

The Regional Arctic System Model (RASM) - Overview

The Regional Arctic System Model is a limited-area, fully coupled ice-ocean-atmosphere-land model (Maslowski et al. 2012). It includes the Weather Research and Forecasting (WRF) model, the LANL Parallel Ocean Program (POP) and Community Ice Model (CICE) and the Variable Infiltration Capacity (VIC) land hydrology model configured for the pan-Arctic region (Figure 1). The ocean and sea ice models used in RASM are regionally configured versions of those used in CESM, while WRF replaces the Community Atmospheric Model (CAM). A streamflow routing (RVIC) model is a source-to-sink routing model recently implemented in RASM to transport the freshwater flux from the land surface to the Arctic Ocean. These components are coupled using a regionalized version of the CESM flux coupler (CPL7), which includes modifications by Roberts et al. (2014) important for high-resolution polar simulations. RASM's domain (Figure 1) covers the entire Northern Hemisphere marine cryosphere, terrestrial drainage to the Arctic Ocean and its major inflow and outflow pathways, with optimal extension into the North Pacific / Atlantic to model the passage of cyclones into the Arctic.

Regional Arctic System Model Domain

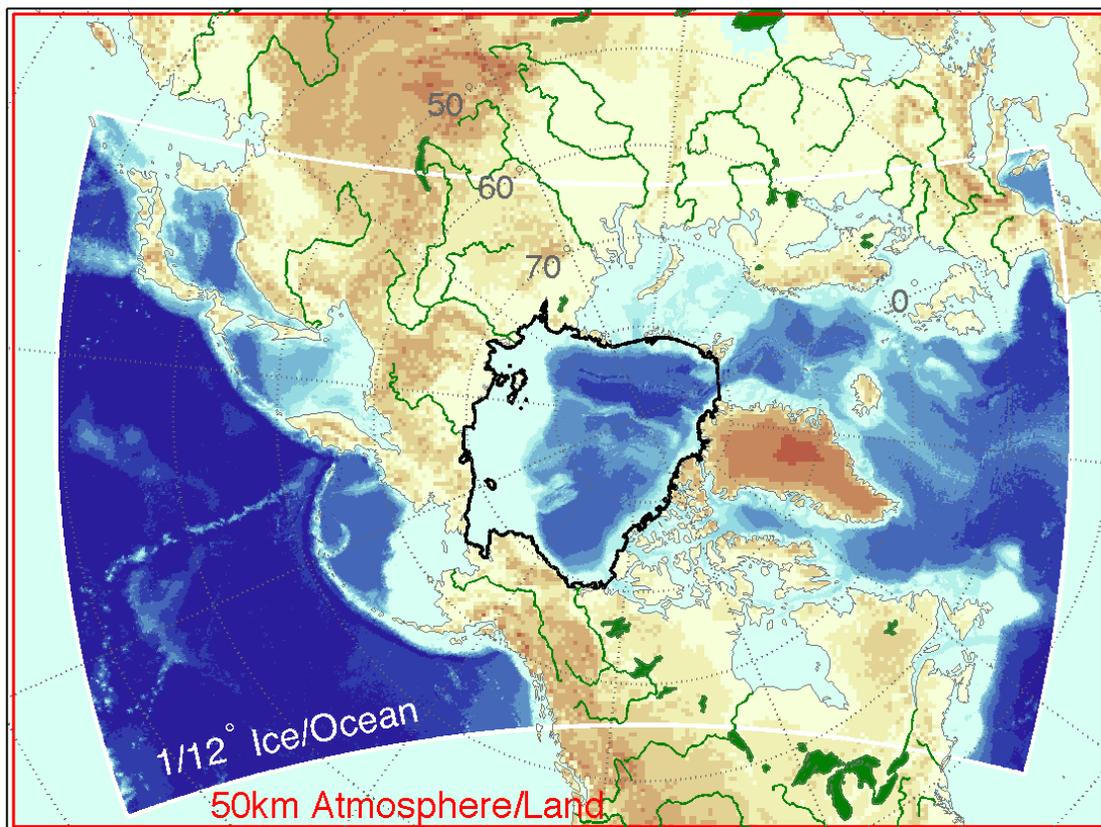


Figure 1. Configuration of the Regional Arctic System Model: The ocean-ice domain (POP/CICE; white boundary) includes the maximum sea ice zone and large marine ecosystems relevant to the Arctic. The atmosphere-land domain (WRF/VIC; red boundary) includes the Arctic System watershed (major inland waterways in green). Topographic and bathymetric pixels (shading) represent single model grid cells on the 50km atmosphere-land and 1/12° ice-ocean domains, respectively. The area encircled by the black line represents the central arctic analysis domain of relevance to inter-comparison of RASM results with satellite observations.

