

HMA Glacier change and runoff in response to 21st century climate projections

or

Modelling 100,000 (**really 55k**) Glaciers

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Impacts Assessment to **Support W**Ater **R**esources **M**anagement and Climate Change Adaptation for China
(**SWARM**)



Met Office Climate Science for Service Partnership China (CSSP China)

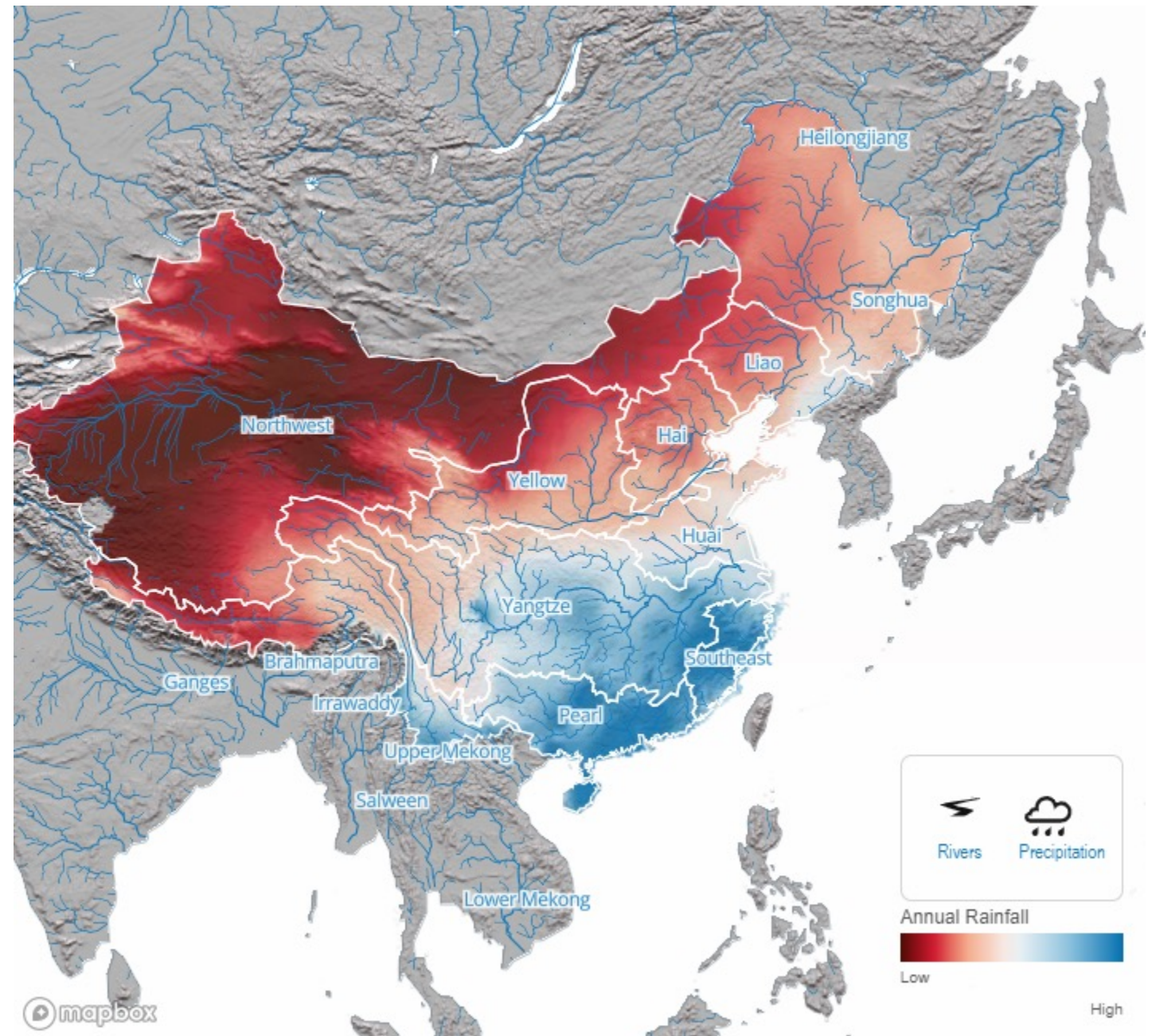
Supported by the Newton Fund and the Department for Business, Energy & Industrial Strategy (BEIS)



SWARM

Motivation

- Uneven distribution of water resources between the North and the South of China, the North is more reliant on groundwater than the South. 6 out of China's 9 main river basins receive less rainfall than South Sudan (900mm/a).
- Floods and droughts are among the most frequent natural disasters in China.



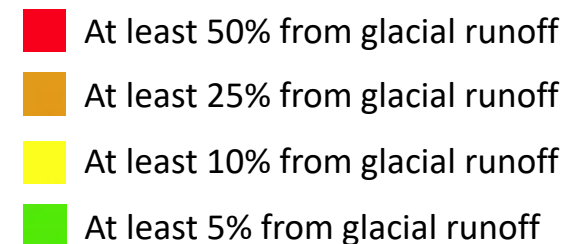
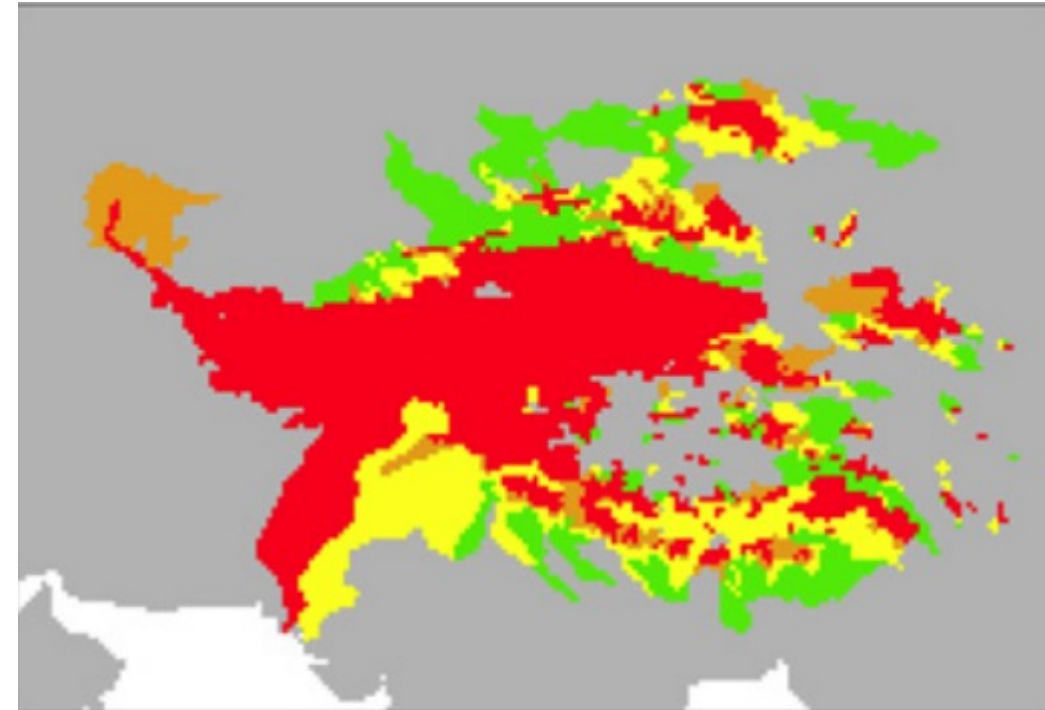
SWARM Motivation

