Predicting the effect of mountain glacier recession on water resources: coupled glacio-hydrological modeling of tropical and temperate river basins

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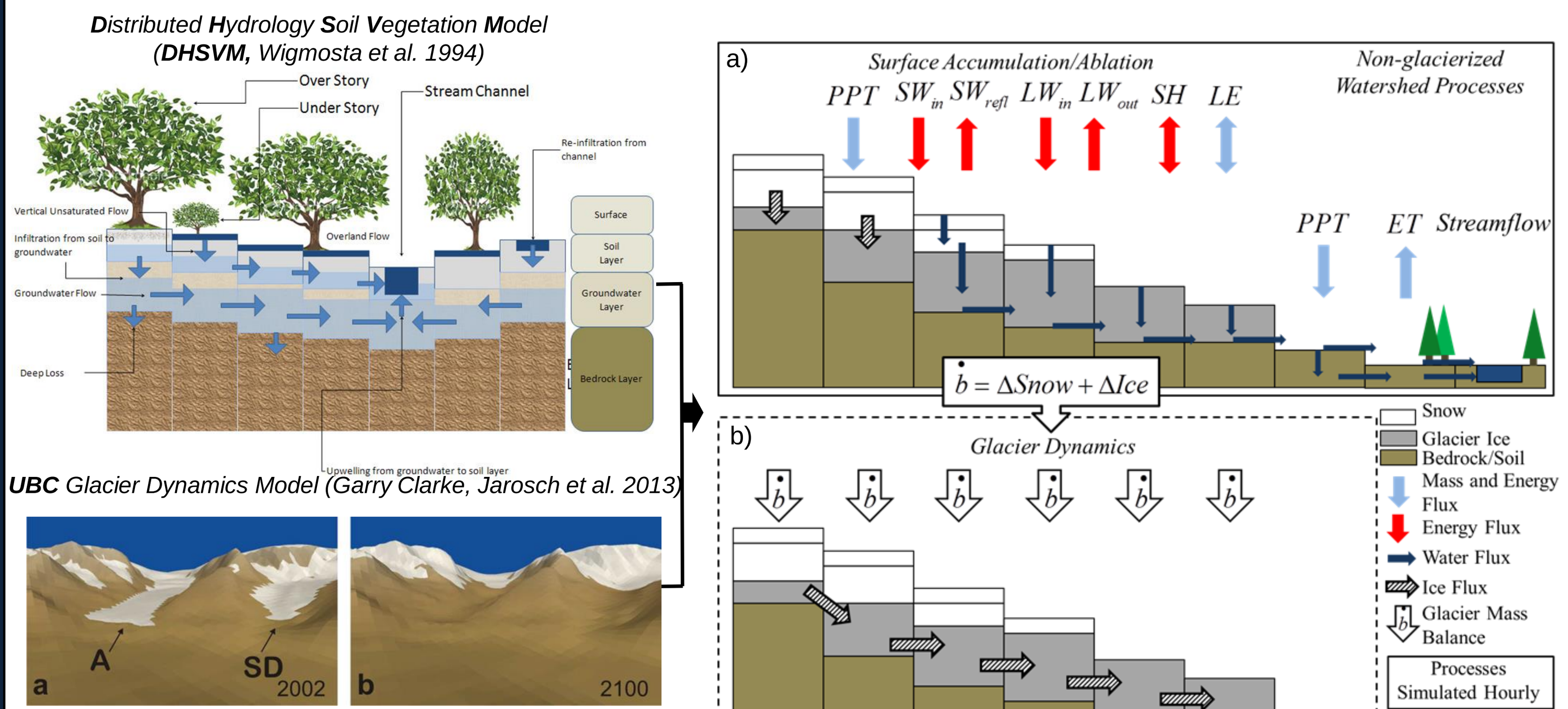
Introduction

In many partially glacierized watersheds climate-forced glacier recession has altered and will continue to alter seasonal water availability, leading to profound implications for water supply and ecologic systems. Where available in situ and remotely sensed data are available, observations can be used to understand historical and current changes in these systems. Applications of hydrological models allow users to analyze systems beyond spatial and temporal constraints provided by observations alone and provide a platform to infer future change. Until recently, most hydrological models lacked an adequate representation of coupled glacio-hydrological processes. In particular, most did not account for changes in glacier area through the flow of ice. This presentation describes and demonstrates a recently developed glacio-hydrological modeling methodology that integrates a dynamic ice flow model into a distributed physically based hydrology model. Historical applications and future projections are demonstrated for tropical and temperate river basins.

