New developments in the Canadian Hydrological Model (CHM) and large-extent simulations

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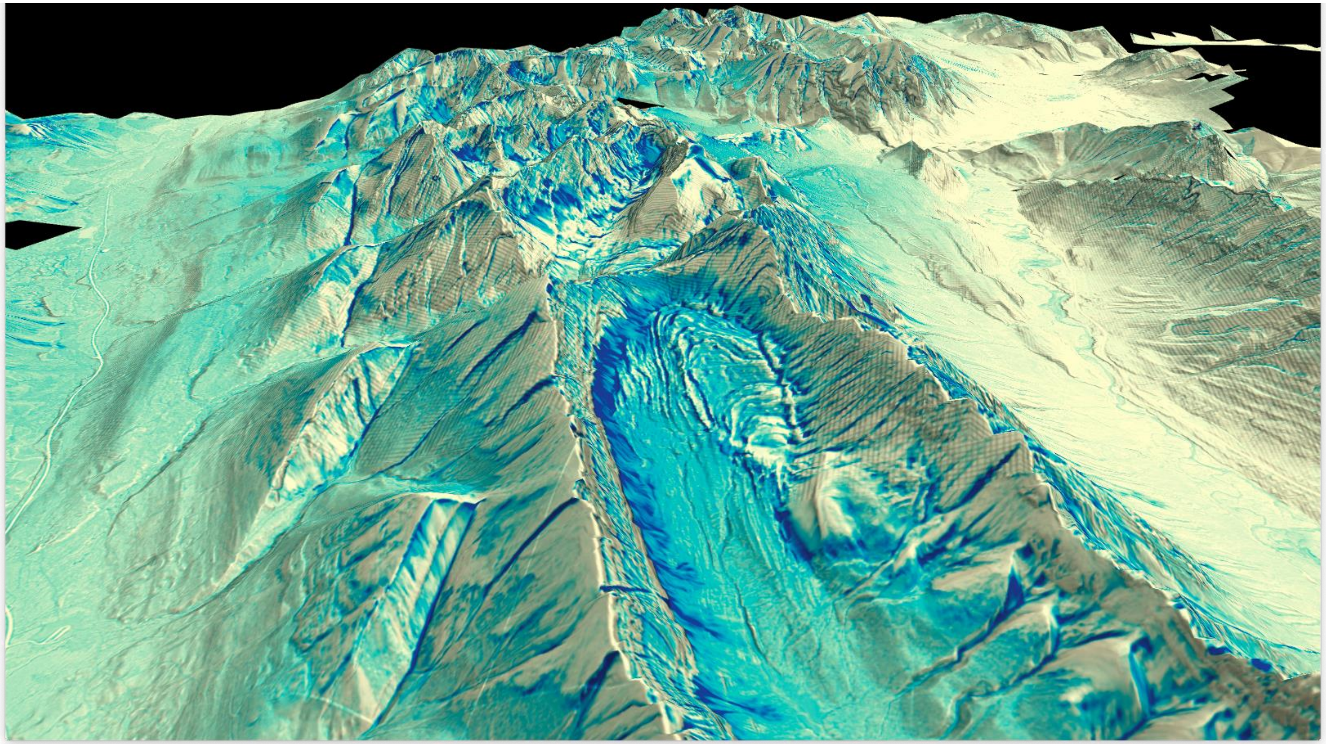
Motivation

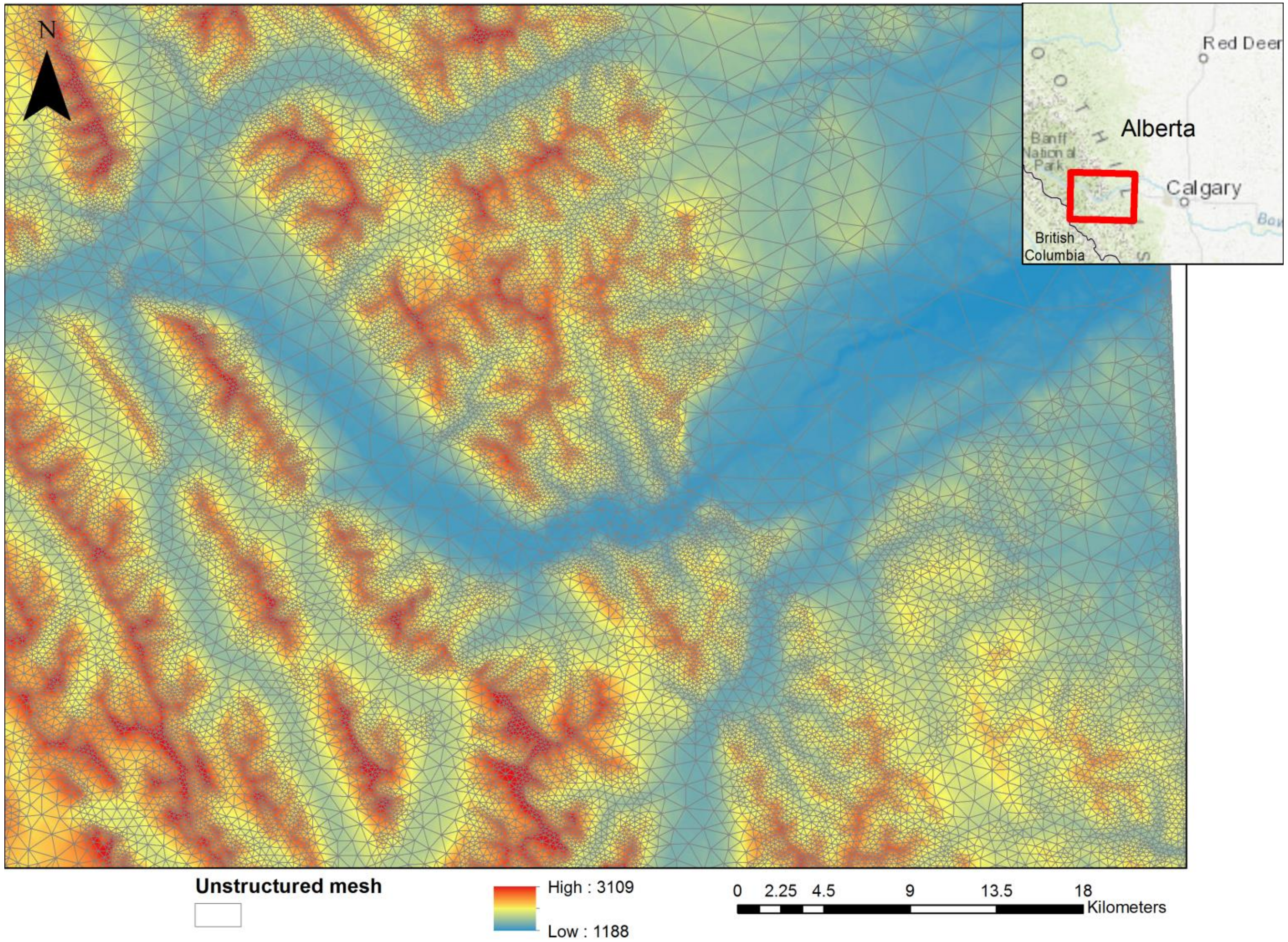
- Water models need to account for the substantial spatial and temporal **heterogeneity in mass and energy fluxes, especially in mountains**
- Heterogeneity of the seasonal snowpack motivates the use of **“snowdrift permitting”** (0.1m – 200m) scales for distributed predictive models (Vionnet, et al., 2021)
- Estimating spring snowpacks over areas >1M km^2 critical for quantifying late lying snowpacks



5-m 3D map of snow depth derived from **airborne Lidar** over the Kananaskis region (Alberta), Canada on 27 April 2018

Canadian Hydrological Model (CHM)

- **Variable resolution triangular mesh** depending on topography, soils, vegetation
- Large decrease in computational and data demands over rectangular gridded models
- Algorithms for downscaling meteorological data
- CHM currently accounts for:
  - **slope** and **aspect**; terrain **shading**
  - **Variable wind** fields
  - **gravitational redistribution (avalanches)**
  - **blowing snow (**redistribution + sublimation**)**
  - **Snow interception and sublimation** from forest canopies
  - **energy balance** snowmelt as impacted by complex terrain and forest cover
  - Snowmelt runoff

