Final Technical Report
DE-FG02-07ER64462

Collaborative Research: Towards Advanced Understanding and Predictive Capability of Climate Change in the Arctic Using a High-Resolution Regional Arctic Climate System Model

August 2007 to August 2012

Research Activities

Development of the fully coupled RACM

The primary research task completed for this project was the development of the Regional Arctic Climate Model (RACM). This involved coupling existing atmosphere, ocean, sea ice, and land models using the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM) coupler (CPL7). RACM is based on the Weather Research and Forecasting (WRF) atmospheric model, the Parallel Ocean Program (POP) ocean model, the CICE sea ice model, and the Variable Infiltration Capacity (VIC) land model. All partner institutions (University of Colorado, Naval Postgraduate School, Iowa State University, and University of Washington) as well as scientists at the University of Alaska – Fairbanks International Arctic Research Center (IARC) and Arctic Region Supercomputing Center (ARSC) assisted with this activity.

The atmospheric portion of RACM development included modification of WRF to allow communication with CPL7 and the other RACM component models. Extensive testing and debugging of the coupled model occupied much of our effort over the duration of this project. At the end of the project the fully coupled atmosphere – ocean – sea ice – land model was able to run stably for decadal length simulations although some biases in the model climate still existed.

The version of RACM developed as part of this project was configured to run on a large pan-Arctic model domain (Figure 1) that included all sea ice covered waters in the Northern Hemisphere and all Arctic Ocean draining watersheds. WRF and VIC use a 50 km horizontal grid and POP and CICE use a ~9 km horizontal grid.

Evaluation of decadal fully coupled RACM simulations, and comparison with comparable stand-alone WRF simulations, indicates that atmospheric biases are similar in magnitude to those found in WRF-only simulations. Simulation of the annual evolution of sea ice is reasonable, with some biases related to biases in the WRF simulations. We found that the RACM simulation of circulation (Figures 3 and 4) and precipitation is comparable to stand-alone WRF. Near surface temperatures are better simulated over the Arctic Ocean in RACM as a result of a more realistic time evolving sea ice state compared to the simplified specified sea ice state in stand-alone WRF (Figure 5). Near surface temperatures over the high latitude land areas of the pan-Arctic model domain showed larger biases in RACM compared to WRF (Figure 5). The source of this increased land surface temperature bias was eventually identified as a model error related to strong static stability during the winter over land areas and was corrected after the end of this award. A manuscript (Higgins et al. 2012) describing the atmospheric climate in RACM was submitted before the end of this project but was subsequently

withdrawn after several errors in the model were identified. This manuscript is being re-written as part of our continuing RACM / RASM effort funded by DOE.

The primary outcomes from the development of RACM include:

- RACM is stable and produces a reasonable climate for decade length simulations

- the atmospheric state simulated by RACM is comparable to that simulated in stand-alone WRF. This is a very positive result given the increased degrees of freedom in the coupled model compared to the stand-alone WRF and provides confidence that the basic model coupling that was completed as part of this project is correct.

- Some aspects of the RACM simulation exhibit improvement compared to stand-alone WRF due to the inclusion of more realistic coupled physical processes. The clearest example of this is in the near surface temperature over the Arctic Ocean where fine scale representation of leads and varying ice thickness allow for more realistic energy transfer from the ocean to the atmosphere and results in a removal of the stand-alone WRF Arctic Ocean near surface cold bias.

Evaluation of stand-alone WRF simulations

A secondary research task for this project was testing and evaluation of WRF for climate-scale simulations on the large pan-Arctic model domain (Figure 1) used in RACM. This involved identification of a preferred set of model physical parameterizations for use in our coupled RACM simulations and documenting any atmospheric biases present in RACM. This work led to the publication of Cassano et al. (2011). The Polar Meteorology Group at the Byrd Polar Research Institute at Ohio State University assisted with this effort and were supported on this project with a sub-contract from the University of Colorado. The research efforts at Ohio State University led to publication of Bromwich et al. (2009) and Hines and Bromwich (2008).

Evaluation of stand-alone WRF simulations relied on observational data from the Surface Heat Budget of the Arctic (SHEBA) field campaign, data from the Barrow Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) site, and observations from the International Systems for Observing the Atmosphere (IASOA) sites as well as global reanalysis data. The WRF simulations were designed to evaluate radiation and cloud microphysics parameterizations and tested 30 different physics combinations. It was found that many of the physics combinations produced similar results, although some physics combinations were clearly not appropriate for use in the Arctic. Our conclusion from these simulations was that the CAM shortwave and longwave radiation parameterizations perform best in the Arctic environment and were selected as the radiation parameterizations for RACM.

Based on the stand-alone WRF simulations completed as part of this project we were able to identify a preferred set of WRF physical parameterizations for use in climate-scale pan-Arctic simulations with WRF and RACM as described in Cassano et al. (2011). We also identified significant circulation biases in WRF when run on a large pan-Arctic model domain, that were related to model errors that accumulate at the model top boundary. It was found that the use of spectral nudging in the top half of the WRF model

domain can eliminate these circulation biases (Figure 2). Therefore, all fully coupled RACM simulations use the WRF spectral nudging option.

As part of the stand-alone WRF testing two WRF simulations on the pan-Arctic model domain were completed. These simulations covered the time period 1989 to 2009 and output from these simulations will be provided to the Coordinated Regional Downscaling Experiment (CORDEX) data archive. One simulation was run with prescribed lateral boundary conditions, provided by the ERA-Interim reanalysis, while the second used the same lateral boundary conditions as well as spectral nudging in the upper half of the model domain to further constrain the model.