- Much less research has focused on the impacts of climate change on China's water resources. *Glaciers are overlooked* as an important component in water resources.
- There are ~46000 glaciers in China, covering an area of 59,425 km² with est. volume of 5600 km³* and annual runoff of 61.6 km³**.
- *Total glacier area has receded by about 5.5%. (Li et al. 2008, DOI: 10.1016/j.gloplacha.2008.02.001)*
- Glacier melt contribution to river catchments are *variable* (right), but may serve as *important hydrological buffer* during drought years (Pritchard, 2019)

*area-volume estimation

**based on 1980 mass balance modelling

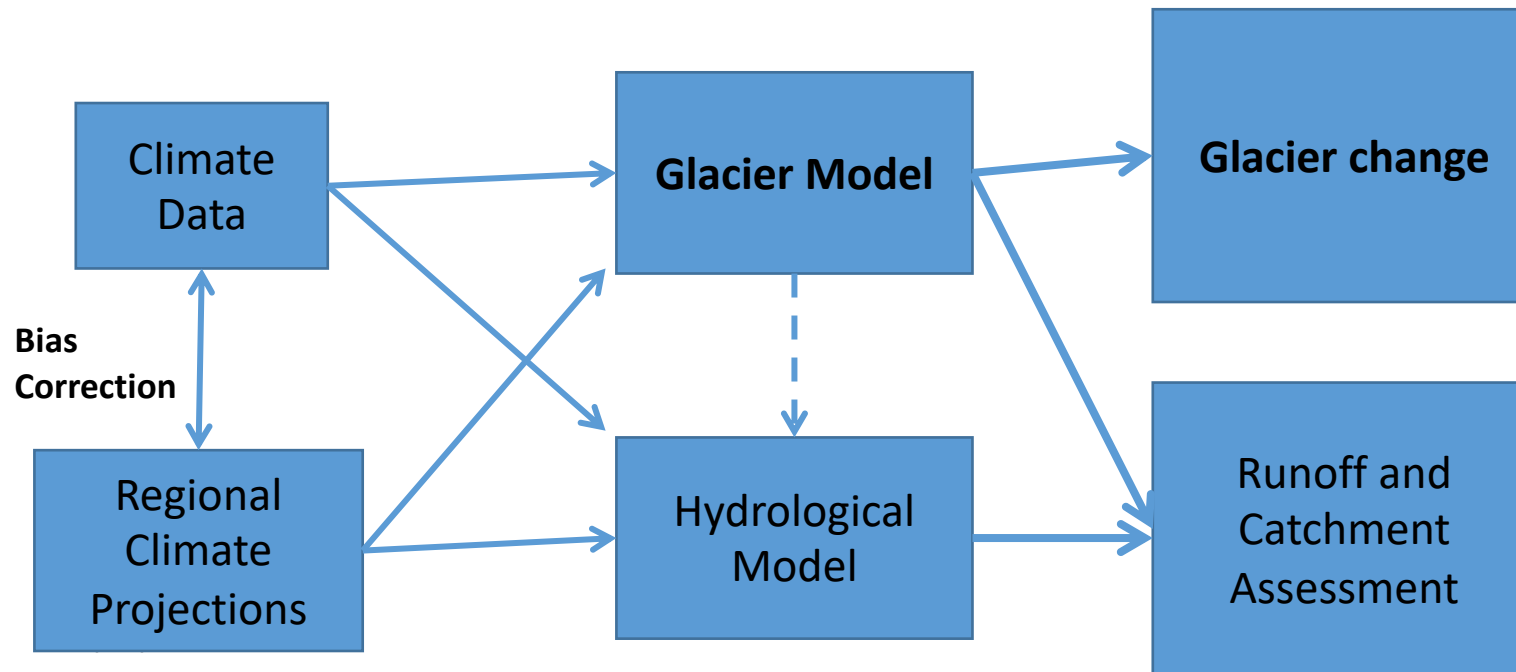
Contribution of glacier melt to basin
(Schaner et al, 2012)



SWARM Aims

Aims of SWARM:

*Use multi-model ensembles to drive a **global glacier model** and **multiple hydrological models** to provide holistic and rigorous assessment of water resources over the whole of China.*

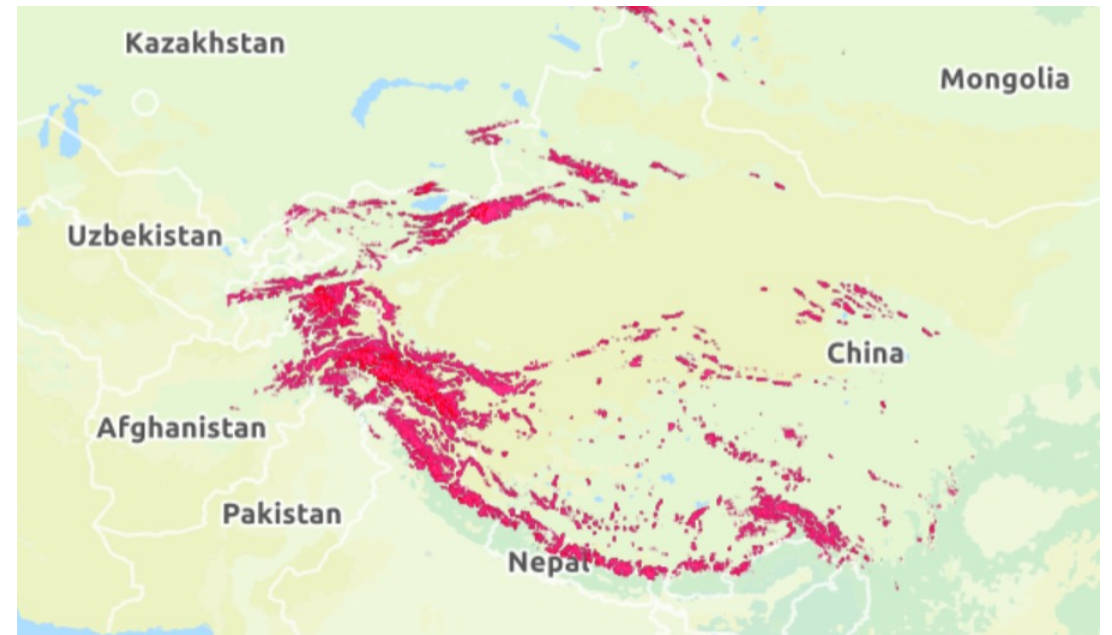


Source: Wan-Jun Yun zeitung@donga.com

Lotsa Glaciers!

A challenge to glacier modelling: there are a lot of them!

