

Greenland freshwater runoff for glaciated and non-glaciated landscapes – distribution and trends, 1960-2010

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Abstract

A gridded runoff routing model *HydroFlow* was developed and tested to simulate the linkages between runoff production from land-based snow and ice melt processes and the associated freshwater fluxes to downstream areas and surrounding oceans. *HydroFlow* was specifically designed to account for glacier, ice sheet, and snow-free and snow-covered land applications. As part of its discharge simulations, *HydroFlow* creates a flow network that links the individual grid cells that comprise the simulation domain. The collection of networks that drain to the ocean produced a range of runoff values that varied most strongly according to catchment size and percentage and elevational distribution of glacier cover within each individual catchment. The time-evolution of spatially distributed grid-cell runoff values required by *HydroFlow* were provided by the SnowModel (Liston and Elder 2006) snow-evolution modeling system. Runoff magnitudes, the spatial patterns from individual Greenland catchments, and their changes through time (1960–2010) were simulated in an effort to understand runoff variations to adjacent seas, and to illustrate the capability of SnowModel and *HydroFlow* to link variations in terrestrial runoff with ocean processes and other components of Earth's climate system. Significant increases in air temperature, net precipitation, and local surface runoff lead to enhanced, and statistically significant, Greenland Ice Sheet (GrIS) surface mass balance (SMB) loss. Total Greenland runoff to the surrounding oceans increased 30%, averaging 481485 km³ y⁻¹. Averaged over the period, 69% of the runoff to the surrounding seas originated from the GrIS, and 31% came from outside the GrIS from rain and melting glaciers and ice caps. Regionally, runoff was greater from western than eastern Greenland. Since 1960, the data showed pronounced runoff increases in west Greenland, with the greatest increase occurring in the southwest and the lowest increase in the northwest.

Method and data

HydroFlow is a spatially distributed model that divides the simulation domain into individual drainage basins, linking each grid cell within each drainage basin via an eight-compass-direction water-flow routing network (Liston and Mernild 2012, Mernild and Liston 2012). The water flow is transported through the routing network via linear reservoirs. For runoff routing, *HydroFlow* assumes there exist different transport mechanisms within each individual model grid cell: a slow-response runoff system (representing the time it takes for any available snow and ice melt, including liquid precipitation, to be transported within a model grid cell to the fast-response reservoir) and a fast-response system (representing flow processes such as those represented by supra-, en-, sub-, and proglacial water transport) that moves water down-network. As part of the modeling system, locally generated runoff from snow-covered ice, snow-free ice, snow-covered land, and snow-free land, all have different residence times associated with them and they evolve with time as the snow and ice melts, and this is taken into account as part of the runoff routing simulations. The equations solved by *HydroFlow* are,

$$Q_{f,t} = Q_{s,t-1} \exp\left(-\frac{\Delta t}{k_f}\right) + (Q_{s,t} + Q_{m,t}) \left[1 - \exp\left(-\frac{\Delta t}{k_f}\right)\right]$$

and

$$Q_{s,t} = Q_{s,t-1} \exp\left(-\frac{\Delta t}{k_s}\right) + Q_{m,t} \left[1 - \exp\left(-\frac{\Delta t}{k_s}\right)\right]$$

where Q_f is the fast-response flow, Q_s is the slow-response flow, Q_m is the melt- and rain-water generated runoff at an individual model grid cell (e.g., the slow time scale, grid-box runoff produced by each SnowModel grid cell), $Q_{f,i}$ is the fast time-scale inflow from any adjacent grid cells, k_f and k_s are the fast-response and slow-response transfer functions, respectively, Δt is the model time increment, and i and $i-1$ are the current and previous time steps, respectively. This set of equations, when applied to each grid box of the runoff routing model, is connected via the flow network through the presence of the $Q_{f,i}$ term. To solve the *HydroFlow* water routing equations, individual watersheds and the associated grid connectivity within each watershed must be defined. Expanding $Q_{f,i}$ to highlight the network connectivity, yields

$$Q_{f,i} = Q_{s,N} + Q_{s,NE} + Q_{s,E} + Q_{s,SE} + Q_{s,S} + Q_{s,SW} + Q_{s,W} + Q_{s,NW}$$

where the subscripts N, NE, E, SE, S, SW, W, and NW indicate the compass direction of the adjacent connecting grid box. One of the right-hand-side terms will be zero (the one corresponding to the outflow boundary), and possibly all eight will be zero (for the case of a grid box located at the head of a watershed), depending on the gridded representation of the flow network.

