Coupled Streamflow Routing in the Regional Arctic System Model (RASM)

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RASM

Regional Arctic System Model Configuration

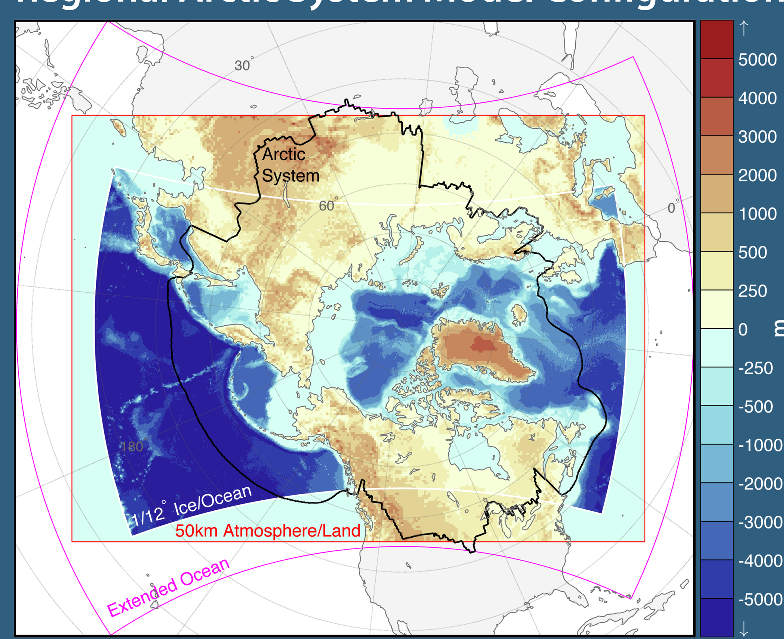


Figure: RASM model domain. There are three main grid domains in RASM, 1) Ice/Ocean, 2) Atmosphere/Land, and 3) Extended Ocean. The color bar represents elevation above or below sea level.

The Regional Arctic System Model (RASM) is a high-resolution Earth System model that covers the Arctic drainage basin and is developed to better understand polar climate variability, system inter-connectivity and improve and understand constraints on decadal predictions in high northern latitudes. RASM uses the Community Earth System Model (CESM) flux coupler (CPL7) to couple regional configurations of the Weather Research and Forecasting model (WRF), the Parallel Ocean Program (POP), the Los Alamos sea ice model (CICE) and the Variable Infiltration Capacity (VIC) model. Additional functionality, including component models to represent dynamic vegetation and land ice are currently being added.

Recent work has focused on the development of a routing model (RVIC) to complete the hydrological cycle and represent the freshwater flux from the land surface to the Arctic Ocean. The routing model is a source-to-sink model that solves a linearized version of the Saint-Venant equations. In RASM, as with recent versions of CESM, the routing scheme is coupled independently of the land model. This provides more flexibility for delivery of fresh water runoff and biogeochemical constituents to the Arctic Ocean, the former of which has been shown to be an important driver of recent changes in Arctic Ocean circulation.