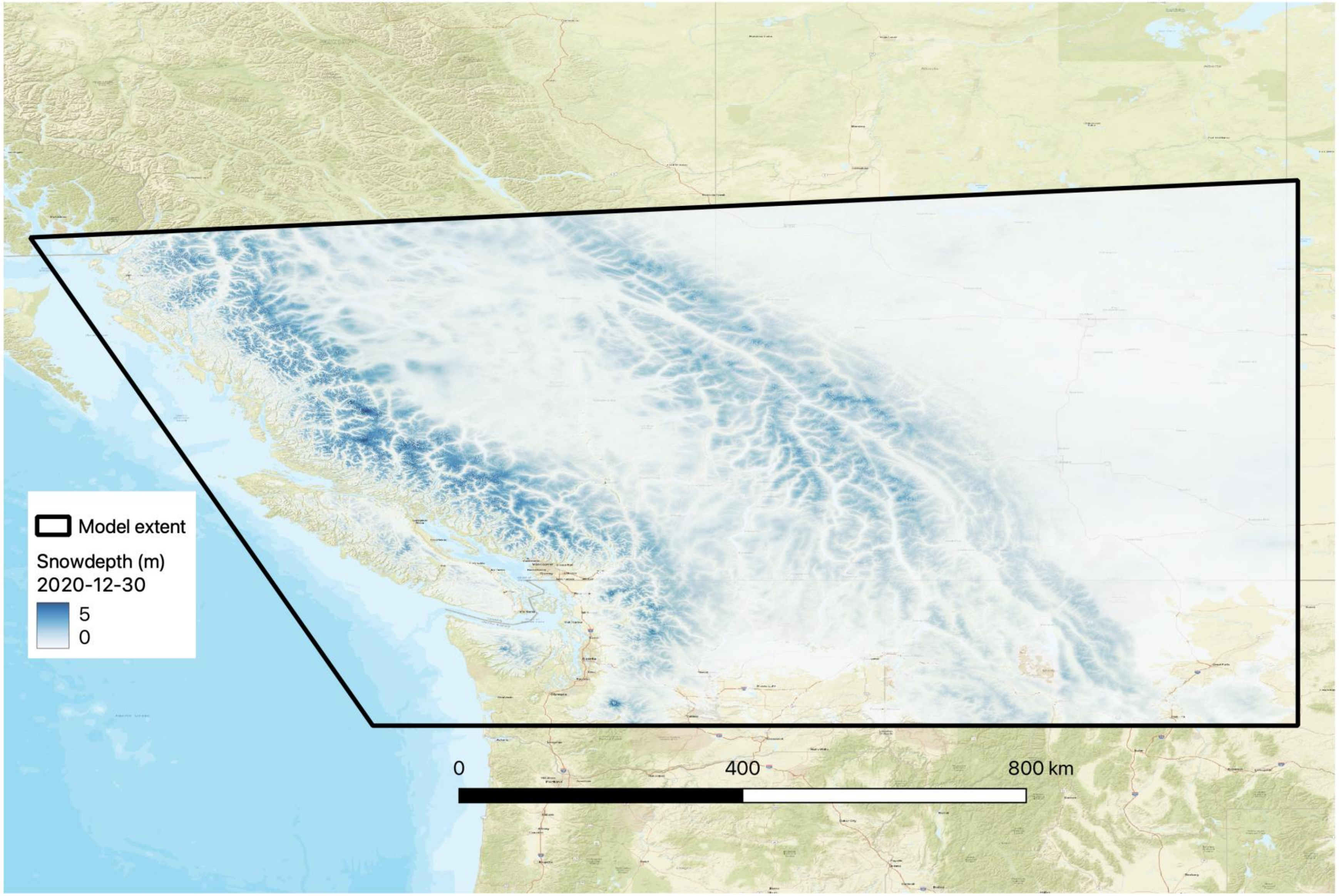


Marsh et al. (2019)

Simulation domain

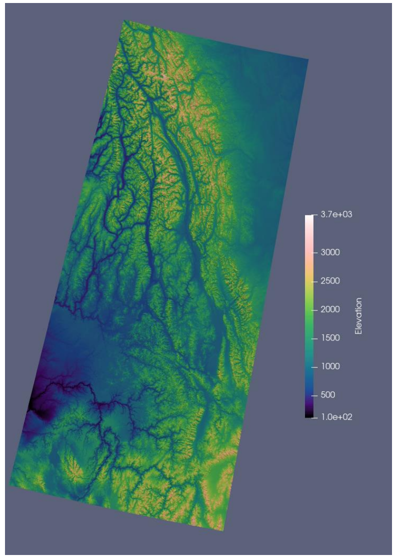
- Large extent snowpack modelling
  - ≈ 1.3M km^2
- 3B raster cells reduced to 34M triangles
  - **Minimum 50m length scale**
  - Elevation + canopy + water
- Downscale ECCC HRDPS 2.5 km forcing
  - 1hr time step
- Oct 2020 – June 2021
- Same model configuration as Vionnet et al, (2021)

- Blowing snow, avalanching, canopy interactions, energy balance snow model
  - FSM + PBSM3D
  - Snobal + PBSM3D
- 800 CPUs, ~20hrs wallclock

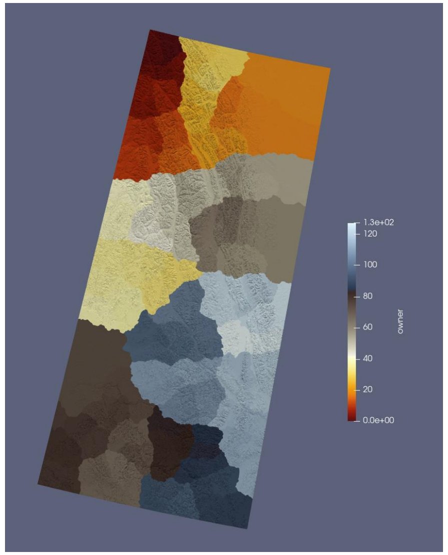


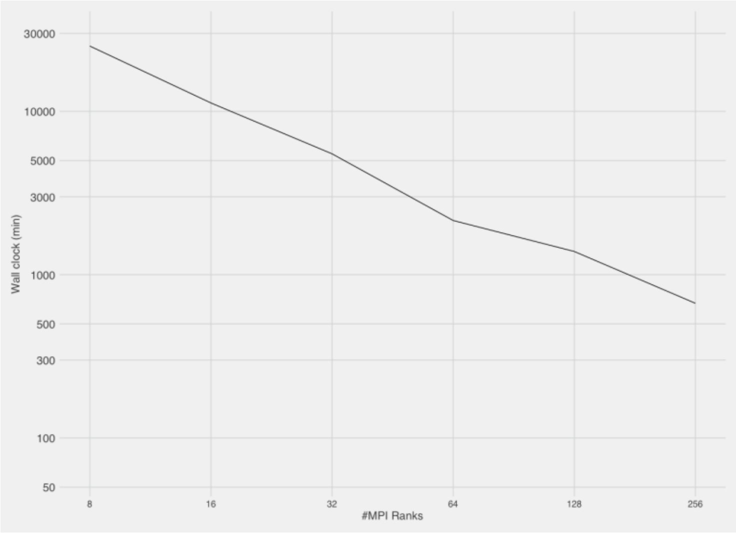
Key challenges and innovations

- Requires high performance computing paradigms and process representations
  - Implemented a new **domain partitioning scheme** for optimal Message Passing Interface (MPI) throughput
  - New **MPI-compatible version of SnowSlide** (Bernhard and Schulz, 2010)
    - Parallel scheme that tracks mass transport across partitions
  - Lower memory footprint to allow more processes per node
  - Solve blowing snow linear system using **Trilinos solver**
  - Parallel regridding via ESMF
    - Triangles -> Grid

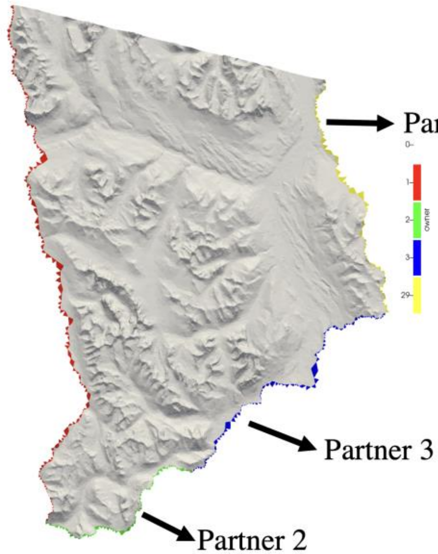


Domain Partition →





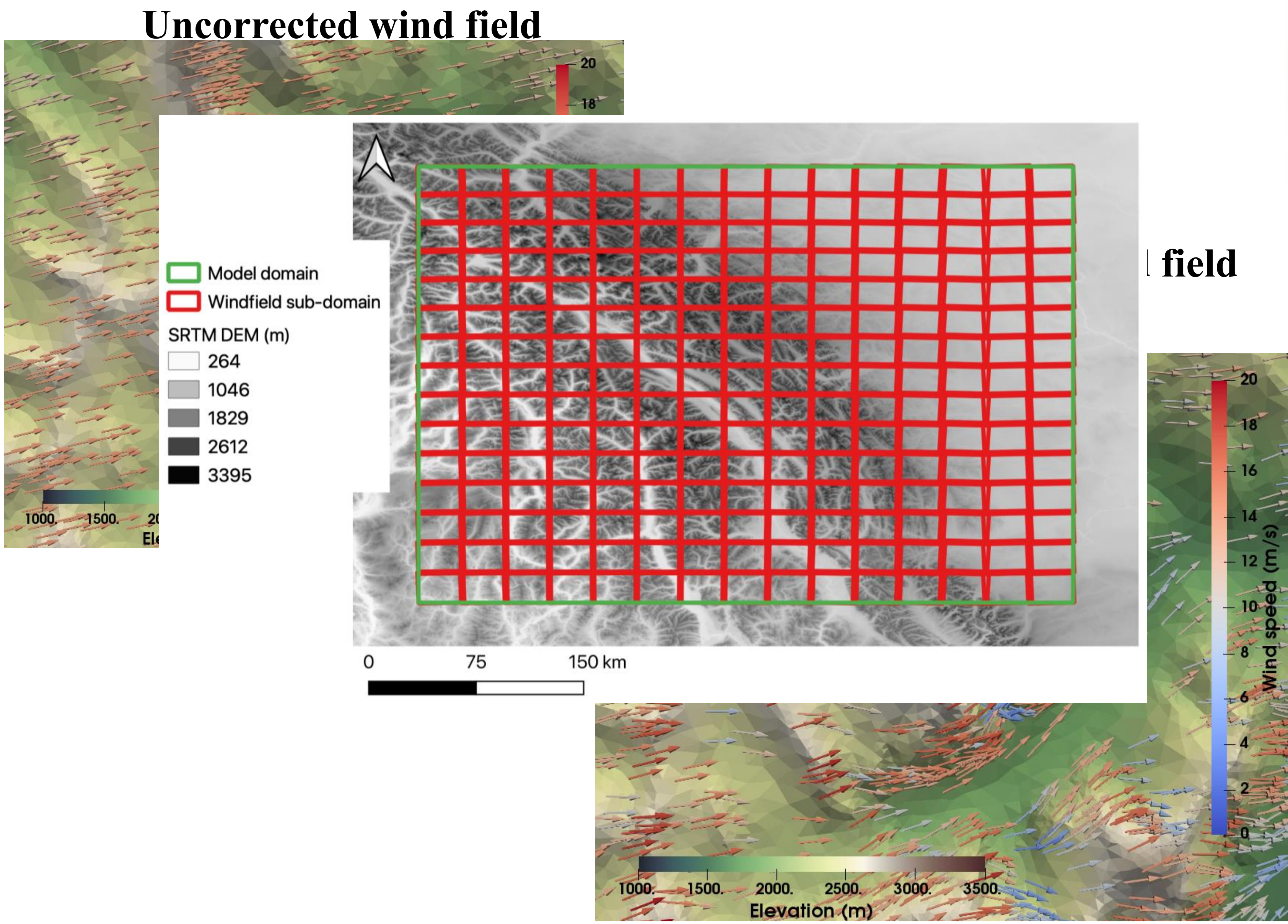
Near linear runtime scaling of CHM.
Doubling available CPUs leads to halving total runtime