Related research activities

Research activities related to the primary RACM development and WRF evaluation led to two publications. These papers include an analysis of land surface response to reduced Arctic sea ice (Higgins and Cassano 2011) and an analysis of Arctic atmospheric circulation regimes (Fisel et al. 2011).

Publications

Bromwich, D.H., K.M. Hines, and L.-S. Bai, 2009: Development and Testing of Polar Weather Research and Forecasting Model: 2. Arctic Ocean. J. Geophys. Res., 114, D08122, doi:10.1029/2008JD010300.

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. Wea. Rev.,* **139,** 3469-3488, doi:10.1175/MWR-D-10-05065.1.

Fisel, B.J., W.J. Gutowski Jr., J.M. Hobbs, and J.J. Cassano, 2011: Multi-regime states of the Arctic atmospheric circulation. *J. Geophys. Res.,* **116,** D20122, doi:10.1029/2011JD015790.

Higgins, M.E. and J.J. Cassano, 2011: Northern Alaskan land surface response to reduced Arctic sea ice extent. *Clim Dyn.*, in press, DOI 10.1007/s00382-011-1095-0.

Higgins, M.E., J. He, J.J. Cassano, A. Craig, W. Gutowski, J. Jakacki, D.P. Lettenmaier, W. Maslowski, A. Roberts, and C. Zhu, 2012: The Regional Arctic Climate Model (RACM): Atmospheric implementation and validation. *J. Clim.,* withdrawn.

Hines, K.M., and D.H. Bromwich, 2008: Development and testing of Polar WRF. Part I. Greenland ice sheet meteorology. Mon. Wea. Rev., 136, 1971-1989.

Meetings Attended / Presentations

Year 1: August 2007 – May 2008

Attend DOE Climate Change Prediction Program Science Team meeting, Sept 2007
Poster presentation: Maslowski, W., J. Cassano, W. Gutowski, and D. Lettenmaier, Towards Advanced Understanding and Predictive Capability of Climate Change in the Arctic Using a High-Resolution Regional Arctic Climate System Model (RACM) – New Project Overview

Meet with project co-PI Dennis Lettenmaier, Seattle, WA, Oct 2007

Attend SEARCH for DAMOCLES workshop, Paris, France, Oct 2007
Oral presentation: Cassano, J.J., Atmospheric Modeling in an Arctic System Model
Oral presentation: Bromwich, D.H., K.M. Hines, and J.J. Cassano, Polar Optimized WRF

American Geophysical Union fall meeting, San Francisco, CA, Dec 2007
Poster presentation: Roberts, A., J. Hutchings, W.D. Hibler III, and M. Seefeldt, Atmospheric and Oceanic Forcing of Sea Ice Drift and Deformation During the SEDNA Field Campaign

Attend project meeting with all project PIs, San Francisco, CA, Dec 2008

Attend Little Alaska Weather Symposium, Fairbanks, AK, May 2008
Invited oral presentation: Cassano, J.J., M.W. Seefeldt, and E.N. Cassano, Development and Evaluation of Polar WRF

Attend project meeting with all project PIs, Boulder, CO, May 2008

Year 2: June 2008 – May 2009

Attend Antarctic Meteorological Observation, Modeling and Forecasting Workshop, Madison, WI, June 2008
Oral presentation: Cassano, J.J. and M.W. Seefeldt: Development and evaluation of Polar WRF.

Attend WRF Users' workshop, Boulder, CO, June 2008
Poster presentation: Seefeldt, M.W., and J.J. Cassano: Evaluation of long duration WRF simulation in the Arctic.

Oral presentation: Seefeldt, M.W. and J.J. Cassano: An overview of the regional Arctic Climate System Model (RACM)

Attend project collaborative meeting, Ames, IA, September 2008

Attend Regional Arctic Climate System Model project meeting, Seattle, WA, December 2008

Oral presentation: Seefeldt, M.W. and J.J. Cassano: ASM Project Update: Atmospheric Component.

Attend AGU Fall meeting, San Francisco, CA, December 2008

Poster presentation: Hinzman, L, A. Roberts, J. Walsh, J. Cassano, R. Doescher, M. Holland, M. Mitsudera: A science plan for the development of an Arctic System Model

Poster presentation: Seefeldt, M.W. and J.J. Cassano: Evaluation of WRF across the Arctic using surface observations

Attend Alaska Weather Symposium, Fairbanks, AK, March 2009

Invited oral presentation: Seefeldt, M.W.: The application of the Weather Research and Forecasting (WRF) model in the Arctic

Attend Climate Change Prediction Program meeting, Bethesda, MD, April 2009

Poster presentation: Cassano, J.J. and M.W. Seefeldt: An Evaluation of the Physics Parameterizations in the Weather Research and Forecasting (WRF) Model for Use in the Polar Regions

Poster presentation: Maslowski, W., J. Cassano, W. Gutowski, and D. Lettenmaier: Regional Arctic Climate Model Development - Status and Progress To Date

Attend 21st Century Challenges in Regional-scale Climate Modeling workshop, Lund, Sweden, May 2009

Oral presentation: Cassano, J.J., W. Maslowski, W. Gutowski, and D. Lettenmaier: Development of a Regional Arctic Climate System Model (RACM)

Attend American Meteorological Society Polar Meteorology and Oceanography conference, Madison, WI, May 2009