- High Mountain Asia inventory: about 90,000 (Pfeffer et al, 2014)
- Including only those in catchments which intersect with China: about 80,000
- **Including only those over 0.15 km²: about 55,000**
 - Accounts for 97% area, >99% volume
 - Emphasis is on glacier *dynamics*; exp. dynamic contribution of smaller glaciers *minimal*

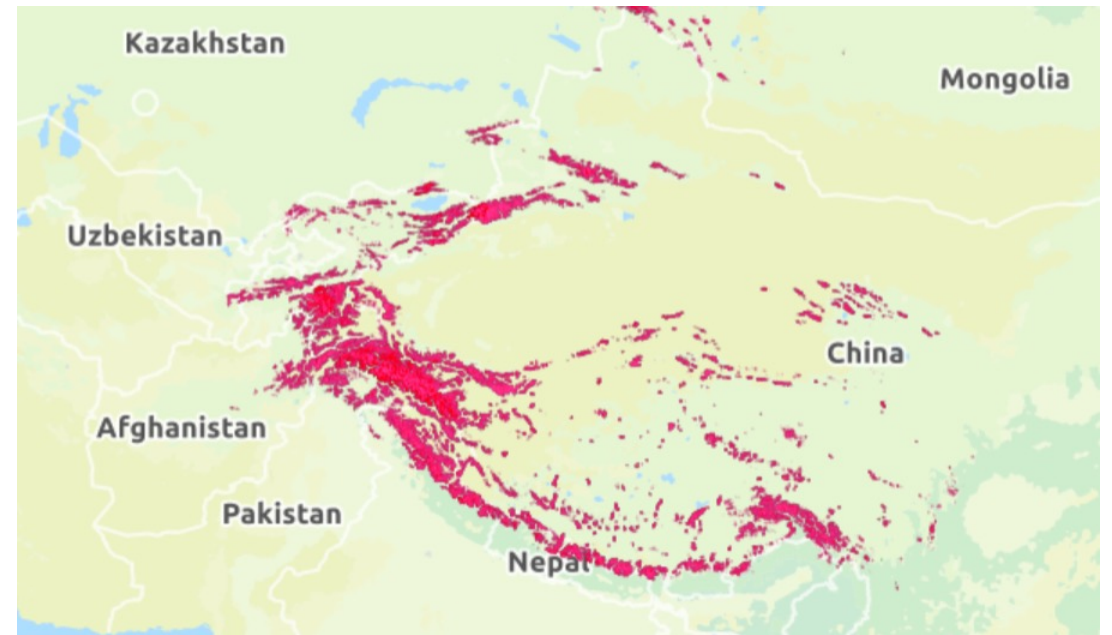


<https://www.glims.org/maps/glims>

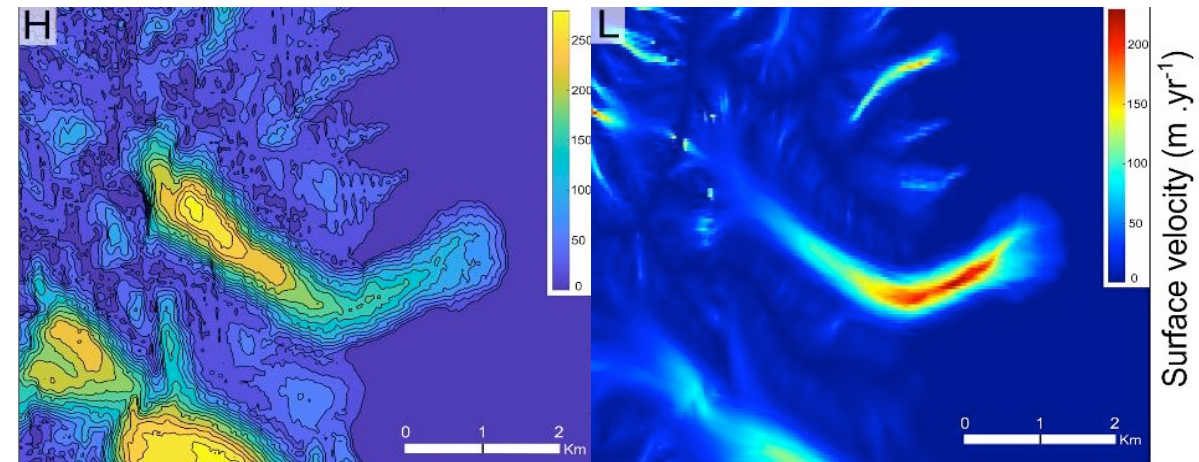
Lotsa Glaciers!

A challenge to glacier modelling: there are a lot of them!

- Simple methods exist to model mountain glaciers
- However, methods become costly when considering 10s of thousands! (Flowline network, rather than 2D Planform, needed...)
- Sourcing of data (thickness, extent, topography, downscaled climate data) also becomes problematic – and needs automation! (Also tributary detection...)



<https://www.glims.org/maps/glims>



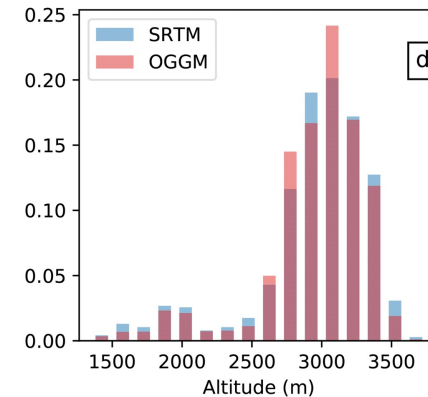
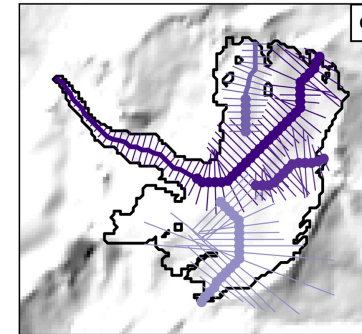
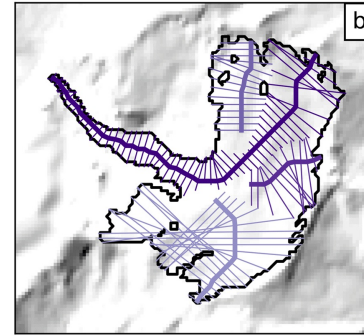
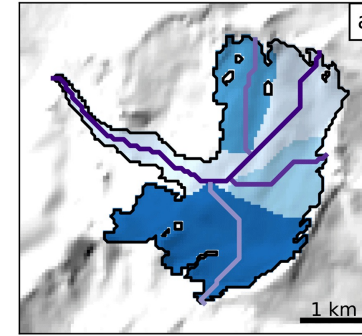
Leger et al, in prep.

Open Global Glacier Model (OGGM)

- A python code designed to automate modelling of large inventories of glaciers (**parallel processing**)
- Glaciers simulated with **Shallow Ice Approximation** on flowline network
- Geometric & topographic data automatically sourced (and climate/GCM data, *unless customized*)