Inter-node communication

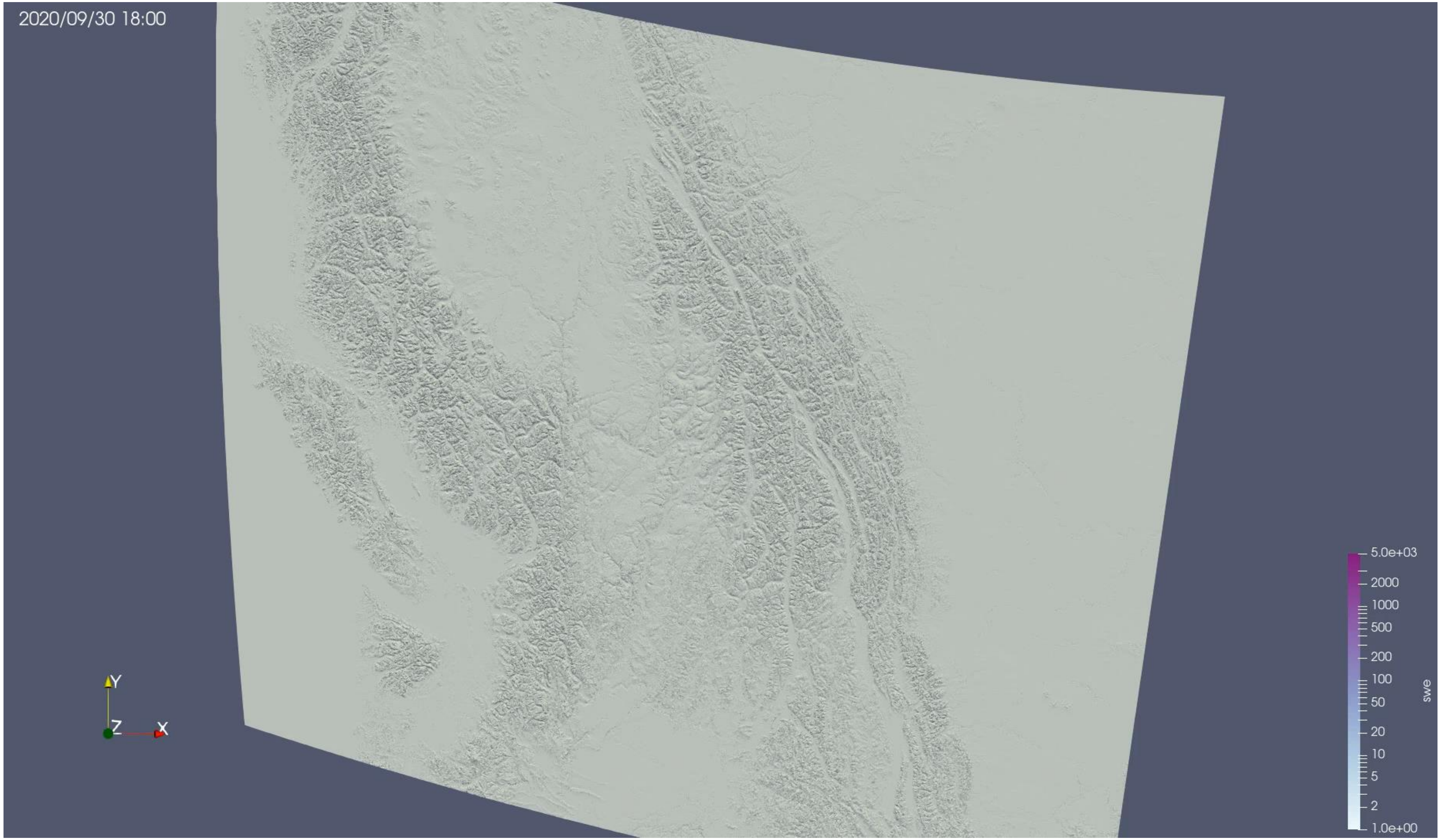
WindMapper

- Key challenge for water modelling in mountains is forcing the model with realistic wind fields
- Use CFD model WindNinja to produce wind speedup map library for *N* directions
- Winstral, et al. (2002) Sx parameter to identify leeward recirculation zones
- Model agnostic Python library
- Full description Marsh, et al. (2022; submitted)



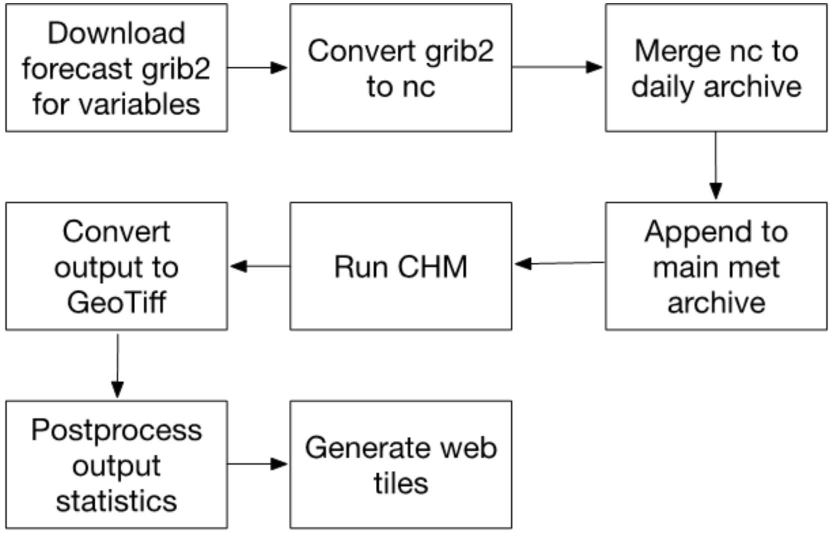
Regional Snowpack Simulation

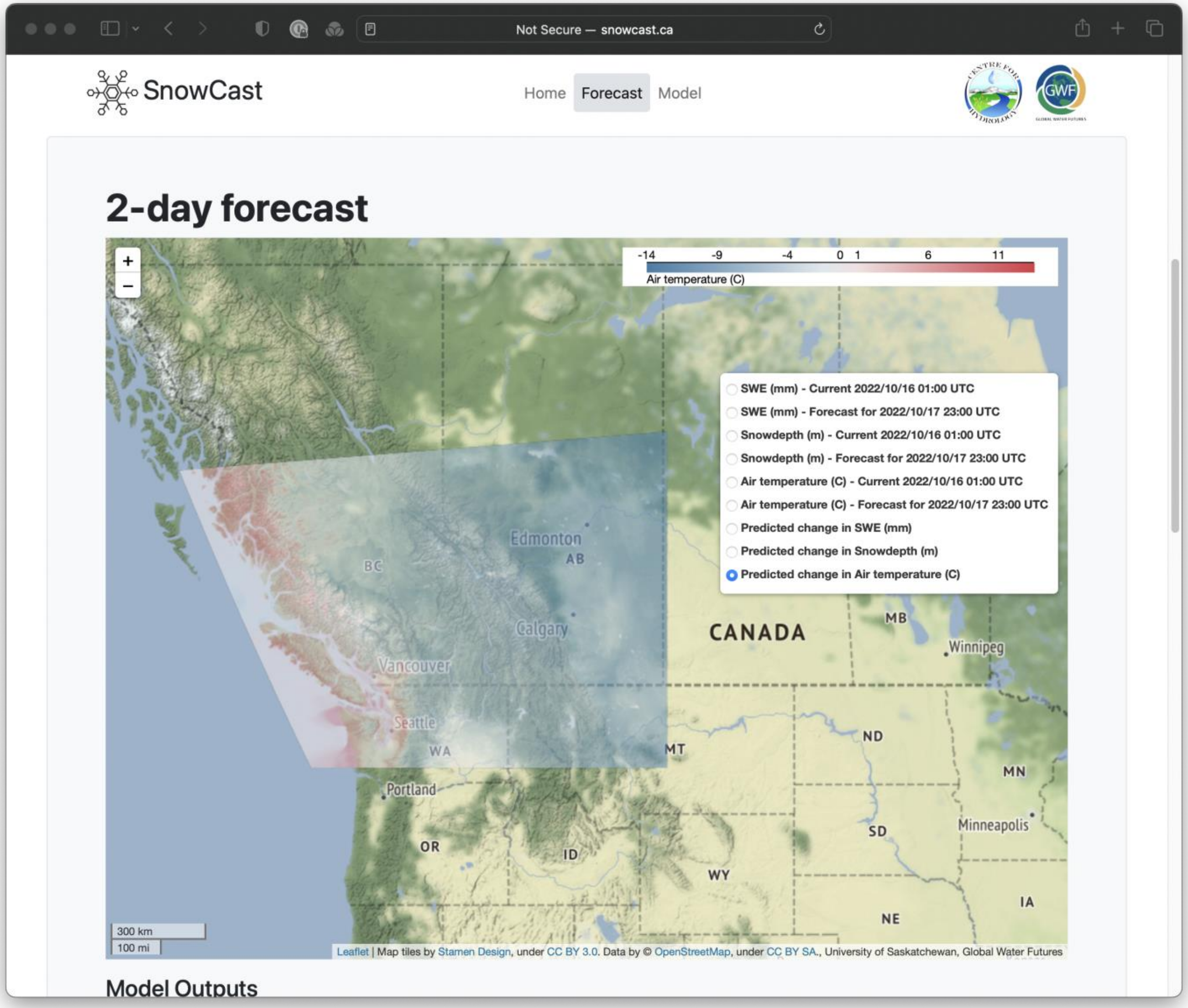
- Includes: blowing snow, avalanching, canopy processes



