Water and energy balance of the Upper Indus Basin using CTSM - Hillslope Hydrology: A proof of concept

Samar Minallah (minallah@ucar.edu),
Sean Swenson (swensosc@ucar.edu), Andy Wood (andywood@ucar.edu)

Climate & Global Dynamics Laboratory, NSF National Center for Atmospheric Research, Boulder, CO

I. Introduction

Project Objectives:

- Characterize the various hydroclimatic regimes within the Indus Basin by assessing:
  - the terrestrial energy and water budgets
  - seasonal and sub-seasonal runoffs in the tributaries of the Indus River
- Identify the hydrological tipping points where the dominant drivers of variability and sub-basin characteristics irreversibly shift to a new state.

We are adapting the Hillslope Hydrology configuration of CTSM to **establish process-based understanding of the energy and water cycle components and their variability in this region.**

A secondary objective is to compute glacial mass balance using a surface-energy-balance (SEB) scheme for the mountain glaciers in Indus and the larger high-mountain Asia region.

II. Domain description

- The Indus River Basin hosts remarkably diverse hydroclimatic regimes including:
  - glaciated Upper Indus Basin (Himalaya-Karakoram-Hindukush mountains)
  - fertile and agriculture-based central plains
  - large deserts in the southeast
  - mangrove ecoregion of its delta
- Due to the diverse landscape and strong human dependence on its resources, the Indus Basin is highly vulnerable to climate change.
- It experiences both ends of the climate extreme spectrum with multiple floods and droughts in different parts of the basin.

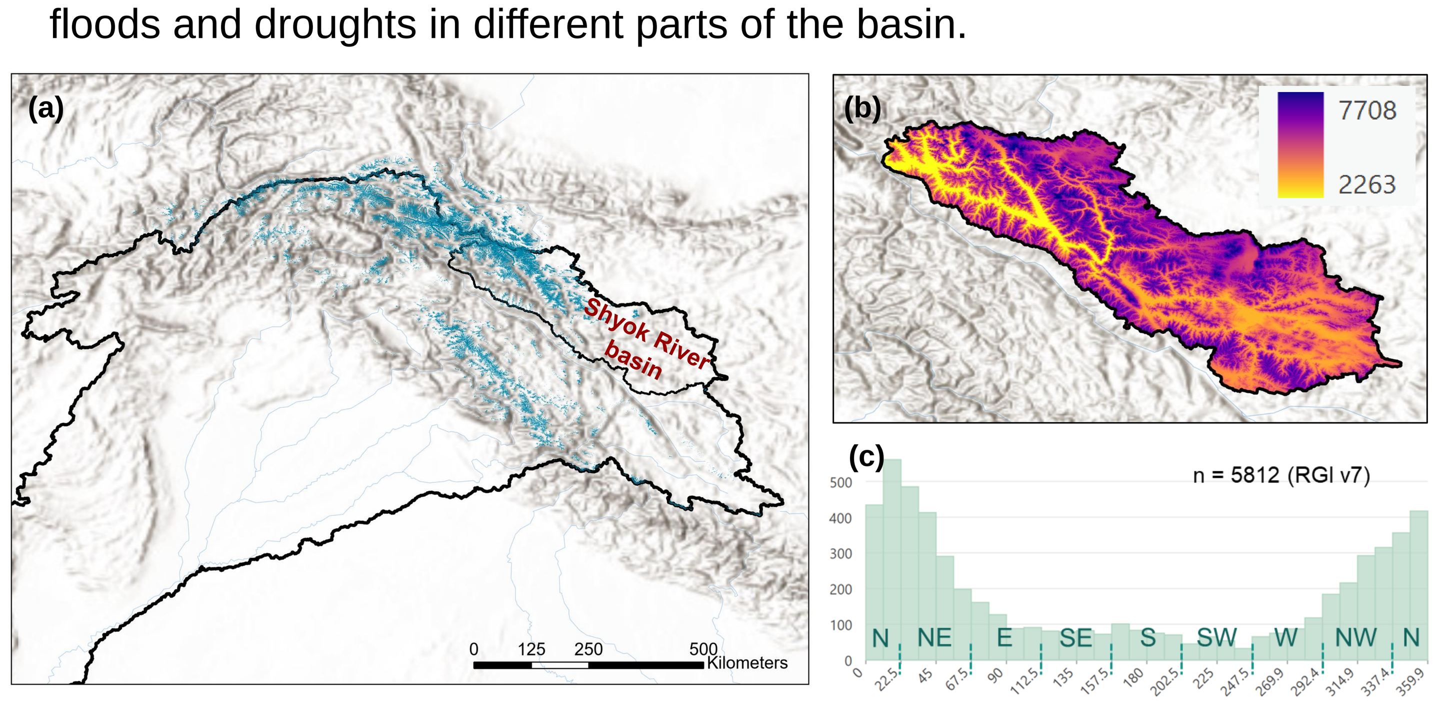

Fig. 1: (a) The Indus River Basin (south region not shown), with glaciers in blue. (b) Elevation (m) profile of the Shyok River Basin, a tributary of Indus, in the Karakoram region. (c) Aspect distribution of glaciers in Shyok (RGI v6).