Poster presentation: Cassano, J.J., A. Roberts, L. Hinzman, J.E. Walsh, R. Doescher, M.M. Holland, H. Mitsudera, and A. Sumi, A science plan for development of an Arctic System Model

Oral presentation: Seefeldt, M.W. and J.J. Cassano, 2009: The identification of preferred physics parameterizations in the Weather Research and Forecasting (WRF) model for use in polar regions

Year 3: June 2009 – May 2010

Attend DOE regional Arctic climate system model project meeting, San Diego, CA, June 2009

Oral presentation: Seefeldt, M.W., J.J. Cassano, and M.E. Higgins, 2009: Project update: Atmospheric component, University of Colorado

Attend Weather Research and Forecasting (WRF) Model Users' Workshop, Boulder, CO, June 2009

Oral presentation: Cassano, J.J., W. Maslowski, W. Gutowski, D. Lettenmaier, M. Seefeldt, J. He, 2009: Development of a regional Arctic climate system model (RACM)

Poster presentation: Seefeldt, M.W., and J.J. Cassano, 2009: The identification of preferred physics parameterizations in the Weather Research and Forecasting (WRF) model for use in the polar regions

Attend Antarctic Meteorological Observation, Modeling and Forecasting workshop, Charleston, SC, July 2009

Oral presentation: Cassano, J.J., M.W. Seefeldt, M. Higgins, and D. Porter, 2009: Identification of preferred physics options for Polar WRF simulations in the Arctic

Attend IAMAS-IAPSO-IACS MOCA-09 Joint Assembly, Montreal, Canada, July 2009

Poster presentation: Cassano, J.J. and M.W. Seefeldt, 2009: Polar atmospheric modeling in an Arctic system model

Attend DOE regional Arctic climate system model project meeting, Santa Cruz, CA, December 2009

Oral presentation: Cassano, J.J., M. Higgins, and M. Seefeldt, 2009: Evaluation of WRF for pan-Arctic simulations

Attend American Geophysical Union fall meeting, San Francisco, CA, December 2009

Poster presentation: Higgins, M. and J.J. Cassano, 2009: Development of a regional Arctic climate system model: Performance of Polar WRF for regional pan-Arctic simulations

Attend State of the Arctic meeting, Miami, FL, March 2010

Oral presentation: Cassano, J.J., W. Maslowski, W. Gutowski, D. Lettenmaier, and J. He, 2010: Development of a regional Arctic climate system model (RACM)

Poster presentation: Gutowski, W., J. Cassano, J. Glisan, B. Fisel, M. Higgins, and M. Seefeldt, 2010: Evolution of the Arctic climate system simulated by pan-Arctic WRF as sea ice changes

Attend DOE Integrated Climate Change Modeling Science Team meeting, Gaithersburg, MD, April 2010

Poster presentation: Maslowski, W., W. Gutowski, J. Cassano, and D. Lettenmaier, 2010: Development of a regional Arctic climate system model (RACM): Progress report and future plans

Poster presentation: Gutowski, W., J. Cassano, B. Fisel, M. Higgins, and M. Seefeldt, 2010: Development of a regional Arctic climate system model (RACM): Performance of Polar WRF for regional pan-Arctic atmospheric simulations

Attend European Geophysical Union annual meeting, Vienna, Austria, May 2010

Poster presentation: Higgins, M.E. and J.J. Cassano: 2010: Development of a Regional Arctic Climate System Model: Performance of Polar WRF for regional pan-Arctic atmospheric simulations

Organize and attend DOE regional Arctic climate system model project meeting, Boulder, CO, May 2010

Oral presentation: Higgins, M.E. and J.J. Cassano, 2010: WRF update. Regional Arctic Climate Model project meeting, Boulder, CO.

Year 4: June 2010 – May 2011

Attend International Polar Year Oslo Science Conference, Oslo, Norway, June 2010.

Poster presentation: Higgins, M.E. and J.J. Cassano, 2010: Northern Alaska land surface response to future sea ice projections. International Polar Year Oslo Science Conference, Oslo, Norway.

Poster presentation: Cassano, J.J. and M.E. Higgins, 2010: Development of a regional Arctic climate system model: Performance of WRF for regional pan-Arctic atmospheric simulations. International Polar Year Oslo Science Conference, Oslo, Norway.

Attend WRF Users' workshop, Boulder, CO, June 2010

Oral presentation: Cassano, J.J., M.E. Higgins, and M. Seefeldt, 2010: Evaluation of WRF for pan-Arctic simulations. Weather Research and Forecasting (WRF) Model Users' Workshop, Boulder, CO.

Attend International Meeting of Statistical Climatology, Edinburgh, United Kingdom, July 2010.

Mechanical Engineering Departmental Seminar, University of Colorado, Boulder, CO, October 2010

Invited oral presentation: Cassano, J.J., W. Maslowski, W. Gutowski, and D. Lettenmaier, 2010: Development of a regional Arctic climate model (RACM), Department of Mechanical Engineering Fluid Connections seminar, Boulder, CO.

Attend Regional Arctic Climate Model project meeting, Ames, IA, December 2010.

Oral presentation: Higgins, M. and J. Cassano, 2010: Coupled RACM update. Regional Arctic Climate Model project meeting, Ames, IA.

Attend American Geophysical Union Fall meeting, San Francisco, CA, December 2010.

Oral presentation: Cassano, J.J. and M.E. Higgins, 2010: Atmospheric results from a regional Arctic climate model: Comparison of coupled and uncoupled simulations. American Geophysical Union fall meeting, San Francisco, CA.