SnowCast

- Nightly runs of CHM
  - Incl. blowing snow @ 50 m length scale
- ≈1.3 km^2
- CHM forced with 2-day, 2.5 km meteorological forecasts from ECCC's High Resolution Deterministic Prediction System (HRDPS)
- Zoomable Leaflet-based webUI



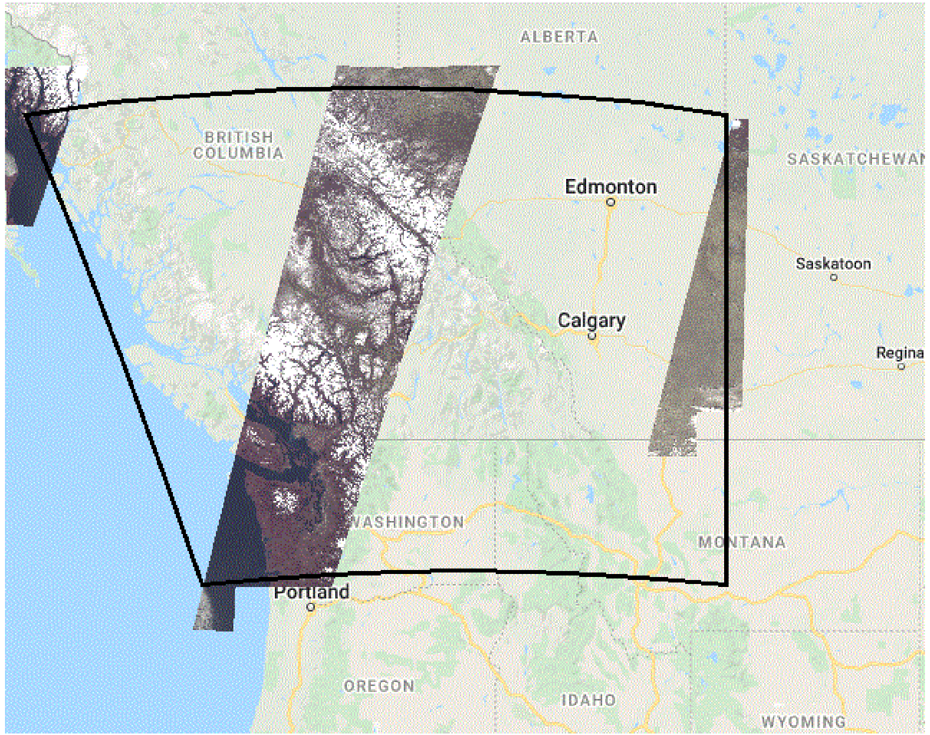


Snowcast.ca

Predicted Snowcovered Area Evaluation

1. Weekly SCA from Landsat 8 (LS8) + Sentinel2 (S2) resampled to 150 m
2. Cloud, water, shadow, and forest in S2 imagery masked out
3. Corresponding grid cells of HRDPS-CHM output extracted to match weekly extent of images

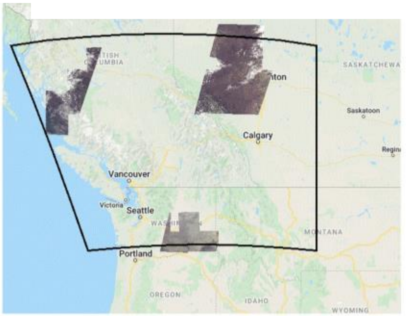
- Note: each week will have a different set of images



CHM domain in grey, weekly acquisitions shown

SCA Results

Gaps are due to a post processing issue



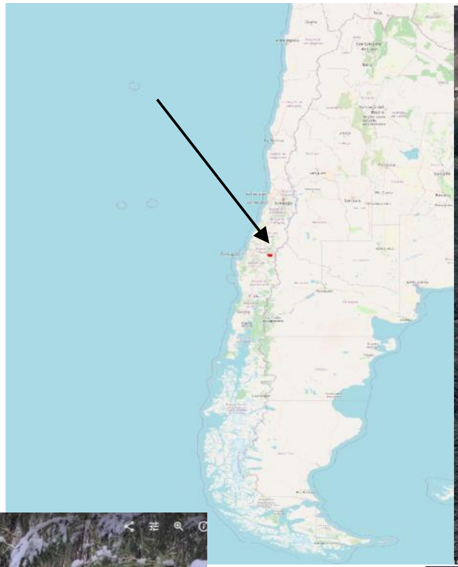
Oct.. 1 2020

Apr. 15 2021

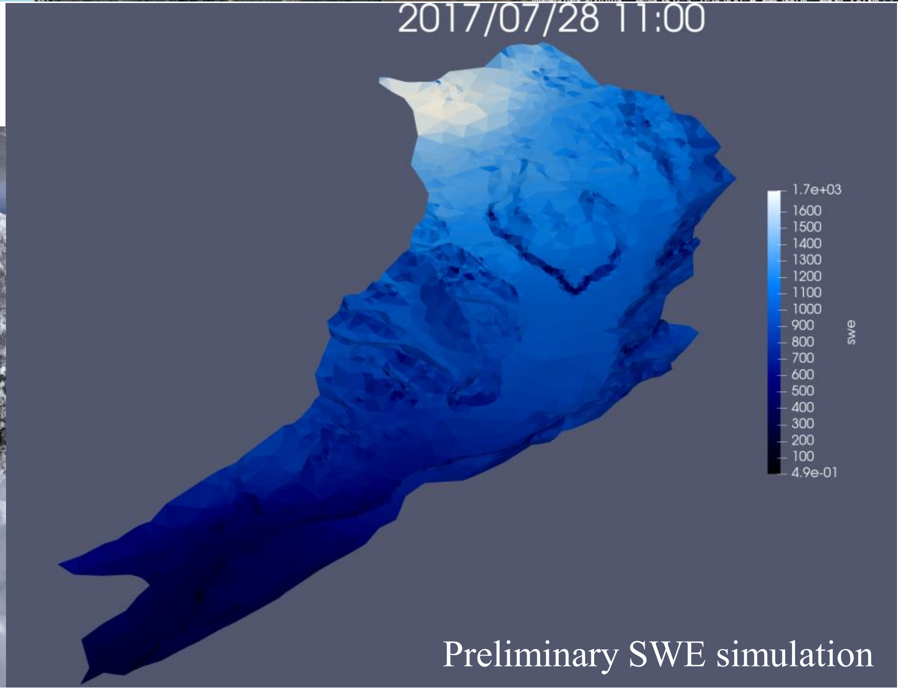
Jun. 30 2021

Cuenca Renegado, Andes

- Collaboration with Sebastián Krogh and Lucia Scaff
- COPE basin
- Met
  - South America Affinity Group (SAAG)
  - Historical 20yr WRF 4km
- Preliminary research questions:
  - Can CHM provide reliable SWE estimates in this catchment?
  - Are new vegetation parameterizations required?
- Evaluation:
  - Snow transects
  - Ground-based Lidar



