A study of the energy-balance and melt regime on Juncal Norte glacier, dry Andes of central Chile, using melt models of different complexity

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Motivations and background

Broader project (www.mountain-waters.ethz.ch):
study the impact of climatic variations on water resources in areas where contribution from snow and ice is dominant to the total runoff and where water is crucial because of scarcity and potential conflicts on its use.

Aconcagua River Basin

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Aim of work

- Test ablation models that have been developed and tested in the Alps in the different climatic settings of these latitudes.
- Understand which types of models can be used (energy-balance and temperature-index models).
  - How much are temperature-index models (enhanced temperature index models) transferable?
Study site

Juncal Norte glacier


- Two Automatic Weather Stations (AWSs)
- One Ultrasonic Depth Gauge (UDG) and ablation stakes
- Runoff measurements at the glacier snout
- Terrestrial photos from a slope facing the glacier
- GPS measurements
Meteorological settings: cloudiness

• Solar radiation is very high and overcast conditions are extremely rare (2 days out of 64)

• Relative humidity is low (mean over the period of record: 42%)
Meteorological settings: albedo

• No precipitation and therefore no strong variations in albedo

Daily albedo at AWS1

Daily albedo at the Uppermost Station on Haut Glacier d’Arolla, 2001
Melt modelling

1. The glacier energy-balance was simulated using two energy-balance models:
   - **Surface** energy-balance model (Brock and Arnold, 2000): no sublimation and subsurface fluxes: EB1
   - Energy-balance model (Corripio, 2002) including sublimation and subsurface fluxes: EB2

2. An enhanced temperature-index model was also applied (Pellicciotti et al., 2005, J. Glaciol.): ETI

   - All models were run at the location of the AWS at hourly resolution
Energy balance models

1. **EB1** (Brock and Arnold, 2000, Rimkus 2006)

\[ Q_M = Q_I + L + Q_H + Q_L \]

Zero-degree assumption: snow surface is always at melting point

2. **EB2** (Corripio, 2002)

\[ Q_M = Q_I + L + Q_H + Q_L + Q_S \]

\[ Q_M \]: net energy flux, latent heat used to melt snow or ice  
\[ Q_I \]: net shortwave radiation flux  
\[ L \]: net longwave radiation flux  
\[ Q_H \]: turbulent sensible heat flux  
\[ Q_L \]: latent heat flux  
\[ Q_S \]: internal heat flux within the snowpack
Enhanced temperature-index model

1. **ETI model (Pellicciotti et al., 2005)**
   Temperature-index model including the shortwave radiation balance

\[
M = TF \cdot T + SRF \cdot (1 - \alpha) \cdot I \quad T > T_T
\]

*Longwave radiation and turbulent sensible fluxes*

*Shortwave radiation flux*

- \(M\): melt rate (mm w.e.)
- \(T\): air temperature (C)
- \(\alpha\): albedo
- \(I\): incoming shortwave radiation
- \(TF, SRF\): empirical factors

- Temperature is measured
- Incoming shortwave radiation and albedo can be measured or modelled/parameterised
Results: testing the EB models

Comparison of cumulative ablation computed using **EB1** and **EB2** with measurements at the UDG and stakes readings

Comparison of cumulative ablation simulated by EB1 (green) and EB2 (black), cumulative melt recorded by the UDG (red), and stakes readings (red diamonds). Both stakes and UDG measurements of surface lowering are converted into mm w.e. using a measured density of **524.3 kg m\(^{-3}\)**

Tot. ablation **EB1**: **4310.59** mm w.e.

Tot. ablation **EB2**: **3434.67** mm w.e.
Comparison of hourly melt rates

EB1 simulates too high ablation, especially in the night and morning hours, because of the zero-degree assumption, which forces the glacier to be always at melting point whereas energy is needed to warm up the snow or ice when cooling occurs.

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ETI model simulations: cumulative melt

Comparison of cumulative ablation simulated by EB1 and EB2 and by the ETI model calibrated for the Alps: TF = 0.04, SRF = 0.0094
ETI model optimisation

The ETI model was re-optimised against hourly melt rate simulated by EB2:

\[
\begin{align*}
TF &= -0.02 \\
SRF &= 0.0102 \\
R^2 &= 0.9724
\end{align*}
\]

Haut Glacier d’Arolla:

\[
\begin{align*}
TF &= 0.04 \\
SRF &= 0.0094
\end{align*}
\]

Physically-based SFR:

\[
SRF = 0.00107
\]
ETI model results: hourly melt rates

Hourly melt rates simulated by the ETI model with different parameters sets compared to the simulations of EB1 and EB2.

The ETI model with negative TF:
• simulates negative (low) melt at night and
• overestimates ablation in the first hours of the morning:
EB2 simulations start few hours later.
Comparison of hourly melt rates

Negative TF are needed to compensate the overestimation of ablation by the ETI model taking place in the first hours of the day, when, due to the intense radiative cooling of the surface at night, part of the energy is needed to warm the snowpack and is not available for melt.

Differences of hourly melt rates simulated by EB2 and ETI models with different parameters sets
ETI model parameters robustness

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Conclusions (1)

• The factors driving the ablation process are different from those in the Alps: no rainfall and therefore albedo variations; temperatures always > 0 C; no clouds affecting the shortwave radiation flux

• There is no need for some of the parameterisations commonly used in the Alps: in particular albedo (two constant values for snow and ice) and cloud factor

• The melt process is dominated by incoming shortwave radiation

• Consideration of sublimation and of heat exchange between the surface and the snow/ice is crucial. Neglecting it leads to overestimation of about 1 m w.e. over a period of 64 days:
  - total melt EB1: 4310.59 mm w.e.
  - total melt EB2: 3434.67 mm w.e.

• EB1 overestimates ablation both during the early morning and at night because of neglecting internal heat conduction (zero degree-assumption)
Conclusions (2)

• Enhanced temperature-index models or simplified energy-balance approaches can also be used (and require less data), but extrapolation tout-court to a different climatic setting is not appropriate. They need to reflect the different processes of such climatic setting:
  • higher solar radiation input resulting in a higher contribution from the shortwave radiation: higher SRF (very close to its physically-based value)
  • strong cooling, especially at night resulting in less energy available for melt in the first hours of the day (used to heat up the snowpack): negative or zero contribution from the temperature-dependent fluxes: TF <0
• Once the ETI model is adapted to the climatic setting, however, it can be successfully used, because it is more physically-based than the standard temperature-index method
Outlook

• **Distributed application** of both energy-balance model (EB2) and the enhanced temperature index model (ETI)

• Test the ETI model transferability and parameters variations with data from another season on Juncal

• Application of the distributed rainfall-runoff model Topkapi including the ETI routine for snow and ice melt simulation, to the upper Aconcagua River Basin
Thank you for your attention

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