Attend International Conference on the Coordinated Regional Downscaling Experiment – CORDEX, Trieste, Italy, March 2011.

Oral presentation: Cassano, J.J. and M.E. Higgins, 2011: CORDEX Arctic simulations: Initial results from the Weather Research and Forecasting model. International Conference on the Coordinated Regional Downscaling Experiment – CORDEX, Trieste, Italy.

Attend Arctic Science Summit Week, The Arctic: New Frontier of Global Science conference, Seoul, Korea, 27 March 2011.

Oral presentation: Cassano, J.J., W. Maslowski, W. Gutowski, D. Lettenmaier, W. Lipscomb, S. Tulaczyk, X. Zeng, M. Higgins, and A. Roberts, 2011: Modeling Arctic climate with a regional Arctic climate model. Arctic Science Summit Week, Seoul, Korea.

Poster presentation: Cassano, J.J., W. Maslowski, W. Gutowski, D. Lettenmaier, W. Lipscomb, S. Tulaczyk, X. Zeng, M. Higgins, and A. Roberts, 2011: Development of a regional Arctic system model (RASM). Arctic Science Summit Week, Seoul, Korea.

Attend American Meteorological Society 11th Polar Meteorology and Oceanography Conference, Boston, MA, May 2011.

Oral presentation: Cassano, J.J. and M.E. Higgins, 2011: Synoptic climatology of pan-Arctic WRF simulations. American Meteorological Society 11th Conference on Polar Meteorology and Oceanography, Boston, MA.

Poster presentation: DuVivier, A. and J.J. Cassano, 2011: Understanding the effects of model resolution on winds and surface fluxes for an easterly tip jet during the Greenland Flow Distortion Experiment. American Meteorological Society 11th Conference on Polar Meteorology and Oceanography, Boston, MA.

Oral presentation: Fisel, B.J., W.J. Gutowski, J.M. Hobbs, and J.J. Cassano, 2011: Multi-regime states of Arctic atmospheric circulation. American Meteorological Society 11th Conference on Polar Meteorology and Oceanography, Boston, MA.

Oral presentation: Higgins, M.E., J.J. Cassano, T. Craig, J. Jakacki, and C. Zhu, 2011: Initial results from the Regional Arctic climate system model (RACM). American Meteorological Society 11th Conference on Polar Meteorology and Oceanography, Boston, MA.

Year 5: June 2011 – August 2012

Attend Regional Arctic Climate Model (RACM) project meeting, Sopot, Poland, 15-17 May 2011.

> Oral presentation: Maslowski, W., J. Cassano, W. Gutowski, D. Lettenmaier, A. Craig, A. DuVivier, B. Fisel, J. Glisan, M. Higgins, J. Jakacki, R. Osinski, A. Roberts, and C. Zhu, 2011: Regional Arctic Climate Model (RACM): Overview, selected results and future plans.

Attend International Union of Geodesy and Geophysics general assembly, Melbourne, Australia, 28 June – 2 July 2011.

> Oral presentation: Cassano, J.J., M.E. Higgins, A. DuVivier, W. Maslowski, A. Roberts, W. Gutowski, and D. Lettenmaier, 2011: Modeling Arctic climate with a regional Arctic climate model.

Attend World Climate Research Programme Polar Grand Challenges workshop, Sienna, Italy, 23-24 September 2011.

Attend International Arctic Science Committee Atmosphere Working Group workshop on Arctic Ocean drifting observatory, Potsdam, Germany, 26-27 September 2011.

> Oral presentation: Cassano, J.J. and M.E. Higgins, 2011: Comparison of atmosphere-land and coupled atmosphere-land-ocean-sea ice CORDEX Arctic simulations.

Attend World Climate Research Programme Open Science Conference, Denver, CO, 24-28 October 2011.

> Poster presentation: Cassano, J.J. and M.E. Higgins, 2011: CORDEX Arctic simulations with WRF.

Attend Workshop on Polar Simulations with the Weather Research and Forecasting (WRF) model, Columbus, OH, 2-3 November 2011.

> Oral presentation: Cassano, J.J., M. Higgins, A. DuVivier, W. Maslowski, W. Gutowski, D. Lettenmaier, and A. Roberts, 2011: Modeling the Arctic atmosphere with the Regional Arctic System Model (RASM).

Attend American Geophysical Union Fall Meeting, San Francisco, CA, 5-9 December 2011.

> Oral presentation: Cassano, J.J., M. Higgins, A. DuVivier, W. Maslowski, W. Gutowski, D. Lettenmaier, and A. Roberts, 2011: Modeling the Arctic atmosphere with the Regional Arctic System Model (RASM).
>
> Oral presentation: Fisel, B.J., W.J. Gutowski, J.M. Hobbs, and J.J. Cassano, 2011: Multi-regime states of the Arctic atmospheric circulation.

Oral presentation: Roberts, A., W. Maslowski, J. Jakacki, M. Higgins, T. Craig, J.J. Cassano, W.J. Gutowski, and D.P. Lettenmaier, 2011: High frequency and wavenumber ocean-ice-atmosphere coupling in the Regional Arctic Climate Model.

Poster presentation: Glisan, J.M., W.J. Gutowski, M. Higgins, and J.J. Cassano, 2011: The effects of spectral nudging on Arctic temperature and precipitation extremes as produced by the pan-Arctic WRF.

Attend ADSIMNOR-CORDEX workshop on Arctic climate modeling results and needs, Norrköping, Sweden, 20-21 March 2011.