WRF's standard configuration in RASM uses a polar stereographic grid at a resolution of 50 km and 40 vertical levels, with the finest vertical resolution in the boundary layer. A higher resolution grid configuration at 25 km has already been tested and it is planned for use in WRF. WRF has undergone considerable development and testing for high-latitude use (e.g. Hines and Bromwich 2008; Bromwich et al. 2009; Cassano et al. 2011), including demonstration of stability in long duration (years) simulations. As implemented in RASM, WRF uses spectral nudging in the upper half of the model atmosphere to constrain large-scale features (wavenumbers less than 4) to be similar to the driving reanalysis data. This allows use of WRF for downscaling Global Climate / Earth System Models (GC/ESMs) and atmospheric reanalyses for focused studies of the coupled Arctic System on seasonal to decadal timescales, while allowing sensitive ice-ocean-atmosphere interactions across the coupled boundary layer to freely evolve. The RASM WRF configuration includes several important changes from other standard WRF implementations, including options for either the CAM (Collins et al. 2004) or RRTMG (Clough et al. 2005) radiation schemes, which are coupled to Morrison microphysics (Morrison et al. 2009) via modeled liquid and ice effective particle sizes, found to be important for the surface radiation balance over sea ice. We have also found important sensitivity of the atmospheric simulations in WRF to sea ice state when run in a fully coupled mode, as in RASM, compared to stand-alone WRF. For the fully coupled simulations, the more realistic time varying representation of sea ice thickness and leads allows for a more accurate simulation of near surface air temperature over the Arctic compared to stand-alone WRF. Atmospheric boundary layer stability is determined from area-weighted turbulent fluxes and variable surface roughness passed to WRF from sea ice, ocean, and land surface models. The atmospheric model in RASM uses diagnostic surface albedo calculated in the sea ice, land, and ocean flux coupling.

VIC has added process representations that are of particular importance to high latitude processes, including (1) seasonally and permanently frozen soil (Cherkauer and Lettenmaier 1999, Cherkauer et al. 2003), (2) a snow accumulation and ablation model that represents the interaction of vegetation with snow sublimation and other ablation processes (Andreadis et al. 2009), (3) lakes and wetlands (Bowling and Lettenmaier 2010), and (4) sublimation and snow redeposition from blowing snow (Bowling et al. 2004). These arctic process representations have been used to investigate snow pack dynamics and hydrological fluxes in the high arctic (Su et al. 2005; Shi et al. 2011; Shi et al. 2013). Recent improvements have focused on the representation of micro-topography and wetlands in the Arctic (Bohn et al. 2013).

In the standard RASM configuration, the VIC land surface model shares the WRF horizontal grid. Surface and subsurface flows generated at the grid cell level are assumed to reach a channel within each horizontal cell. These flows are routed using the RVIC runoff model that is separately coupled to the RASM framework, delivering freshwater to POP at all of the coastal grid cells. Most of the water is transported via major rivers, as displayed in Figure 1.

POP, developed at LANL, is an energy-conserving ocean model that solves the three-dimensional primitive equations for fluid motion on the sphere under hydrostatic and Boussinesq approximations. It uses a free-surface formulation, which when combined with high spatial resolution, allows an unsmoothed, realistic bathymetry. The standard POP configuration in RASM uses 45 vertical z-coordinate levels and a $1/12^\circ$ rotated sphere mesh with an equator extending across the North Pole, resulting in ~ 9 km resolution in the Arctic Ocean, and minimal area distortion near the boundaries. Ice-ocean stress obeys standard quadratic drag laws, with 7 ocean layers in the upper 42 m to resolve Ekman layer dynamics. Turbulent atmospheric surface flux and albedo calculations passed from the ocean to WRF are performed within CPL7, which also accounts for observed surface temperature and salinity at the perimeter of the POP domain. The extended ocean domain supplies boundary conditions to WRF consistent with its lateral constraints (Figure 1).