Coupled glacio-hydrological modeling

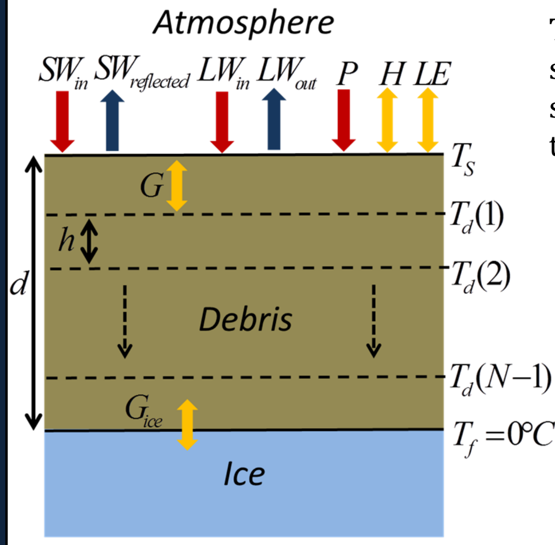
Integration of Glacier Dynamic Ice Flow in a hydrological model [Naz et al. 2014]:



Continuous simulation of glacier area and thickness through representation of creep and basal sliding in response to surface accumulation and ablation

The UBC Glacier Dynamics Model was recently integrated in the Distributed Hydrology Soil Vegetation Model (DHSVM). **(Upper Right)** A schematic showing the first order processes simulated by the coupled glacier-hydrology model. (a) Land surface and hydrology component of the coupled model illustrating the fluxes of mass and energy between the atmosphere and land surface implemented on snow, glacier ice, and soil/vegetation surfaces. Arrows indicate precipitation, PPT; incoming shortwave radiation, SW_{in}; reflected shortwave radiation, SW_{refl}; downwelling longwave radiation, LW_{in} ; emitted longwave radiation, LW_{out}; sensible heat, SH; latent heat, LE; evapotranspiration, ET. (b) Illustration of the glacier dynamics component of the model that simulates lateral dynamic ice flow driven with ice mass balance ($\dot{b}$) from the land surface component of the model.

Modeling Glacier melt on debris covered glaciers:



The presence of debris on a glacier's surface can exhibit strong control over surface energy dynamics and glacier melt rates. Algorithms representing the storage of and conductance of energy in supraglacial debris were developed into the model:

Numerical Simulation following *Reid and Brock* (2010):
Determine surface temperature, numerically solving the surface energy balance conservation equation:

$$SW_{net} + LW_{in} + LW_{out}(T_s) + H(T_s) + LE(T_s) + G(T_s) + P(T_s) = 0$$

Compute debris internal temperature profile and heat flux to ice:

Temperature Profile:

$$\rho c \frac{\partial T(z,t)}{dt} = \frac{\partial}{\partial z}\left(k_{debris}\frac{dT(z,t)}{dz}\right)$$

Heat Flux to Ice:

$$G_{ice} = k_{debris}\frac{T_d(N-1) - T_f}{dz}$$

Steps in model application:

1. Estimate spatially distributed mean annual mass balance — Derived from climate and glaciological observations
2. Initialize historical distribution of glacier ice — Force glacier dynamics model with constant mass balance field to grow steady state glaciers that match observed historical extent
3. Fully coupled glacio-hydrological *historical* simulations — Iteratively evaluate and calibrate model with observed glacier mass, extent, and discharge measurements.
4. Captures observed historical hydrological and glaciological patterns? — Yes: Fully coupled glacio-hydrological *future* simulations; No: return to step 3