Oral presentation: Cassano, J.J., M. Higgins, W. Maslowski, W. Gutowski, D. Lettenmaier, and A. Roberts, 2012: Comparison of WRF and RACM Arctic CORDEX simulations.

Attend International Polar Year Knowledge to Action Science Conference, Montreal, Canada, 23-27 April 2012.

Poster presentation: Cassano, J.J., M.E. Higgins, A. DuVivier, D. Porter, W. Gutowski, D. Lettenmaier, W. Maslowski, A. Roberts, and C. Zhu, 2012: Lessons learned from the devolpment of a fully coupled regional Arctic climate model (RACM).

Project Participants

John Cassano, University of Colorado principal investigator, 8.3% FTE (August 2007 – August 2012)

Mark Seefeldt, University of Colorado post-doctoral scientist, 100% FTE (August 2007 to August 2009), 15% FTE (September 2009 – April 2011)

Matthew Higgins, University of Colorado associate scientist, 100% FTE (September 2009 – May 2010)

Matthew Higgins, University of Colorado post-doctoral scientist, 100% FTE (May 2010 – September 2011), 10% FTE (November 2011 – August 2012)

Alice DuVivier, University of Colorado graduate student, supported by CIRES / NOAA graduate student fellowship (May 2010 – April 2011), 100% FTE (April 2012 – July 2012)

David Porter, University of Colorado post-doctoral scientist, 50% FTE (January 2012 – May 2012)

Tony Craig, scientific programmer, sub-contract support

Figures

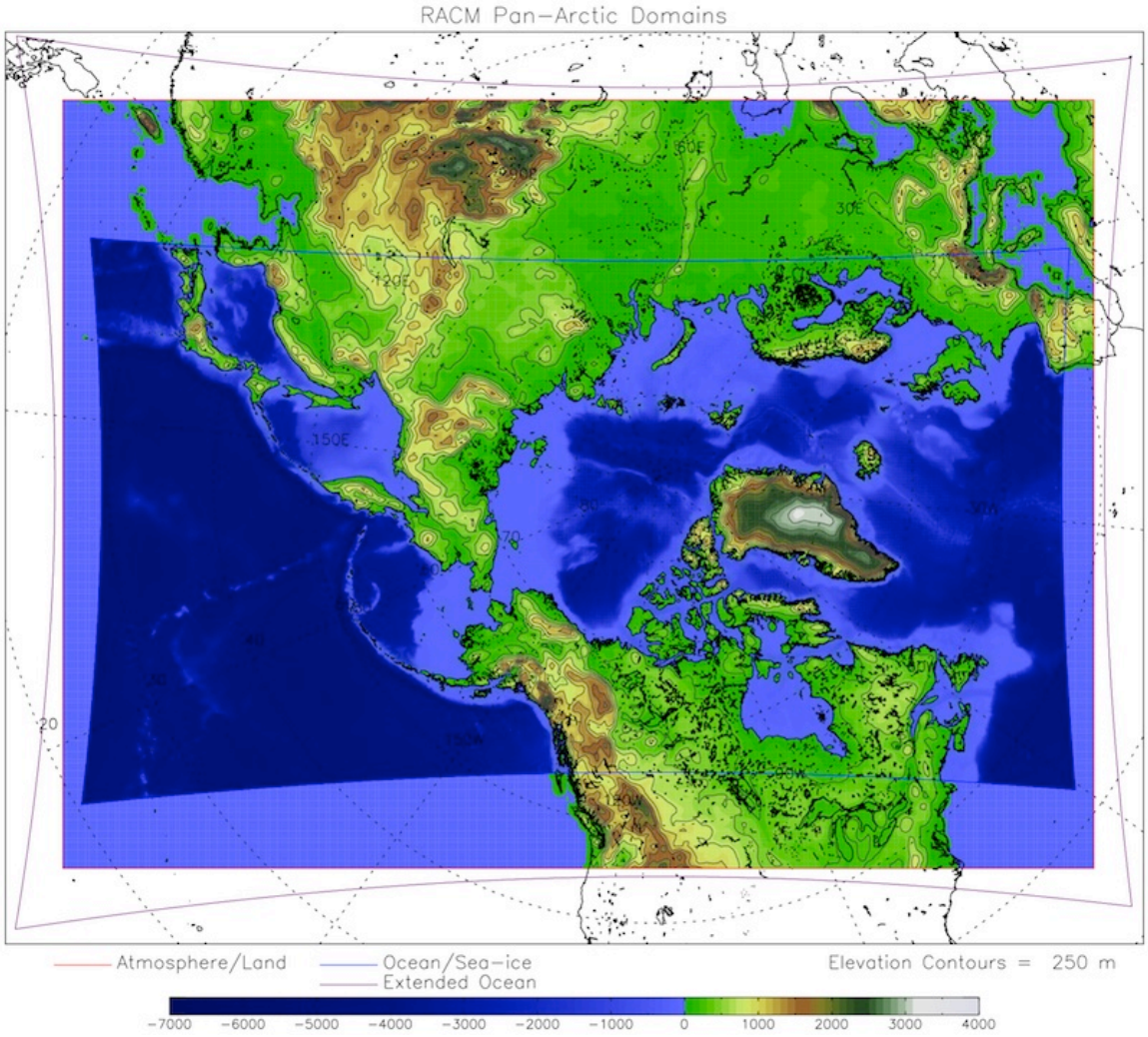

Figure 1: Pan-Arctic regional Arctic climate model (RACM) model domain. The red line indicates the extent of the atmosphere and land model domains and the blue line indicates the extent of the ocean and sea ice model domains.