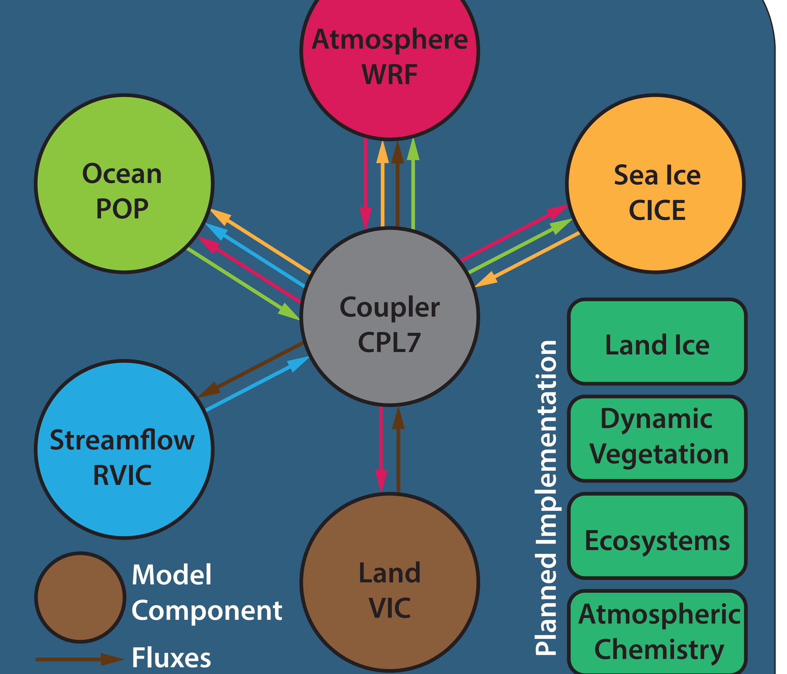


Figure: Schematic of RASM coupled configuration. Arrows denote direction of flux between model components. Adapted from Alexander & Easterbrook (2011).

Importance of Land-Ocean Coupling

Terrestrial Runoff

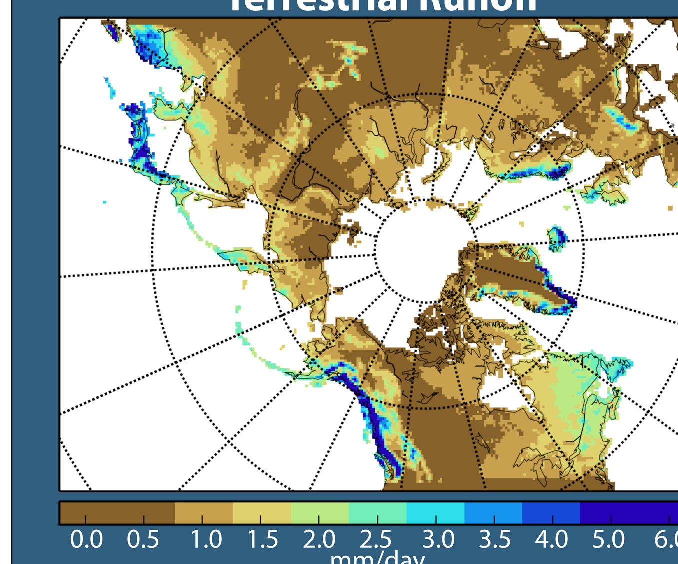


Figure: 1990-1999 mean terrestrial freshwater flux produced by the land surface model (VIC). This quantity is passed to the RVIC streamflow routing model.

The direct coupling mechanism from the land to the ocean is through streamflow. Realistic streamflow is of high importance to the coastal ocean hydrography and ocean processes as well as to sea ice formation and melt. The freshwater signal from runoff is the primary source of buoyancy-driven coastal currents, such as the Alaska Coastal Current (ACC), Siberian Coastal Current, Norwegian Coastal Current, and East Greenland Coastal Current. Such currents redistribute both fresh water and heat, which locally play an important role in the shelf dynamics and shelf-basin interaction. For example, results from the RASM ocean model component suggest that over 60% of all the heat from the Chukchi shelf is advected within 20-30 km of the Alaskan coast by the ACC into the Beaufort Sea.

Another important aspect is the effect of buoyancy and heat fluxes delivered by rivers on the onset of sea ice formation in winter and melt in spring/summer. First, less salty water freezes at higher temperature, i.e. it does not have to be cooled as much as higher salinity water. Second, heat delivered with runoff combined with the ice-albedo effect can make a big difference on the local retreat of sea ice from a shelf. Finally, long-term river runoff maintains the surface freshwater layer in the Arctic Ocean and is a critical source required to balance freshwater export through Fram Strait and the Canadian Arctic Archipelago into the North Atlantic.