References

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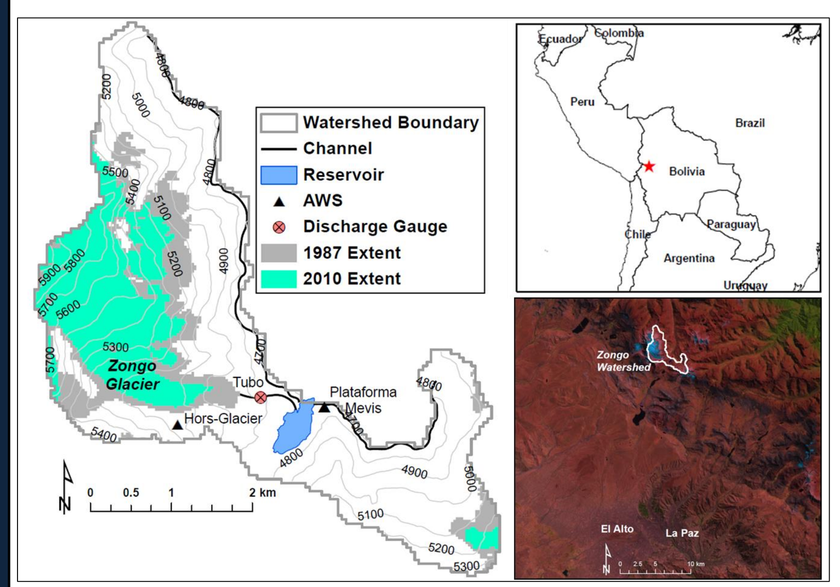
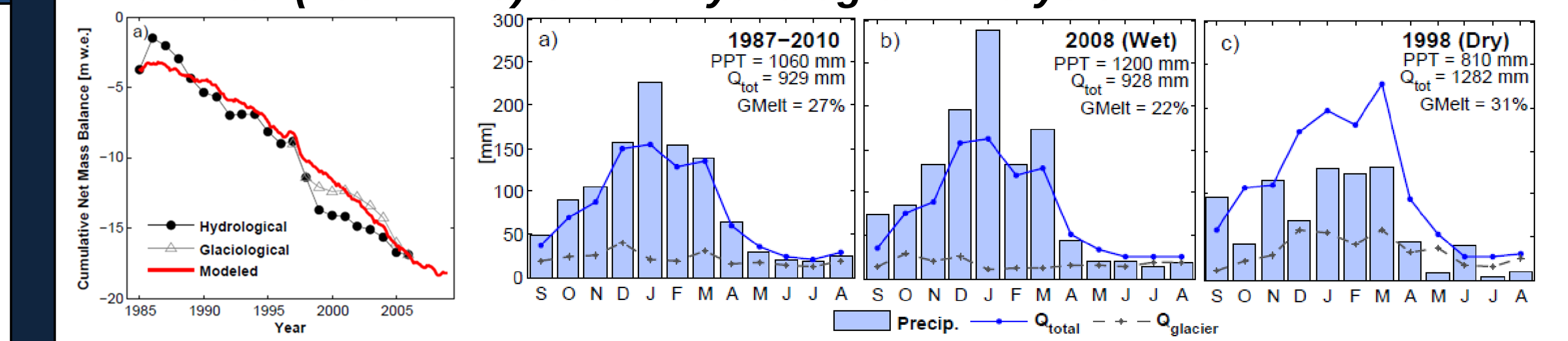
Tropical River Basin: Zongo River, Bolivia



The Zongo River is located is in the Cordillera Real of the South American Andes. Glacier and snow melt originating in headwater catchments in the Cordillera Real provide water for downstream drinking water supply, energy production, and ecological services. In particular the Zongo River hosts hydro electric facilities that provide much of the energy for the nearby heavily populated areas of La Paz and El Alto. We conduct historical and future glacio-hydrological modeling analyses to understand historical and project future patterns of discharge with ongoing glacier recession. This application leverages long-term hydrological and glaciological measurements (conducted by the Institute of Research for Development, IRD)for model implementation and evaluation. The results presented below are described in Frans et al. (in review).