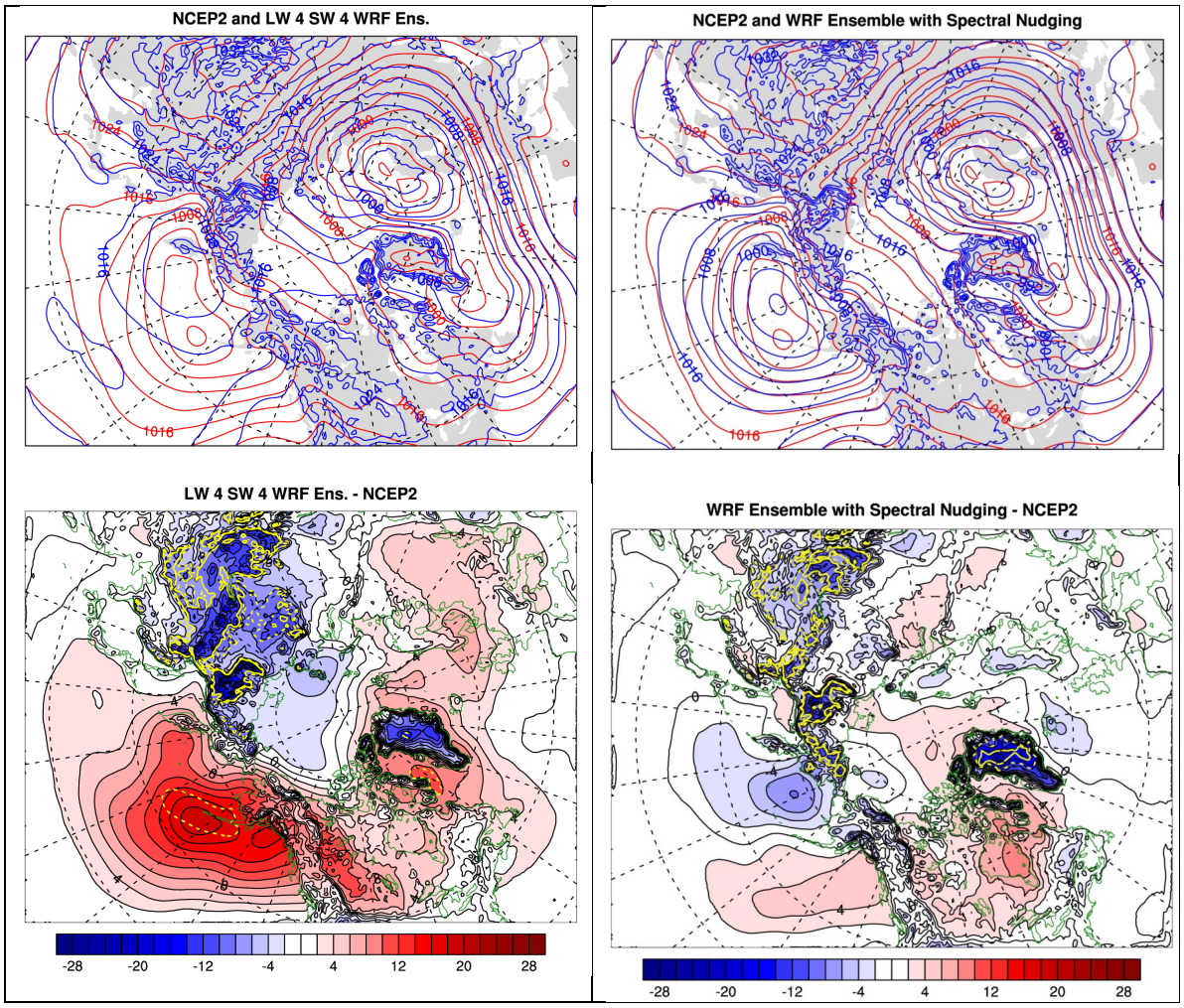

Figure 2. SLP for January 2007. Top plots show overlay of WRF (blue) and NCEP reanalysis (red) SLP contours. Bottom plots show monthly mean bias of WRF simulations compared to NCEP reanalysis (WRF-NCEP). Results are shown for WRF using preferred physics options (left) and WRF with the same physics options as at left plus spectral nudging (right).

