Modelling Glacier Runoff from the Canadian Rockies

Shawn Marshall, University of Calgary
Modelling Glacier Response to Climate Change in the Canadian Rockies

Basis: mixture of field and modelling studies at Haig Glacier, a headwaters catchment for the Kananaskis River.

Haig is the main outlet of a small icefield that flows eastward from the continental divide.

Observations: meteorological, hydrological, and glaciological (i.e. mass balance)
Update, 2015 Field Studies

Eight trips to Haig Glacier from May-October 2015

An interesting summer:

- below normal snowpack, but not unusual: $b_w = 1220$ mm, vs. longterm (2002-2015) average of $1360 \pm 230$ mm
Haig Glacier spring snow surveys, 2009-2015

Elevation (m)

swe (mm)
Update, 2015 Field Studies

Eight trips to Haig Glacier from May-October 2015

An interesting summer:

- below normal snowpack, but not unusual: $b_w = 1220$ mm, vs. longterm (2002-2015) average of $1360 \pm 230$ mm

- the summer was also not extreme – 2003 was warmer – but it was the warmest June on record, leading to early loss of the snowpack and $b_n \approx -2400$ mm.
Haig Glacier Temperature and Snow Surface, Summer 2015

AWS site: upper glacier, 2695 m
Modelled Mass Balance, Haig Glacier, 2002-2014

Mean, Haig, 2002-2014: −970 mm
Cumulative thinning = 12 m
Reconstructing historical discharge

Interested in the interannual variability of monthly mean glacier runoff.

Requires modelling, as there are no historical observations of monthly discharge. Snowfall, melt and discharge need to be estimated from climate model or station data. Our approach:

- local EC station records, 1961-2014
- NARR climatology, 1979-2014
Meteorological downscaling for glacier modelling
NARR grid cell over Haig Icefield

~32 km

Latitude °N

Longitude °W

z (m)
Subgrid topography, NARR grid cell over Haig Glacier

$z_{NARR} = 2216 \text{ m}$

$\text{mean} = 2034 \text{ m}$
The challenge: How to distribute meteorological fields across the terrain, based on grid-cell values from an atmospheric model.

Grid cells are generally lower than the altitude of the glaciers.
The challenge:

How to distribute grid cell meteorological fields across elevation/aspect bands in a way that conserves energy and mass?

Current approach: apply vertical ‘corrections’ to distribute the surface meteorological fields.

This can be through prescribed ‘lapse rates’ and/or RCM near-surface vertical gradients
Energy and mass conservation

In general, conservation is not honoured in statistical downscaling of meteorological fields.

e.g., bias corrections for precipitation or radiation fluxes; even lapse rates for temperature:

$$\frac{\partial T}{\partial z} = \beta_T$$

Temperatures can be redistributed this way within a grid cell, e.g.

$$T(x, y, z) = \bar{T} + \beta_T(z - \bar{z})$$

Values are conserved for linear extrapolation from the mean grid cell value, i.e.

$$\frac{1}{N} \sum_{N} T(x, y, z) = \bar{T}$$
Energy and mass conservation

But, of course, internal energy

\[ u = \rho c T \]

is what we are interested in conserving, not temperature, and air density does not vary linearly with elevation (also true for pressure, humidity variables, wind, etc.)

It is possible to rescale temperatures with a lot of book-keeping, under the constraint that:

\[ \bar{u} = \bar{\rho} c \bar{T} \equiv \int_N \rho c T \]

Alternatively, keep it linear, i.e.

\[ \frac{\partial P}{\partial z} = -\bar{\rho} g \quad \rightarrow \quad \rho(z) = P(z)/RT(z) \]
Applying this approach to the NARR grid cell for energy balance modelling on Haig Glacier, vertical gradients have the form:

\[
\frac{\partial T}{\partial z} = \beta_T
\]

\[
\frac{\partial e_v}{\partial z} = -\overline{\rho_v} g
\]

\[
\frac{\partial P}{\partial z} = -\overline{\rho} g
\]

\[
\frac{\partial q_v}{\partial z} = \frac{\varepsilon_v g}{\overline{P}} \left( \frac{\overline{e_v \rho}}{\overline{P}} - \overline{\rho_v} \right)
\]

RCM boundary-layer gradients can be taken for the variation of LW, SW, and wind with altitude.
Sample result

<table>
<thead>
<tr>
<th></th>
<th>$T$ (°C)</th>
<th>$q$ (g/kg)</th>
<th>$e_v$ (mb)</th>
<th>RH (%)</th>
<th>$P$ (mb)</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$u$ (kJ/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NARR</td>
<td>-0.9</td>
<td>3.59</td>
<td>4.53</td>
<td>79.2</td>
<td>784</td>
<td>0.996</td>
<td>274</td>
</tr>
<tr>
<td>mean</td>
<td>0.2</td>
<td>3.56</td>
<td>4.59</td>
<td>74.2</td>
<td>802</td>
<td>1.014</td>
<td>280</td>
</tr>
</tbody>
</table>

We have made it a little warmer and drier, with a bit of energy added to the system.

The biases here are due to the 180 m bias in the elevation of the NARR grid cell vs. the underlying 100-m DEM. This could be handled by bias-adjusting the RCM grid cell elevations.
Observed vs. NARR Climatology, Haig Glacier

2002-2013

- Temperature ($^\circ$C)
- Shortwave radiation ($Q_S$ (W/m$^2$))
- Longwave radiation ($Q_L$ (W/m$^2$))
- Specific humidity ($q$ (g/kg))
- Relative humidity (RH (%))
- Wind speed ($v$ (m/s))
NARR-based* melt model, Haig Glacier

* Bias corrected

Mean specific glacier melt (mm w.e.), 1979-2014
NARR mass balance model, Haig Glacier
Modelled glacier runoff from the Canadian Rockies, 1979-2014

runoff (10 m³/yr)

year


all Alberta basins
Next Steps

Decisions about bias correction and whether we want to worry about conservation.

Evaluate at sites with longterm mass balance records.

Energy flux, meteorological, and seasonal mass balance data are generally unavailable, however.

Evaluate CRCM fields offline and continue to develop strategies for conservative subgrid ‘distribution’ of meteorological fields.

Eventual two-way coupling within CRCM.
Thanks and Questions?