Equations (1 and 2) describe a coupled system of equations whose solution yields a discharge hydrograph for each grid cell. These equations can be solved for any grid cell who's up-network inputs are known. Given knowledge of which grid cells flow into down-network grid cells, and first solving the grid cells at the head of a watershed (the grid cells that make up the watershed boundary) where there are no inflows, and continuing to solve grid cells that are fed with cells that have already have a solution, the entire solution matrix can be solved at any given time step. As part of the flow network generation, only a single flow outlet into the ocean is allowed for each individual watershed. Also, conservation of mass principles between inflow, storage change, transit times, and outflow from each cell in the routing network, must be defined to simulate the catchment runoff and generate discharge hydrographs for the routing grid cells.

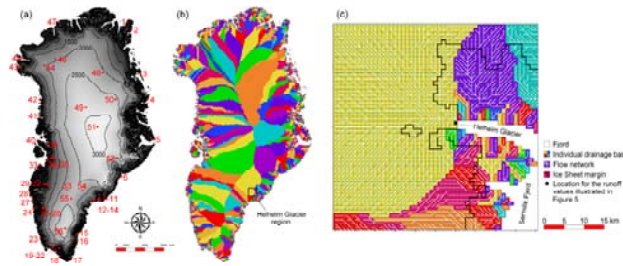


Figure 1: (a) Greenland simulation domain with topography (500-m contour interval) and the location of the coastal and GrIS meteorological tower stations (red dots) used for the simulations. The GrIS is marked with a color scale from gray to white (related to elevation), and the area outside the GrIS with black color. (b) Simulated individual Greenland drainage basins (represented by multi colors). (c) A close-up example of the individual drainage basins and flow network for the Helheim Glacier region, at the innermost part of the Sermilik Fjord, SE Greenland.

The Greenland simulation domain, individual modeled drainage catchments, and a detailed example of the simulated flow network for the Helheim Glacier region in SE Greenland, are illustrated in Figure 1. *HydroFlow* divided the GrIS into ~400 individual drainage basins and Greenland into ~3,150 individual basins (Figure 1b). Each of these basins include their own flow network that drains runoff to down-slope areas and into the adjacent seas (Figure 1c). For Greenland, the individual simulated drainage basins range in area from 50 km² to 154,800 km² (averaging ~700 km²), with 85% of the drainage basins equal to or less than 250 km²; these relatively small basins cover 10% of the total Greenland area, and are mainly located in the land area between the GrIS and the oceans.

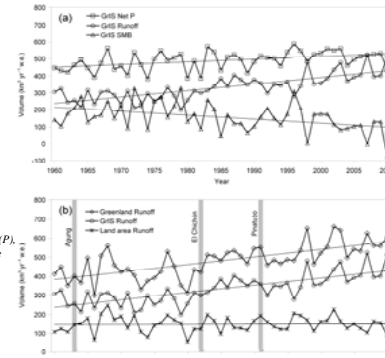


Figure 2: (a) GrIS simulated net precipitation (P), surface mass balance ($SMB = \Delta S$), and surface runoff (R) time series for 1960–2010; and (b) simulated surface GrIS runoff, land strip area (area outside the GrIS) runoff, and Greenland runoff time series for 1960–2010. The Agung (1963; Bali), El Chichón (1982; Mexico), and Pinatubo (1991; Philippines) volcanic eruptions are marked in (d).