Coastal Runoff

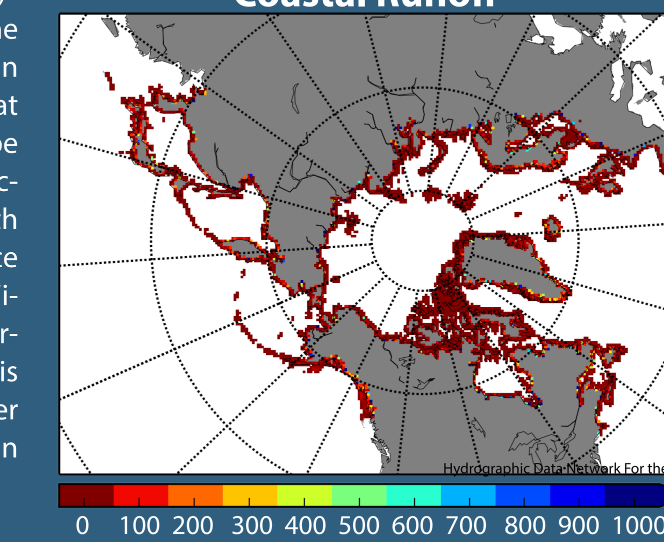


Figure: 1990-1999 mean coastal freshwater flux produced by the RVIC streamflow routing model. Runoff is delivered to the edge of every coastal grid cell in the land model.

RVIC Streamflow Model

The RVIC model is a modified version of the streamflow routing model typically used as a post-processor with the Variable Infiltration Capacity (VIC) hydrology model. The routing model is a source-to-sink model that solves a linearized version of the Saint-Venant equations. This model, developed by Lohmann et al. (1996)[2], has been used in many offline studies at a variety of spatial scales. Key points of the RVIC routing model, as implemented in RASM, are:

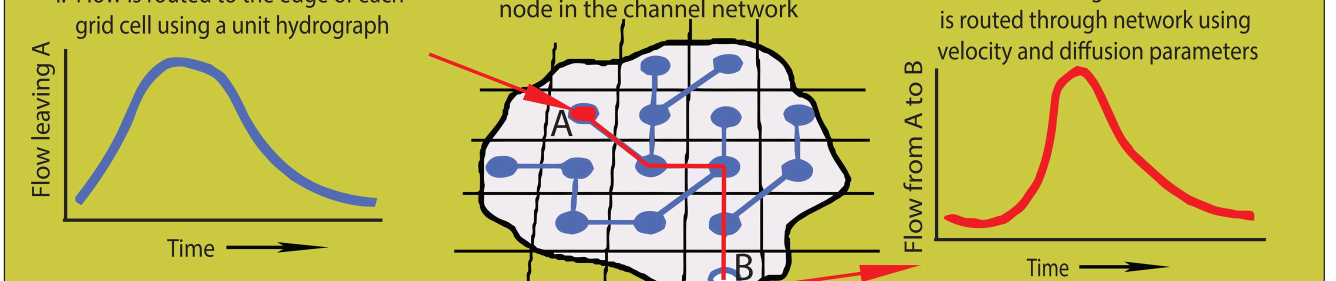
1. Utilizes Impulse Response Functions (i.e. Unit-Hydrographs) to represent distribution of flow at the outlet point with respect to time from an impulse input at each source point.
2. Impulse Response Functions (IRFs) are linear and time invariant.
3. Flow velocity and diffusion are calibratable parameters.
4. Development of the IRFs on high-resolution (1/16th degree) standard latitude-longitude grid, rather than on the land model grid. This avoids the requirement of developing flow direction inputs on individual model grids.
5. High-resolution impulse response functions are upscaled to the RASM-land grid using a conservative area remapping technique. This approach maintains the fine-scale response features present in the high-resolution flow networks.
6. Development of IRFs is done as a pre-process so that the only step to be completed in the coupled model is the flow convolution, significantly reducing computation time.
7. Hourly streamflow flux is delivered to every coastal land grid cell. Freshwater flux is then distributed among the neighboring ocean grid cells.
8. The ocean model represents the freshwater flux as a negative salinity flux.

Development of Impulse Response Fuctions

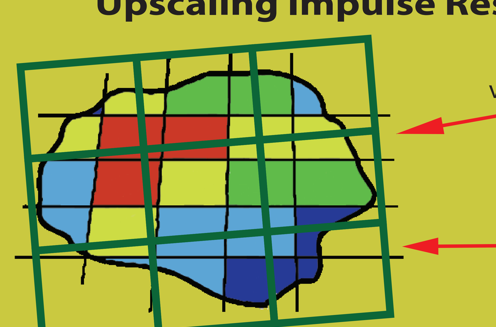
I. Flow is routed to the edge of each grid cell using a unit hydrograph

II. Each grid cell is represented as a node in the channel network

III. Flow from each grid cell in the basin is routed through network using velocity and diffusion parameters



Upscaling Impulse Response Functions



IV. Impulse response functions are developed on a high resolution grid (1/16° regular grid)

V. Impulse response functions are remapped to RASM grid (50 km x 50 km) using conservative area remapping techniques.

Flow Convolution

VI. Runoff and Baseflow from the land surface model are combined.

VII. Convolution of IRF and runoff flux for all source points upstream of each outlet point produces a timeseries of streamflow at the outlet.

