VIC-Glacier (VIC-GL)

Modelling Glacier Dynamics with the HydroConductor Model

VIC Generation 2 Deployment Report

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About PCIC

The Pacific Climate Impacts Consortium is a regional climate service centre at the University of Victoria that provides practical information on the physical impacts of climate variability and change in the Pacific and Yukon Region of Canada. PCIC operates in collaboration with climate researchers and regional stakeholders on projects driven by user needs. For more information see http://pacificclimate.org.

Disclaimer

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1 Purpose

The VIC-GL model is not designed to allow lateral communication between cells; hence, it can't be used to directly model hydrologic or cryospheric features that occupy more than a single cell (such as large lakes or ice fields), or that flow from one cell into another cell (such as valley glaciers). Consequently, glacier dynamics is simulated by coupling VIC-GL to the UBC Regional Glaciation Model (RGM). The RGM model is described in detail by Jarosch et al. (2013) and Clarke et al. (2015), and summarized in §2.1 below. The VIC-GL model is a version of VIC (Liang et al. 1994, 1996; Cherkauer et al. 2003) with additional features to allow modelling of glacier mass balance (see Schnorbus 2018 for a complete description).

The Hydro-Conductor is a set of python wrapper scripts used to run the fully coupled VICGL- RGM hydrologic modelling system. The "conductor" executes each model as a sub process while translating inputs and outputs from each model to match the scale and requirements of the other. The Hydro-Conductor is also used to output data that tracks the evolution of surface elevation, glacier mask and surface mass balance.

The Hydro-Conductor code is available from https://github.com/pacificclimate/hydro-conductor.

2 General Design

The main functions of the Hydro-Conductor are to run the VIC-GL and RGM models, couple the two models (by passing surface mass balance and glacier information between the models) and to enforce conservation of mass and energy during model coupling. The coupling of the two models also must address a number of technical issues related to spatial mismatch, temporal mismatch and mass/energy conservation

Due to the timescales involved with glacier flow, the glacier dynamics model is typically run using an annual timestep. This results in a temporal mismatch with the VIC-GL model, which normally operates at daily or sub-daily resolution. To resolve the temporal mismatch, VIC-GL and RGM are run essentially independently, but coupled once per simulation year. This is practically accomplished by sub-dividing the total integration period into several annual sub-integration steps. For each sub-integration step, VIC-GL and RGM are run sequentially over an annual period that is defined by a coupling date (e.g., a coupling date of 30 September defines a sub-integration period of 1 October, Year1 to 30 September, Year2). The sub-integration steps are run in series, with the start state of the current sub-period initialized by the end-state from the previous sub-period. The total duration of the sub-integrations is equal to (or can be less than) the total model integration period. The integration period of the VIC-GL model is specified in the global parameter file in the usual manner. The annual sub-integration period for estimating cumulative glacier surface mass balance is specified in the global parameter file by indicating the coupling date by day and month (usually based on a water year, i.e., 30 September).

The VIC-GL and RGM models utilize very different spatial structures. Although the VIC-GL model runs on a coarsely discretized grid, each cell in the grid is sub-divided computationally into hydrologic response units (HRUs). These HRUs, which are used to represent sub-grid variability, are abstractions that have no explicit topology or location. On the other hand, the glacier dynamics model runs on a very high resolution, equal area and spatially explicit computational mesh. It is also likely that both models will use different spatial projections for their computational grids. Hence, some manner of spatial translation between VIC-GL cells/HRUs and RGM pixels is required. Spatial translation is required when disaggregating (or downscaling) surface mass balance from VIC-GL to RGM (§2.3.2) and when aggregating (or upscaling) glacier area and topographic data from RGM to VIC-GL (§2.3.3) and is implemented via spatial mapping between the two model grids (§3.1).

Any changes in glacier area or surface topography arising from glacier dynamical processes can result in changes in the HRU vector (changes in occurrence and area of HRUs) in any give cell. During this process, conservation of mass and energy is enforced by adjusting water and energy stores in affected HRUs and applying the updates to the VIC-GL state file prior to the initialization of each sub-integration (see §2.3.4).

2.1 Regional Glaciation Model (RGM)

Simulation of glacier dynamics utilizes the ice dynamics component of the RGM. The model is 2.5D (two-dimensional vertically integrated) with a grid spacing of 100 m that "assumes the shallow-ice approximation and isothermal ice. Evolution equations for surface elevation are approximated as finite-difference expressions and solved using a super-implicit numerical scheme and flux-limiters" (Clarke et al. 2015). The model relies on a gridded representation of the model domain to represent surface mass balance, current ice extent and topography. The surface mass balance drives ice flow, resulting in a new surface topography. Using a DEM of hidden sub-glacial topography (Clarke et al. 2013), the updated ice extent can be subsequently derived from the updated surface topography. Further details are available in Jarosch et al. (2013) and Clarke et al. (2015).

2.2 Modelling Domain

Once a VIC-GL model domain is identified (based on VIC-GL basin delineation), an overlapping RGM domain is defined. It is useful to include a buffer region of several kilometres to the RGM domain. As the two modelling domains are based on different grids (different resolutions and projections), they are neither expected nor required to align. Pixels that overlap with the VIC-GL model grid (i.e. pixel-centres are contained within the VIC-GL domain) are referred to as 'assigned' pixels, while those that fall outside the VIC-GL domain are termed 'unassigned' (see Figure 1).

2.3 Hydro-Conductor

2.3.1 Overview

The HydroConductor is a python wrapper script that runs the VIC-GL and RGM models. Within the wrapper, VIC-GL produces the mass balance information that is used to force the RGM model and the updated surface topography from the RGM model is used to update glacier cover in VIC-GL and the process repeats until the full integration is complete. This coupling process is detailed in Figure 2 and described in the following steps:

1. VIC-GL is run at a daily or sub-daily timestep over a sub-integration period *N* (e.g., 1 October, Year0 to 30 September, Year1), during which the cumulative glacier mass balance is estimated for each glacier HRU. A VIC-GL model state file is generated for sub-integration period *N* (e.g., for 30 September, Year1).
2. The annual glacier surface mass balance field (at the RGM model resolution) for sub-integration period *N* is estimated for the entire model domain (see §2.3.2).
3. The RGM is forced with the estimated mass balance field for the period *N*, producing an updated surface topography for the end of the period (e.g., 30 September, Year1).
4. Updated glacier area is derived from the bed topography and updated surface topography, and the updated glacier area and surface topography are then used to generate a new HRU vector, from which updated vegetation parameter and elevation band files are written (see §2.3.3).
5. The VIC-GL state file is updated to be consistent with the new HRU vector and to ensure conservation of mass and energy (see §2.3.4).
6. VIC-GL is re-initialized with the updated state file and executed with the updated parameter files for the sub-integration period *N*+1 (e.g., 1 October, Year1 to 30 September, Year2).
7. The process repeats until the end of the overall simulation.

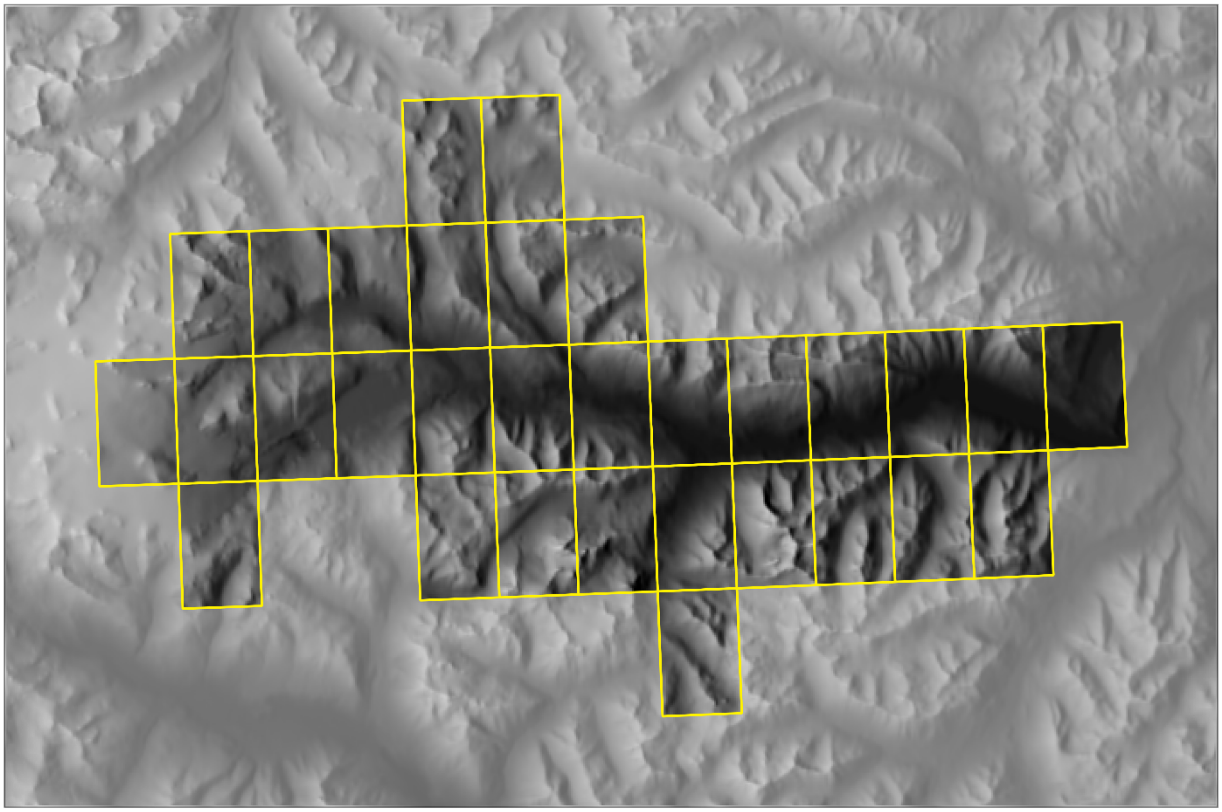

Figure 1. Hydro-conductor modelling domain for the Bridge River above La Joie Dam (BCHLJ) watershed showing the VICGL model grids (yellow outline; 0.0625° resolution; geographic coordinates) along with the extent of RGM the surface elevation (raster image; 100-m resolution; BC Albers projection), showing 'assigned' (clear raster image) and 'unassigned' pixels (shaded raster image).