CICE has been developed at LANL (Hunke et al. 2013a) for use in GC/ESMs and is

designed to be compatible with POP. RASM has recently been upgraded to CICE Version 5.0 (CICE5.0). The new prognostic salinity thermodynamic model of Turner et al. (2013) is being adopted in RASM to model sea ice growth and melt. Early inter-comparison between Elastic-Viscous-Plastic sea ice mechanics (EVP; Hunke and Dukowicz 1997) and a new anisotropic rheology (EPA; Tsamados et al. 2013) in CICE5.0 is proving the benefit of anisotropic sea ice dynamics, especially for RASM which resolves the ‘multi-floe scale’ (2-10km) as defined by McNutt and Overland (2003). In RASM, CICE is configured with incremental remapping for sea ice advection (Lipscomb and Hunke 2004) using five sea ice thickness categories for vertical growth, deformation and melt (Lipscomb 2001). Shortwave albedo is calculated using the Delta-Eddington scheme for two bands partitioned at 700nm (Briegleb and Light 2007), influenced by one of two new explicit melt pond parameterizations (Flocco et al. 2010; Hunke et al. 2013b) and then used by WRF to calculate dual-band net downward surface shortwave radiation. Whereas previously ice-ocean and ice-atmosphere stress neglected sea ice morphology, CICE now includes form drag to approximate these drag coefficients (Tsamados et al 2014), which is part of the new RASM default configuration. High frequency coupling has recently been incorporated into CICE from changes made in RASM to resolve ice-ocean inertia and hence improve simulated Ekman transport for polar seas (Roberts et al. 2014).

References

- Andreadis, K., P. Storck, and D. P. Lettenmaier (2009), Modeling snow accumulation and ablation processes in forested environments, *Water Resources Research*, *45*, W05429, doi:10.1029/2008WR007042.
- Bohn, T. J., E. Podest, R. Schroeder, N. Pinto, K. C. McDonald, M. Glagolev, I. Filippov, S. Maksyutov, M. Heimann, X. Chen, and D. P. Lettenmaier (2013), Modeling the large-scale effects of surface moisture heterogeneity on wetland carbon fluxes in the West Siberian Lowland, *Biogeosciences*, *10*, doi:10.5194/bg-10-6559-2013.
- Bowling, L.C., J.W. Pomeroy and D.P. Lettenmaier (2004), Parameterization of blowing snow sublimation in a macroscale hydrology model, *J. Hydromet.*, *5*, 745-762. doi: 10.1175/1525-7541.
- Bowling, L.C. and D.P. Lettenmaier (2010), Modeling the effects of lakes and wetlands on the water balance of Arctic Environments, *J. Hydromet.*, *11*, 276-295, doi: 10.1175/2009JHM1084.1.
- Briegleb, B. P., and B. Light (2007), A Delta-Eddington Multiple Scattering Parameterization For Solar Radiation In The Sea Ice Component Of The Community Climate System Model, *National Center for Atmospheric Research*, USA.
- Bromwich, D. H., K. M. Hines, and L. Bai (2009), Development and testing of Polar Weather Research and Forecasting model: 2. Arctic Ocean, *J. Geophys. Res.*, *114*(D8), 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.
- Cherkauer, K. A. and D. P. Lettenmaier (1999), Hydrologic effects of frozen soils in the upper Mississippi River basin, *J. Geophys. Res.*, *104*(D16), 19599-19610, doi:10.1029/1999JD900337.
- Cherkauer, K. A., L. C. Bowling and D. P. Lettenmaier (2003), Variable Infiltration Capacity (VIC) cold land process model updates, *Global and Planetary Change*, *38*(1-2), 151-159.
- Clough, S. A., M. W. Shephard, E. J. Mlawer, J. S. Delamere, M. J. Iacono, K. Cady-Pereira, S. Boukabara, and P. D. Brown (2005), Atmospheric radiative transfer modeling: A summary of the AER codes, *J. Quant. Spectrosc. Radiat. Transfer*, *91*, 233–244.
- Collins, W. D., P. J. Rasch, B. A. Boville, J. J. Hack, J. R. McCaa, D. L. Williamson, J. T. Kiehl, and B. Briegleb (2004), Description of the NCAR Community Atmosphere Model (CAM