Model Hydrology

Precipitation, 1990-1999 Mean

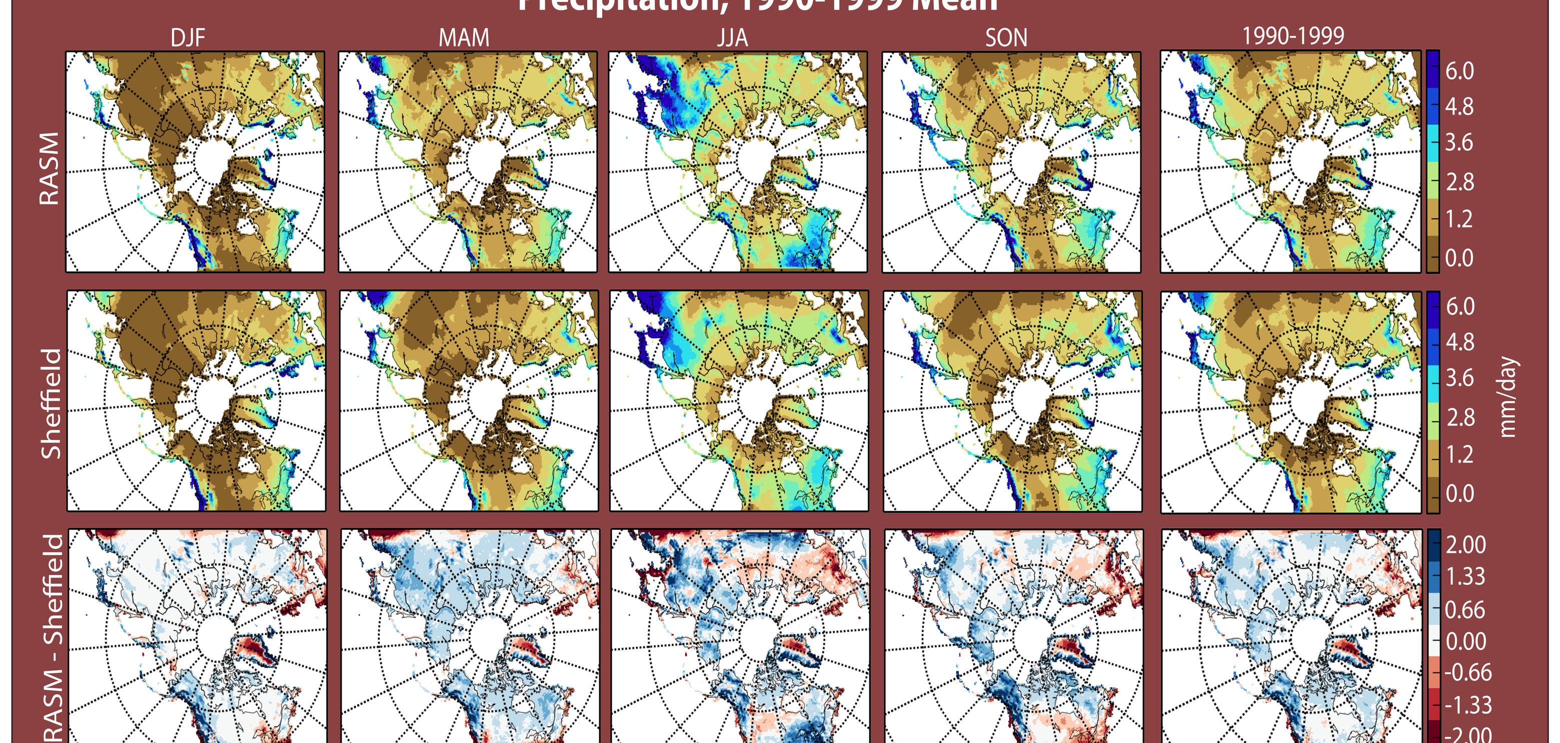


Figure: Mean seasonal precipitation comparing RASM (top) to the Sheffield et al., (2006) dataset (middle)[4]. The third row represents the difference between the two datasets.