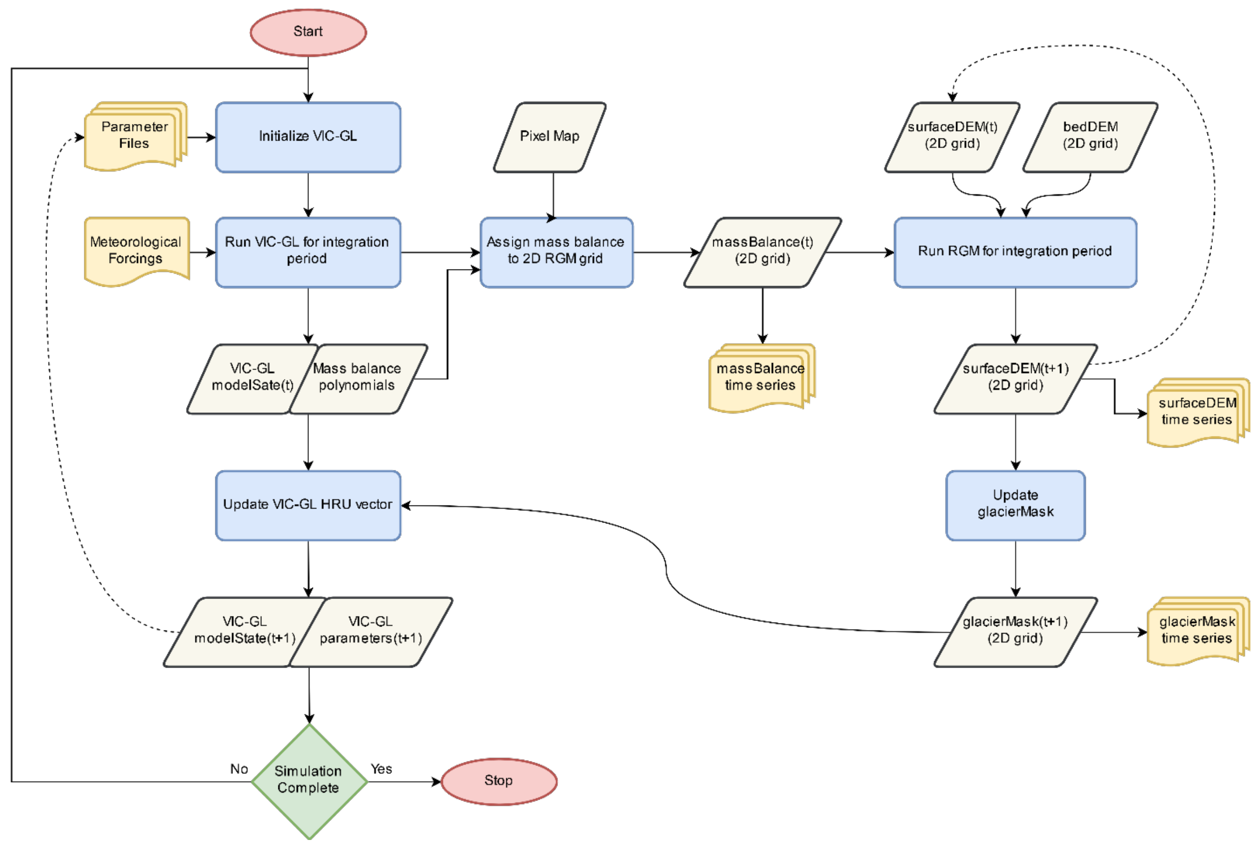

Figure 2. HydroConductor flowchart

2.3.2 Mass Balance Field

The glacier dynamics model is forced using glacier surface mass balance, which must be supplied as a two-dimensional gridded field at the native resolution of the RGM. This entails the conversion of the VIC-GL HRU-based mass balance data into a high-resolution spatially explicit mass balance field. The spatial mismatch between the two models is addressed by building a mapping relationship between the VIC-GL model cells and the RGM pixels. In addition, it is assumed that the surface mass balance varies only with elevation, and that the elevation gradient is uniform within an individual VIC-GL cell. The mass balance elevation profile for each VIC-GL cell is estimated by fitting a second-order polynomial to the mass balance results and elevation for each glacier HRU. An example mass balance elevation profile is given in Figure 3. The final high-resolution mass balance field is then created by predicting the mass balance values at each 'assigned' surface DEM pixel using the fitted polynomial model specific to that VIC-GL cell (e.g., Figure 4).

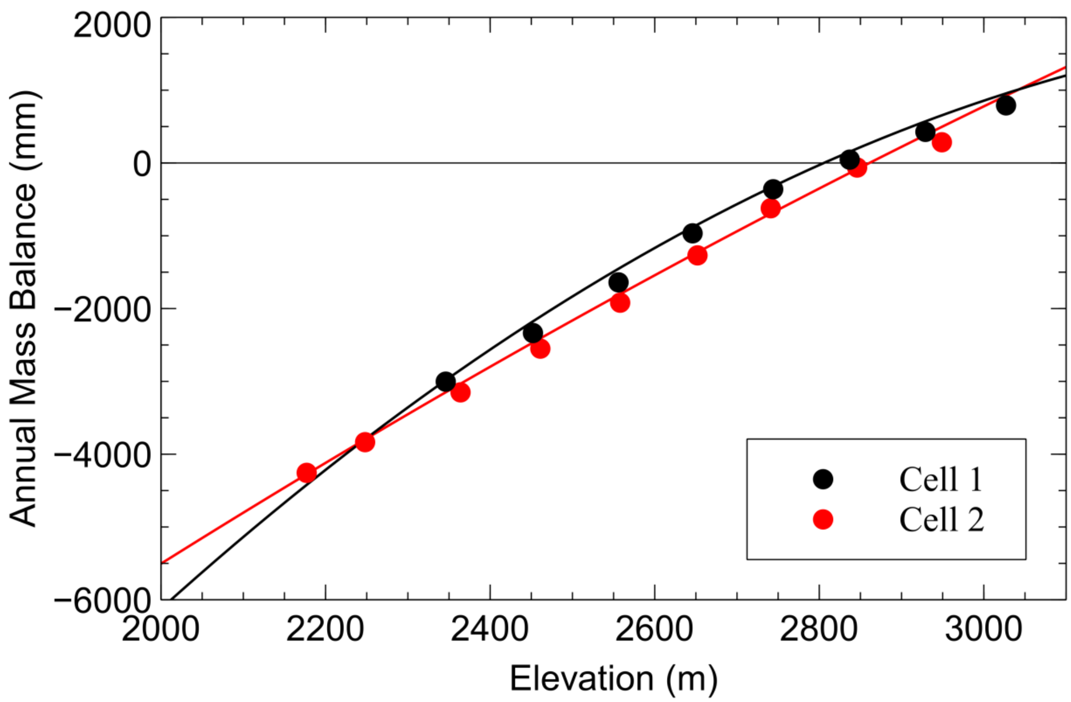

Figure 3. Example mass balance elevation profile with fitted polynomials for test model of two VIC-GL cells with 100-m elevation bands.

The RGM requires mass balance data for all model pixels, including those without glacier cover (to simulate the possible expansion of glaciers into unglaciated terrain). However, in a typical application of the VIC model, the HRU vector for each grid cell is built based on observed vegetation cover, such that glacier HRUs only exist for glaciated terrain. However, to satisfy the requirements of the RGM model (i.e., mass balance forcing over the entire model domain), the use of 'dummy' glacier HRUs has been utilized. In effect, the vegetation parameter file is built ensuring that a glacier HRU exists in all elevation bands of all VIC grid cells in each modelling domain. For grid cells and elevation bands where glaciers exist (at some given time during the simulation) the glacier HRUs are 'real' and will have an area greater than zero. The remaining 'dummy' glacier HRUs have an area equal to zero and exist solely for estimating glacier mass balance but are otherwise invisible to the VIC model.

For unassigned cells outside the VIC-GL domain, a mass balance value must be estimated for the RGM model to function properly. Assigning a default constant value (such as 0 m), although simple, can introduce unrealistic spatial discontinuities at the VIC-GL basin boundary. The adopted approach is to fit a second-order polynomial to the assigned pixel balance values, and then to extrapolate to unassigned RGM pixel values based on elevation. In effect, pixels that overlap the VIC-GL domain use a 'local' mass balance gradient, while pixels outside the VIC-GL domain use a 'regional' mass balance gradient (Figure 4).

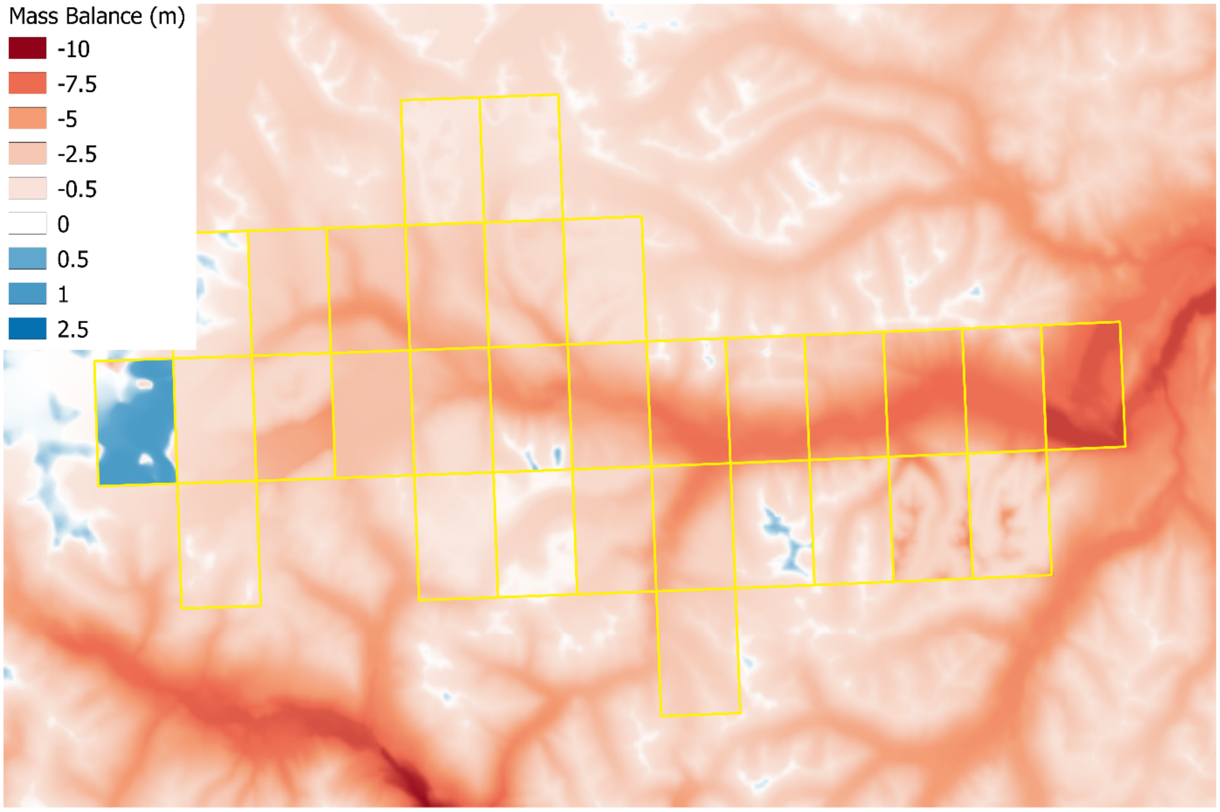

Figure 4. Example of gridded mass balance forcing field, based on the BCHLJ watershed.

2.3.3 Glacier Mask and HRU Area Updating

At the completion of an integration step, the RGM produces a digital elevation model of updated surface topography. As part of the coupling process, the updated surface topography is used in conjunction with the bed topography to generate an updated glacier mask as follows:

$$I_{i,j} = \begin{cases} 1 & H_{i,j} > h_m \\ 0 & H_{i,j} \le h_m \end{cases} \qquad (1)$$

where $H_{i,j} = S_{i,j} - B_{i,j}$, H is ice thickness, S is surface elevation and B is bed elevation corresponding to Cartesian coordinates x_i and y_j, and h_m is a thickness threshold to filter out the effect of seasonal snow. Using the updated surface topography and updated glacier mask, the HRU vector for each grid cell is then updated to reflect changes in glacier area (due to advance or retreat) and local hypsometry (due to thinning). Changes in glacier area and surface elevation are incorporated into the VIC model via updating of the vegetation parameter file and the elevation band (or snowband) file. Note that the vegetation parameter file describes the distribution of Hydrologic Response Units (HRUs) by providing a fractional area for different land cover types within specific elevation bands. The RGM only explicitly describes changes in the area of a single land cover type: glaciers. Consequently, area changes of other land cover types in the same band as the affected glacier HRU must be inferred. Although the snowband and vegetation parameter files are updated separately, the area information in both files must be consistent. The specifics of the HRU area updating process are provided in Appendix A.

We note that only glacier area is transferred back to VIC-GL, not volume (i.e., thickness). VIC-GL does not explicitly track glacier volume as glaciers are assumed to be infinitely thick. Hence, glaciers do not 'melt away' in the VIC-GL model and the 'existence' or 'presence' of a glacier at a specific location (e.g., glacier retreat or advance) is determined strictly by the dynamics.

2.3.4 VIC HRU State Updating

One of the main features in the coupling of the VIC model to the RGM is the feedback of changes in glacier area and surface elevation from the RGM to VIC, and incorporated into the VIC model via updated vegetation parameter and elevation band files. A side-effect of this updating step is the need to adjust certain state variables to ensure conservation of mass and energy within the individual VIC cells because of area and elevation updating. Conceptually, this entails the redistribution of water and energy within individual HRUs. For example, the goal of water re-distribution between hydrologic response units (HRUs) is to conserve the volume of water within a grid cell. In general, the following must hold for a given cell:

$$\sum_{h=1}^{H(t)} \Omega(h,t) \cdot A(t) = \sum_{h=1}^{H(t^*)} \Omega(h,t^*) \cdot A(h,t^*) \tag{2}$$

where H is the number of HRUs in the given VIC cell, Ω is a state variable (e.g., water equivalent depth of snow), A is the area fraction of HRU number h, and t and t^* represent the model state before and after glacier updating, respectively. Further details on state updating are provided in Appendix B.

2.3.5 Parameter File Initialization

Due to differences in source data, potential discrepancies may exist between the RGM topography and glacier mask fields and the accompanying VIC-GL vegetation and snowband parameter files. Hence, an initial binning process, as described in §2.3.3, is undertaken to reconcile the VIC-GL snowband and vegetation parameter files to the hypsometry and glacier coverage described by the RGM input raster.

