Land Surface Hydrology and the Land-Ocean Freshwater Flux in the Regional Arctic System Model (RASM)

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RASM

Regional Arctic System Model Configuration

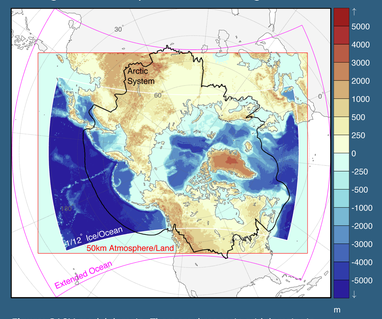


Figure: RASM model domain. There are three main grid domains in RASM, 1) Ice/Ocean, 2) Atmosphere/Land, and 3) Extended Ocean. The color bar represents elevation above or below sea level.

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 to complete the hydrological cycle and represent the freshwater flux from the land surface to the Arctic Ocean. The routing model is a sink-to-source model that solves a linearized version of the Saint-Venant equations. Whereas previous hydrology models coupled to CPL7 have routed runoff within the land model, the routing scheme being developed will be independently coupled to RASM as a separate entity. 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.

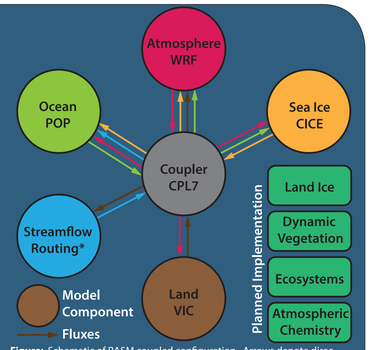


Figure: Schematic of RASM coupled configuration. Arrows denote direction of flux between model components. Adapted from Alexander & Easterbrook (2011).

Importance of Land-Ocean Coupling

The direct coupling mechanism from the land to the ocean is through streamflow. Realistic river runoff is of high importance to the coastal ocean hydrography and dynamics 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 plays 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 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 and necessary source required to balance freshwater export through Fram Strait and the Canadian Arctic Archipelago into the North Atlantic.

Sea Ice Dynamics

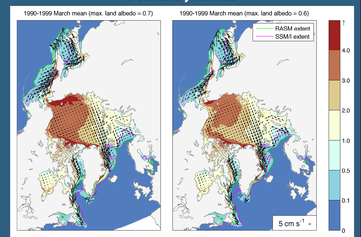


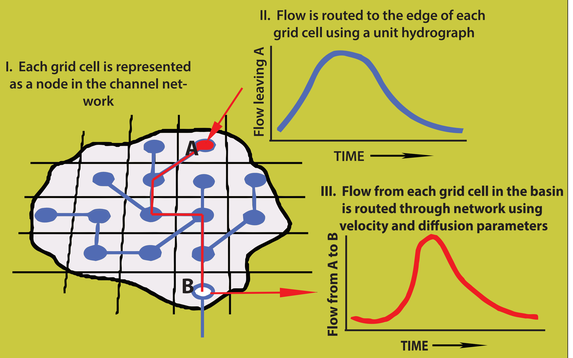
Figure: 1990-1999 mean March Arctic sea ice extent, thickness, and velocity from the r33RBVIC max land albedo sensitivity simulations. The observed SSM/I sea ice extent is contoured in purple.

Flow Routing Model

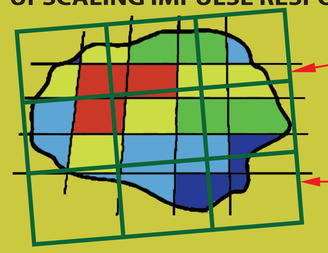
The flow routing scheme that is being implemented in RASM has been adapted from the model typically used as a post-processor with the Variable Infiltration Capacity (VIC) hydrology model. The routing model is a source-to-sink model that solves a linearized version of the Saint-Venant equations. This model, developed by Lohmann et al. (1996), has been used in many offline studies at a variety of spatial scales. The key differences between this approach and the typical offline approach are:

- The time-invariant parameters for the impulse response functions are preprocessed. This calculation is separated from the flow routing (convolution step) and simplifies the implementation of the routing model in the coupled model.
- The response functions are developed using high-resolution (1/16°) flow networks (Wu et al., 2012), which are then upscale them to the 50 km RASM grid. This makes it possible to incorporate high resolution details about the flow network into the coarser RASM implementation.

Development of Impulse Response Fuctions



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.

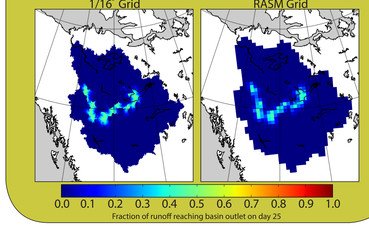
The process of upscaling the impulse response functions produced by the routing model is done using a 1st order conservative remapping technique developed by Jones (1999). Because the remapping scheme is conservative, the unit response to runoff (unit hydrograph) from each RASM grid cell is maintained. The routing and regridding process is repeated for every streamflow location of interest in the model domain, such as basin outlets and stream gauging sites.

Routing Model Key Points

- Impulse Response Functions (IRFs) are linear and are time invariant.
- Calibration parameters are flow velocity and diffusion.
- Development of the IRFs on a standard latitude-longitude grid allows us to use existing high-resolution flow networks rather than creating new flow networks on the RASM grid.
- Upscaling of IRFs maintains the fine-scale response features present in the high-resolution flow networks.
- 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.