Snow Covered Area - North of 50° Latitude

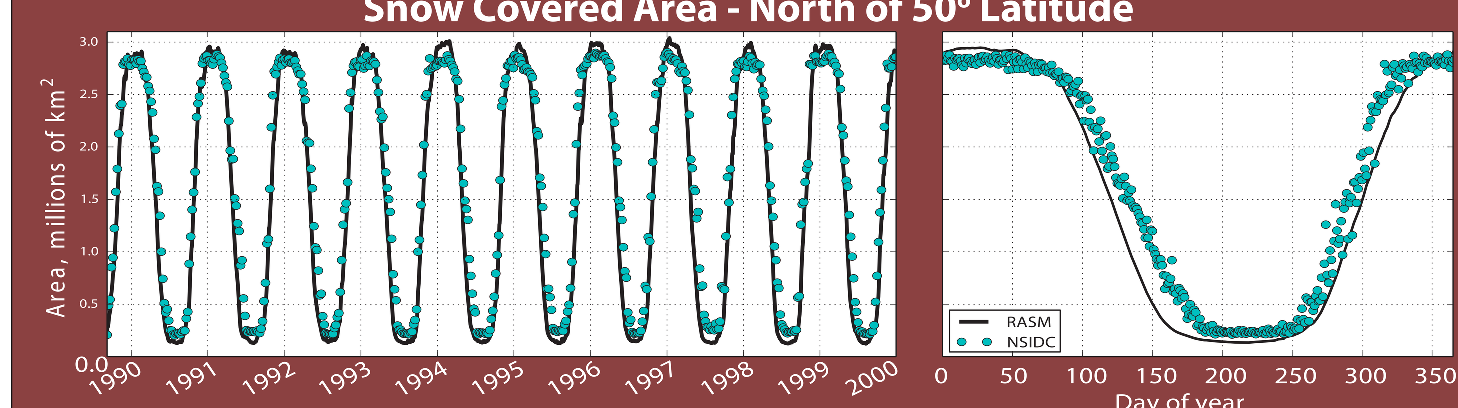


Figure: Snow covered extent comparing fully coupled RASM (black), and the National Snow and Ice Data Center's Weekly Snow Cover Extent Version 4 dataset (cyan). While RASM produces a reasonable seasonal cycle of snow coverage, the rate of retreat in snow-covered area is too high compared with observations.

Ocean Freshwater Flux

RVIC delivers a freshwater flux to each coastal land grid cell. Comparing RASM monthly and seasonally averaged to the Coordinated Ocean-ice Reference Experiments - Phase II (CORE II[1]) coastal runoff flux product, we consider how seasonal differences in both the total and regional freshwater may influence the coupled system.

Total Coastal Freshwater Flux North of 60° Latitude

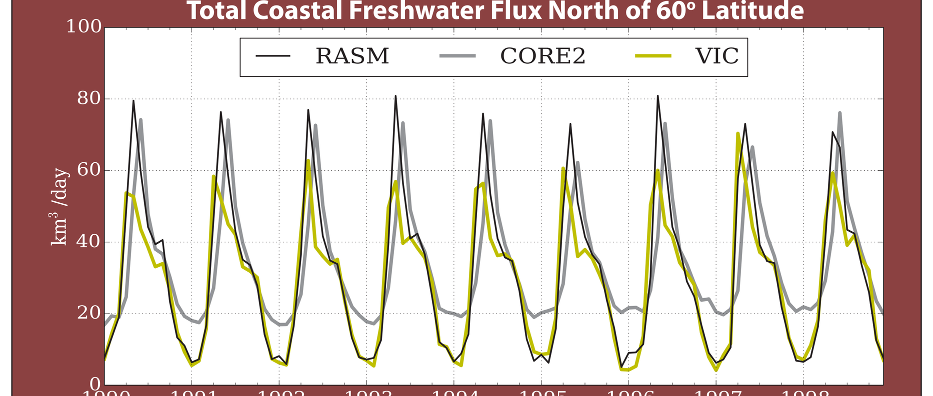


Figure: Total freshwater flux North of 60° latitude. Current land surface parameterization under-produces streamflow in the winter and peaks a month earlier than the CORE II dataset. The yellow line represents the results from a stand-alone VIC experiment forced with Sheffield et al. (2006)[4] atmospheric forcings.