3 Using the Coupled Model

3.1 Input Files and Parameters

Once installed and compiled, the HydroConductor is run using a command such as the following:

```
> python3 ~/code/hydro-conductor/scripts/hydro_conductor.py --g VICGL-
RGM_BULWA.conf --rgm-params global_params_RGM.txt --sdem srf_dem_BULWA.gsa
--bdem bed_dem_BULWA.gsa --pixel-map pixel_map_BULWA.txt --glacier-mask
glac_mask_BULWA.gsa --trace-files --band-size 200 --loglevel DEBUG --
```

```
plots  --vic-path /home/mschnorb/code/vic/vicNl --rgm-path
/home/mschnorb/code/rgm/rgm --output-path /home/mschnorb/vic/out
```

The mandatory and optional command line parameters required to run the HydroConductor model are described in Table 1 and the required input files area described in the sections that follow. Some additional notes for select parameters are provided below.

`--band-size`: this value must be equivalent to the band size used to generate the HRUs and consistent with band relief used in the band parameter file.

`--open-ground-root-zone`: this is an optional parameter that overrides the default rooting depth values for open ground HRUs in the vegetation parameter file

`--glacier-root-zone`: this is an optional parameter that overrides the default rooting depth values for glacier HRUs in the vegetation parameter file

`--glacier-min-thickness`: this is parameter that defines the depth threshold used to filter out seasonal snow when calculating the glacier mask as the difference between surface and bed elevations. If omitted, the default value is 2.0 m

3.1.1 RGM Parameter File

This file provides the parameter values that control ice dynamics in the RGM model. An example file is provided as Appendix C, which also contains the recommend default parameters values as used by Clarke et al. (2015).

3.1.2 Pixel Map

Transfer of mass balance and glacier area and surface topography between VIC-GL and RGM requires a definition of the spatial link between the two model grids. This is accomplished via the pixel map file, which describes the one-to-many spatial join between the individual VIC-GL cells and the overlapping RGM pixels. Spatial overlap is determined based on the intersection of RGM pixel centres. An example pixel mapping file is given in Appendix D.

3.1.3 Bed and Surface DEMs

The RGM model requires a DEM of sub-glacial topography. As glacier thickness is not widely observed, subglacial topography has to be estimated (e.g. Clarke et al. 2009, 2013). The RGM model must be initialized with a surface topography provided as a surface DEM file. The surface topography will specify the thickness and location of glaciers at the start of the RGM integration. It is important to ensure that for all pixels, surface elevation must equal or exceed the bed elevation, or an error will occur. Note that the surface DEM can also be set equal to the bed DEM (i.e., the RGM model is initialized without any glaciers present), which may be relevant for long initialization runs.

It will often be the case that model integration begins a point in time when observation of surface elevation are sparse or non-existent. In such an event, it will be necessary to estimate an initial value for surface topography. Appendix E details on such approach.

3.1.4 Glacier Mask

An initial glacier mask must be provided in the form of a raster file. The glacier mask should be consistent with the bed and surface DEMS provided as parameters to the HydroConductor.

3.1.5 Initial Band and Vegetation Parameter Files

Although not directly specified as input parameters to the HydroConductor, the initial vegetation and band parameter files are assigned via the VIC-GL global parameter file. When running the coupled models, certain additional details are required. The band file should contain one lower dummy band (band area is zero) and one upper dummy band to allow for cell topography to evolve beyond the observed elevation range (i.e. if a thinning or retreating glacier exposes a surface below the minimum elevation or a thickening surface rises above maximum elevation, creating new bands). An exception includes cells that include tidewater, in which case no lower dummy band should be specified. The vegetation parameter file must also contain one glacier HRU per elevation band. If no glacier terrain actually exists, dummy glacier HRUs (i.e. area is zero) must be included.

Table 1. HydroConductor Command Line Parameters

Parameter	Meaning	File Type	Optional?
--vic-path	Full path to the VIC executable (include *vicNl* at the end of it)		No
--rgm-path	Full path to the RGM executable (include *rgm* at the end of it)		No
--g	VIC global parameter file	txt	No
--rgm-params	RGM parameter file	txt	No
--pixel-map	RGM-pixel-to-VIC-cell map	txt	No
--bdem	Initial bed DEM file	surfer/GSA	No
--sdem	Initial surface DEM file	surfer/GSA	No
--glacier-mask	Initial glacier mask	surfer/GSA	No, but can be all zeros
--glacier-min-thickness	Minimum thickness in meters where snow on top of the DEM is to be considered as glacier (default 2.0)		Yes
--glacier-root-zone	Substitute custom root zone parameters for the glacier vegetation type		Yes
--open-ground-root-zone	Substitute custom root zone parameters for the open ground vegetation type		Yes
--band-size <*meters*>	Set custom elevation (snow) band relief in meters. Default is 100.		Yes
--trace-files	Keep temporary files produced (7 files per simulation year)	txt and nc	Yes
--plots	Display plots of surface DEM, glacier mask, and glacier thickness. If --trace-files is enabled, writes a PNG image for each annual plot.	png	Yes
--loglevel <*debug/info/warning/error*>	Set verbosity of logging to file. Default is *info* if loglevel not provided.		Yes
--output-path	Path to where output files should be written (and temporary files will go in a *hydrocon_temp* subdirectory that will be created)		No

3.2 Output

In default mode, the output from the RGM and intermediate VIC-GL parameter files for each sub-integration are treated as temporary and not retained. If desired, however, the user may capture as output the temporary, or intermediate files, produced by VIC-GL and RGM. This is set by adding the command line parameter `--trace-files` to the HydroConductor command. This output can often be quite useful for model analysis and diagnosis. Eight files are produced for each sub-integration. This includes VIC-GL model parameter and states files, which are described below with the format "description: *filename*":

- VIC-GL global parameter file: *gpf_temp_yyy0-10-01.txt*
- Elevation band file: *snb_temp_yyy0-10-01.txt*
- Vegetation parameter file: *vpf_temp_yyy0-10-01.txt*
- Raw VIC-GL state file: *vic_hydrocon_state_yyy1-09-30*
- Updated VIC-GL state file: *vic_hydrocon_state_yyy1-10-01*

The filename suffixes are dates in yyyy-mm-dd format where *yyy0* in the filename represents the year at the start of the sub-integration period, *yyy1* represents the year at the end of the sub-integration period and mm-dd used here assume a 30 September coupling data. The HydroConductor also preserves the RGM model input and output files for each sub-integration period. These files are described below using a "description: *filename*" format:

- Interpolated glacier surface mass balance: *mass_balance_grid_yyy1-09-30.gsa*
- RGM Input surface elevation raster: *rgm_surf_dem_in_yyy1-mm-dd.gsa* (same as *rgm_surf_dem_out_yyy0-09-30.gsa*)
- RGM Output surface elevation raster: *rgm_surf_dem_out_yyy1-09-30.gsa*
- Derived glacier mask: *glacier_mask_yyy1-09-30.gsa*

These are raster files in Surfer ASCII grid format (GSA), where filename suffixes are as previously defined.

4 References

Cherkauer, K. A., L. C. Bowling, and D. P. Lettenmaier, 2003: Variable infiltration capacity cold land process model updates. *Glob. Planet. Change*, **38**, 151–159, https://doi.org/10.1016/S0921-8181(03)00025-0.

Clarke, G. K. C., E. Berthier, C. G. Schoof, and A. H. Jarosch, 2009: Neural Networks Applied to Estimating Subglacial Topography and Glacier Volume. *J. Clim.*, **22**, 2146–2160, https://doi.org/10.1175/2008JCLI2572.1.

——, F. S. Anslow, A. H. Jarosch, V. Radić, B. Menounos, T. Bolch, and E. Berthier, 2013: Ice Volume and Subglacial Topography for Western Canadian Glaciers from Mass Balance Fields, Thinning Rates, and a Bed Stress Model. *J. Clim.*, **26**, 4282–4303, https://doi.org/10.1175/JCLI-D-12-00513.1.

——, A. H. Jarosch, F. S. Anslow, V. Radić, and B. Menounos, 2015: Projected deglaciation of western Canada in the twenty-first century. *Nat. Geosci.*, **8**, 372–377, https://doi.org/10.1038/ngeo2407.

Compo, G. P., and Coauthors, 2011: The Twentieth Century Reanalysis Project. *Q. J. R. Meteorol. Soc.*, **137**, 1–28, https://doi.org/10.1002/qj.776.

Jarosch, A. H., C. G. Schoof, and F. S. Anslow, 2013: Restoring mass conservation to shallow ice flow models over complex terrain. *The Cryosphere*, **7**, 229–240, https://doi.org/10.5194/tc-7-229-2013.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges, 1994: A simple hydrologically based model of land-surface water and energy fluxes for general-circulation models. *J. Geophys. Res.-Atmospheres*, **99**, 14415–14428, https://doi.org/10.1029/94JD00483.

Liang, X., E. F. Wood, and D. P. Lettenmaier, 1996: Surface soil moisture parameterization of the VIC-2L model: Evaluation and modification. *Glob. Planet. Change*, **13**, 195–206, https://doi.org/10.1016/0921-8181(95)00046-1.

Schnorbus, M. A., 2018: *VIC-Glacier (VIC-GL): Description of VIC Model Changes and Upgrades*. VIC Generation 2 Deployment Report, Volume 1, Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC, 40 pp.

Appendix A

Algorithm Specification – VIC Area Updating

A1 Background

This specification details the method for updating the VIC model snowband and vegetation parameter files following glacier updating. One of the main features in the coupling of the VIC model of the UBC Regional Glaciation model (RGM) is the feedback of glacier area and surface elevation from the RGM to VIC. Changes in glacier area (passed from RGM to VIC as an updated glacier mask) and surface elevation are incorporated into the VIC model via updating of the vegetation parameter file and the elevation band (or snowband) file. Specifically, the snowband file is updated to reflect changes in surface topography (due to changes in glacier thickness) and the vegetation parameter file is updated to reflect changes in glacier cover. Note that the vegetation parameter file describes the distribution of Hydrologic Response Units (HRUs) by providing a fractional area for different land cover types within specific elevation bands. The RGM only explicitly describes area changes of a single land cover type: glaciers. Consequently, area changes of other land cover types in the same band as the affected glacier HRU must be inferred. To do so, we make the following assumptions:

1. If a glacier HRU shrinks in area, and non-glacier HRUs also occupy the same elevation band, then
    a. An existing “open ground” HRU is expanded to fill the band; or
    b. A new “open ground” HRU is added to fill the band.
2. If a glacier HRU expands in area, and non-glacier HRUs also occupy the same elevation band, then:
    a. An existing “open ground” HRU is shrunk; and/or
    b. Each of any vegetated HRUs is shrunk by an amount proportional to the original vegetated HRU area.
3. If a glacier HRU changes size/area, and no other HRUs occupy the current band, then only the glacier HRU area is modified.

The identification of the appropriate land cover type to use for “open ground” will be specified by the user via the global parameter file.

Although the snowband and vegetation parameter files are updated separately, the area information in both files must be consistent. The updated band area in the snowband file must equal the updated area of all HRUs in the same band *b* in the vegetation parameter file. This is described mathematically as follows:

$$A_b[t^*] = \sum_{h=1}^{H(b)} A_h[b, t^*]$$

where t^* is the state after updating, $A_b[t^*]$ is the band area, $A_h[b,t^*]$ is the area of HRU *h*, and *H*(*b*) is the number of HRUs in band *b*.

This specification employs the area definitions given in Figures A1, A2 and A3, where all areas are given as grid cell fractions.

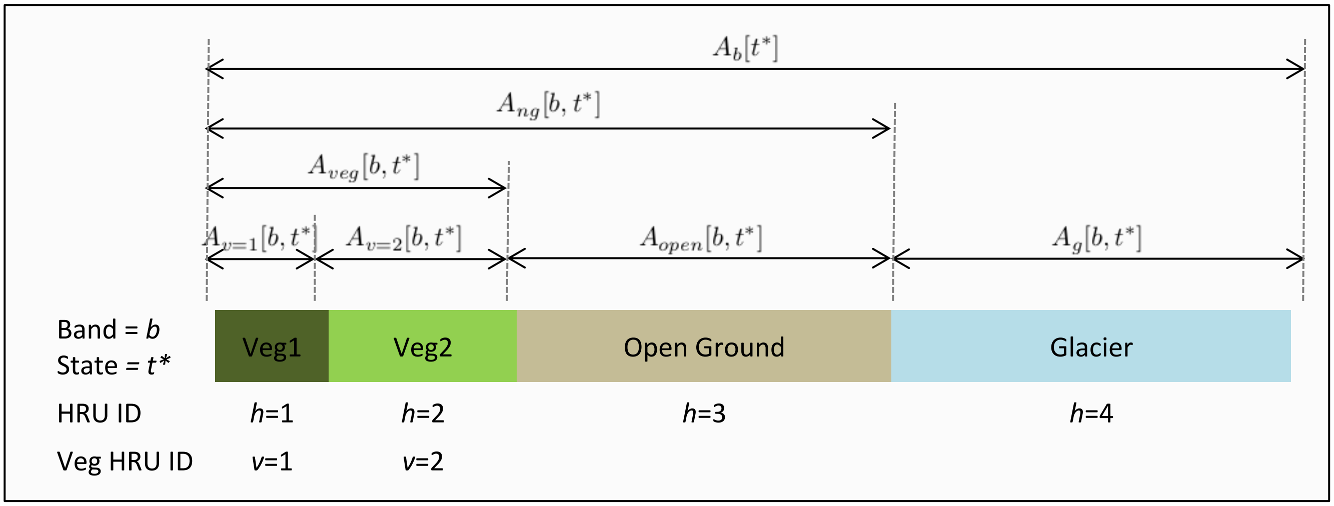

Figure A1. Schematic of HRU area definitions. Note that all areas are quantified as grid cell fractions.