Historical (1987-2010) Glacio-hydrological Analysis

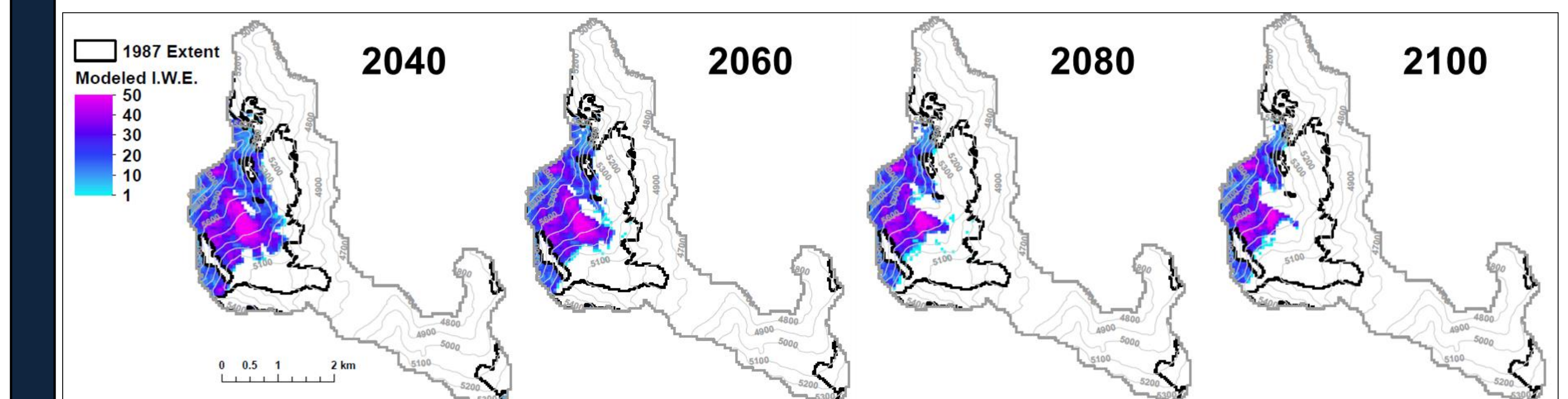


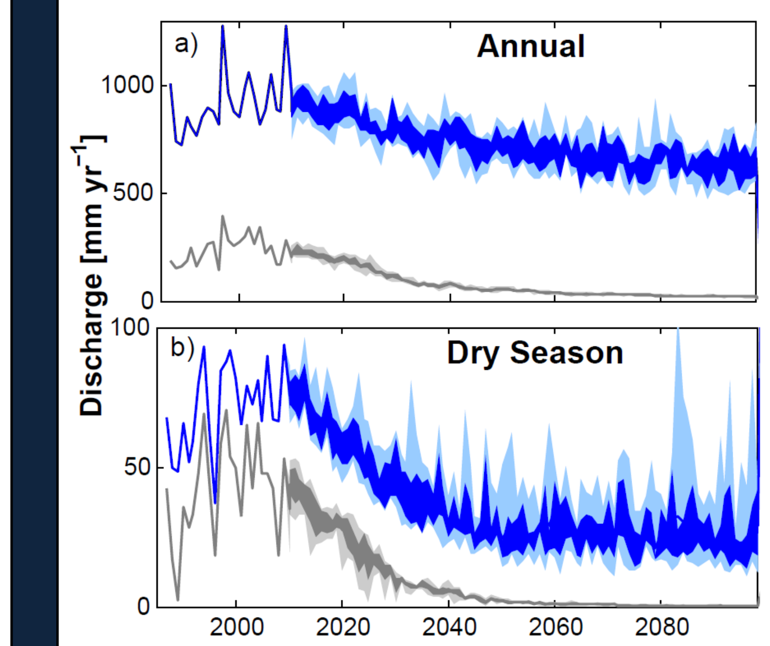
(Upper left, a) Modeled (red), and observed cumulative net mass balance of Zongo glacier estimated from hydrological measurements (black) and adjusted glaciological measurements (gray). Observations were digitized from *Soruco et al.* [2009).

