Meltwater runoff from Haig Glacier, Canadian Rocky Mountains, 2002-2013

Review comments

General Comments:

As the author points out, little has been reported on glacier runoff from the Canadian Rocky Mountains, so this paper addresses an important need. It has been thought that the long standing mass balance program at Peyto Glacier would one day address this need, but detailed runoff records there ended well before AWS records began at Peyto, where only recently have efforts been made to acquire runoff data that coincide with AWS records. Runoff data for Haig Glacier do not cover lengthy periods but those that were obtained coincide with some of the twelve years of AWS records obtained at the glacier, such as to give credibility to the 2002-2013 runoff simulations.

Notwithstanding the long list of specific comments stated below, I did find this to be an interesting and stimulating paper to read. Most of my comments have to do with presentation and curiosity about the results. There is need for editorial corrections to text, tables and figures, and to tighten and clarify the presentation in some parts of Sections 2 (such as instrumentation list) and 3 (notably, topographical corrections to radiation inputs). Little modification is required beyond that other than responding where appropriate to points that I raise out of curiosity, certainly none that requires reanalysis because the paper appears to be technically sound.

Specific comments follow.

Specific Comments:

p.8356, l.19: 'mountain' rather than 'mountains'
p.8357, l.25: Delete 'all of' and 'of' at beginning of l.27.
p.8358, l.7: Here and wherever else it occurs, state 'time scales' rather than 'timescales'.
p.8359, l.19: I suggest replacing 'other' with 'some European' to expand the scope of the narrative.
p.8360, l.1: 'Sections' rather than 'Sects.'
p.8361, l.18-27: 'Each AWS measures...' The author should state station instrumentation in tabular form rather than as part of the text, where it can be difficult to keep track. I found reference to the SR50 near the end of Section 3.1, where its role in calibrating the energy balance model is stated. Perhaps data from this sensor was also useful in calibrating the stochastic summer precipitation model that is introduced later in the paper though I see no mention of this.
p.8361, l.29: Delete 'a total of'.
p.8362, l.9-10: The GAWS is not listed as such in Table 1, but is listed there as AWS?
p.8362, l.17-18,29: Despite the statement of 'data' in the plural being lost to writing, this reads better if you state 'Data are recorded', 'represent' rather than 'represents', remove 'a' before 'snapshot' and 'These data' in l.29.
p.8363, l.16: 'approximately' rather than '~'
p.8364, l.6-14: It may be better to state 'Net surface energy, Q_N, is determined by:

$$Q_N = Q^{\downarrow}_S - Q^{\uparrow}_S + Q^{\downarrow}_L - Q^{\uparrow}_L + Q_H + Q_E + Q_C \qquad (1)$$

in which $Q^{\downarrow}_S$ and $Q^{\uparrow}_S$ are the incoming and reflected short-wave radiation, $Q^{\downarrow}_L$ and $Q^{\uparrow}_L$ the incoming and outgoing long-wave radiation, Q_H and Q_E the turbulent fluxes of sensible and latent heat, Q_C the subsurface conductive heat flux, and heat transport by precipitation and runoff are taken to be negligible.' The sentence in l.6-8 of p.8365 can then be deleted. Units are stated in Table 5, so there is no need to state them here, and the definition of albedo can be left until p.8366, l.9, where reference is made to it as an indicator of seasonal transition from snow to ice surface.
p.8365, l.8: 'one-dimensional' rather than '1d'

p.8365, l.14-p.8366, l.14: In fact, this is a standard bulk transfer method, best stated simply as

$$Q_H = \rho_a c_{pa} C_H v(\theta_a(z) - \theta_o)$$
$$Q_E = \rho_a L_{s/v} C_E v(q_v(z) - q_o) \qquad (3)$$

where $C_{H/E} = k^2/\{[\ln(z/z_o) + \Phi][\ln(z/z_{oH}) + \Phi]\}$ and Φ is the stability correction, assuming similarity. While I appreciate the theoretical purity of defining θ_a at z_{oH} and q_v at z_{oE}, surface values, θ_o and q_o are used in practice because they are assumable for melting snow and ice, and so should be stated here. I would also recommend the use of T notation rather than potential temperature notation. Monin-Obukov theory works well for stability corrections to the bulk transfer approach over melting snow and ice (e.g., Munro (2004)), but Oerlemans (2000) achieved closure simply by tuning the $C_{H/E}$ value directly, without reference to Φ or z_o. So it is suitable to tune C_H through z_o selection alone as the author does here for Table 2 because the effect of stability correction over a melting surface is to reduce the turbulent fluxes to a fairly consistent 80 percent of their neutral values. This implies underestimation of z_o due to the fact that Φ is not included, but probably not to any significant degree. Alternatively, Klok and Oerlemans (2002) used combined geostrophic and katabatic transfer coefficients but I don't think that this would work for a small glacier like the Haig, so the 'tuned' bulk transfer procedure used here is as well as one can do.

p.8368, l.17: '...derived from 2005 Aster imagery...' My experience of working with Aster imagery is that it provides more local spatial variability than is obtainable from digital national topographic map data, but that absolute elevation across the DEM can be off by more than 50 m, so there was the need in my case to tie it in to a local benchmark.