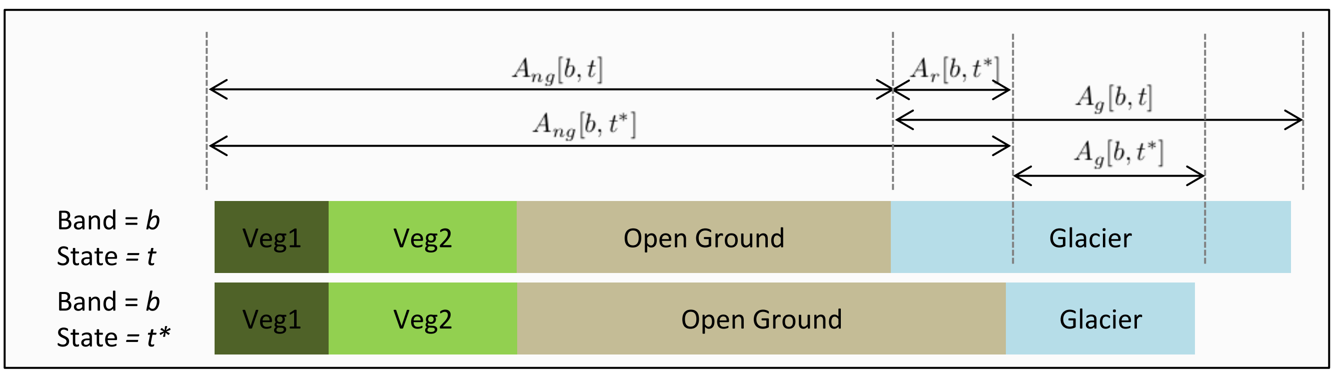

Figure A2. Schematic of HRU area change definitions for case when glacier and elevation band shrink, where $A_r[b,t^*] > 0$ and $\Delta A_{veg}[b,t^*] = 0$. Note that all areas are quantified as grid cell fractions.

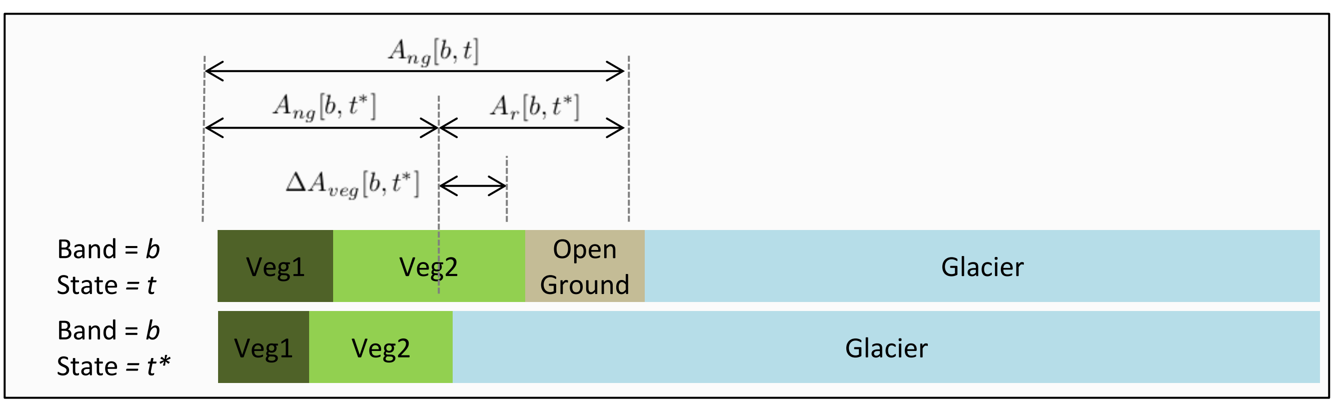

Figure A3. Schematic of HRU area change definitions for case when glacier expands, where $A_r[b,t^*] < 0$ and $\Delta A_{veg}[b,t^*] < 0$. Note that all areas are quantified as grid cell fractions.

The specifications that follow are broken into three sections: Section 3 deals with snowband updating, Section 4 deals with HRU area updating during model integration, and Section 5 deals with HRU area updating during model initialization.

A2 Assumptions and General Specifications

The specifications described in the following sections are based on several assumptions. These are outlines as follows:

1. The VIC model will be parametrized such that the original snowband file will contain "extra" elevation bands (with area and median elevation set to zero; the cell will be padded with several NULL bands). In other words, allowance will be made within the snowband file for changes in elevation relief that exceed that given by the original DEM used for parameterization. For instance, the model must be generalized to accommodate situations where glacier thickening would cause topographic relief to migrate into a new elevation band.
2. If topographic relief expands beyond the range accommodated by the specified elevation bands (including "padded" bands), an exception will be thrown, and the model will cease operation with a meaningful error description
3. Within the vegetation parameter file, all elevation bands will include a glacier HRU. The glacier HRU area will be set to a value greater than or equal to zero. In the case that a glacier is present, the area will be greater than zero. In the case that no glacier is present, the area will be set to zero (i.e., the band is padded with a NULL glacier). NULL glacier HRUs are present to facilitate calculation of glacier mass balance throughout the entire study domain as input to the coupled RGM model.
4. If an existing HRU disappears following updating (i.e., the area becomes zero), the vegetation parameter file is updated as follows:
    a. Records for glacier HRUs are retained but the area is set to zero (i.e., glacier HRU is Nulled); and
    b. Records for non-glacier HRUs are removed from the file.

A3 Snowband Parameter File

A3.1 Pseudo-code

Conceptually, the updating of VIC elevation bands from state *t* to *t** following glacier updating with the RGM follows the following general steps:

1. Calculate elevation hypsometry for a given grid cell, i.e. bin RGM pixels by elevation band for state t*
2. Calculate area fractions for each band

3. Calculate median elevations for each band

This procedure is described using the following pseudo-code:

```
for (c in cells) { //Loop through cells
    #Build elevation hypsometry, i.e. construct histogram of number of RGM pixels per elevation band
    for (b in bands) { //Loop through elevation bands (e.g. index 0 to index B-1)
        # Calculate band area and band median elevation from histogram; Equations (3), (4), and (5)
        # Replace band area and elevation (state t) with updated area and elevation (state t*)
    }
}
#Write updated snow band file
```

A3.2 Equations

For a given VIC cell, the area of band *b* at state *t** is calculated as

$$A_b[t^*] = \frac{\sum_{p=1}^{P} \mathbf{1}_b\left(z_p[t^*]\right)}{\sum_{p=1}^{P} 1} \tag{3}$$

where $z_p[t^*]$ is the elevation of RGM pixel *p* (for pixels *p* = 1, …, *P*) at state *t**, and $\mathbf{1}_b\left(z_p\right)$ is the indicator function given as

$$\mathbf{1}_b\left(z_p\right) = \begin{cases} 1 & if\ z_p \in b \quad\quad (i.e.\ \ z_b^- \le z_p < z_b^+) \\ 0 & if\ z_p \notin b \quad (i.e.\ \ z_p < z_b^-\ or\ \ z_p \ge z_b^+) \end{cases} \tag{4}$$

where z_b^- and z_b^+ are the lower and upper elevation, respectively, of band *b*. For a given VIC cell, the median elevation of band *b* is calculated as[1]

$$Median\{z_p \in b\} \tag{5}$$

[1] Assuming that python contains some convenient function for calculating medians

A4 Vegetation Parameter File

A4.1 Pseudo-code

Conceptually, the updating of VIC HRU areas from state *t* to *t** following glacier updating with the RGM follows the following general steps:

1. Calculate updated glacier area fraction for band *b* at state *t**
2. If glacier area changes in band *b* then:
    a. Calculate band residual area fraction for band *b* (change in non-glacier area)
    b. Update area of "open ground" HRU, if present in band
    c. Update area of remaining "vegetated" HRUs
    d. Update HRU areas for band *b* at state *t**
3. Update vegetation parameter file

The updating of the vegetation parameter file is demonstrated using the following pseudo-code:

```
for (c in cells) {  //Loop through cells
    for (b in bands) { //Loop through elevation bands (e.g. index 0 to index B-1)
        #Calculate A_g[b,t*] using Equation (6)
        if (!A_g[b,t]) then A_g[b,t]=0
        if (A_g[b,t*] != A_g[b,t]) { //Glacier HRU in band b changes area
            #Calculate A_ng[t*], and A_r[b,t*] using Equations (7), and (8)
            if (!A_open[b,t]) then A_open[b,t]=0
            # Calculate A_open[b,t*] using equation (9)
            # Calculate area changes in remaining vegetated HRUs using equations (10), (11) and (12)
            if A_g[b,t*] + A_ng[b,t*] ≠ A_b[t*] then exception/warning
            # Replace HRU areas (state t) with updated areas (state t*)
        }
    }
}
#Write updated vegetation parameter file
```

A4.2 Equations

For a given VIC cell, the glacier area in band *b* at state *t** is calculated as

$$A_g[b,t^*] = \frac{\sum_{p=1}^{P[b]} m_p[t^*]}{\sum_{p=1}^{P} 1} \tag{6}$$

where m_p[t*] is the glacier mask for RGM pixel *p* at state t* (where $m_p[t^*] \rightarrow \{0, 1\}$), *P*[*b*] is the number of pixels in band *b*, and *P* is the total number of pixels in the VIC cell.

The non-glacier area in band *b* at state *t** is

$$A_{ng}[b, t^*] = A_b[t^*] - A_g[b, t^*] \tag{7}$$

The residual non-glacier area fraction (i.e., change in non-glacier area) for band *b* at state t* is

$$A_r[b, t^*] = A_{ng}[b, t^*] - A_{ng}[b, t] \tag{8}$$

where *t* is the state prior to the current iteration of glacier updating. If glacier area in band *b* changes, then the priority is to first adjust the area of any "open ground" HRUs that may be present in the same band. The updated area of the open ground HRU is calculated as

$$A_{open}[b, t^*] = max\{0, A_{open}[b, t] + A_r[b, t^*]\}. \tag{9}$$

Following changes in the area of any the open ground HRU (if present), the remaining HRUs (i.e., vegetated HRUs) each change area proportionately by an amount given by

$$\Delta A_v[b, t^*] = \Delta A_{veg}[b, t^*] \cdot \frac{A_v[b, t]}{A_{ng}[b, t] - A_{open}[b, t]} \tag{10}$$

where *v* is the index of the any remaining vegetated HRUs (*v* = 1, …, *V*), and the change in "vegetated area", $\Delta A_{veg}[b, t^*]$, is given by

$$\Delta A_{veg}[b, t^*] = min\{0, A_{open}[b, t] + A_r[b, t^*]\}. \tag{11}$$

Hence, the updated area for each remaining HRU *v* is

$$A_v[b, t^*] = A_v[b, t] + \Delta A_v[b, t^*]. \tag{12}$$

Note that if $\Delta A_{veg}[b, t^*]$ is equal to zero, either because $A_r[b, t^*]$ is positive (glacier shrinks) or $A_{open}[b, t] + A_r[b, t^*]$ is greater than zero (glacier expands, but only bare ground affected), then $\Delta A_v[b, t^*]$ is also zero and $A_v[b, t^*]$ will simply equal $A_v[b, t]$.

A5 Vegetation Parameter File – Model Initialization

A5.1 Pseudo-code

This section provides the specifications for modifying HRU areas to accommodate changes in initial surface topography and glacier mask prior to running the coupled VIC-RGM models. These specifications are necessary as the coupled VIC-RGM model may be required to start from a surface topography and glacier mask that differs from the contemporary surface topography and glacier mask used to provide the baseline VIC model parametrizations (i.e., snowband file and vegetation parameter file).