(Upper right, a-c) Monthly mean precipitation (bars), modeled total discharge (blue, solid line) entering the reservoir, and glacier melt (gray, dashed line) plotted for: (a) the historical period (1987-2010); (b) a wet year (2008); and (c) a dry year (1998). In the inset annual precipitation (PPT), runoff (Q_{tot}), and percent of glacier melt contribution (%GMelt) are reported.

Projected glacio-hydrologic change: 1987-2100 (RCP4.5)

For the future time period we run the model with transient meteorological forcing data statistically downscaled from 11 CMIP5 GCM outputs using a stochastic weather generator (Fatichi et al. 2011). 30 realizations of the most probable future climate (as predicted by the GCMs) are generated to represent a range of stochastic variability of climate.

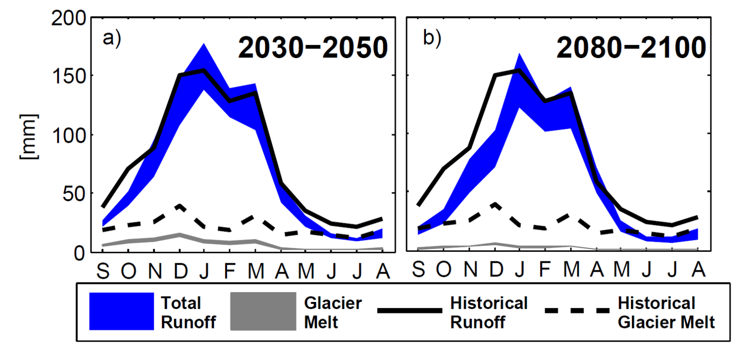


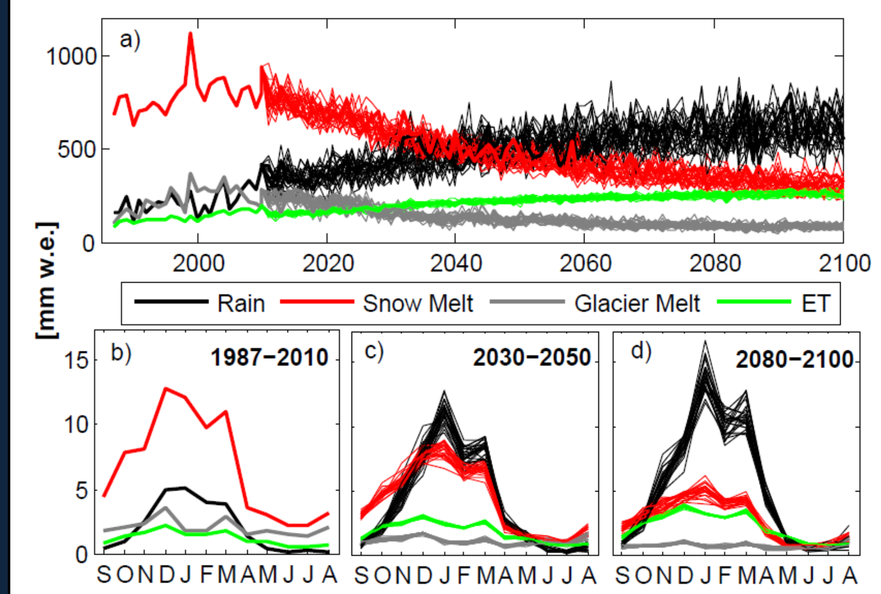


(Top Panel) Projected glacier area and thickness at the end of WY 2040, 2060, 2080, and 2100. Historical satellite (Landsat) derived glacier extent estimates are shown with a solid black outline.

(Left, a-b) (a) Annual and (b) dry season (JJA) total runoff (rain + snowmelt + glacier melt, blue) and glacier melt (gray) for the entire watershed. Lighter colors indicate the full range of future projections using multiple stochastic realizations of the transient future climate and dark colors denote the interquartile range of the projections.