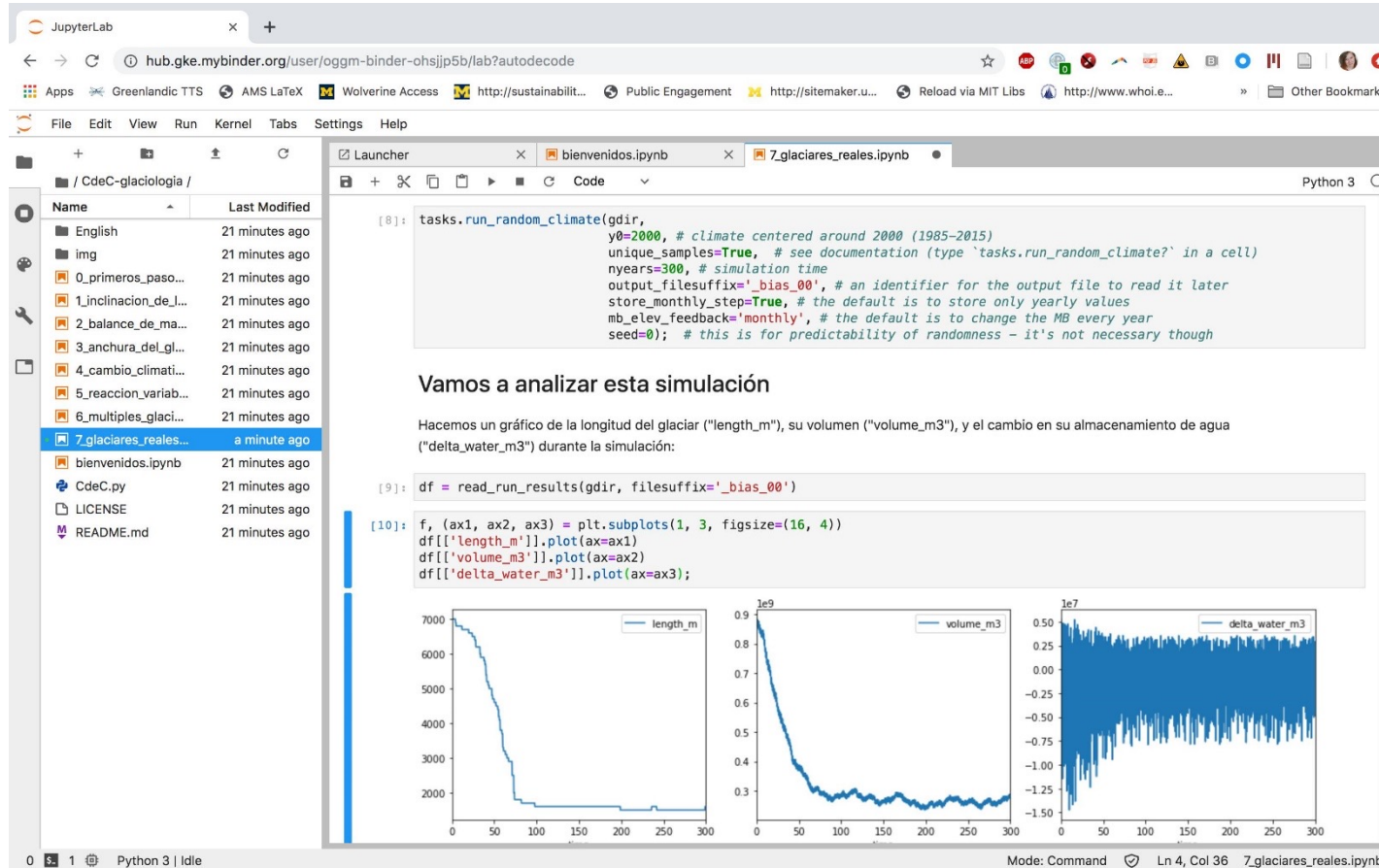
4 Processing Steps:

1. Set up geometry & downscale climate data
2. Calibrate mass balance parameters with “reference glaciers”
3. Invert for thickness from mass balance and surface
4. Time stepping → Results



Maussion et al, 2019, GMD

Aside: OGGM online



- OGGM can be run remotely through provided notebooks with tutorial examples (oggm.org)
- However, for 55,000 glaciers, one must install on a powerful computer (or HPC)

2. Calibrate mass balance parameters with “reference glaciers”

OGGM Mass balance equation: $m(z) = p_f P_i^{solid}(z) - \mu(T_i(z) - T_{melt}, 0)$

p_f and T_{melt} : Global parameters

μ (degree-day factor): per glacier, *must be calibrated*

Simple approach: Using climate data, calibrate μ for subset of *reference glaciers with known MB*, and interpolate
However, μ is too complex for this to work well!

Complicated approach: t^* Method of Marzeion et al 2012

1. For each year (t), find μ such that net MB is zero in this year
2. Determine bias of MB observations using $\mu(t)$
3. μ^* : μ with smallest bias; t^* is corresponding t
4. Interpolate t^* from reference glaciers to non-reference glaciers

Rationale: optimal t^* should be when the glacier was actually stable, and it is assumed nearby glaciers were as well

2. Calibrate mass balance parameters with “reference glaciers”

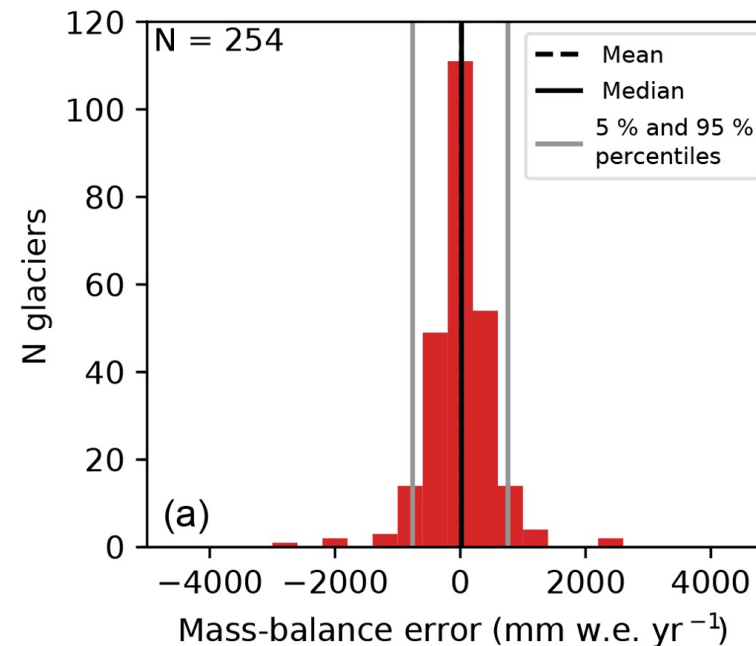
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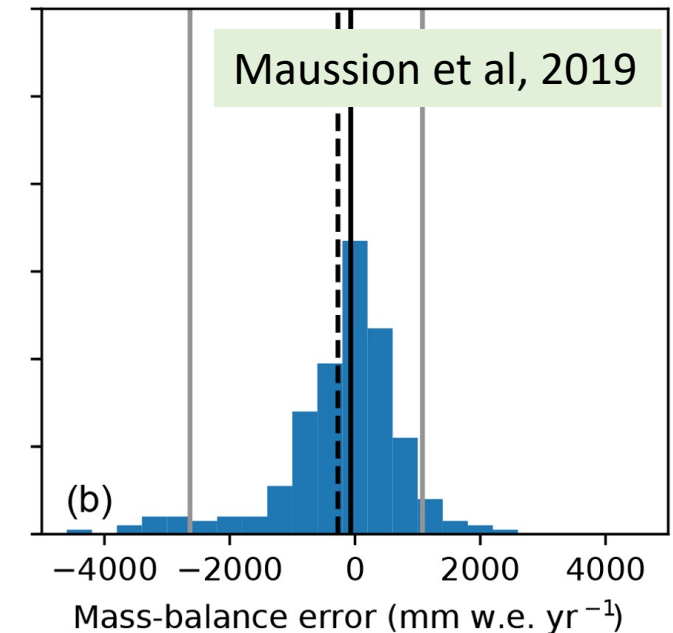
μ (degree-day factor): per glacier, *must be calibrated*

Importantly, error of calibration can be checked with **“Leave One Out”** calibration on the reference glacier sample

Results for *global calibration* with **Hadley CRU TS** data:



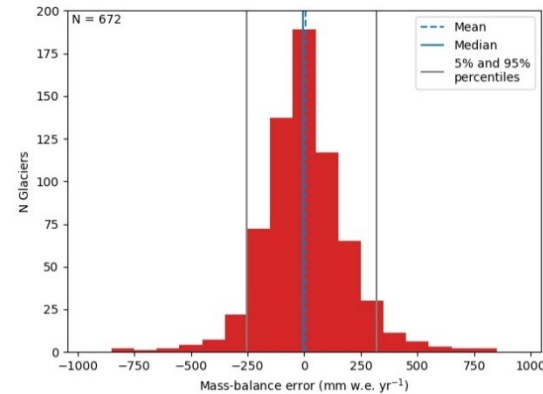
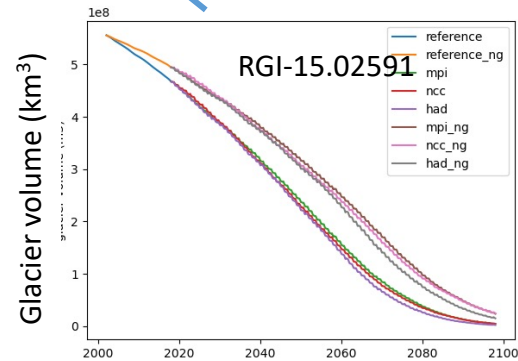
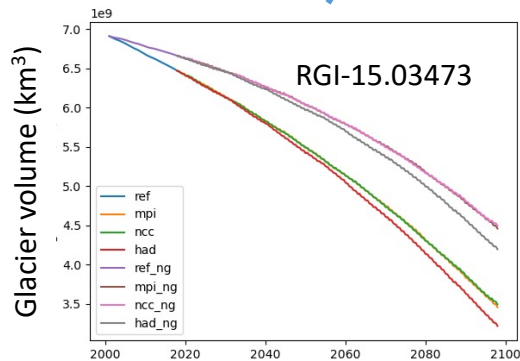
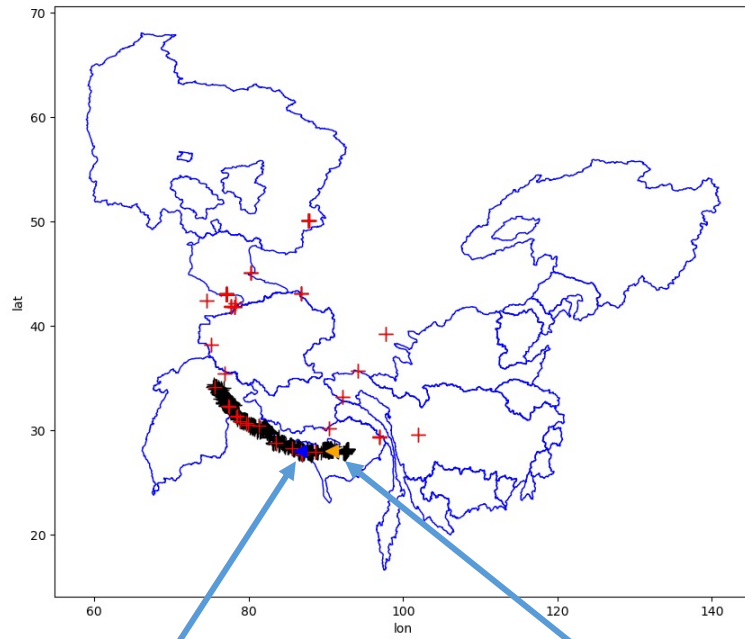
Interpolating t^*



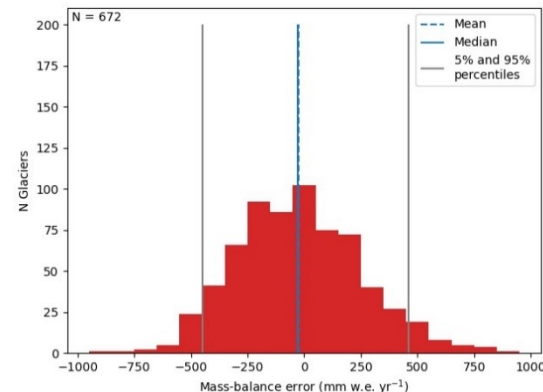
Interpolating μ^*

2. Calibrate mass balance parameters with “reference glaciers”

- OGGM uses WGMS reference glaciers (48 within HMA region)
- Addition of Geodetic Mass Balance constraints (Maurer et al, 2019, NSIDC) increases calibration glaciers from 48 to 672
- Clustered predominantly in Himalaya
- Has large effect on *some* glaciers
- *Approximately 3,000 glaciers across region could not be calibrated**



Cross-validation results with WGMS + Geodetic reference glaciers



Calibration with WGMS, tested on WGMS+Geodetic

*Possibly result of short duration of reference climate data

2. Calibrate mass balance parameters with “reference glaciers”

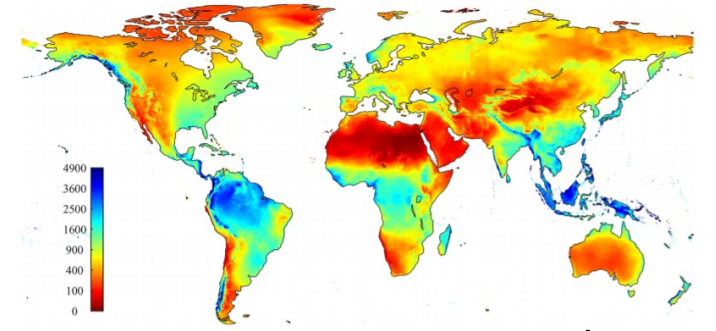
“Reference” Climate data:

- Used to calibrate OGGM degree day factors
- Also used to force “reference period” glacier simulation

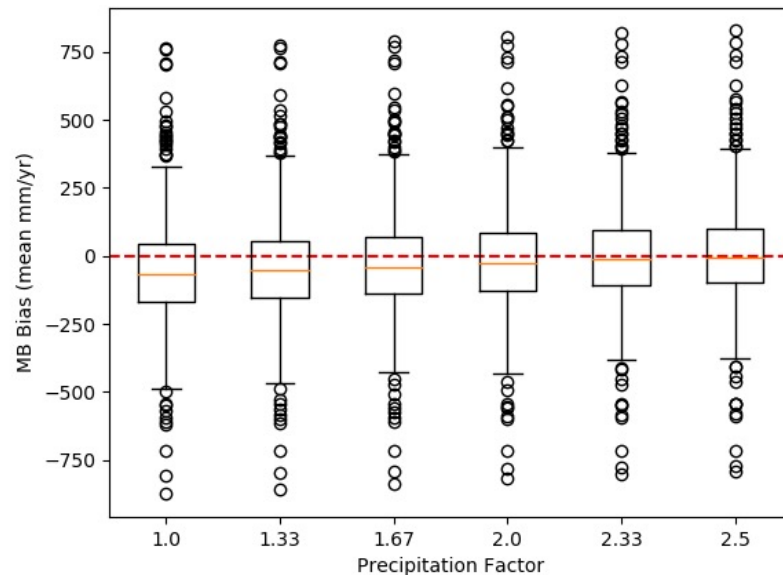
Temperature: ERA5

Precipitation: Multi-Source Weighted-Ensemble Precipitation (Beck et al, 2019)

Time Period : 1979-2019 (not ideal for t^* method, but accurate)