Indus	Area (km²)	# of glaciers
RGI v6 glaciers	33,568	27,988
RGI v7 glaciers	33,075	37,562
Debris covered area	3,663	

Table 1: Cumulative glacier area and number in the Indus basin from the Randolph Glacier Inventory (RGI).

III. Model description

Hillslope Hydrology:

- Captures sub-grid details related to Aspect, Relief, and Slope
- These terrain characteristics are important for snow-covered and glaciated domains

Hillslope Categorization:

- Input mesh and surface data as a regular grid (lat/lon) or irregular polygons (e.g., watersheds)
- Each grid or polygon can have multiple land units (e.g., glacier, vegetation, lake, etc.)
- We can classify each cell into multiple representative hillslopes or "columns" (user defined)
- These hillslope columns are used to downscale at sub-grid levels

Shyok Watershed Case Study:

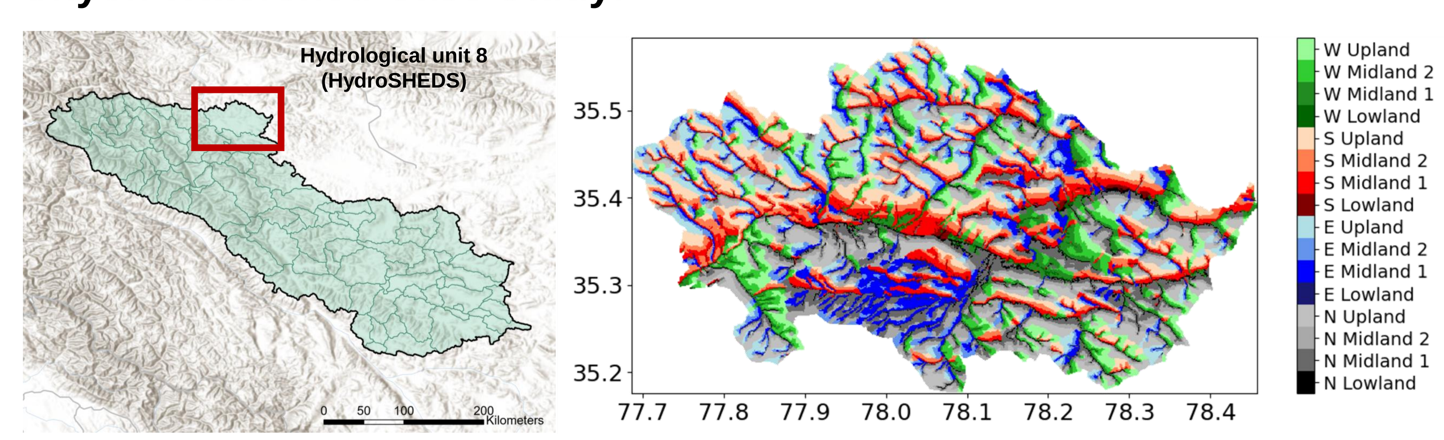

Fig. 2: (Left) Shyok Watershed divided into smaller hydrological units. (Right) Hillslope categorization for a single cell into 16 columns (4 aspect x 4 elevation).

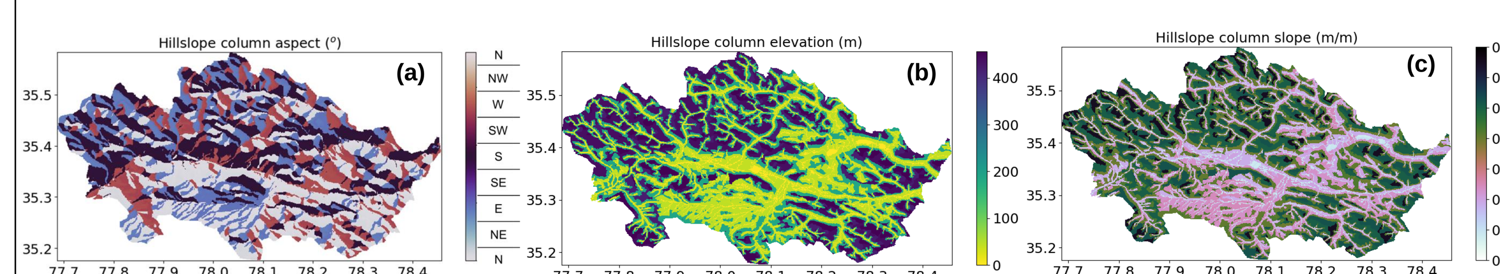

Fig. 3: Hillslope (a) aspect, (b) elevation, and (c) slope profiles for the sub-watershed.