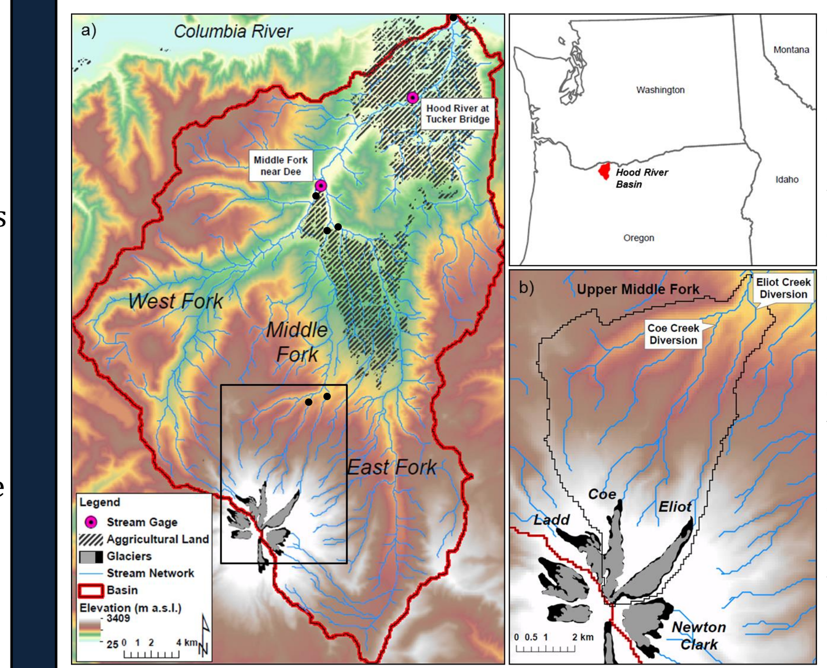
(Right, a-b) Mean monthly discharge (sourced from rain, snowmelt, and glacier melt) entering the reservoir predicted for (a) the near future (2030-2050) and (b) far future (2080-2100). Discharge volumes projected to decrease by as much as 71% (July) by the end of century.





(Left) Transitioning historical and projected annual (a) and seasonal (b-d) hydrological fluxes in the watershed. Unlike the trajectory of changes in glacier melt, changes in rain, snowmelt and evapotranspiration show near linear patterns of change (a) and closely reflect increasing air temperature. As air temperature gradually warms above the freezing point (at the 5050 m reference location) evapotranspiration losses increase, by as much as 86% by the end of century. This demonstrates the importance of the response of the non-glacierized portions of the watershed to a changing climate for future runoff patterns.

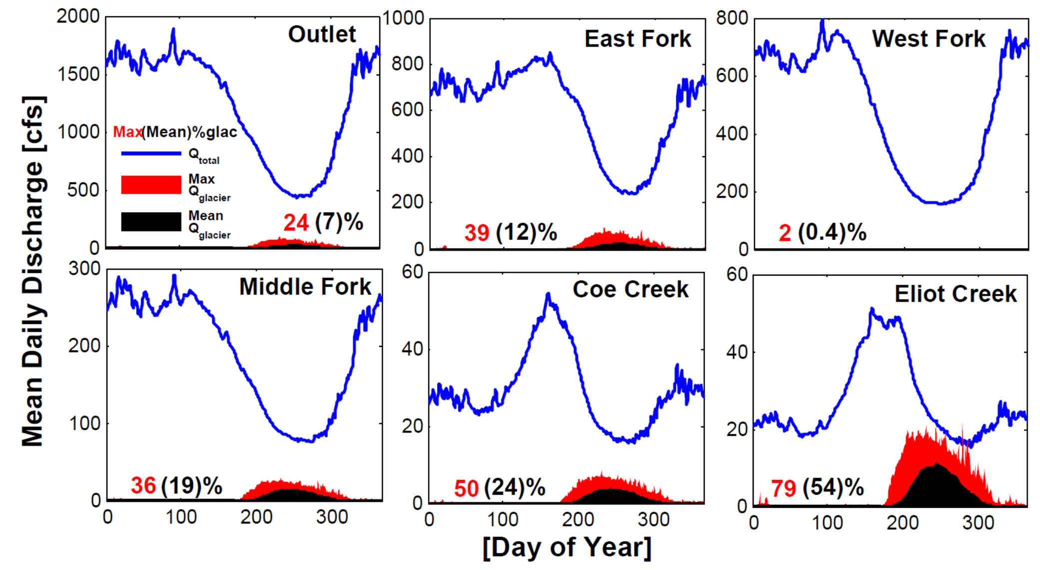
Temperate River Basin: Hood River, OR, USA