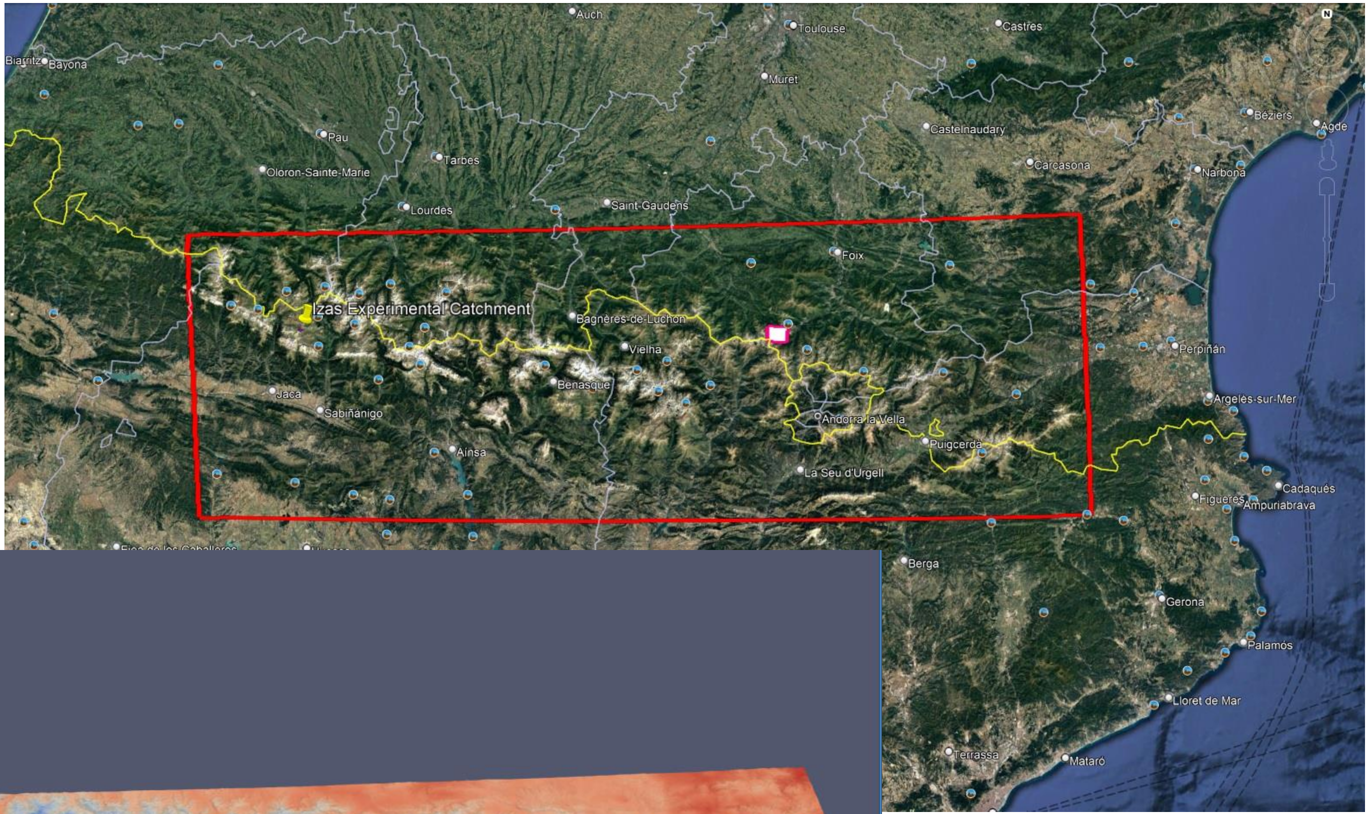
Photos: Seba

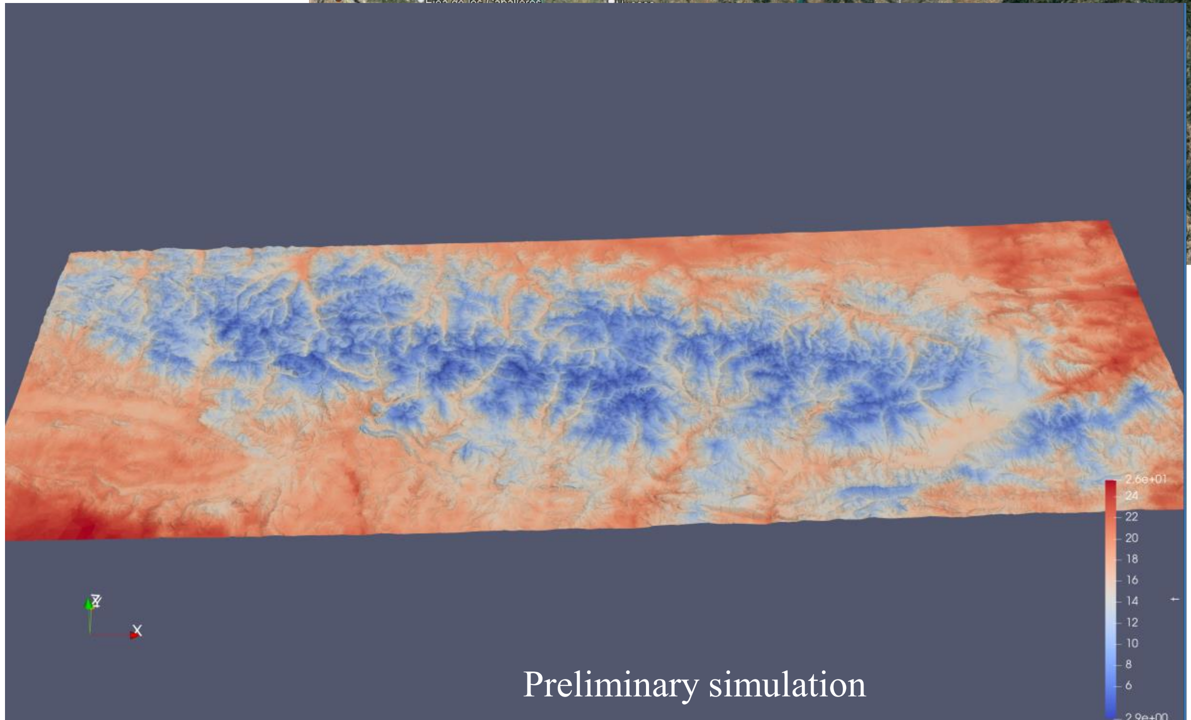


Preliminary SWE simulation

Izas, Pyrenees

- Collaboration with Jesus Revuelto, Nacho
- Pyrenees extent
  - 27 000 km^2
- Izas catchment
  - COPE basin
- Met
  - AROME (2.5km)
- Evaluation of CHM:
  - Izas catchment with UAV-derived snowdepth
  - SCA at large spatial extents





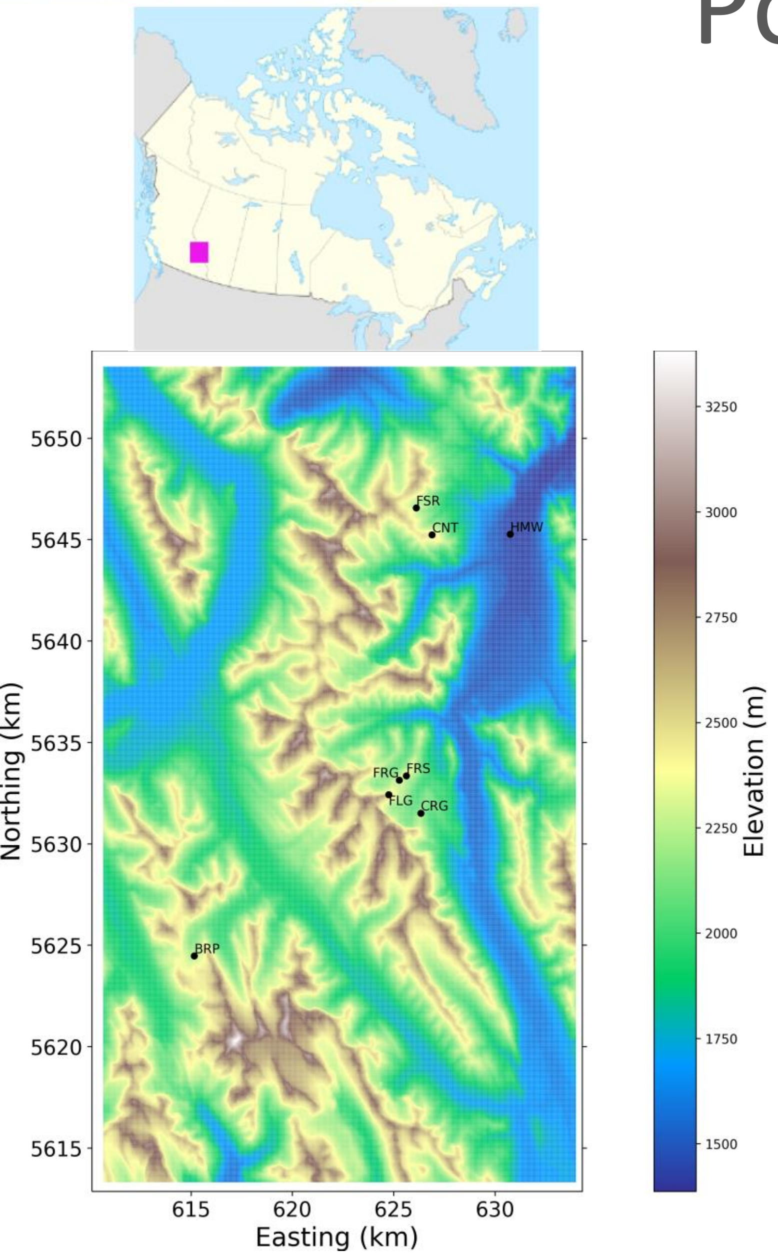
Conclusions

- First simulation of snow redistribution and ablation using a distributed model at a snowdrift-permitting resolution across the Canadian Cordillera and adjacent Prairies (1.3M km^2) demonstrates the feasibility of continental scale snow predictions