Downscaled Forcing:

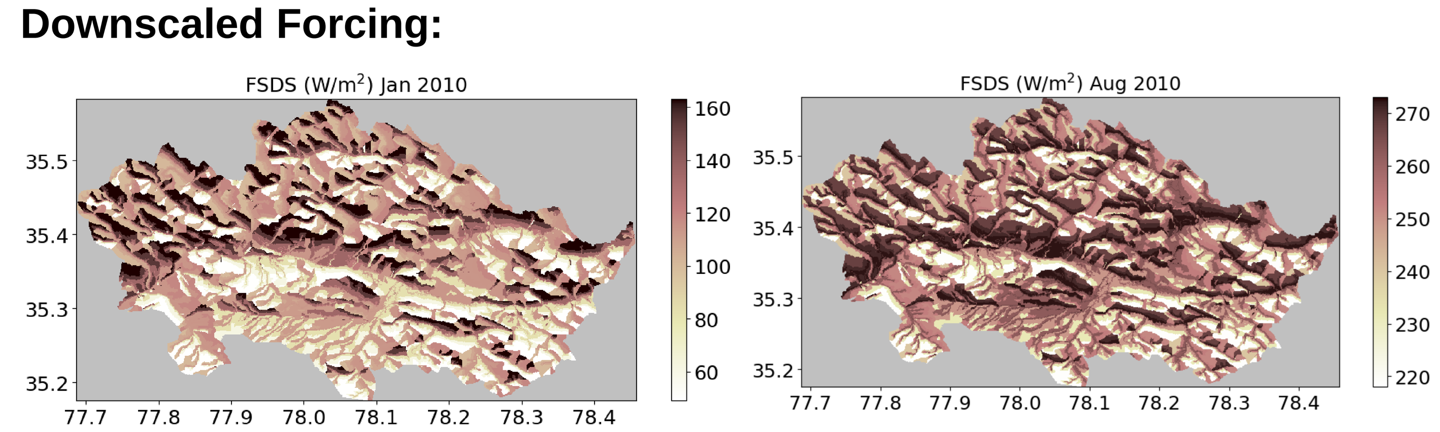

Fig. 4: Downscaled incoming solar radiation for January and August 2010.

Winter:

- North-facing slopes receive 50% less as compared to south-facing slopes
- Northern lowlands receive twice the radiation compared to northern uplands; southern lowlands receive three-fourth the amount of southern uplands

Summer:

- Difference between north- and south-facing slopes is smaller (10 – 15%)
- Elevation-based differences between lowlands and uplands are also relatively small

V. Preliminary results

Snowfall and Ground Snowpack:

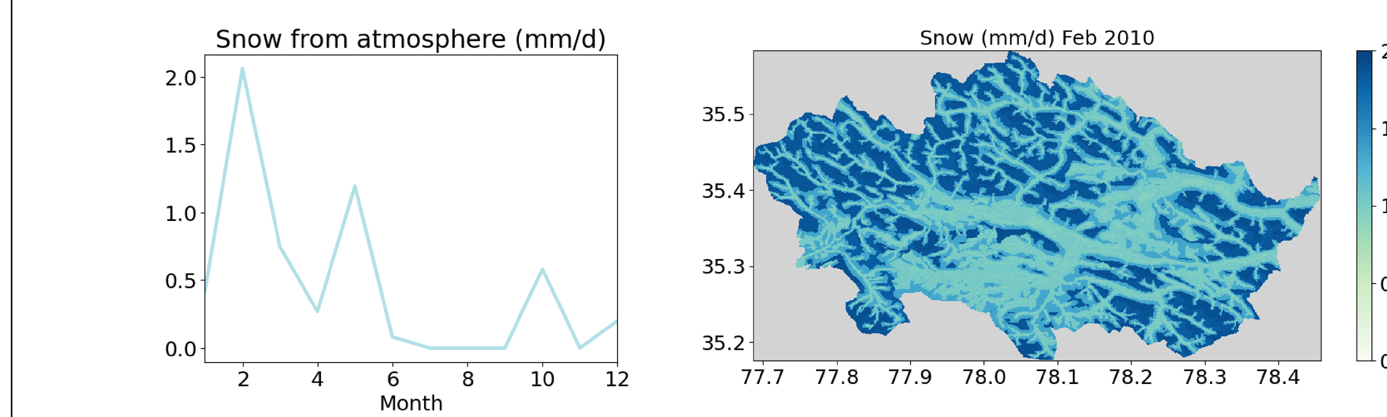

Fig. 5: Snow from atmosphere after precipitation repartitioning (left) and hillslope downscaled snow for February 2010 (right).