- 3.0). NCAR Tech. Note NCAR/TN-4641STR, National Center for Atmospheric Research, Boulder, CO, 214 pp.
- Flocco, D., D. L. Feltham, and A. K. Turner (2010), Incorporation of a physically based melt pond scheme into the sea ice component of a climate model, *J. Geophys. Res.*, *115*(C8), doi:10.1029/2009JC005568.
- 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.
- Hunke, E. C. and J. K. Dukowicz, (1997), An elastic-viscous-plastic model for sea ice dynamics. *J. Phys. Oceanogr.*, *27*, 1849-1867.
- Hunke, E. C., W. H. Lipscomb, A. K. Turner, N. Jeffery, and S. Elliott (2013a), CICE: The Los Alamos Sea Ice Model Documentation and Software User's Manual Version 5.0 LA-CC-06-012, *Los Alamos National Laboratory*, USA.
- Hunke, E. C., D. A. Hebert, and O. Lecomte (2013b), Level-ice melt ponds in the Los Alamos sea ice model, CICE, *Ocean Model.*, *71*, 26–42.
- Lipscomb, W. H. (2001), Remapping the thickness distribution in sea ice models, *J. Geophys. Res.*, *106*, 13,989-14,000.
- Lipscomb, W. H. and E. C. Hunke (2004), Modeling sea ice transport using incremental remapping, *Mon. Wea. Rev.*, *132*, 1341-1354.
- Maslowski W., J. Clement Kinney, M. Higgins, and A. Roberts (2012), The future of arctic sea ice, *Annual Review of Earth and Planetary Sciences*, *40*, 625-654.
- McNutt, S. L., and J. E. Overland (2003), Spatial hierarchy in Arctic sea ice dynamics, *Tellus*, *55*(A), 181–191.
- Morrison, H., G. Thompson, and V. Tatarskii, (2009), Impact of cloud microphysics on the development of trailing strati- form precipitation in a simulated squall line: Comparison of one- and two-moment schemes, *Mon. Wea. Rev.*, *137*, 991– 1007.
- Roberts, A., A. P. Craig, W. Maslowski, R. Osinski, A. DuVivier, M. Hughes, B. Nijssen, J. Cassano and M. Brunke (2014), Simulating transient ice-ocean Ekman transport in the Regional Arctic System Model and Community Earth System Model, *Ann. Glaciol.*, accepted.
- Shi, X., P. Y. Groisman, S. J. Déry and D. P. Lettenmaier (2011), The role of surface energy fluxes in pan-Arctic snow cover changes, *Environmental Research Letters*, *6*, 035204, doi:10.1088/1748-9326/6/3/035204.
- Shi, X., S. J. Déry, P. Y. Groisman, and D. P. Lettenmaier (2013), Relationships between recent pan-Arctic snow cover and hydroclimate trends. *J. Climate*, *26*, 2048-2064, doi:10.1175/JCLI-D-12-00044.1.
- Su, F., J. C. Adam, L. C. Bowling, and D. P. Lettenmaier (2005), Streamflow simulations of the terrestrial Arctic domain, *J. Geophys. Res.*, *110*, D08112, doi:10.1029/2004JD005518.
- Tsamados, M., D. L. Feltham, and A. V. Wilchinsky (2013), Impact of a new anisotropic rheology on simulations of Arctic sea ice, *J. Geophys. Res. Ocean*, *118*(1), doi:10.1029/2012JC007990.
- Tsamados, M., D. L. Feltham, D. Schröder, D. Flocco, S. L. Farrell, N. Kurtz, S. W. Laxon, and S. Bacon (2014), Impact of Variable Atmospheric and Oceanic Form Drag on Simulations of Arctic Sea Ice, *J. Phys. Oceanogr.*, *44*(5), 1329–1353, doi:10.1175/JPO-D-13-0215.1.
- Turner, A. K., E. C. Hunke, and C. M. Bitz (2013), Two modes of sea-ice gravity drainage: A parameterization for large-scale modeling, *J. Geophys. Res. Ocean.*, *118*(5), doi:10.1002/jgrc.20171.