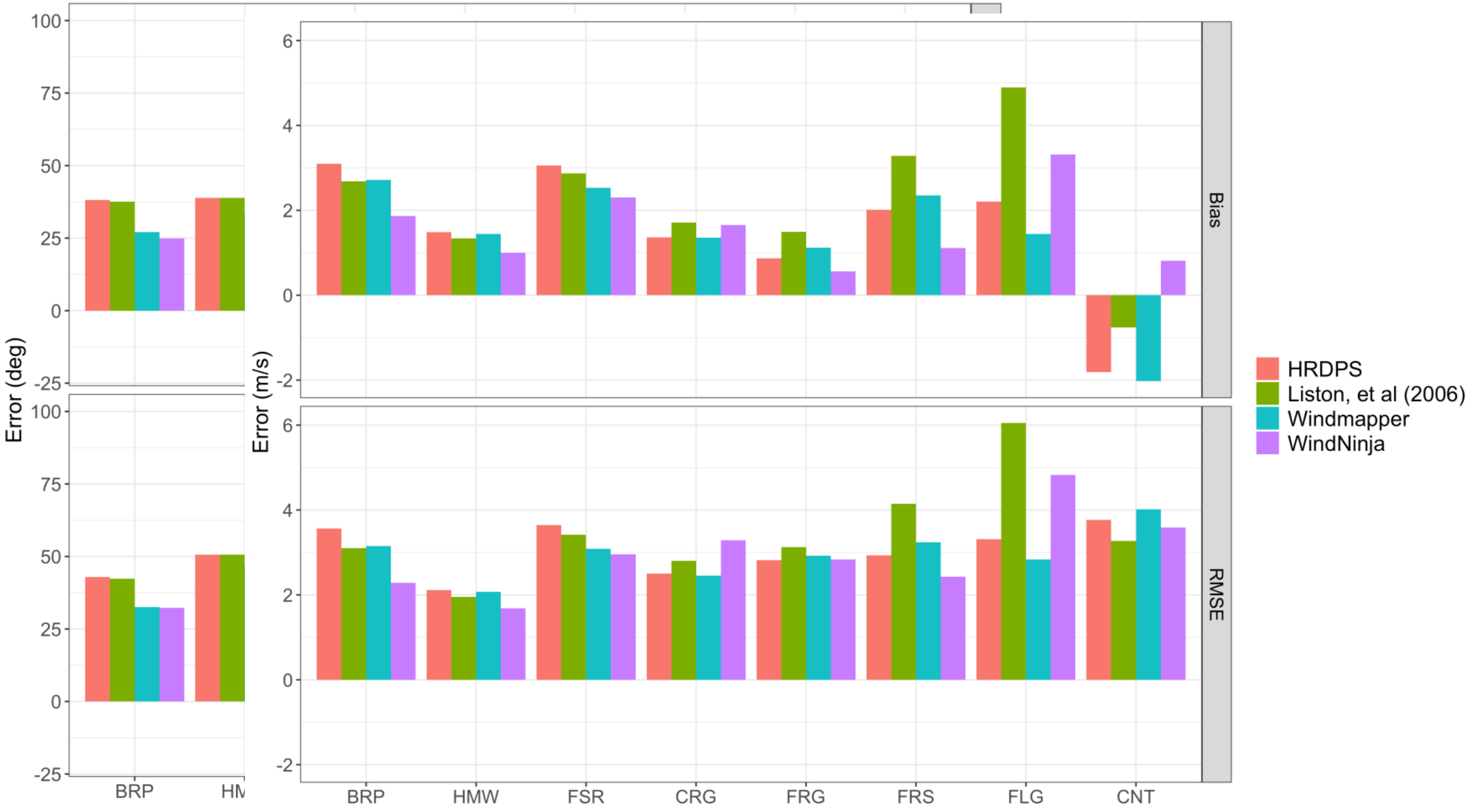
- Significant improvements in high performance computing capabilities of CHM

- Next Steps:
  - Continue application at two COPE basins
  - < 150 m comparison of Research Basin observations and CHM SCA to improve snow physics
  - On-going work to validate and improve simulations over the Canadian Prairies
  - Implementation of complete set of water processes in CHM
  - Quantify how climate change may impact late lying snowcovers and spring runoff in mountain headwaters

Point evaluation of WindMapper



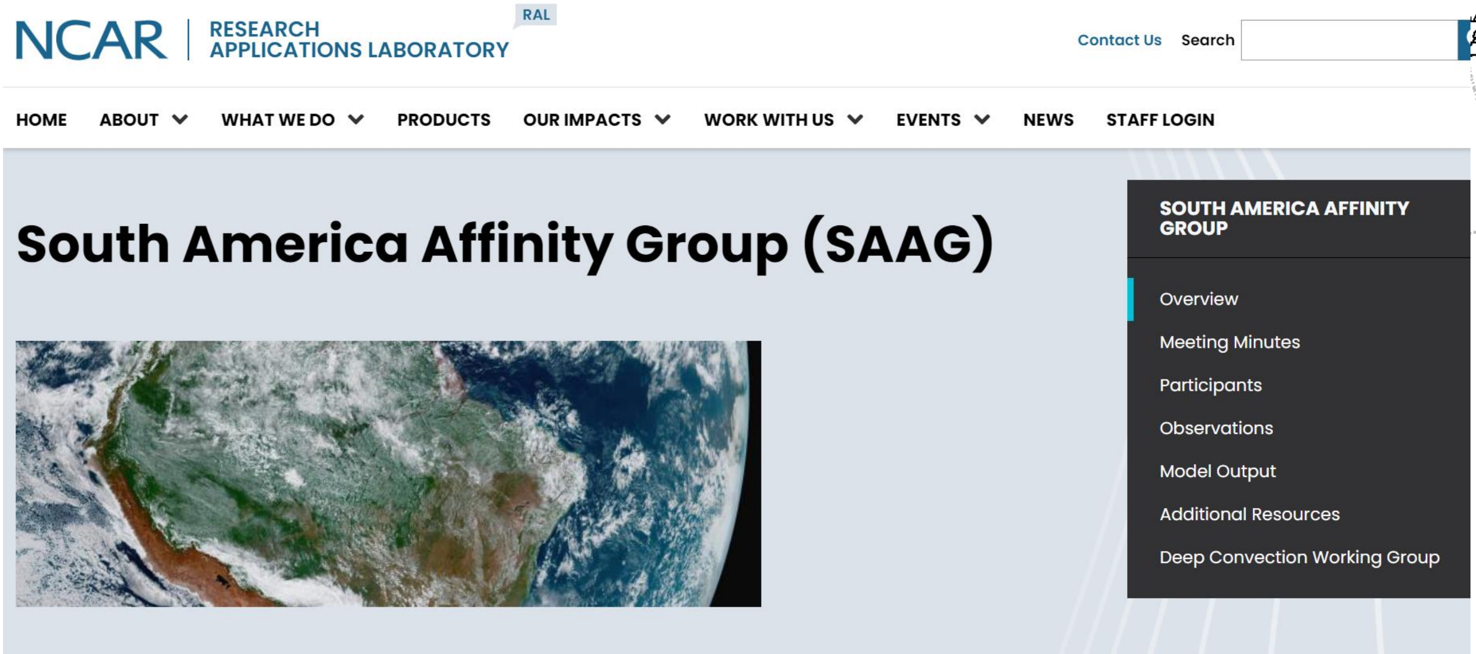
Kananaskis Valley, Alberta

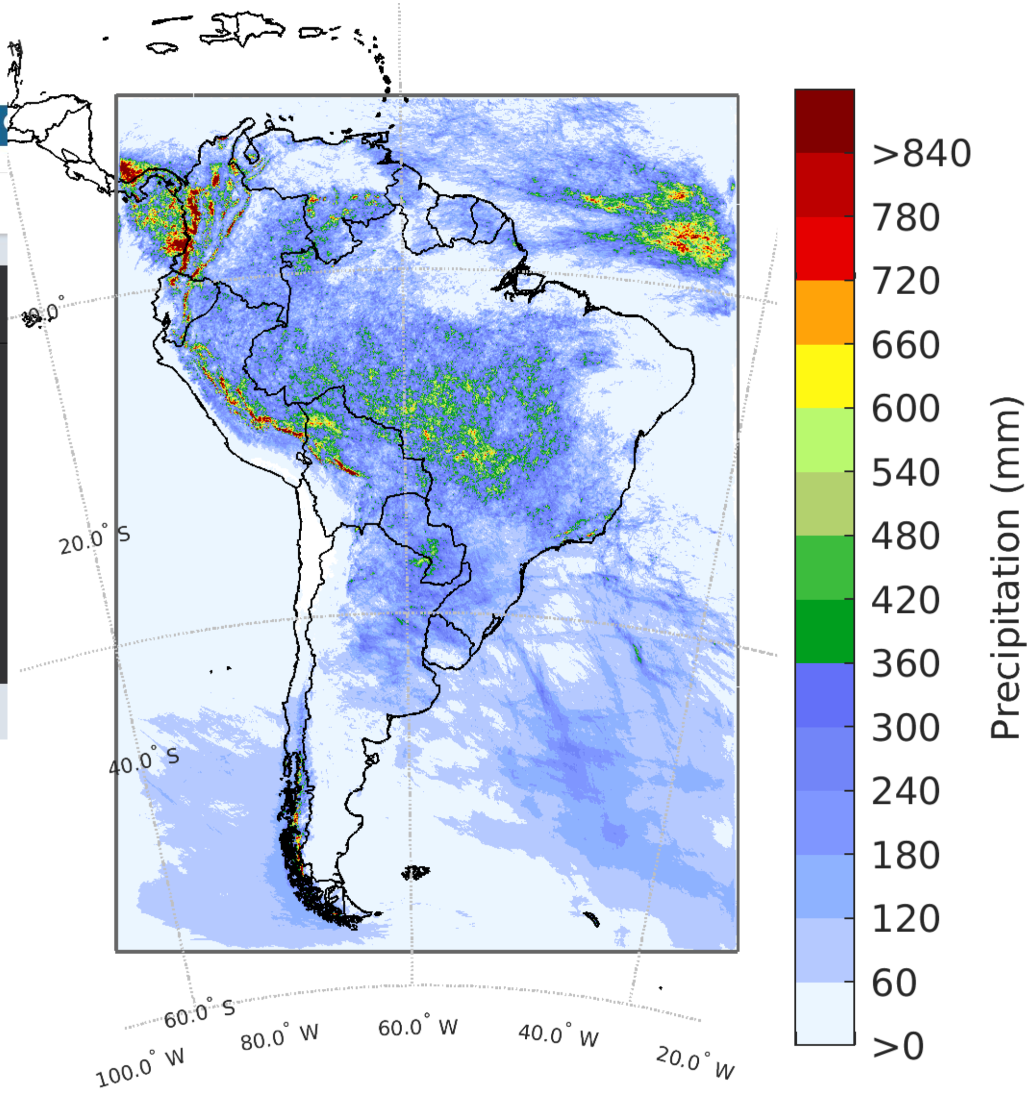


Full name	Code	Latitude (°)	Longitude (°)	Elevation (m)	TPI (m)
Centennial Ridge	CNT	50.9447	−115.9370	2470	248
Fisera Ridge	FSR	50.9568	−115.2044	2325	−10
Hay Meadow	HMW	50.9441	−115.1389	1492	−33
Fortress Ledge	FLG	50.8300	−115.2285	2565	216
Fortress Ridge	FRG	50.8364	−115.2209	2327	99
Fortress Ridge South	FRS	50.8382	−115.2158	2306	129
Canadian Ridge	CRG	50.8215	−115.2063	2211	68
Burtsall Pass	BRP	50.7606	−115.3671	2260	−90