Upscaled Impulse Response Functions

Mackenzie River at Arctic Red River

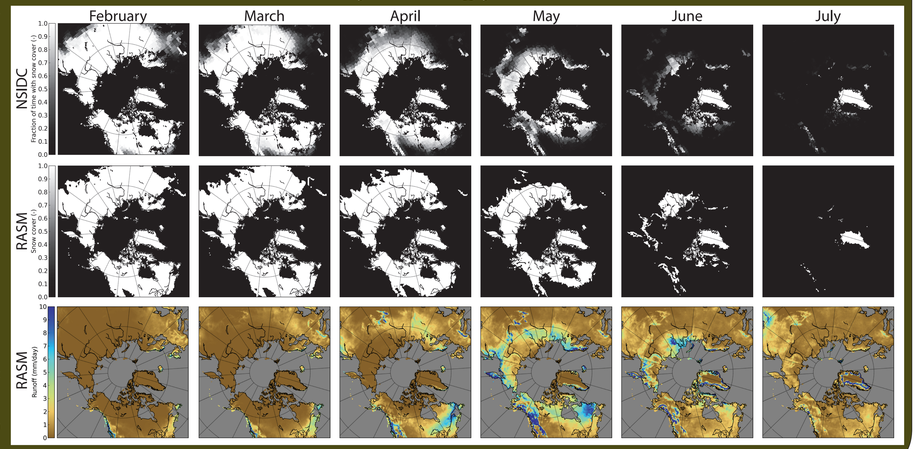


Arctic Hydrology

Runoff generation in the Arctic is dominated by melt, resulting in a large streamflow peak in late spring to early summer.

The panels to the right show RASM-simulated snow cover extent (row 2, RASM run r33RBVIC70) and runoff generation (row 3) for the period 1990-1999, compared with the satellite-based Northern Hemisphere EASE-Grid Weekly Snow Cover Product (version 3) from the National Snow and Ice Data Center (row 1).

The progression of spring melt and the associated reduction in snow cover extent is simulated reasonably well, with large runoff generation in the areas of maximum snowmelt.



Ongoing Work

Streamflow Routing

- Systematic calibration of routing model parameters.
- Implementation of flow convolution within coupled modeling framework.
- Comparison between upscaled impulse response methods and traditional grid routing methods.

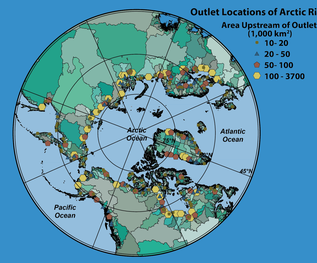
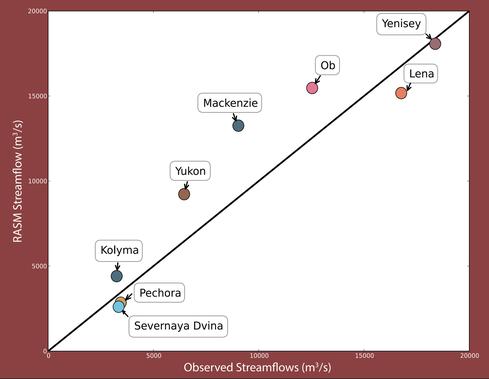


Figure: A key step in coupling the land and ocean models is identifying the locations where individual river basins drain into the ocean. This figure shows the major river basins in north of 45° latitude. For basins larger than 1000 km², basin area and outlet location are shown with colored symbols.

Mean Annual Streamflow

RASM-simulated runoff fields for eight Arctic river basins were routed offline for the period 1990-1999 and compared with long-term, mean annual streamflow estimates derived from observations (note that the averaging period for the observed flows depends on the availability of the observations and does not correspond to the 1990-1999 period). While the flow volume is overestimated in North America, the figure illustrates that 1) RASM is producing water fluxes on annual scales at the same order of magnitude as the observed records, and 2) the upscaling scheme is conservative.



Arctic Streamflow

Simulated mean monthly hydrographs for the same eight Arctic rivers are shown to the right. Again, the simulations were for the period 1990-1999 (RASM simulation r33RBVIC70), while the observations represent the long-term, climatological mean flow at the most downstream gauging station for which observations were available.

All basins show a strong snowmelt dominated peak in late spring and early summer, and in most of the basins, the timing of the rising and falling limbs in the monthly hydrograph matches the observations well.

The exception is the Ob, for which the simulated hydrograph peaks too early. The magnitude of the spring peak is significantly overestimated in the Yukon and Mackenzie. It is not yet clear whether this overestimation results from a positive bias in the precipitation over those basins, or whether the hydrology model underestimates the amount of evapotranspiration.

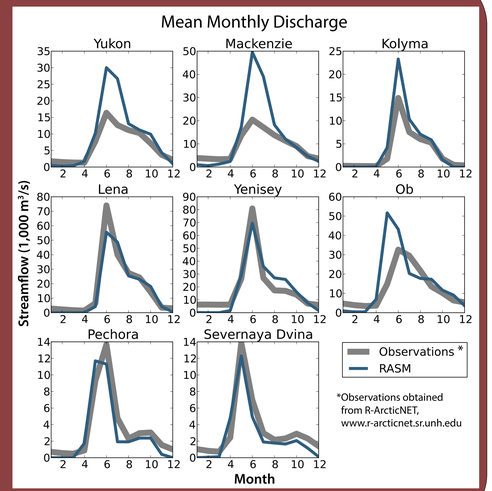


Figure: Mean monthly streamflows routed to gauged locations. RASM streamflows were extracted from a recent albedo sensitivity run from 1990-1999 (RASM simulation r33RBVIC70). Observed streamflows are climatological means and span the length of the observed streamflow record.

References

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