Beck, 2017

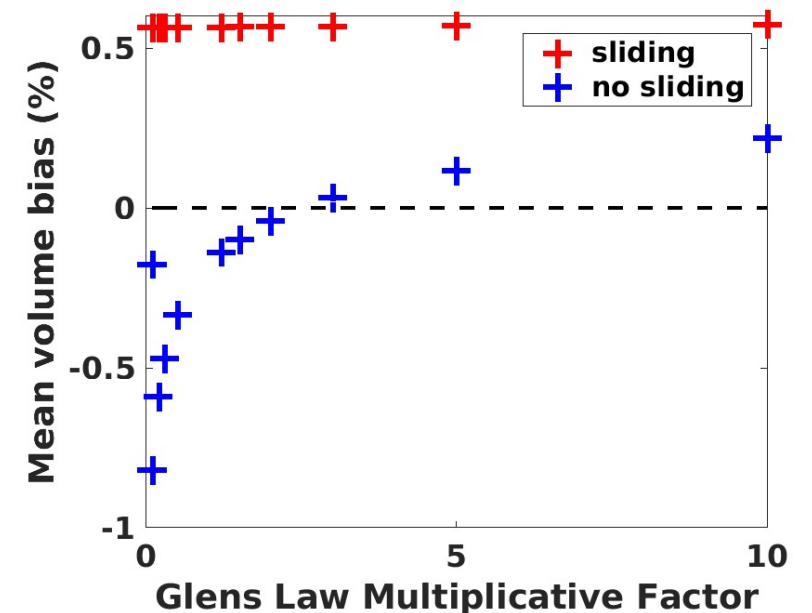


Calibration of global parameters

- p_f (precipitation factor)
- T_{melt} (melting point of prec, -1.8 C)

3. Thickness inversion

- Glacier thickness needs to be estimated for ALL glaciers in order to model dynamics
- Method very similar to Huss and Farinott 2012:
 - (a) mass flux estimated from Mass Balance
 - (b) thickness found from glacier flow law
- *Potential inaccuracy with debris covered glaciers (Bisset 2020)*
- Flow law parameters must be calibrated *(globally)*
 - For present study, Farinotti (2019) consensus estimate used as “truth”
 - 500 glaciers sampled and mean bias minimized
 - Lack of sliding (or minimal sliding) produces a better fit (possibly due to Farinotti method)



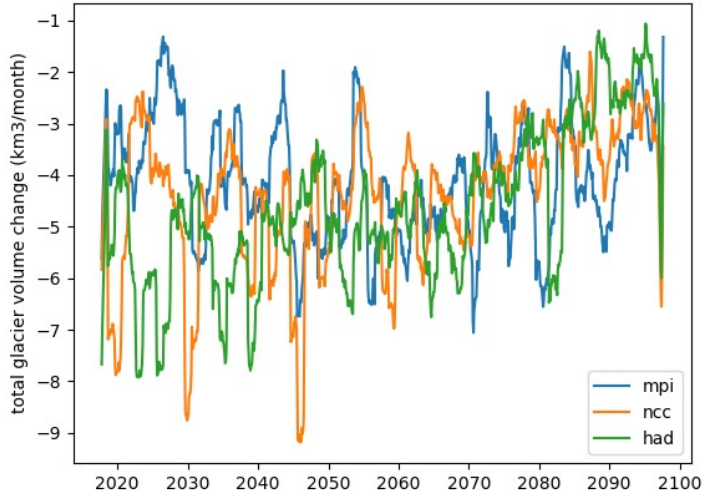
4. Simulation / Results

Region-wide time series, forced with CORDEX-EA 8.5 Bias-corrected Sub-Ensemble

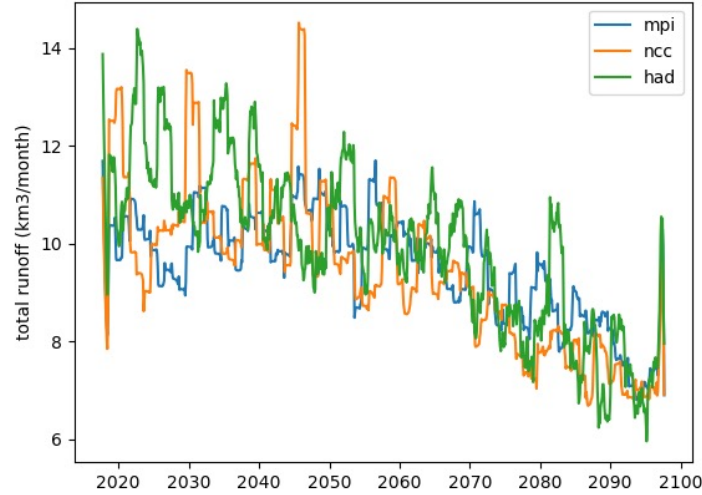
ncc = NorESM

Had = Hadley Centre Model

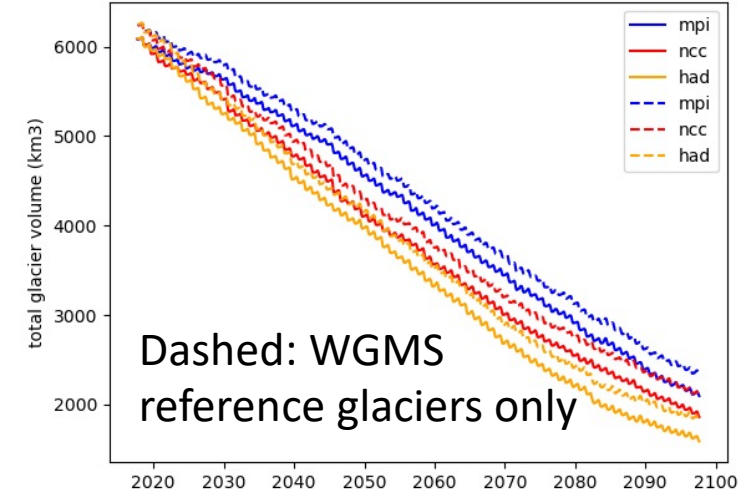
mpi = Max Planck Inst



Total HMA* monthly glacier volume change, km³



Total HMA* monthly runoff, km³



Total HMA* volume, km³

*Excluding glaciers outside China catchments

- Runoff is **not provided** by OGGM but is calculated on monthly basis from **precipitation, area, and volume change diagnostics**, and transformed from per-glacier to grid.
- Total volume loss is in line with that of another study (Rounce et al, 2020) which used CMIP5 RCP8.5 as forcing (but geometric scaling rather than dynamics)**