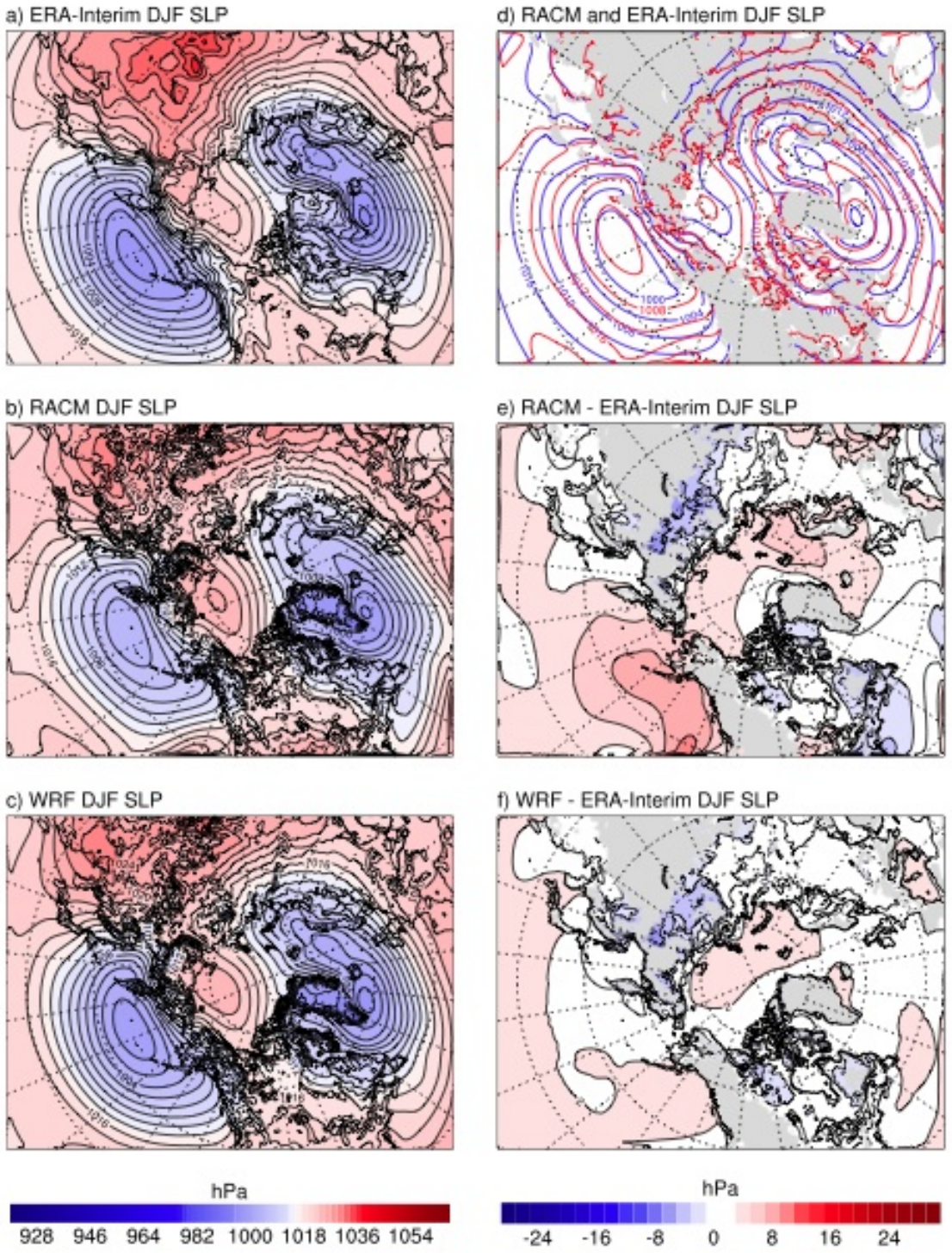

Figure 3. Sea-level pressure for DJF in (a) ERA-Interim, (b) RACM, (c) WRF, (d) RACM and ERA-Interim contour lines, (e) RACM – ERA-Interim, and (f) WRF – ERA-Interim. All panels are averaged from 1989-2007. In panel d, the blue contour lines indicate ERA-Interim SLP and the red contour lines indicate RACM SLP.