Conceptually, the initialization of VIC HRU areas to accommodate modifications in the study domain surface topography follows the general steps:

1. Calculate updated glacier area fraction for band *b* at state *t**
2. Calculate band residual area fraction for band *b* (change in non-glacier area)
3. Update area of “open ground” HRU, if present in band
4. Update area of remaining “vegetated” HRUs
5. Update HRU areas for band *b* at state *t**
6. Update vegetation parameter file

The initialization of the vegetation parameter file is demonstrated using the following pseudo-code:

```
for (c in cells) {  //Loop through cells
    for (b in bands) { //Loop through elevation bands (e.g. index 0 to index B-1)
        #Calculate A_g[b,t*] using Equation (6)
        #Calculate A_ng[t*], and A_r[b,t*] using Equations (7), and (8)
        if (!A_open[b,t]) then A_open[b,t]=0
        # Calculate A_open[b,t*] using equation (9)
        # Calculate area changes in remaining vegetated HRUs using equations (10), (11) and (12)
        if A_g[b,t*] + A_ng[b,t*] ≠ A_b[t*] then exception/warning
        # Replace HRU areas (state t) with updated areas (state t*)
        }
    }
}
#Write updated vegetation parameter file
```

Appendix B

Algorithm Specification – VIC State Updating

List of Symbols

Symbols	Description
	Variables
A	HRU or band area (as fraction of grid cell)
B	Number of elevation bands per cell
H	Number of HRUs per cell
Ω	State variable (generic)
	Index Variables
b	Band index
c	Cell ID
h	HRU index
t	Initial model state index (i.e., prior to updating)
*t**	Final model state index (i.e., after updating)
	Subscripts
g	Glacier HRU
op	Open ground HRU
v	Vegetated HRU (i.e., not glacier or open ground)

B1 Background

This specification details the method for updating the VIC state file following glacier updating. One of the main features in the coupling of the VIC model to the UBC Regional Glaciation model (RGM) is the feedback of glacier area and surface elevation from the RGM to VIC. Changes in glacier area (passed from RGM to VIC as an updated glacier mask) and surface elevation are incorporated into the VIC model via updating of the vegetation parameter file and the elevation band file. A side-effect of this updating step is the need to adjust certain state variables to ensure conservation of mass and energy within the individual VIC cells because of area and elevation updating. Conceptually, this entails the redistribution of water and energy within individual HRUs. For example, the goal of water re-distribution between hydrologic response units (HRUs) is to conserve the volume of water within a grid cell. In general, the following must hold for a given cell:

$$\sum_{h=1}^{H(t)} \Omega(h,t)\cdot A(t) = \sum_{h=1}^{H(t^*)} \Omega(h,t^*)\cdot A(h,t^*) \qquad (13)$$

where *H* is the number of HRUs in the given VIC cell, *Ω* is a state variable (e.g., water equivalent depth of snow), *A* is the area fraction of HRU number *h*, and *t* and *t** represent the model state before and after glacier updating, respectively.

The specifications described in the following sections for state updating is considered within the context of the pseudo-code shown in the text Box 1 below. The pseudo-code describes an algorithm for looping through cells and HRUs, and then checking for various situations (or cases) that describe the context under which an HRU can be updated. Five of these cases have been indicated (which should cover all possibilities).

The state variables being considered by this specification are summarized in Table B1 through Table B3. The state variables listed in Table B1 are considered mandatory for proper model check pointing. Table B2 list state variables that are considered miscellaneous at this time; they are not actually necessary for proper state updating (their inclusion in the state file is simply an artefact of earlier programming efforts) and they may be dropped from future implementations. Table B3 list state variables that are only required when certain code options are selected (i.e., *DIST_PRCP*, *EXCESS_ICE*, *LAKES*, *SPATIAL_FROST* and *SPATIAL_SNOW*). However, as these code options are currently untested and their use discouraged, these state variables are not explicitly updated.

The pseudo-code algorithm provides specifications for updating VIC cell and HRU metadata state variables and identifies five cases requiring unique specifications for updating HRU state variables:

1) Case 1: In this situation a new HRU appears, either in an existing elevation band (GLACEIR or OPEN) or in a new elevation band (GLACIER).
2) Case 2: This is the trivial case wherein the area of the HRU *h* does not change between states *t* and *t**, hence no state updating needs to occur.
3) Case 3: This is the case wherein the area of HRU *h* changes ($\Delta A(h,t^*)\neq 0$), but the HRU persists in both states *t* and *t**. In this situation state is updated within the HRU

4) Case 4: In this case an HRU disappears but the elevation band persists, either because a GLACIER HRU shrinks (and disappears) or expands (and neighbouring OPEN and/or VEG HRUs disappear). In this situation, state must be transferred from the disappearing HRU to one of the remaining HRUs in the same elevation band *b*.
5) Case 5: This situation is similar to Case 4, but in this particular case a GLACIER HRU disappears and the elevation band *b* along with it. In this situation, state must be transferred to one of the remaining HRUs in the elevation band below, *b*-1. The target HRU in band *b*-1 is prioritized, such that a GLACIER is chosen first, if no GLACIER HRU exists, then the OPEN-GROUND HRU is chosen, and if no OPEN-GROUND HRU exists, then the largest VEGETATED HRU is chosen. Note that it is impossible for a grid cell to have zero elevation bands as there must always be at least one band per cell for the cell to exist. Hence, a band can only disappear if there is an existing band below it (i.e., the lowest elevation band can never disappear).

Note that multiple cases can occur in the same VIC cell and or elevation band, and that an HRU may be subject to several updating operations as certain cases can occur simultaneously. As much as is practicable, the specifications that follow were written to be independent of the order-of-operations. However, the specific requirement to conserve the mass and energy of disappearing HRUs (by 'adding' to neighbouring HRUs) forces some dependency.

```
#Loop through VIC cells and HRUs
for c in NUM_CELLS:

    #Initialize new HRUs and missing values for existing HRUs (ensure initialization before other cases)
    for h in NUM_HRU[c,t*]:
        if (A[c,h,t*]>0 and (A[c,h,t] == 0 or A[c,h,t]  is undefined)):
            do CASE1 #set default values for all state variables
        do Set 'missing' values to defaults #For Mandatory variables only

    #Update State
    for h in NUM_HRU[c,t*]:
        BAND_DISAPPEARS = FALSE
        GLACIER_IN_LOWER_BAND = FALSE
        OPEN_ IN_LOWER_BAND = FALSE

        #Get band index and calculate area change for current HRU
        b = band_index[c,h]
        deltaA = A[c,h,t*] - A[c,h,t]

        if (Aband[c,b,t*]==0 and Aband[c,b,t]>0)
            BAND_DISAPPEARS = TRUE

        if veg_index[c,b,h]==glacier_veg_class:
            GLACIER=TRUE
        else:
            GLACIER=FALSE

        #The intent of the next statements is to determine if a GLACIER or OPEN HRUs exist in the next lower band
        if glacier_veg_class in vegetation_indexes[c,b-1,t*]: GLACIER_IN_LOWER_BAND = TRUE
        if open_ground_veg_class in vegetation_indexes[c,b-1,t*]: OPEN_IN_LOWER_BAND = TRUE

        if deltaA==0:
            do CASE2 #trivial case; no change in area, therefore no change in state values
        elif A[c,h,t*]>0: #Change in area implied (i.e. deltaA<>0) and HRU exists at current state
            if not NEW_HRU:
                do CASE3  #HRU h exists at current and previous state
            else:
                skip to next HRU #New HRU already initialized; skip to next HRU
        else: #Change in area implied (i.e. deltaA<>0), and also implied that HRU no longer exists at current
            if not BAND_DISAPPEARS: #CASE 4 - HRU h disappears but band b remains
                if GLACIER:
                    do CASE4a  #GLACIER disappears - implies OPEN expanding; add state to OPEN
                else:
                    do CASE4b  #non-GLACIER disappears - implies GLACIER expanding; add state to GLACIER
            else: #CASE 5 - Both HRU h and band b disappear - in this case h can only be a GLACIER
                if GLACIER_IN_LOWER_BAND:
                    do CASE5a #add state to GLACIER HRU in band b-1
                elif OPEN_IN_LOWER_BAND:
                    do CASE5b #add state to OPEN HRU in band b-1
                else:
                    do CASE5c #add state to largest VEGETATED HRU in band b-1

        do SANITY_CHECK
```

Box 1. Pseudo-code for VIC state updating

Table B1. Summary of state variables requiring mandatory updating, including default values

State Variable	Description	Default Value
	Cell Metadata	
lat	Grid cell centre latitude	*LAT*
lon	Grid cell centre longitude	*LON*
GLAC_MASS_BALANCE_INFO	Cell ID & mass balance polynomial terms and error	[0,0,0,0,0]
GRID_CELL	Grid cell ID number	*cellID*
NUM_BANDS	Number of bands (set in global file)	*B*
NUM_GLAC_MASS_BALANCE_INFO_TERMS	Number of glacier mass balance terms	5
SOIL_DZ_NODE	Soil thermal node deltas	*SOIL_DZ_ NODE*(*h*-1)
SOIL_ZSUM_NODE	Soil thermal node depths	*SOIL_ZSUM_ NODE*(*h*-1)
VEG_TYPE_NUM	Number of HRUs in grid cell	*H*(*c*,*t**)
	HRU Metadata	
HRU_BAND_INDEX	Band index	*b*
HRU_VEG_INDEX	HRU vegetation class	*vegIndex*(*h*)
	HRU Water Balance	
LAYER_ICE_CONTENT	Ice content in each soil layer [*SPATIAL_FROST* = FALSE]	0
LAYER_MOIST	Total soil moisture in each layer	0
HRU_VEG_VAR_DEW	Water stored on surface/vegetation	0
SNOW_CANOPY	Snow stored in the canopy	0
SNOW_DENSITY	Snow density	0
SNOW_DEPTH	Snow depth	0
SNOW_PACK_WATER	Water stored in snow pack layer	0
SNOW_SURF_WATER	Water stored in snow surface layer	0
SNOW_SWQ	Total snow water equivalent	0
	HRU Glacier Water Storage	
GLAC_WATER_STORAGE	Water stored in the glacier	0
	HRU Glacier Mass Balance	
GLAC_CUM_MASS_BALANCE	Glacier cumulative mass balance	0
	HRU Snow Pack, Glacier and Soil Energy	
ENERGY_T	Soil temperature at each soil node	0
ENERGY_TFOLIAGE	Vegetation temperature	0
GLAC_SURF_TEMP	Temperature of glacier surface Layer	0
SNOW_COLD_CONTENT	Cold content of snow surface layer	0
SNOW_PACK_TEMP	Temperature of snow pack layer	0
SNOW_SURF_TEMP	Temperature of snow surface layer	0
	HRU Snow Surface Properties	
SNOW_ALBEDO	Albedo of snow	0
SNOW_LAST_SNOW	Days since last snowfall	0
SNOW_MELTING	Snow melting flag [TRUE or FALSE]	"FALSE"
	HRU Program Terms	
ENERGY_TCANOPY_FBCOUNT	*TCANOPY* fallback count	0

State Variable	Description	Default Value
ENERGY_T_FBCOUNT	*T* fallback count	0
ENERGY_TFOLIAGE_FBCOUNT	*TFOLIAGE* fallback count	0
ENERGY_TSURF_FBCOUNT	*TSURF* fallback count	0
GLAC_SURF_TEMP_FBCOUNT	*GLAC_SURF_TEMP* fallback count	0
SNOW_SURF_TEMP_FBCOUNT	*SNOW_SURF_TEMP* fallback count	0

Table B2. Summary of miscellaneous state variables with default values

State Variable	Description	Default Value
GLAC_QNET	Glacier surface net energy balance	0
GLAC_SURF_TEMP_FBFLAG	*GLAC_SURF_TEMP* fallback flag	0
GLAC_VAPOR_FLUX	Glacier vapor flux	0
NONE	???	0
SNOW_CANOPY_ALBEDO	Albedo of snow stored in the canopy	0
SNOW_SURFACE_FLUX	Sublimation from blowing snow	0
SNOW_SURF_TEMP_FBFLAG	*SNOW_SURF_TEMP* fallback flag	0
SNOW_TMP_INT_STORAGE	Temporary canopy interception storage	0
SNOW_VAPOR_FLUX	Snow evaporation and sublimation	0

Table B3. Summary of deferred state variables (for untested code paths) with default values