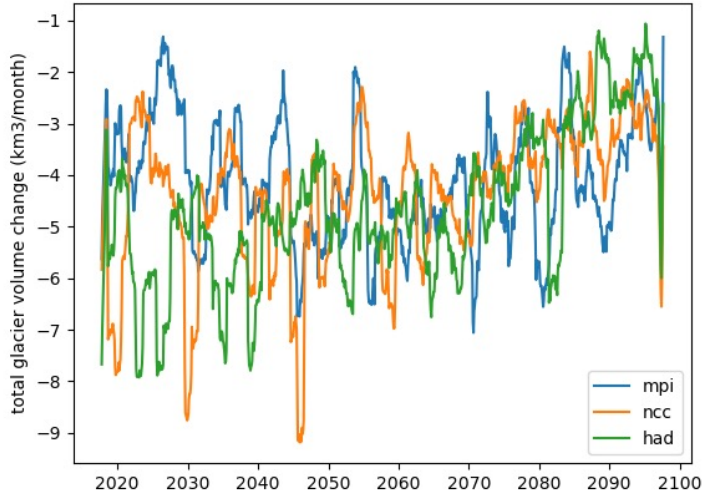
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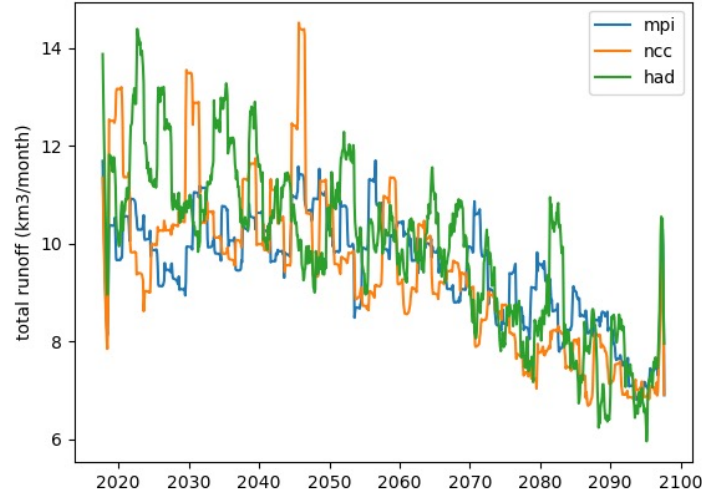
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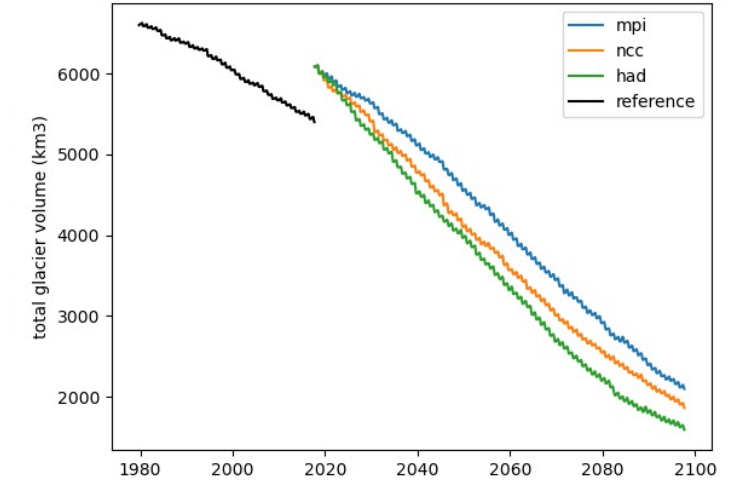
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Total HMA* monthly glacier volume change, km³



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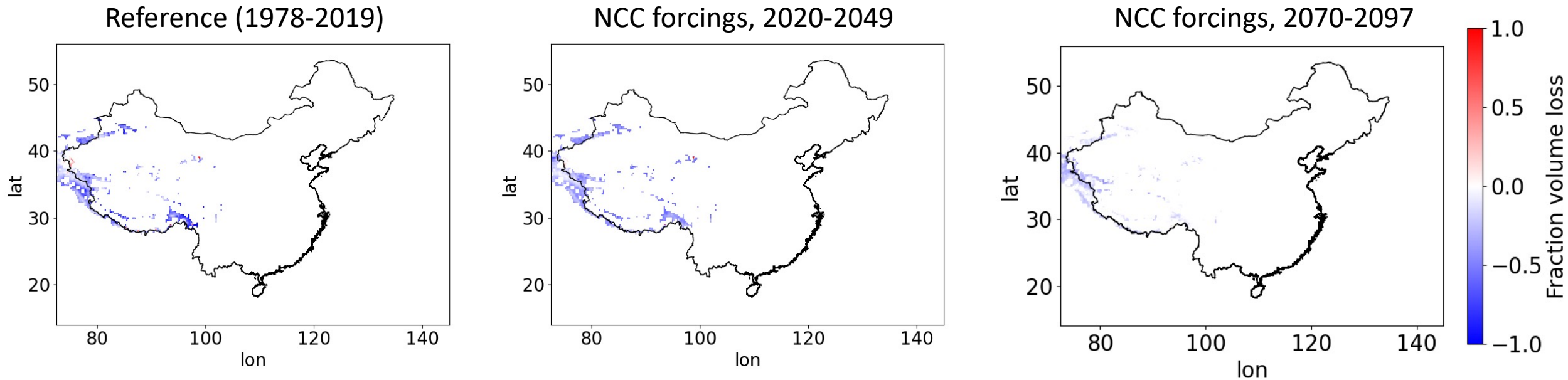
Total HMA* volume, km³

*Excluding glaciers outside China catchments

- Volume change shown for reference period: **DISCONTINUITY** is because in projections, each glacier is started from its RGI date – but reference run is from 1979
- Reference period loss in broad agreement with remote sensing estimate ~19 Gt/yr (Shean et al, 2019)

4. Simulation / Results

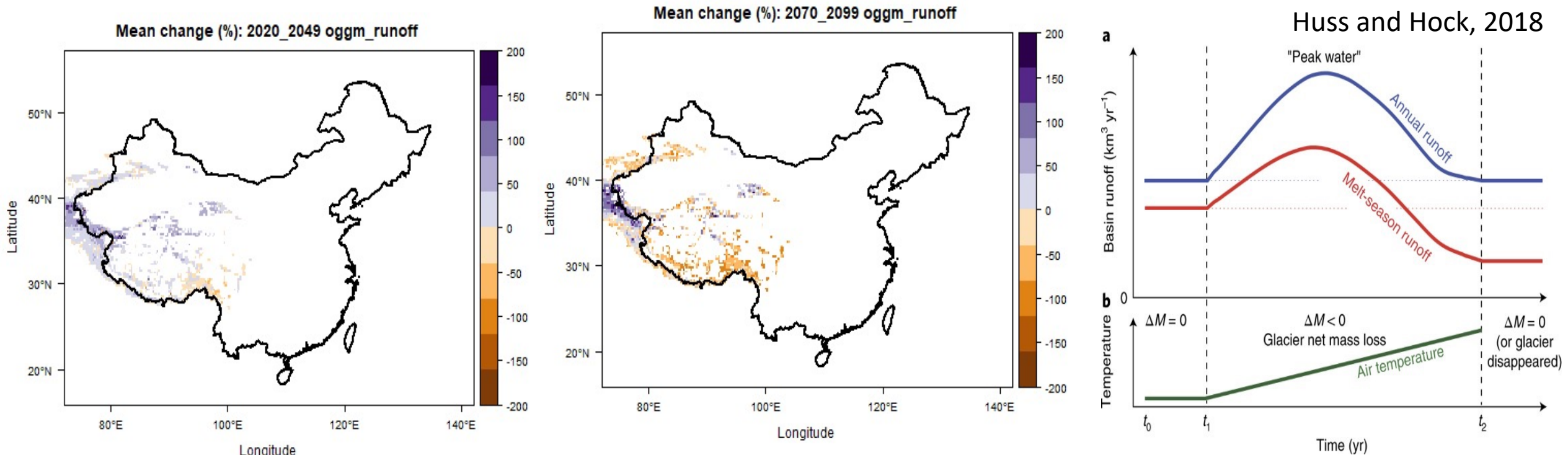
Gridded Glacier volume loss (percentage) on 0.25 x 0.25 grid



- Small loss / slight gain in Karakoram/Pamir in reference period, but largest losses mid-century
- Large losses in Himalaya initially but decreasing over 21st century (glaciers disappearing?)