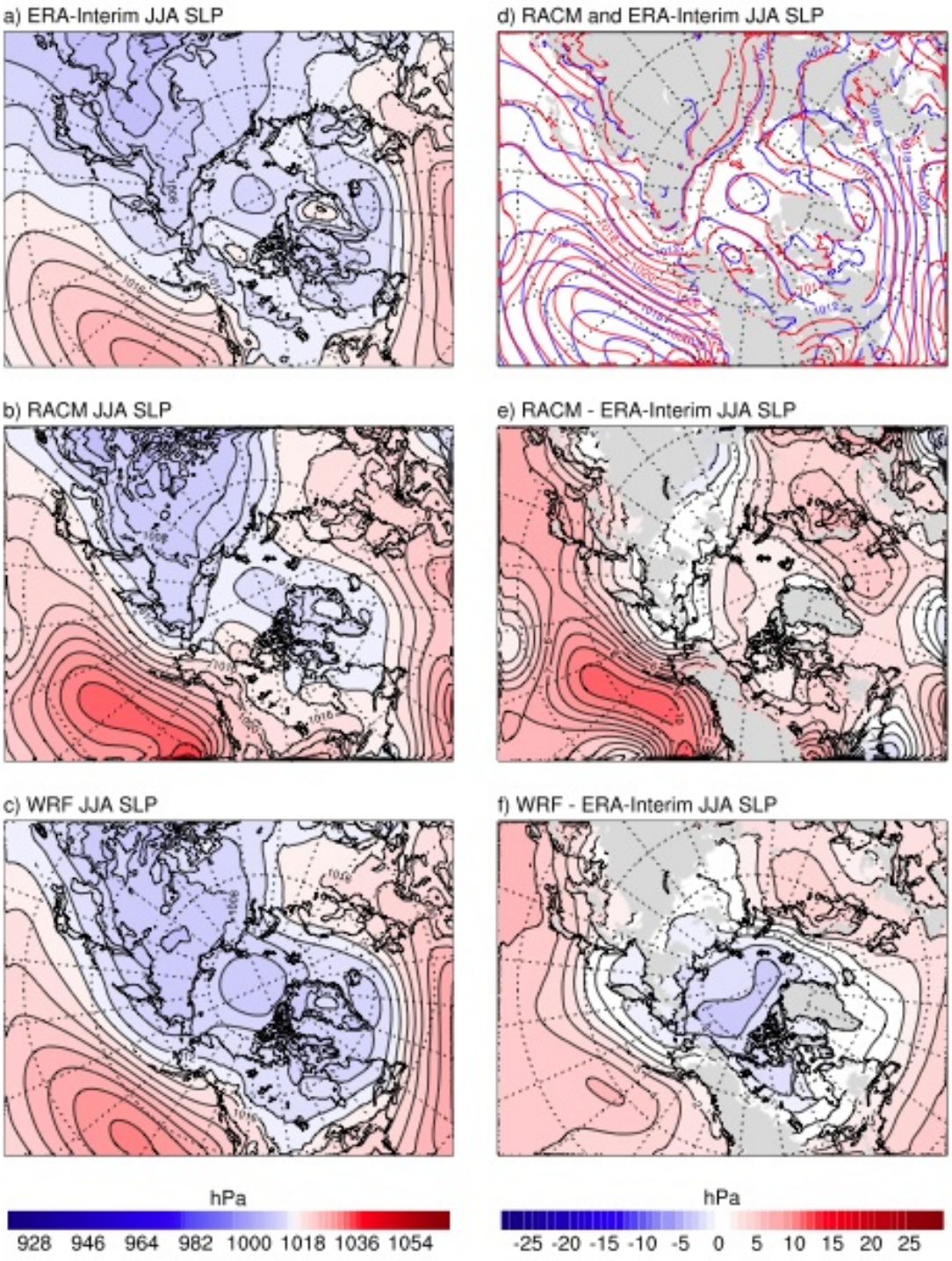

Figure 4. Same as Figure 3, but for JJA.

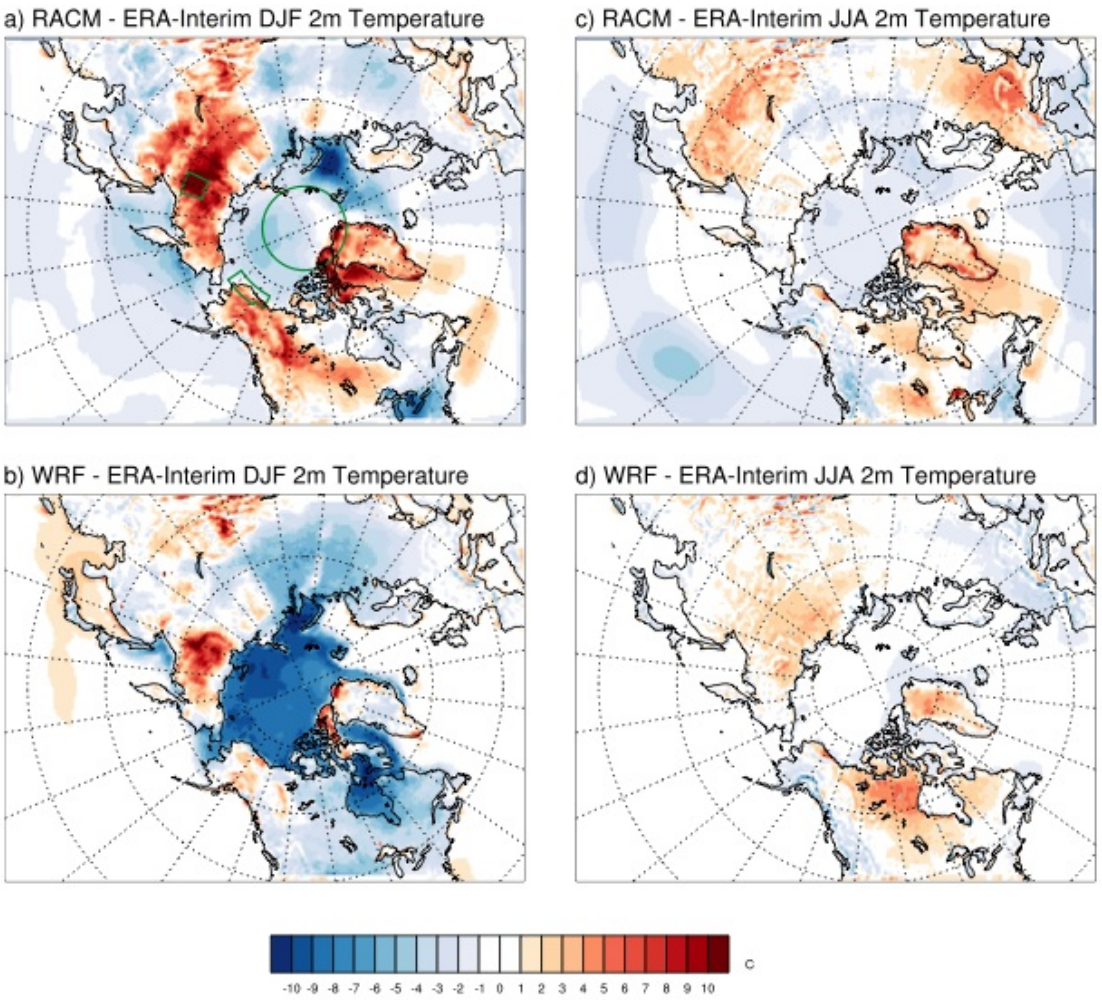

Figure 5. Difference in 2m temperature between (a) RACM and ERA-Interim for DJF, (b) WRF and ERA-Interim for DJF, (c) WRF and ERA-Interim for JJA, and (d) WRF and ERA-Interim for JJA.