Arctic Ocean Freshwater Flux, Mean 1990-1999

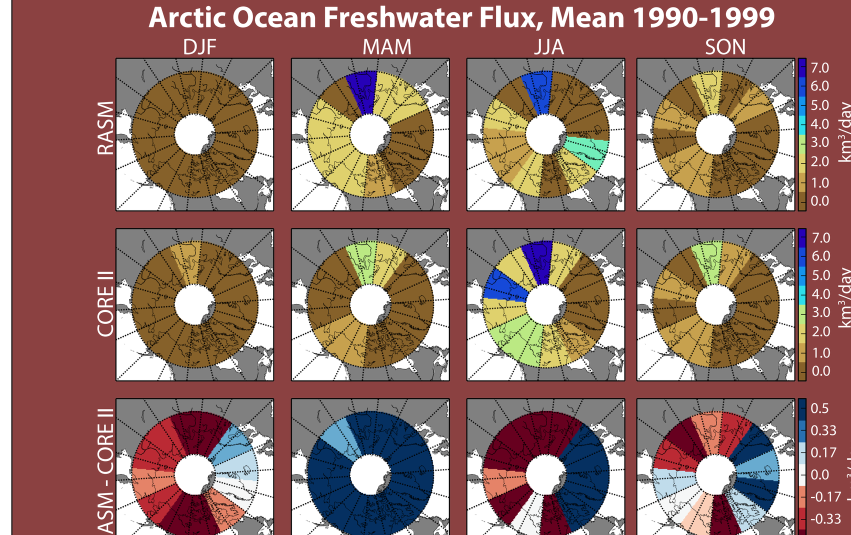


Figure: Distribution of seasonal volumetric freshwater flux between 60° N. and 80° N. aggregated into 20° longitude bins for RASM (top) and CORE II (middle).