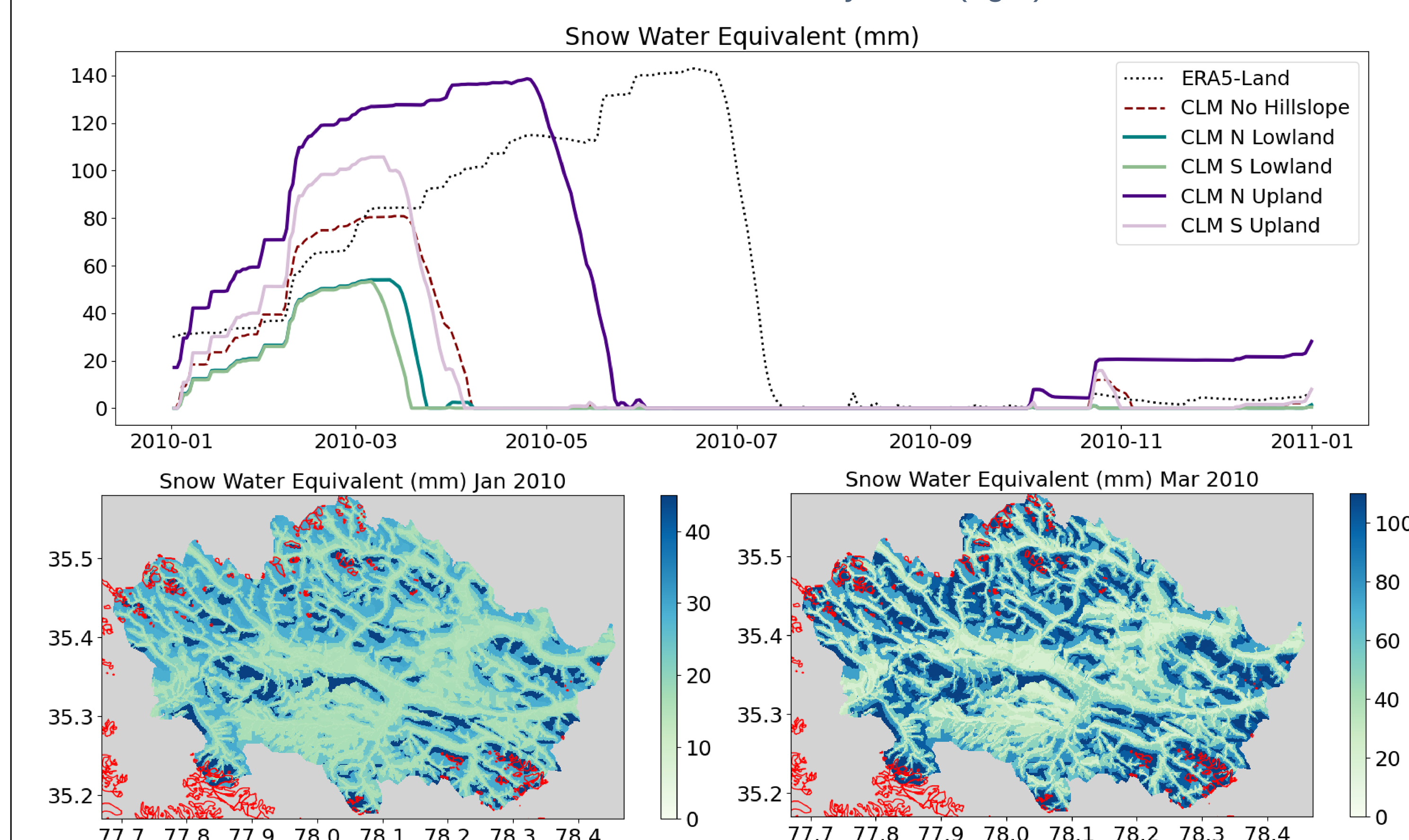

Fig. 6: (Top) Snow water equivalent (SWE) time series for 2010, separated for north and south lowlands and uplands. No hillslope runs are in maroon dashed lines. (Bottom) SWE spatial distribution for January and March, with glaciers shown in red.

Next Steps:

- Further calibration of select tuning factors and validation with additional data (e.g., MODIS daily cloud-gap-filled fractional snow cover dataset; satellite-based ET and soil moisture estimates)
- Water and energy balance assessments

VI. Ongoing and future work

Glacio-hydrology:

- Melt rates, flow accumulation, and drainage patterns → mizuRoute
- CLM presently uses a surface-energy-balance (SEB) scheme to compute glacial mass balance over Greenland and Antarctica only → adapting CTSM-Hillslope for glacial MB computations for mountain glaciers

CTSM – CISM coupling:

- Two-way coupling between CTSM and CISM (the Community Ice Sheet Model) for dynamic evolution of mountain glaciers (already in place for Greenland and Antarctica)