4. Simulation / Results

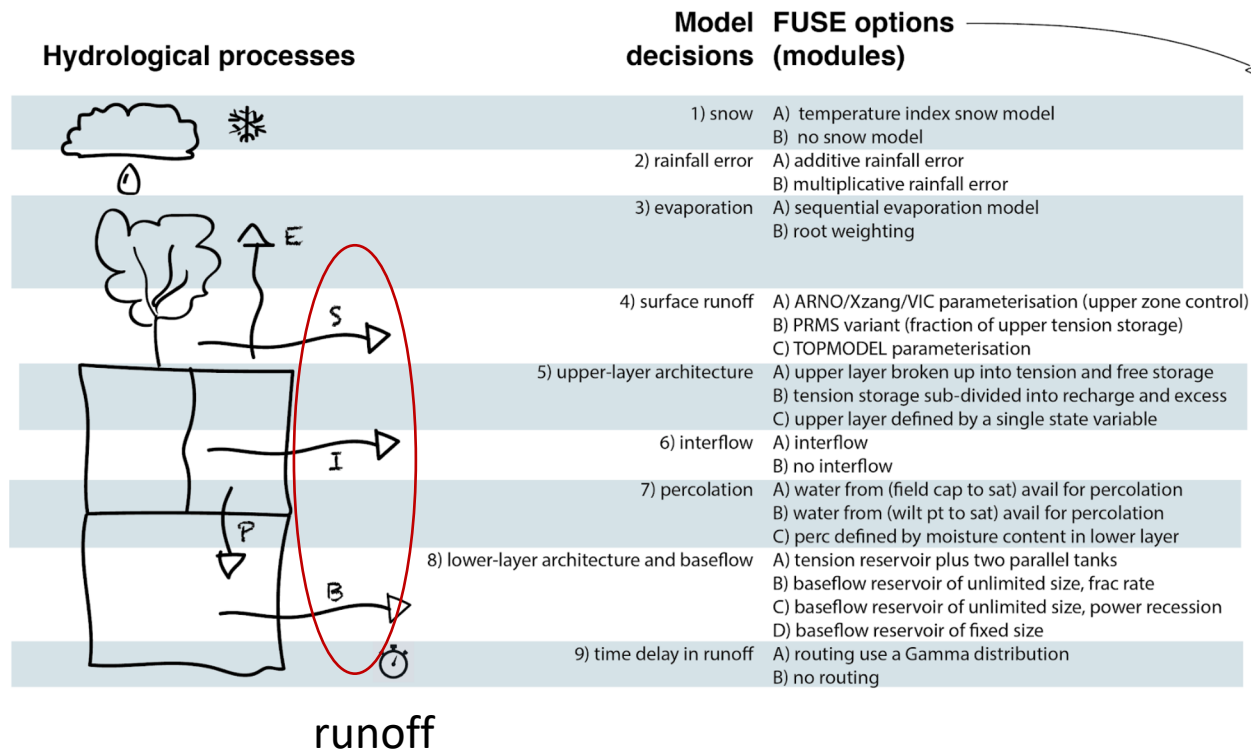
Gridded Glacier runoff changes – comparison with Reference Period (1978-2019)



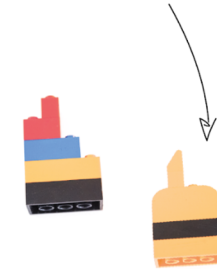
- Glacier runoff calculated as (negative mass change) + (glacier area x precipitation)
- Most areas appear to reach “peak water” early in 21st century (aside from Karakoram/Pamir)

FUSE model

Framework for Understanding Structural Errors (FUSE): A modular framework to diagnose differences between hydrological models. Clark et al (2008, Water Resources Res.)



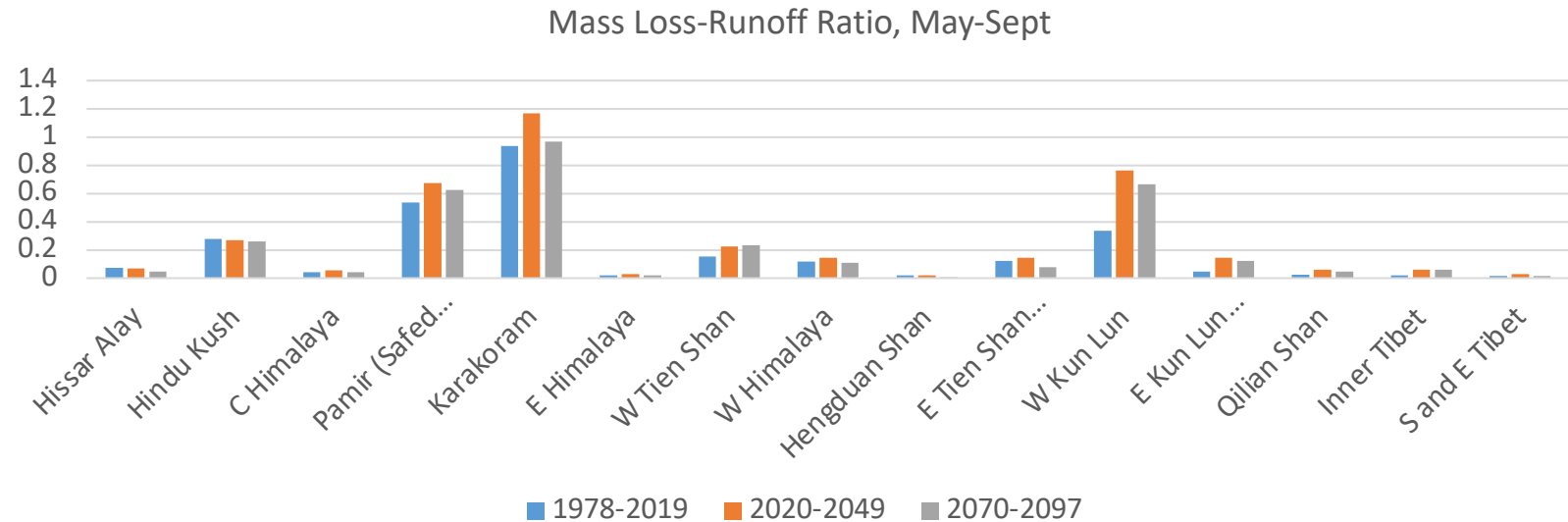
These modules were combined to mimic 3 well-established hydrological models.



- FUSE forced with same Climate Data and Climate Model outputs as OGGM
- Enables systematic comparison of Glacier mass loss with hydrological runoff
- (routing/discharges available in progress)

5. Glacier mass balance and Hydrological Runoff

- **Glacier loss importance by RGI 2nd order region**
- **Runoff: calculated by FUSE model, scaled by non-glaciated area**
- **Glacier loss is NOT equivalent to melt* – but in May – September it is likely close**



*OGGM does not provide liq/solid precipitation

Conclusions and Further Work..

- OGGM modelling tool seems appropriate for large-scale modelling of HMA glaciers
 - In terms of total mass loss, historic mass loss similar to that observed from remote sensing, and projections similar to other modelling approaches
 - Improving calibration has a large per-glacier effect, but a minor effect at regional level
- Over majority of region, mass loss decreases over the 21st century (“peak water”) but in western regions (Pamir, Karakoram) there is increase

To do:

- Forcing with CMIP6 Downscaled climate model output
- Characterisation of glacier importance to basin-scale discharge