Figure 2a presents time series (1960–2010) of GrIS surface hydrological conditions: net precipitation (precipitation minus evaporation and sublimation), surface runoff, and surface mass balance (SMB) on an annual basis for the calendar year. The average 1960–2010 simulated GrIS net precipitation was 489453 km³ y⁻¹, varying from 456446 km³ y⁻¹ in 1960–1969 to 516438 km³ y⁻¹ in 2000–2010. The simulated average GrIS net precipitation was just below the range of recently reported average net precipitation values of 543 to 588 km³ y⁻¹ (e.g., Box et al. 2006, Hanna et al. 2008). The increase in surface runoff led to a cumulative GrIS runoff loss of 17,000 km³ (equal to 47.1 mm SLE), with an annual average surface runoff of 333475 km³ y⁻¹, just above the range of recently reported average runoff values of 232 to 332 km³ y⁻¹ (e.g., Box et al. 2006; Fettweis 2007). For the GrIS, subtracting the average surface runoff (333 km³ y⁻¹) from the net precipitation (489 km³ y⁻¹) yielded a surface mass gain, with an average annual GrIS SMB of 156482 km³ y⁻¹ (1960–2010). The GrIS SMB decadal variability ranged from 220486 km³ y⁻¹ in 1970–1979 to 86472 km³ y⁻¹ in 2000–2010. The simulations showed the largest (most positive) SMB near the beginning of the simulation period, with a subsequent mass loss as temperatures and runoff increased.



Figure 2b presents the time series of Greenland runoff (1960–2010), and individual runoff contributions from the GrIS and from the land area – including thousands of glaciers and ice caps – located between the ice sheet and the surrounding oceans. The 1960–2010 average, simulated Greenland runoff was 481485 km³ y⁻¹, varying from 413456 km³ y⁻¹ in 1960–1969 to 572453 km³ y⁻¹ in 2000–2010, following the trends in air temperature and precipitation. The GrIS runoff was, however, 333475 km³ y⁻¹ (1960–2010), indicating that 69% of the runoff to the surrounding seas originated from the GrIS, and 31% from the land area. For the land area, the trend in runoff was constant, and the average runoff was 148441 km³ y⁻¹. A possible reason for the minimal change in slope of the land-area runoff curve, is because the glaciers and ice caps are already melting all summer, and an enhanced melt season and melt extent have therefore less impact on the trends.

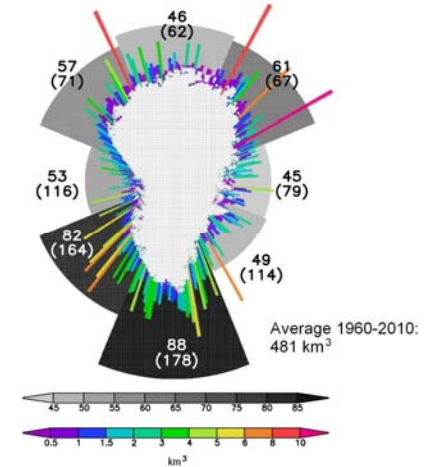


Figure 3: Spatial distribution of simulated runoff from Greenland's individual drainage basins [each radial colored bar represents the accumulated runoff of ten catchments located side by side, and from the eight sectors (N, NE, E etc.), to the adjacent seas. Mean annual Greenland runoff for 1960–2010. The numbers in brackets indicate the length of the discharge season for each region. The regional runoff numbers for each sector have been used to scale radial distance of each grey wedge from the coast to the outside of the wedge, and not from the center of Greenland to the outside of the wedge. So, for example, the 53 and 57 wedge ends are a similar distance from the coast, but have very different total wedge sizes (and 49 and 45 are similar because the coast is a similar distance from the center of the projection). Greenland is slightly distorted from our traditional view in this radial projection.

In Figure 3, the spatial runoff distribution from Greenland to the adjacent seas is illustrated. The individual drainage catchments route varying amounts of runoff to the surrounding seas. The 1960–2010 average discharge for these drainage catchments varied from <0.01 km³ y⁻¹ to 10.1 km³ y⁻¹, with a total Greenland average of 481485 km³ y⁻¹. The spatial variability in catchment runoff to the surrounding seas also varied according to catchment size, ice sheet and glacier elevation range, and ice sheet and glacier areal coverage within each individual catchment. For approximately half of the runoff values (colored radial bars), runoff ranged from <0.01 km³ y⁻¹ to 1.0 km³ y⁻¹ (1960–2010), and contributed 15% of the 481 km³ y⁻¹ total Greenland runoff. In contrast, 15% of the catchments – catchments having a relatively large ice sheet and/or glacier areal coverage – had a mean annual runoff greater than 2.5 km³ y⁻¹ and contributed 40% of the Greenland runoff to the adjacent seas.

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