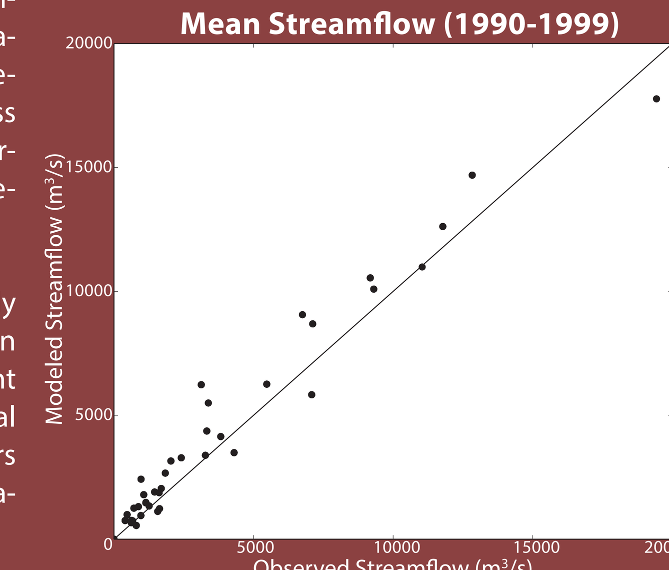
Modeled and Observed Streamflow

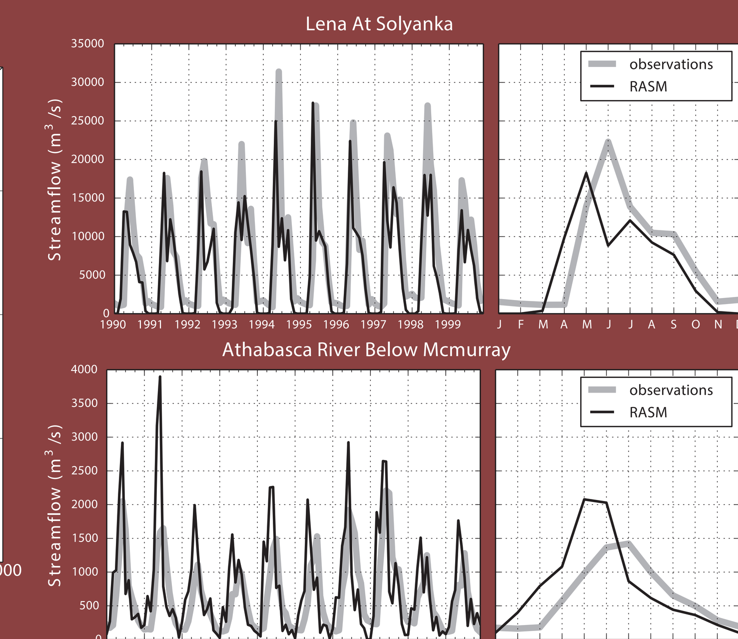
In addition to providing the ocean model with the terrestrial freshwater flux, streamflow serves as an integrator of coupled land-atmosphere processes and is arguably the most accurately measured, large-scale component of the hydrological cycle. Measured and simulated streamflow can therefore be used to evaluate RASM's abilities to capture key features of the hydrological cycle and as validation metrics for both the land surface model and the streamflow routing model. Here, we compare mean monthly streamflows routed to 104 streamflow gauge location in the R-ArcticNET hydrographic database[3].

At annual time scales, RASM streamflows are well aligned with observations (figure right). There is less agreement at time scales of a month or less (two examples, far right), which is currently being addressed through a recalibration of VIC's soil parameters.

The RVIC model does not presently consider any regulatory impacts on streamflow timing. This may present challenges in matching the seasonal cycle of streamflow for those rivers that are subject to substantial regulation.

Mean Streamflow (1990-1999)