State Variable	Description	Default Value
	Option.DIST_PRCP = TRUE	
PRCP_MU	Fraction of grid cell that receives precipitation	1
INIT_STILL_STORM	Storm continuity flag [*TRUE* or *FALSE*]	"FALSE"
INIT_DRY_TIME	Time since last storm	0
	EXCESS_ICE = TRUE	
SOIL_DEPTH	Soil moisture layer depths	0
SOIL_EFFECTIVE_POROSITY	Soil porosity when soil pores expanded due to excess ground ice for each soil layer	0
SOIL_DP	Soil damping depth	0
SOL_MIN_DEPTH	Soil layer depth as given in the soil file	0
SOIL_POROSITY_NODE	Soil porosity at each node	0
SOIL_EFFECTIVE_POROSITY_NODE	Soil porosity when soil pores expanded due to excess ground ice for each soil thermal node	0
SOIL_SUBSIDENCE	Subsidence of soil layer	0
	Option.LAKES = TRUE[b]	
LAKE_LAYER_MOIST	Total soil moisture in each layer	0
LAKE_LAYER_SOIL_ICE	Ice content in each soil layer [*SPATIAL_FROST* = TRUE]	0
LAKE_LAYER_ICE_CONTENT	Ice content in each soil layer [*SPATIAL_FROST* = FALSE]	0
LAKE_SNOW_LAST_SNOW	Days since last snowfall	0
LAKE_SNOW_MELTING	Snow melting flag [TRUE or FALSE]	"FALSE"
LAKE_SNOW_COVERAGE	Snow coverage fraction	0
LAKE_SNOW_SWQ	Total snow water equivalent	0
LAKE_SNOW_SURF_TEMP	Temperature of surface snow layer	0
LAKE_SNOW_SURF_WATER	Water stored in snow surface layer	0
LAKE_SNOW_PACK_TEMP	Temperature of pack snow layer	0
LAKE_SNOW_PACK_WATER	Water stored in snow pack layer	0
LAKE_SNOW_DENSITY	Snow density	0
LAKE_SNOW_COLD_CONTENT	Cold content of snow surface layer	0
LAKE_SNOW_CANOPY	Snow stored in the canopy	0
LAKE_ENERGY_T	Soil temperature at each soil node	0
LAKE_ACTIVENOD	Number of nodes whose corresponding layers contain water	0
LAKE_DZ	Thickness of all water layers below surface layer	0
LAKE_SURFDZ	Thickness of surface (top) water layer	0
LAKE_LDEPTH	Depth of liquid water in lake	0
LAKE_SURFACE	Horizontal x-section area at each lake node	0
LAKE_SAREA	Lake surface area of (ice + liquid)	0
LAKE_VOLUME	Lake water volume (including w.e. of lake ice)	0
LAKE_TEMP	Lake water temperature at each node	0

[b] Many of the *LAKE* state variables are redundant

LAKE_TEMPAVG	Average water temperature of entire lake	0
LAKE_AREAI	Area of ice coverage at beginning of time step	0
LAKE_NEW_ICE_AREA	Area of ice coverage at end of time step	0
LAKE_ICE_WATER_EQ	Water equivalent of lake ice	0
LAKE_HICE	Height of lake ice at thickest point	0
LAKE_TEMPI	Lake ice temperature	0
LAKE_SWE	Water equivalence of lake snow cover	0
LAKE_SURF_TEMP	Temperature of surface snow layer	0
LAKE_PACK_TEMP	Temperature of pack snow layer	0
LAKE_SALBEDO	Albedo of lake snow	0
LAKE_SDEPTH	Depth of snow on top of ice	0
	SPATIAL_FROST = TRUE	
LAYER_SOIL_ICE	Ice content of the frozen soil sublayer	0
	SPATIAL_SNOW = TRUE	
SOIL_DEPTH_FULL_SNOW_COVER	Minimum depth for full snow cover	0
SNOW_COVERAGE	Snow coverage fraction	0

B2 General Specifications

This specification will often distinguish between *GLACIER*, *OPEN* (i.e., bare soil) and *VEGETATED* Hydrologic Response Units (HRUs). *GLACIER* and *OPEN* HRUs are explicitly identified by land cover classification; this is done by the user in the global parameter file. By inference, *VEGETATED* HRUs are all land cover classes other than *GLACIER* or *OPEN* classes. Note that the *OPEN* class is explicitly designated by the user using by selecting an entry from the vegetation library file, and it is not to be confused with the VIC model's default bare soil landcover classification.

B2.1 Cell and HRU Metadata

Generally, cell and HRU metadata values will remain unchanged between state *t* and *t**, except for new HRUs. Hence the spec for generic cell metadata state variable Ω for HRU *h* is

CASE 1	$\Omega(h,t^*) = default\ values$
CASE 2	$\Omega(h,t^*) = \Omega(h,t)$
CASE 3	$\Omega(h,t^*) = \Omega(h,t)$
CASE 4	$\Omega(h,t^*) = 0$
CASE 5	$\Omega(h,t^*) = 0$

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B2.2 Conservation of Mass and Energy

B2.2.1 Water Balance, Glacier Water Storage and Glacier Mass Balance

Water Balance, *Glacier Water Storage*, *Glacier Mass Balance*, and *Snowpack, Glacier and Soil Energy* state variables are updated under the principle of conservation of mass and energy. For an HRU *h* equation (2) is re-written and simplified, depending upon the specific case as follows:

CASE 1	$\Omega(h,t^*) = default\ value$
CASE 2	$\Omega(h,t^*) = \Omega(h,t)$
CASE 3	$\Omega(h,t^*) = \Omega(h,t) \cdot \frac{A(h,t)}{A(h,t^*)}$
CASE 4	$\Omega(h,t^*) = 0$ $\begin{cases} \Omega_{op}(b,t^*) = \Omega_{op}(b,t) + \Omega(h,t)\frac{A(h,t)}{A_{op}(b,t^*)}, & if\ veg\_index(h) = GLACIER \\ \Omega_g(b,t^*) = \Omega_g(b,t) + \Omega(h,t)\frac{A(h,t)}{A_g(b,t^*)}, & if\ veg\_index(h) \neq GLACIER \end{cases}$
CASE 5	$\Omega(h,t^*) = 0$ $\begin{cases} \Omega_g(b-1,t^*) = \Omega_g(b-1,t) + \Omega(h,t)\frac{A(h,t)}{A_g(b-1,t^*)}, & if\ A_g(b-1,t^*) > 0, else \\ \Omega_{op}(b-1,t^*) = \Omega_{op}(b-1,t) + \Omega(h,t)\frac{A(h,t)}{A_{op}(b-1,t^*)}, & if\ A_{op}(b-1,t^*) > 0, else \\ \Omega_v(b-1,t^*) = \Omega_v(b-1,t) + \Omega(h,t)\frac{A(h,t)}{A_v(b-1,t^*)} \end{cases}$

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It is noted that the current specification for CASE 1 is not very realistic, i.e., although the process of adding a new HRU with state variables defaulting to zero conserves mass it does not necessarily conserve energy; nevertheless, it greatly simplifies the process of state updating. Some order-of-operations dependency has been unavoidable in the current specification. For example, it is conceivable that a new GLACIER HRU could be operated on twice during state updating: once under CASE 1 (initialization when *h* indexes a new GLACIER in band *b*) and again under CASE 4 (e.g. *h* indexes an OPEN HRU in band *b* that disappears as a result of the appearing GLACIER HRU). In this situation CASE 1 must occur before CASE 4, otherwise updates to the GLACIER state under CASE 4 would be overwritten by CASE 1 initialization (hence, the pseudo-code is written to ensure that CASE 1 updating occurs before all other updating).

B2.2.2 SNOW_DENSITY

SNOW_DENSITY, which is a function of *SNOW_SWQ* and *SNOW_DEPTH*, is updated using

ALL CASES	$SNOW\_DENSITY(h,t^*) = [SNOW\_SWQ(h,t^*)\cdot 1000]/SNOW\_DEPTH(h,t^*)$	SPEC- 3

where *SNOW_SWQ* and *SNOW_DEPTH* are updated according to SPEC- 2.

B2.2.3 GLACIER_WATER_STORAGE

The specification for *GLACIER_WATER_STORAGE*, as it only applies to GLACEIR HRUs, differs slightly from SPEC- 2 (i.e., see CASE 4) as follows

CASE 1	$\Omega(h,t^*) = default\ values$
CASE 2	$\Omega(h,t^*) = \Omega(h,t)$
CASE 3	$\Omega(h,t^*) = \Omega(h,t)\cdot\frac{A(h,t)}{A(h,t^*)}$
CASE 4	$\Omega(h,t^*) = 0$ $\begin{cases}\Omega_{op}(b,t^*) = \Omega_{op}(b,t)+\Omega(h,t)\frac{A(h,t)}{A_{op}(b,t^*)}, & if\ veg\_index(h) = GLACIER\\ \Omega_g(b,t^*) = \Omega_g(b,t), & if\ veg\_index(h) \neq GLACIER\end{cases}$
CASE 5	$\Omega(h,t^*) = 0$ $\begin{cases}\Omega_g(b-1,t^*) = \Omega_g(b-1,t)+\Omega(h,t)\frac{A(h,t)}{A_g(b-1,t^*)}, & if\ A_g(b-1,t^*) > 0, else\\ \Omega_{op}(b-1,t^*) = \Omega_{op}(b-1,t)+\Omega(h,t)\frac{A(h,t)}{A_{op}(b-1,t^*)}, & if\ A_{op}(b-1,t^*) > 0, else\\ \Omega_v(b-1,t^*) = \Omega_v(b-1,t)+\Omega(h,t)\frac{A(h,t)}{A_v(b-1,t^*)}\end{cases}$

SPEC- 4

B2.2.4 GLACIER_CUM_MASS_BALANCE

The state variable *GLACIER_CUM_MASS_BALANCE*, which applies only to GLACIER HRUs, does not need to be conserved (in a mass sense) and has the following unique specification

CASE 1	$\Omega(h,t^*) = default\ values$
CASE 2	$\Omega(h,t^*) = \Omega(h,t)$
CASE 3	$\Omega(h,t^*) = \Omega(h,t)$
CASE 4	$\Omega(h,t^*) = 0$
CASE 5	$\Omega(h,t^*) = 0$

SPEC- 5

B2.2.5 Snowpack, Glacier and Soil Energy

For state variables grouped under the *Snowpack, Glacier and Soil Energy* category, variable updating is applied under the principle of conservation of mass and energy. However, the variables *COLD_CONTENT*, *ENERGY_T, ENERGY_TFOLIAGE* and *GLAC_SURF_TEMP* are treated differently, as described in the following paragraphs. Given the updated *SNOW_SURF_TEMP* and *SNOW_SURF_SWQ* for HRU *h*, *COLD_CONTENT* is updated as

ALL CASES	$COLD\_CONTENT(h,t^*) = SNOW\_SURF\_TEMP(h,t^*) \cdot SNOW\_SURF\_SWQ(h,t^*) \cdot CH\_ICE$ where *CH_ICE* is the volumetric heat capacity of ice[c] and *SNOW_SURF_SWQ*(*h*,*t**) = min[*MAX_SURFACE_SWE*, *SNOW_SWQ*(*h*,*t**)] where *MAX_SURFACE_SWE* is the maximum snow water equivalent of the surface layer[d].	SPEC- 6

For the state variables *GLAC_SURF_TEMP, ENERGY_T* and *ENERGY_TFOLIAGE*, we don't strictly adhere to the conservation of energy principle and simply maintain constant values between state *t* and *t** (continuity principle, see Section **Error! Reference source not found.**).