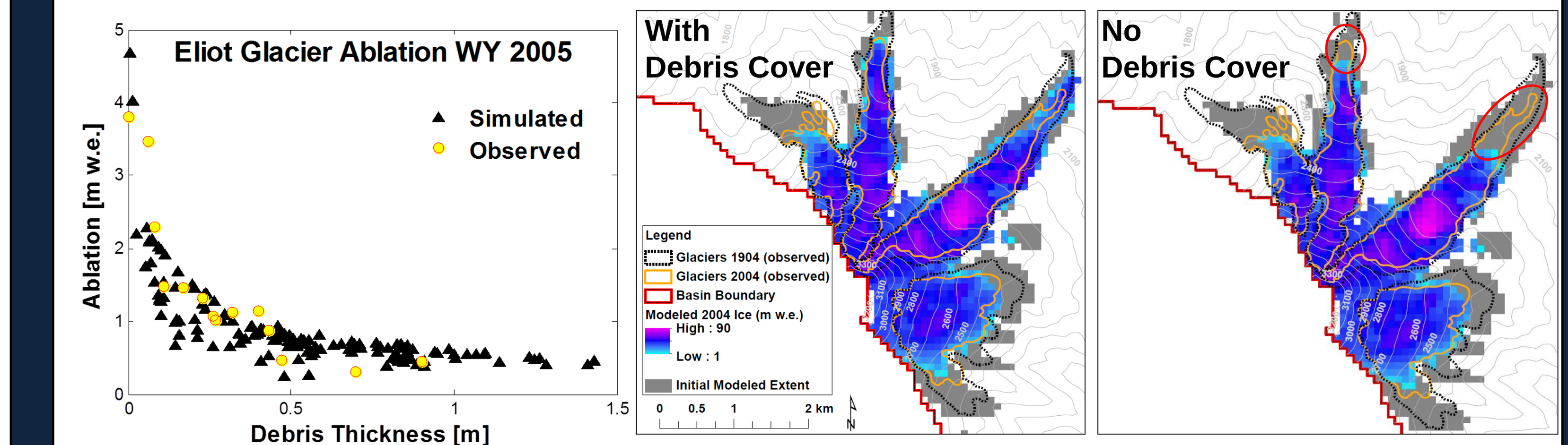
The Hood River originates on the northern flanks of Mount Hood, a glaciated stratovolcano which reaches an elevation of 3429 m a.s.l. The Hood River drainage basin (850 km^2) hosts agricultural land and aquatic habitats that are vital to the regional economy. The agricultural land is largely comprised of perennial crops (e.g, apple and pear orchards and grape vineyards) that have high water demand during summer months and require irrigation. Stream discharge in the basin is managed through flow diversion structures and a small storage reservoir that provide agricultural water supply to meet seasonal irrigation demands. The reservoir and diversion structures are located on streams at *high elevations in close proximity to partially glacierized headwater catchments.* Water extracted from these streams through five irrigation districts is critical for downstream orchards and vineyards.

Historical (1916-2005) Contribution of Glacier Melt

(Right) Modeled mean total discharge and maximum and mean glacier discharge are plotted for each day of year (for the period of 1916-2005). The maximum daily glacier contribution through the time period is printed in red, while the mean annual maximum glacier contribution is printed in black. The contribution of glacier melt to discharge increases substantially in the uplands with a maximum at the agricultural water supply diversion at Eliot Creek (*up to 79% of flow*).