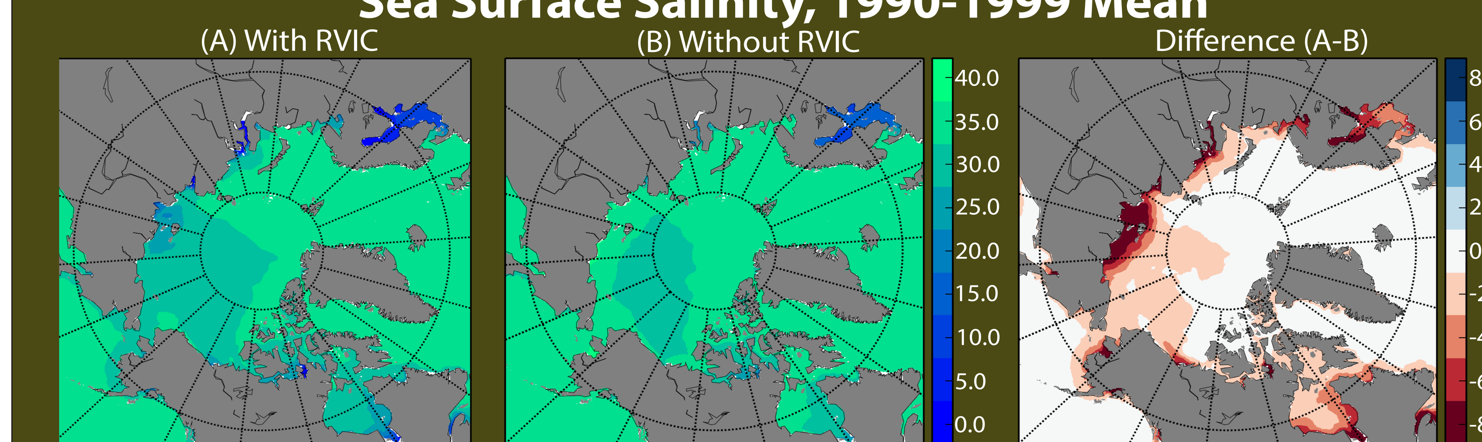




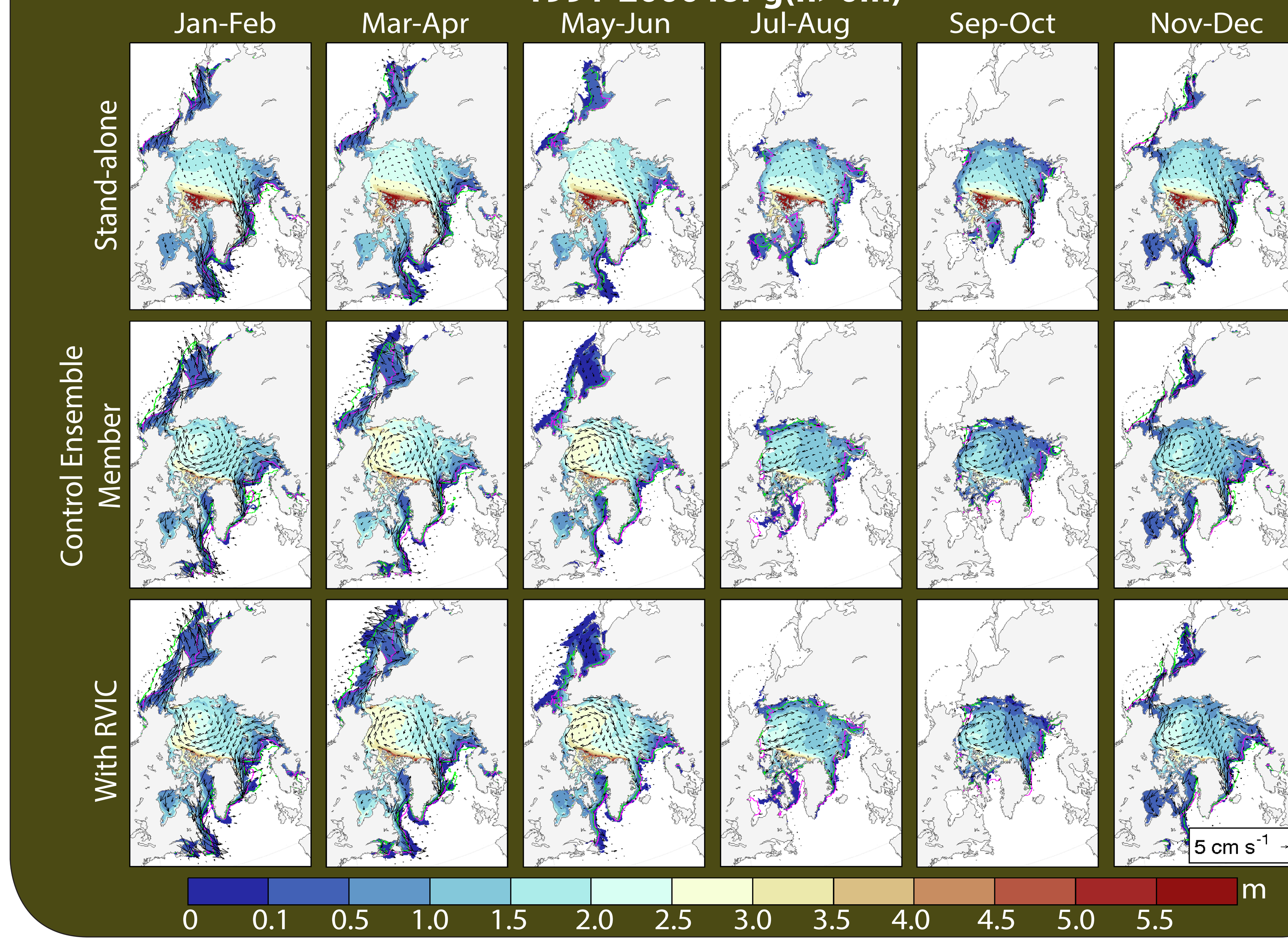
Ocean and Sea Ice Results

Results from preliminary, partially and fully coupled single ensemble member experiments indicate that including coastal runoff reduces surface salinity and moderately improves sea ice distribution. The first set of plots below demonstrates the freshening of the Arctic coastal regions, especially off the Siberian Coast. The second set of plots compares seasonal results of sea ice thickness distribution (g(h>0m)) and velocity for the stand-alone ice-ocean model (top), RASM without RVIC (middle), and RASM with RVIC (bottom).

Sea Surface Salinity, 1990-1999 Mean



RASM difference from NPS CDR concentration 1991-2000 for g(h>0m)



References and Notes

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3. R-ArcticNet database: www.r-arcticnet.sr.unh.edu
4. Sheffield, J., G. Goteti, and E. F. Wood, 2006: Development of a 50-yr high-resolution global dataset of meteorological forcings for land surface modeling, J. Climate, 19 (13), 3088-3111