B2.3 Weighted Assignment

B2.3.1 Snow Surface Properties

For variables in the *Snow Surface Properties* category, state variables are updated for CASES 4 and CASE 5 using an area weighting of values at state *t*, given by

CASE 1	$\Omega(h,t^*) = default\ values$
CASE 2	$\Omega(h,t^*) = \Omega(h,t)$
CASE 3	$\Omega(h,t^*) = \Omega(h,t)$
CASE 4	$\Omega(h,t^*) = 0$

[c] This value for *CH_ICE* is set in the header file vicNl_def.h; currently set to 2100E+03.
[d] This value is set in the header file snow.h; currently set at 0.125 m

	$\begin{cases} \Omega_{op}(b,t^*) = \dfrac{\Omega_{op}(b,t)\cdot A_{op}(b,t)\cdot f_{op}(b,t,\mathrm{I}_{SWQ}) + \Omega(h,t)\cdot A(h,t)\cdot f(h,t,\mathrm{I}_{SWQ})}{A_{op}(b,t)\cdot f_{op}(b,t,\mathrm{I}_{SWQ}) + A(h,t)\cdot f(h,t,\mathrm{I}_{SWQ})}, & if\ veg\_index(h) = GLACIER \\ \Omega_{g}(b,t^*) = \dfrac{\Omega_{g}(b,t)\cdot A_{g}(b,t)\cdot f_{g}(b,t,\mathrm{I}_{SWQ}) + \Omega(h,t)\cdot A(h,t)\cdot f(h,t,\mathrm{I}_{SWQ})}{A_{g}(b,t)\cdot f_{g}(b,t,\mathrm{I}_{SWQ}) + A(h,t)\cdot f(h,t,\mathrm{I}_{SWQ})}, & if\ veg\_index(h) \neq GLACIER \end{cases}$
CASE 5	$\Omega(h,t^*) = 0$ $\begin{cases} \Omega_{g}(b-1,t^*) = \dfrac{\Omega_{g}(b-1,t)\cdot A_{g}(b-1,t)\cdot f_{g}(b-1,t,\mathrm{I}_{SWQ}) + \Omega(h,t)\cdot A(h,t)\cdot f(h,t,\mathrm{I}_{SWQ})}{A_{g}(b-1,t)\cdot f_{g}(b-1,t,\mathrm{I}_{SWQ}) + A(h,t)\cdot f(h,t,\mathrm{I}_{SWQ})}, & if\ A_g(b-1,t^*) > 0 \\ \Omega_{op}(b-1,t^*) = \dfrac{\Omega_{op}(b-1,t)\cdot A_{op}(b,t)\cdot f_{op}(b-1,t,\mathrm{I}_{SWQ}) + \Omega(h,t)\cdot A(h,t)\cdot f(h,t,\mathrm{I}_{SWQ})}{A_{op}(b-1,t)\cdot f_{op}(b-1,t,\mathrm{I}_{SWQ}) + A(h,t)\cdot f(h,t,\mathrm{I}_{SWQ})}, & if\ A_{op}(b-1,t^*) > 0 \\ \Omega_{v}(b-1,t^*) = \dfrac{\Omega_{v}(b-1,t)\cdot A_{v}(b-1,t)\cdot f_{v}(b-1,t,\mathrm{I}_{SWQ}) + \Omega(h,t)\cdot A(h,t)\cdot f(h,t,\mathrm{I}_{SWQ})}{A_{v}(b-1,t)\cdot f_{v}(b-1,t,\mathrm{I}_{SWQ}) + A(h,t)\cdot f(h,t,\mathrm{I}_{SWQ})} & \end{cases}$

where

$$f(h,t,I_{SWQ}) = \mathrm{I}[SNOW\_SWQ(h,t)]$$

and $\mathrm{I}(\cdot)$ is the indicator function, such that

$$\mathrm{I}(X) \coloneqq \begin{cases} 1 & if\ X > 0 \\ 0 & if\ X \leq 0 \end{cases},$$

and for *SNOW_MELTING*(*h*,·) (which must be converted from character to integer)

$$\Omega(h,\cdot) = \begin{cases} 1 & if\ SNOW\_MELTING(h,\cdot) = "TRUE" \\ 0 & if\ SNOW\_MELTING(h,\cdot) = "FALSE" \end{cases}$$

SPEC- 7

For the state variables *SNOW_LAST_SNOW* and *SNOW_MELTING* (which are integer), SPEC- 7 is further modified as

$$z(t^*) = ceil[\Omega(h,t^*)]$$

and

$$SNOW\_LAST\_SNOW(h,t^*) = z(h,t^*)$$

$$SNOW\_MELTING(h,t^*) = \begin{cases} "TRUE" & if\ z(h,t^*) = 1 \\ "FALSE" & if\ z(h,t^*) = 0 \end{cases}$$

SPEC- 8

B2.4 Continuity

B2.4.1. Program Terms, Miscellaneous and Deferred Variables

For HRU variables in the *Program Terms* category (and certain variables from other categories), *Miscellaneous* variables (Table B2) and *Deferred* variables (Table B3), state variables are typically updated under the continuity principle. Unless the HRU *h* is new, values remain constant between state *t* and *t**. For example, for generic state variable *Ω*

CASE 1	$\Omega(h,t^*) = default\ values$
CASE 2	$\Omega(h,t^*) = \Omega(h,t)$
CASE 3	$\Omega(h,t^*) = \Omega(h,t)$
CASE 4	$\Omega(h,t^*) = 0$
CASE 5	$\Omega(h,t^*) = 0$

SPEC- 9

B2.5 Sanity Check

When water storage state variables are transferred between HRUs (i.e., CASE 4 and CASE 5), we may end up with several non-physically plausible situations. Hence, checks and adjustments need to occur once state updating is completed.

For GLACIER HRUs, perform the following checks and adjustments:

If *SNOW_CANOPY*(*h*,*t**) > 0 then *SNOW_SWQ*(*h*,*t**) += *SNOW_CANOPY*(*h*,*t**) and *SNOW_CANOPY*(*h*,*t**) = 0

SPEC- 10

For OPEN HRUs, perform the following checks and adjustments:

If *SNOW_CANOPY*(*h*,*t**) > 0 then *SNOW_SWQ*(*h*,*t**) += *SNOW_CANOPY*(*h*,*t**) and *SNOW_CANOPY*(*h*,*t**) = 0
If *GLAC_WATER_STORAGE*(*h*,*t**) > 0 then *LAYER_MOIST*[Nlayers-1] += *GLAC_WATER_STORAGE*(*h*,*t**) and *GLAC_WATER_STORAGE*(*h*,*t**) = 0

SPEC- 10

For VEGETAED HRUs, perform the following checks and adjustments:

If *GLAC_WATER_STORAGE*(*h*,*t**) > 0 then *LAYER_MOIST*[Nlayers-1] += *GLAC_WATER_STORAGE*(*h*,*t**) and *GLAC_WATER_STORAGE*(*h*,*t**) = 0

SPEC- 10

B3 HRU Specification Summary

The following tables summarize the applicable update specification by state variable. *Mandatory* state variables are summarized in Table B4 and *Miscellaneous* and *Deferred* state variables are summarized in Table B5.

Table B4. Mandatory state variable specification summary

State Variable	Specifications
HRUCELL METADATA	
lat	SPEC- 1
lon	SPEC- 1
GLAC_MASS_BALANCE_INFO	SPEC- 1
GRID_CELL	SPEC- 1
NUM_BANDS	SPEC- 1
NUM_GLAC_MASS_BALANCE_INFO_ TERMS	SPEC- 1
SOIL_DZ_NODE [Nnodes]:	----
SOIL_DZ_NODE [0]	SPEC- 1
SOIL_DZ_NODE [1]	SPEC- 1
⋮	⋮
SOIL_DZ_NODE [Nnodes-1]	SPEC- 1
SOIL_ZSUM_NODE [Nnodes]:	----
SOIL_ZSUM_NODE [0]	SPEC- 1
SOIL_ZSUM_NODE [1]	SPEC- 1
⋮	⋮
SOIL_ZSUM_NODE [Nnodes-1]	SPEC- 1
VEG_TYPE_NUM	SPEC- 1
HRU METADATA	
HRU_BAND_INDEX	SPEC- 1
HRU_VEG_INDEX	SPEC- 1
HRU State Variables	
LAYER_ICE_CONTENT [Nlayers]:	----
LAYER_ICE_CONTENT [0]	SPEC- 2
LAYER_ICE_CONTENT [1]	SPEC- 2
⋮	⋮
LAYER_ICE_CONTENT [Nlayers-1]	SPEC- 2
LAYER_MOIST [Nlayers]	----
LAYER_MOIST [0]	SPEC- 2
LAYER_MOIST [1]	SPEC- 2

State Variable	Specifications
⋮	⋮
LAYER_MOIST [Nlayers-1]	SPEC- 2 & SPEC- 10
HRU_VEG_VAR_WDEW [dist]:	----
HRU_VEG_VAR_WDEW [0]	SPEC- 2
HRU_VEG_VAR_WDEW [1]	SPEC- 2
SNOW_CANOPY	SPEC- 2 & SPEC- 10
SNOW_DEPTH	SPEC- 2
SNOW_DENSITY	SPEC- 3
SNOW_PACK_WATER	SPEC- 2
SNOW_SURF_WATER	SPEC- 2
SNOW_SWQ	SPEC- 2 & SPEC- 10
GLAC_WATER_STORAGE	SPEC- 4 & SPEC- 10
GLAC_CUM_MASS_BALANCE	SPEC- 5
ENERGY_T [Nnodes]:	----
ENERGY_T [0]	SPEC- 9
ENERGY_T [1]	SPEC- 9
⋮	⋮
ENERGY_T [Nnodes-1]	SPEC- 9
ENERGY_TFOLIAGE	SPEC- 9
GLAC_SURF_TEMP	SPEC- 9
SNOW_COLD_CONTENT	SPEC- 6
SNOW_PACK_TEMP	SPEC- 2
SNOW_SURF_TEMP	SPEC- 2
SNOW_ALBEDO	SPEC- 7
SNOW_LAST_SNOW	SPEC- 8
SNOW_MELTING	SPEC- 8
ENERGY_TCANOPY_FBCOUNT	SPEC- 9
ENERGY_T_FBCOUNT [Nnodes]:	----
ENERGY_T_FBCOUNT [0]	SPEC- 9
ENERGY_T_FBCOUNT [1]	SPEC- 9
⋮	⋮
ENERGY_T_FBCOUNT [Nnodes-1]	SPEC- 9
ENERGY_TFOLIAGE_FBCOUNT	SPEC- 9
ENERGY_TSURF_FBCOUNT	SPEC- 9
GLAC_SURF_TEMP_FBCOUNT	SPEC- 9
SNOW_SURF_TEMP_FBCOUNT	SPEC- 9

Table B5. Miscellaneous and deferred state variable specification summary

State Variable	Specifications
Miscellaneous State Variables	
ALL (see Table B2)	SPEC- 9
Deferred State Variables	
ALL (see Table B3)	SPEC- 9

Appendix C

RGM Global Parameter File

The RGM global parameter file is a space-delimited ASCII text file containing parameter values controlling the simulation of ice dynamics. The file is structured by assigning one value per line, where each value can be followed by a comment/description. The order of the parameter values must be as per the example provided, which is provided below using default values:

```
1.0e-15   7.5738e-17   Glen law coefficient, A (Pa^{-n} yr^{-1})
0          Sliding coefficient, C (Pa^{-m} m yr^{-1})
10         Number of sub-year steps (10 gives dt=0.1 yr)
1.5000     Hindmarsh super-implicit parameter
0.125      Diffusion stability parameter for explicit solver
2          Verbosity levels: 0, 1, 2, 3 ....
0          Start year of the transient simulation
0          Set benchmark to 1 if you want to run the Bueler C test
.TRUE.     Transient status -- set false if a steady state run
.FALSE.    Accum status -- set true if using the accumulation function to calculate the mass balance
```

Appendix D

Pixel Map File

The pixel map is supplied as a space-delimited ASCII text file. The first two lines of the file contain header information to specify the number of columns (NCOLS) and number of rows (NROWS) in the corresponding RGM grid. The third line of the file gives the column headers and the remainder of the file is composed of six columns containing one row for each RGM pixel. The data for each row is as follows:

- PIXEL_ID: unique number for each RGM pixel
- ROW: row number of current pixel, where rows are numbered from 0 to NROWS-1 (counted from the northern edge of the RGM grid)
- COL: column number of current pixel, where columns are numbered from 0 to NCOLS-1 (counted from the eastern edge of the RGM grid)
- BAND: index of the band that the pixel is located within in the corresponding VIC-GL cell
- ELEV: surface elevation of pixel
- CELL_ID: Numeric identifier for the corresponding VIC-GL taken from the soil parameter file. Note that if the pixel does not overlap with a VIC-GL cell, a value of NA is assigned

An excerpt from a pixel mapping file is given below:

```
NCOLS  245
NROWS  383
"PIXEL_ID" "ROW" "COL" "BAND" "ELEV" "CELL_ID"
93591 0 0 0 26 NA
93592 0 1 0 30 NA
93593 0 2 0 33 NA
…
77972 64 61 1 264 395689
77973 64 62 1 300 395689
77974 64 63 1 335 395689
…
241 382 240 6 1367 NA
242 382 241 6 1334 NA
243 382 242 6 1292 NA
```

Appendix E

Surface Elevation Initialization

Prior to starting a model simulation, the model must be initialized be specifying values for all state variables (such as snow depth, soil moisture, etc.). Model spin-up is then the time taken for the hydrology model to reach a state of statistical equilibrium under the applied forcing. When running a model, one can employ either a ‘cold start’ or a ‘warm start’. A cold start usually is when a model is spun up from a generic, or default, starting state; a warm start is a restart of a prior model run, which is used to reduce spin-up time. Prior to the introduction of the glacier dynamics component of the model, VIC was initialized with default values for all fields and run from a cold start with a five-year spin-up period. This was acceptable as many of the state variables are highly seasonal and reach statistical equilibrium after only one year. Other more persistent processes, such as soil moisture, can take several years.