Marsh, et al (2022; submitted)

Convection permitting model simulation over South America





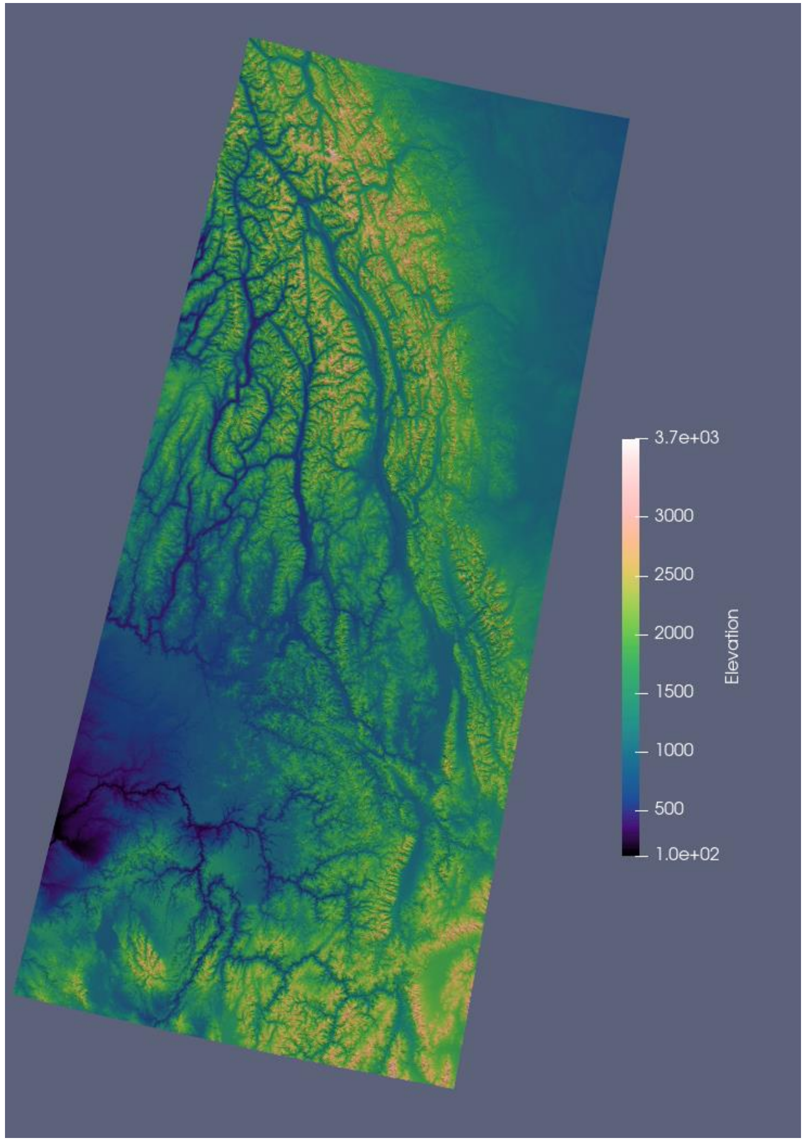
Historical simulation

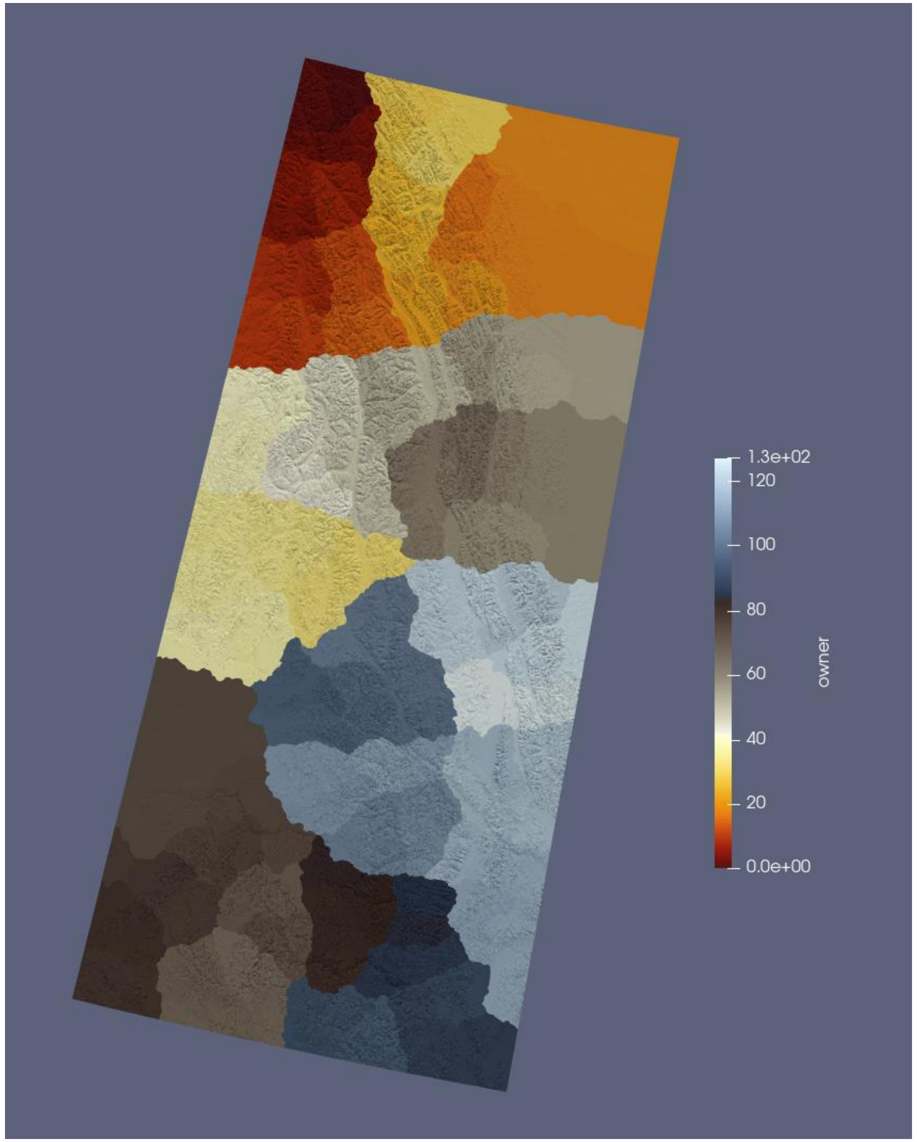
22 years: January 2000 – December 2021

WRF input: ERA5 reanalysis

Domain Partitioning

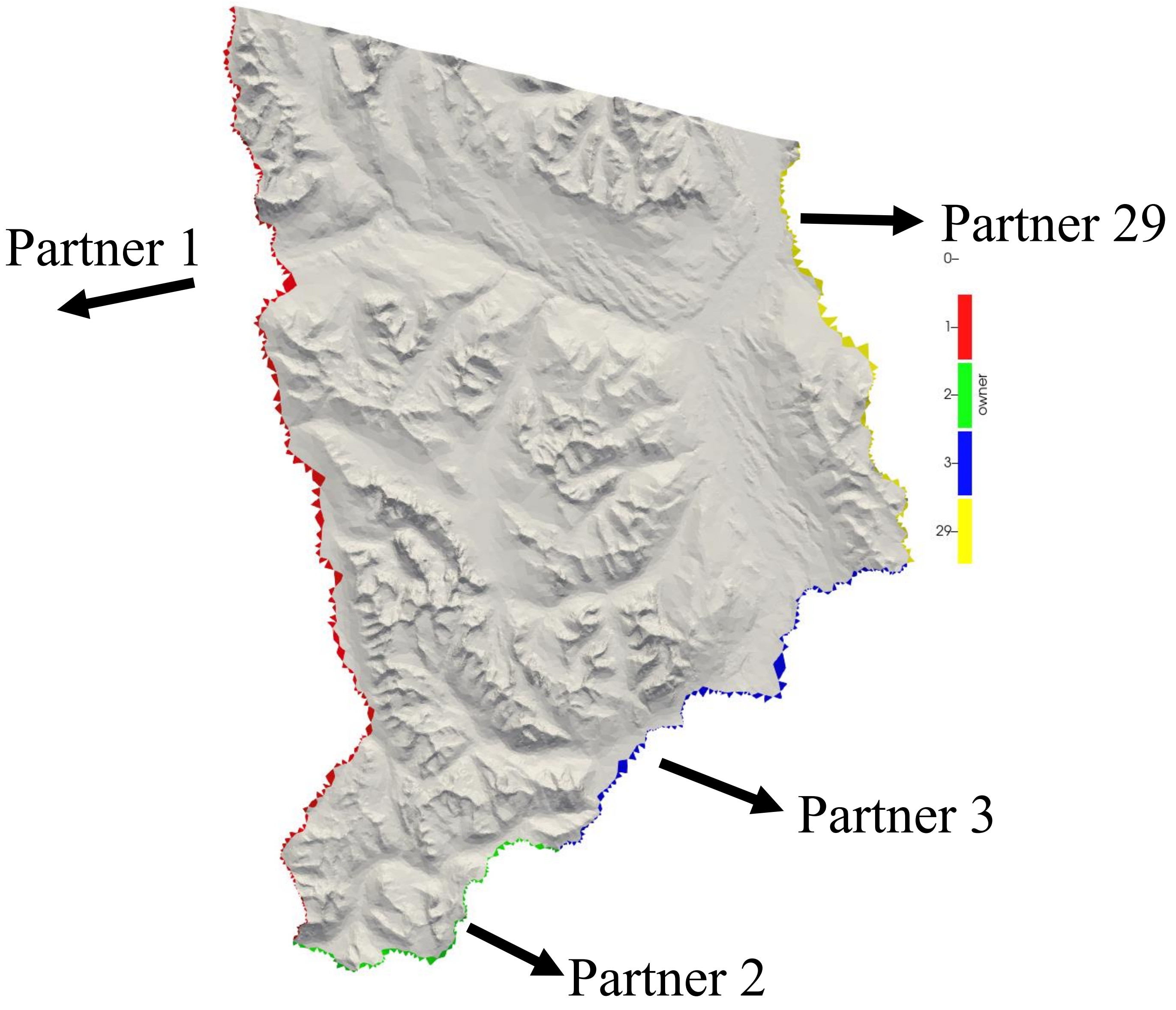
- Each colour represents a different MPI partition (right figure)
- Partitions optimize for:
  - Minimal total communication amount
  - Approx. same number of triangles
  - Uses Metis package