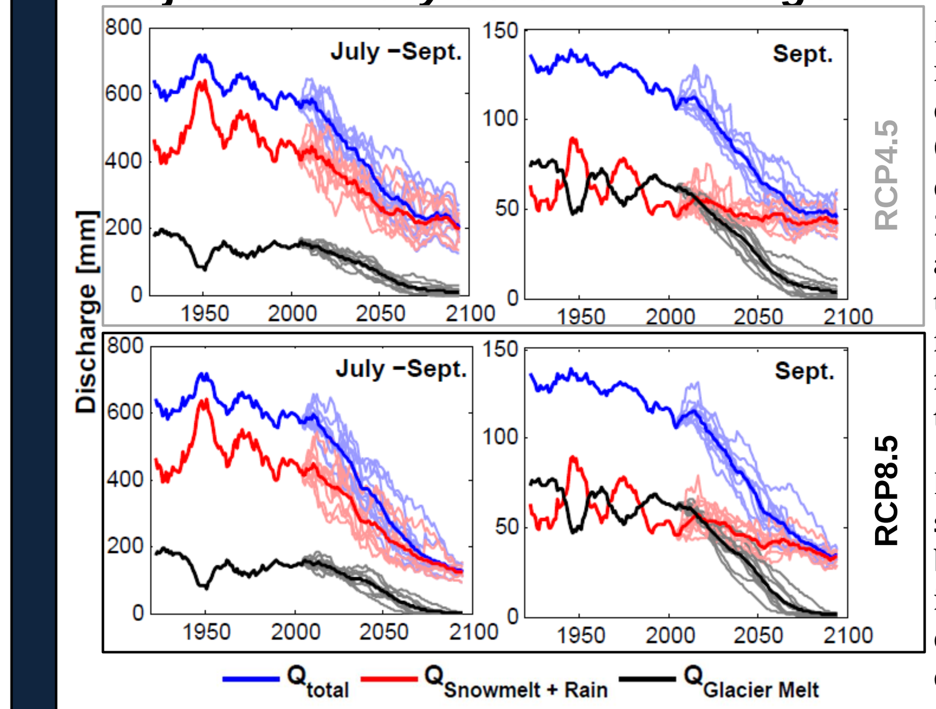


The Role of Debris Cover on Glacier Melt



Ablation and extent observations taken from Jackson and Fountain (2007). Model results are from 1916-2005 simulation.

Projection of dry season discharge at Eliot Creek diversion



Future model simulations are forced with transient meteorological data downscaled from 9 CMIP5 GCM outputs using the Multivariate Adaptive Constructed Analogs (MACA) statistical downscaling method (Abatzgalou and Brown, 2011) . **(Left)** Discharge for the entire dry season and September only (the time where glaciers have the strongest contribution) for the historical and future time periods (1916-2099). Model results from individual GCMs are shown in light colors and the ensemble mean in dark.

Declines in total discharge driven by reduced snowmelt began around 1950 and were partially buffered by sustained glacier melt. However, early in the 21st century glacier melt is projected to decrease intensifying negative trends in total discharge.

Conclusions

Tropical: Zongo River Headwaters

- Historically (1987-2010), on average, water derived from glacier melt accounts for **25%** of discharge from the watershed on an annual basis and **59%** during the dry season (JJA).
- Total discharge and discharge sourced from the melting of glacier ice reached a peak around the year 2000 and has started to decline thereafter.
- An average of an ensemble of climate simulations for the 21st Century projects a **15% and 47% reduction** in annual and dry season discharge by mid-century, respectively. A reduction of annual and dry season discharge of **26% and 60%** is projected by the end of the century.

Temperate: Hood River

- Historically (1916-2005) glacier melt contributed up to **79%** to discharge at water management locations
- Supraglacial debris has slowed the response of the glaciers to warming temperatures.
- At upland stream locations, declining glacier melt early in the 21st century exacerbates declines in total discharge contributing to **~65-75% loss of discharge** by the end of the century.

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NASA Interdisciplinary Research in Earth Science Program - Grant NNX10AP90G.