science and many other DOE co-organized workshops as well as coordinating and planning of the international CORDEX and Arctic-CORDEX activities.