With the inclusion of glacier dynamics into the upgraded VIC-GL model, initialization and spin-up become more involved due to the decadal response time of glaciers to climatic variability. For example, if projections are to begin in 1945, a fully initialized glacier state is required for this year. In the RGM model, glacier state is defined by a surface topography and an estimated sub-glacial (or bed) topography (Clarke et al. 2013) on the RGM computational grid, the difference of which provides an estimate of glacier thickness (e.g. see Figure E1). As no observations of glacial thickness exist for 1945 and bed topography is static, an initial glacier state is estimated by deriving a plausible representation of surface topography.

An initial approach was to warm-start the hydrologic projections using glacier depth estimated from a previous glacier modelling study conducted for British Columbia (Clarke et al. 2015). As part of this work, these researchers generated glacier surfaces for an observation-driven historical run over the period 1902 to 1999. The intent was simply to use output for 1945 from this historical run as the glacier start state. However, due to differences in the digital elevation models used between the two studies, numerical instabilities were introduced to the dynamics modelling, creating spurious and unusable results in many regions of the study domain.

To correct this issue, a more internally consistent, but more computationally involved, initialization approach was developed. The process used is a combined initialization and spin-up process, which is designed to give a plausible description of the spatial distribution of glacier depth for the year 1945. The process has three main steps:

- Derive climatological surface mass balance for 1901-1930
- Derive and initial glacier state (glacier depth) from 500-year steady state run
- Derive final glacier state from 45-year spin-up

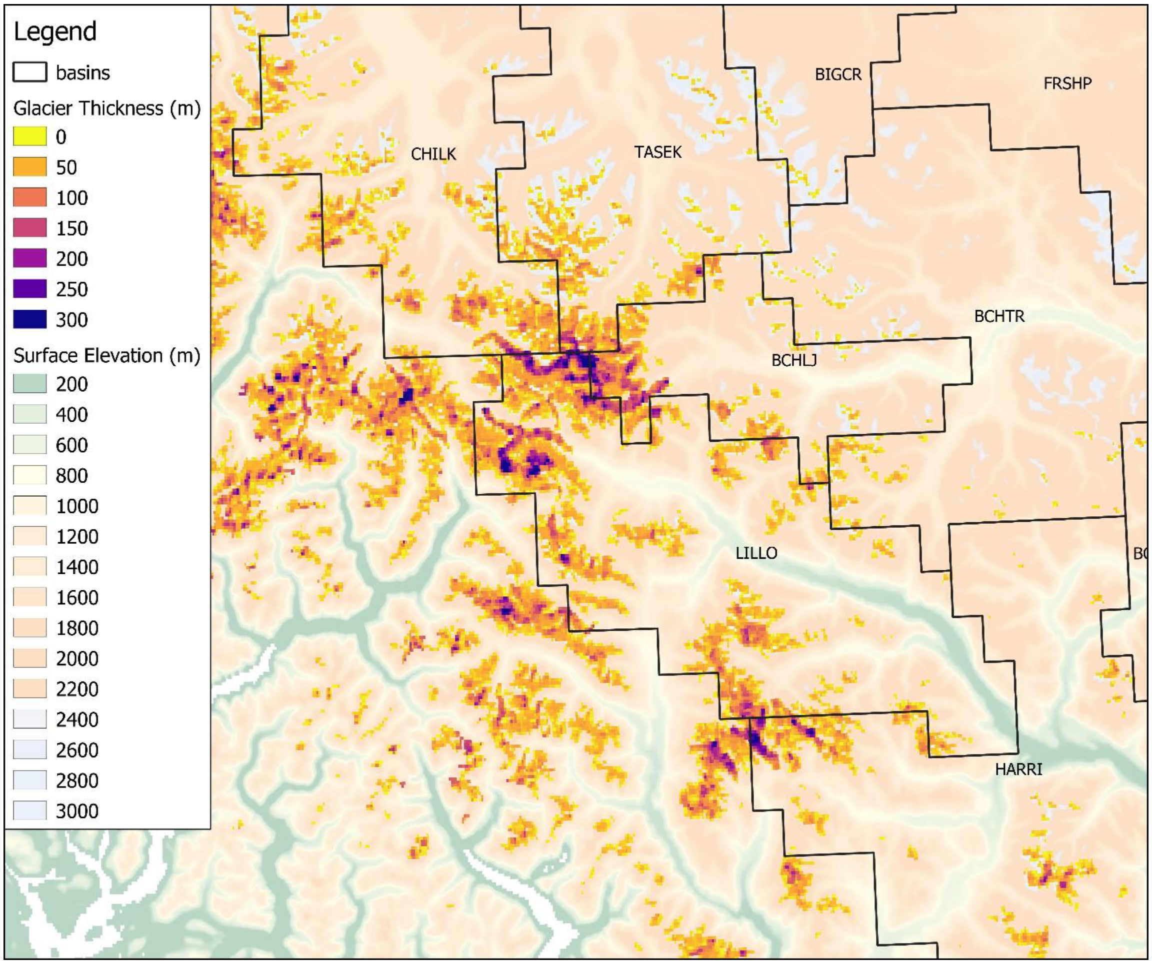

Figure E1. Glacier thickness circa 2005 for south coast region of Fraser study domain. Glacier thickness is estimated as surface topography minus bed topography (see text for details).

Step one involves running the fully-coupled VIC GL model for the period 1901 to 1930, which is used to derive and average 30-year glacier surface mass balance. The surface mass balance is defined as the annual difference between snow accumulation and snow and glacier melt. An example of such a surface mass balance field is given in Figure E2. This turn-of-the-century climatological mass balance is subsequently used in step two to run the glacier dynamics model offline (i.e. uncoupled) in steady state (constant mass balance forcing) for a 500-year period. This step starts with a bare surface topography (i.e. no glaciers) and uses the 500-year period to estimate an initial glacier surface on the landscape to a depth and at locations consistent with the supplied mass balance field. As a steady 30-year average mass balance does not realistically portray actual historical climate variability, a third step incorporates a final spin-up period. This spin-up period uses the fully coupled model to run transient simulations (i.e. climate and mass balance change through time) from 1901 to 1945 and commences with the initialized glacier surface produced during step two. The purpose of this spin-up is to 'fine-tune' the glacier surface so that the glacier state more accurately reflects climate variability experienced in the final decades prior to 1945. All coupled VICGL simulations (steps one and three) are forced using the NOAA-CIRES 20th century reanalysis version 2c (Compo et al. 2011).

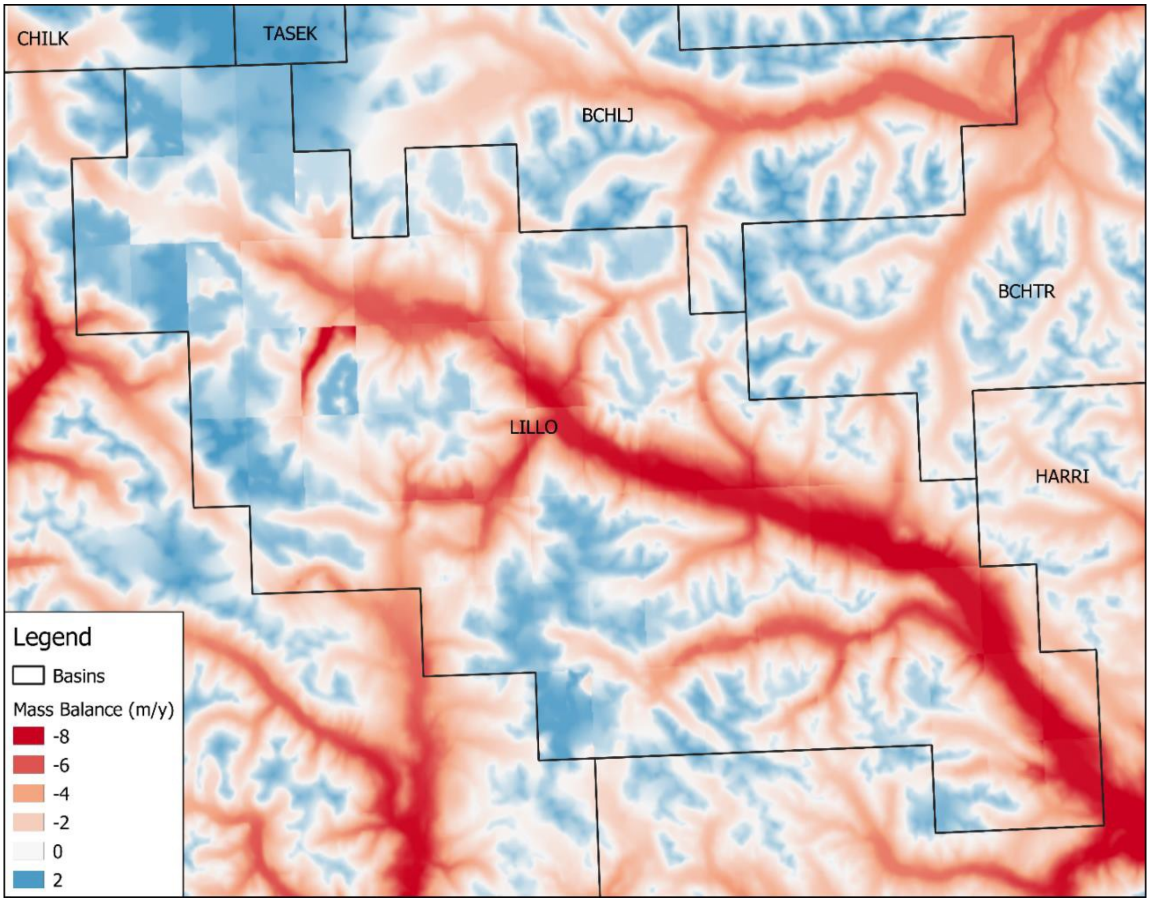

Figure E2. Surface glacier mass balance climatology (1901-1930) for the Lillooet sub-basin and surrounding region.

Figure E3 depicts the evolution of glacier area during the initialization and spin-up process (steps two and three) for the Lillooet sub-basin. Under steady-state surface mass balance forcing, glacier area asymptotically approaches 3700 km^2 after 500 years. The spin-up period experiences a rapid increase in glacier area for 25 years (1901 to 1925), followed by a decreasing trend in the final decades leading up to 1945. The estimated glacier area at 1945 is ~3100 km^2. In addition, Figure E3 shows the continuing decline in glacier area from 1945 to 2012 as simulated using the observation-driven historical run.

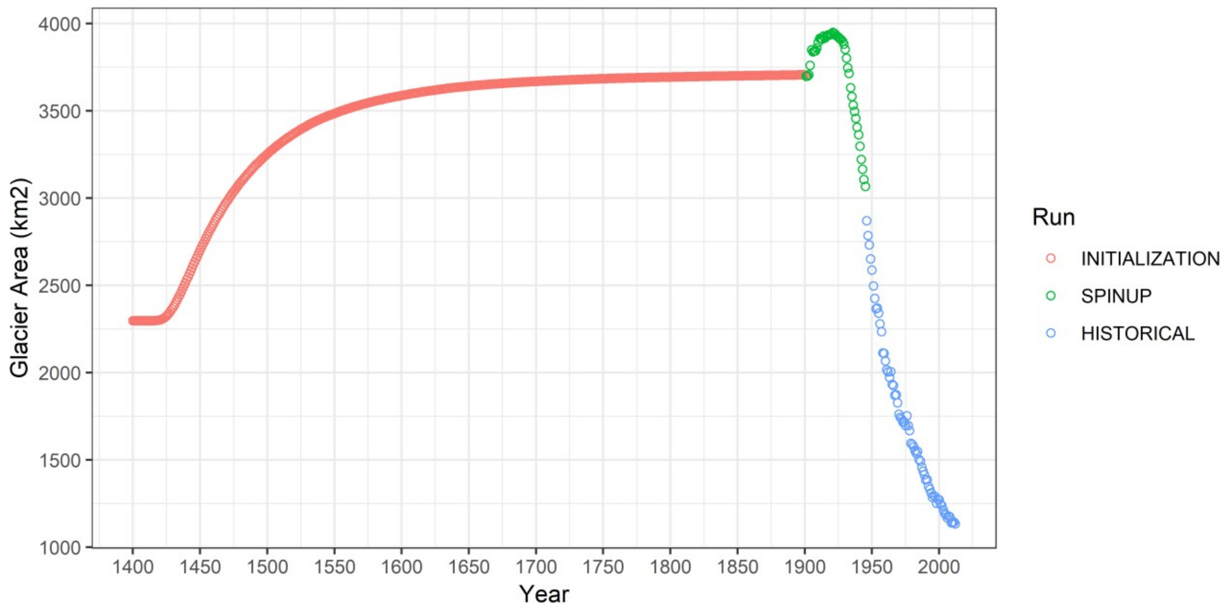

Figure E3. Simulated glacier area for the Lillooet sub-basin during glacier initialization, spin-up and historical simulation, represented as a single time series.