p.8368, l.18-19: 'Potential direct solar radiation....' This needs some expansion so that the reader can better identify it with Oke (1987). The best expression for this appears on p. 345 of Oke, which states $S_i = I_o\Psi_a^m$, where S_i is direct radiation at normal incidence, I_o the solar constant and Ψ_a is transmissivity adjusted for air mass number, m, where m can be omitted if 0.78 is a bulk daily value. Then, turning to the notation used in this paper, $Q_{s\phi} = S_i \cos\theta$, where θ is the angle between the normal to the slope (at angle ϕ ?) and the solar beam, as stated in Eq. (A1.6) of Oke. Presumably the sensors at the FFAWS and GAWS are horizontal, so sensor θ is the solar zenith angle and $Q_{s\phi}$ plus diffuse (say, q_d) fits observations. Otherwise, $Q_{s\phi}$ is a spatially variable quantity to use with q_d, which may itself vary spatially according to Eq.(A1.14) of Oke (not stated if this is the case here). Also, topographic shading is noted among the items in parentheses in line 16 above, but not mentioned further, thus leaving the reader unsure as to what was done in this regard. A few additional sentences on the incorporation of topography, with suitable references (such as Hock and Holmgren, 2005; Klok and Oerlemans, 2002?), would clarify matters for the reader having to restate generally used equations.

p.8368, l.19-20:'...set to a constant 20%.' Twenty percent of what? Taking it to be 20% of 0.78 (i.e. S_i) would imply a downward scattering coefficient of ~0.16 which seems reasonable for this environment.

p.8369, l.7-15: Another way to state Eq. (4) is $Q_L=\varepsilon_a\sigma T_a^4$; $\varepsilon_a = ae_v + be_v/e_s$, where e_s is saturation vapour pressure, thus making it consistent with the style of Table A2.2 of Oke (1987). I am curious to know whether 'locally calibrated' a and b are one set of values throughout and what those values are because that would allow comparison with other schemes that employ vapour pressure, such as the first two that are listed in Table A2.2. Also, does the sky clearness index play a role in estimating Q_L when Q_S is available but Q_L is not?

p.8373, l.2-4: 'The larger differences...' Because warming applies to all snow free areas around the glacier, another interpretation is to see this as the effect of glacier cooling on the overlying air mass and the fact that the cooling effect doesn't extend much beyond the glacier boundary. JAS is the stand out period in this regard due to snow persistence through June, as stated in 4.2, so perhaps this period should be the centre of attention rather than JJA, especially as JAS also seems to be the primary ice melt period.

p.8373, l.12: 'snow years' rather than 'snows years'

p.8374, l.5-8: One other thing to note here is that the net short-wave part of Q_* for JJA, which I make out to be 95 Wm^{-2}, is mostly comparable to Q_N, while the net long-wave part, -32 Wm^{-2} is substantially off-set by Q_H less Q_E, so it is crucial to have a good model of the glacier short-wave radiation regime. In fact the comparisons are closer in Table 5, where a $Q^{\downarrow}_S(1-\alpha)$ value of ~84 Wm^{-2} slightly exceeds a Q_N value of 81 Wm^{-2} and Q_L^{net}, -26 Wm^{-2}, is mostly offset by $Q_H + Q_E$ = 22 Wm^{-2}.
p.8374, l.17:'...May snowpack intializations...' Are these done by interpolating across the GIS between field sampling points, or perhaps by using an altitude relationship based on field measurements? Table 1 values indicates altitude dependency, while Fig. 1d suggests variation across the widths of altitude zones such as occurs at South Cascade Glacier.
p.8376, l.14: '...albedo-influenced impact on summer melt.' Consider replacing this with '... melt reduction due to albedo rise.' to specify the impact.
p.8377, l.19: Delete 'but'.
p.8377, l.25-27: 'Periods of high overnight flows reflect...' They could also reflect runoff delay from storage, as noted by the author in relation to Fig. 10. Further to Fig. 10, I am surprised that the author did not include a linear reservoir in the runoff model, such as described in Hannah and Gurnell (2001) because it is not difficult to do.
p.8382, l.17: '... 7:1 upstream of Calgary and 15:1 over the Bow Basin.' Should these be stated the other way around? I find them difficult to reconcile with annual flow percentages stated in l. 24-25 below.
p.8383, l.12: 'channelized, draining' rather than 'channelized and draining'
Table 1: Replace 'AWS' with 'GAWS'.
Table 2: Use left justification in the units column.
Figure 1: Delete a and b panels.
Figure 3: I suggest using line plots to avoid the visual impression of stacked bar graphs.
Figure 5: A line plot may be better for Fig. 5a as well. Also 'net energy' rather than 'net radiation' in Y-axis caption of Fig. 5b and 'Q_N' rather than 'QN' in the figure caption.

Hannah, D.M. and A.M. Gurnell 2001. A conceptual linear reservoir runoff model to investigate melt season changes in cirque glacier hydrology. *Journal of Hydrology*, 246: 123-141.
Munro, D. S. 2004. Revisiting bulk heat transfer on the Peyto Glacier, Alberta, Canada, in light of the OG parameterization. *Journal of Glaciology*, 50(171): 590-600.
Oerlemans, J. 2000. Analysis of a 3 year meteorological record from the ablation zone of Morteratschgletscher, energy and mass balance. *Journal of Glaciology*, 46(155): 571-579.