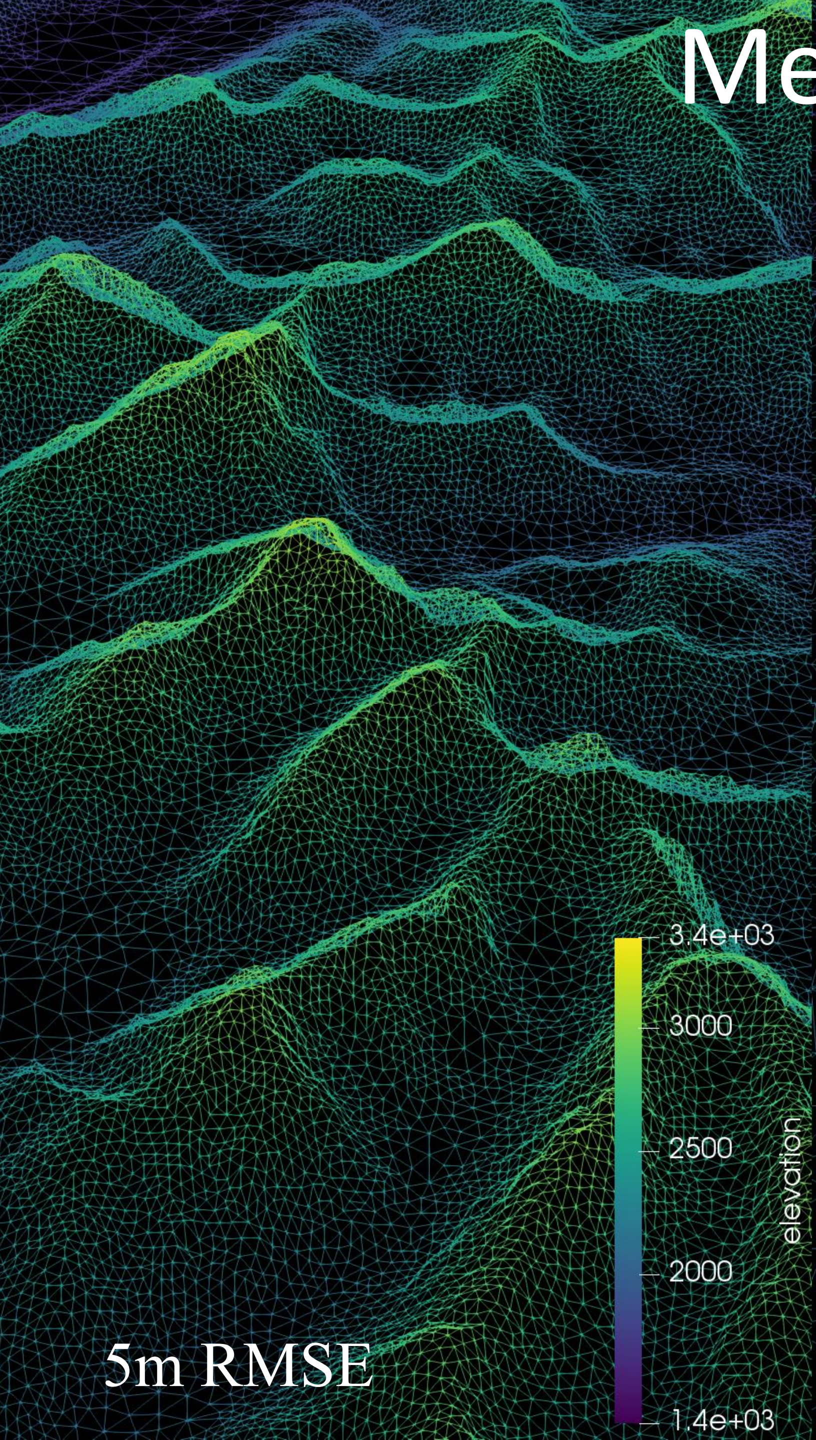
Inter-node communication

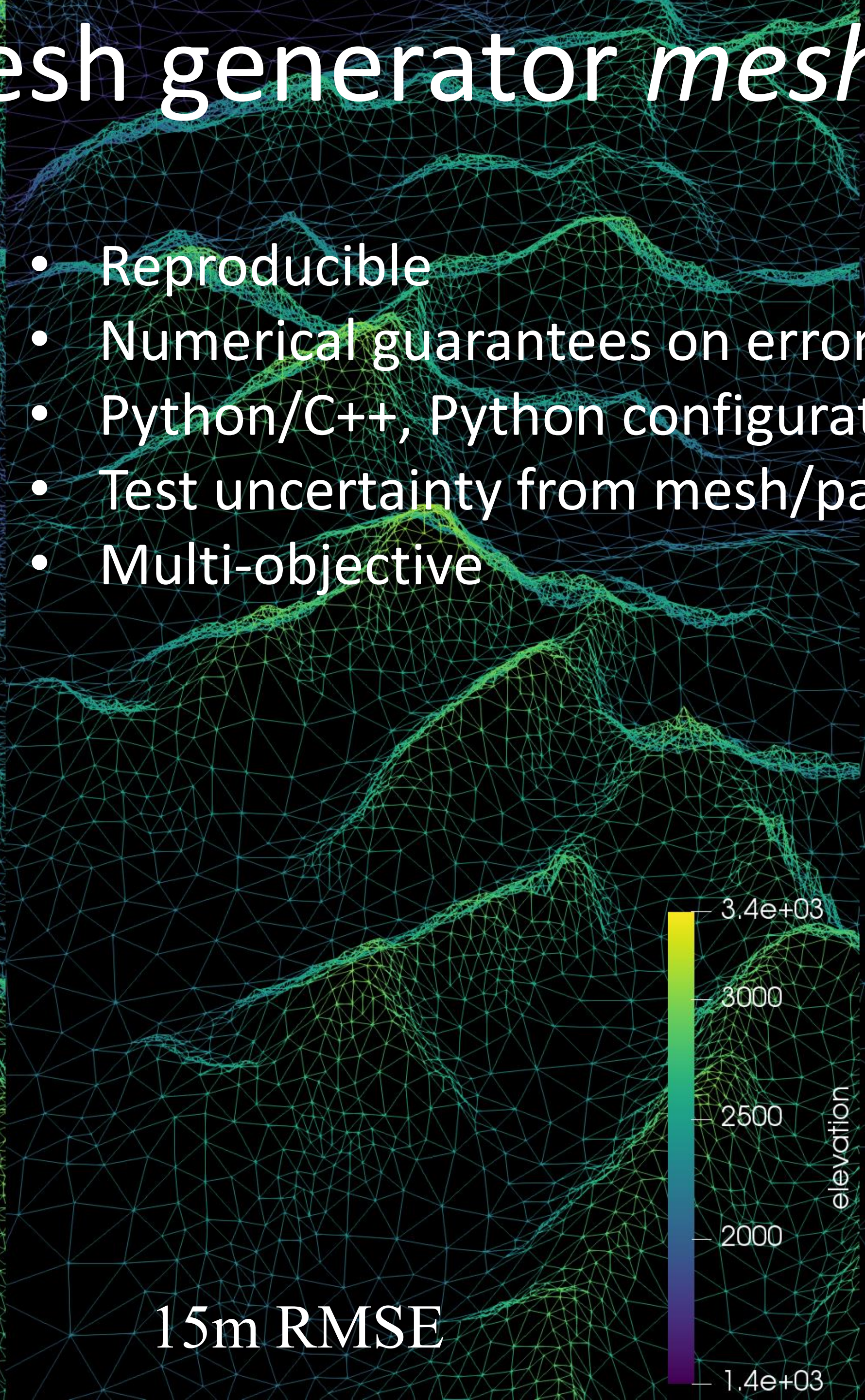
- To transfer a flux between MPI partners
- Coloured triangles are communication partners

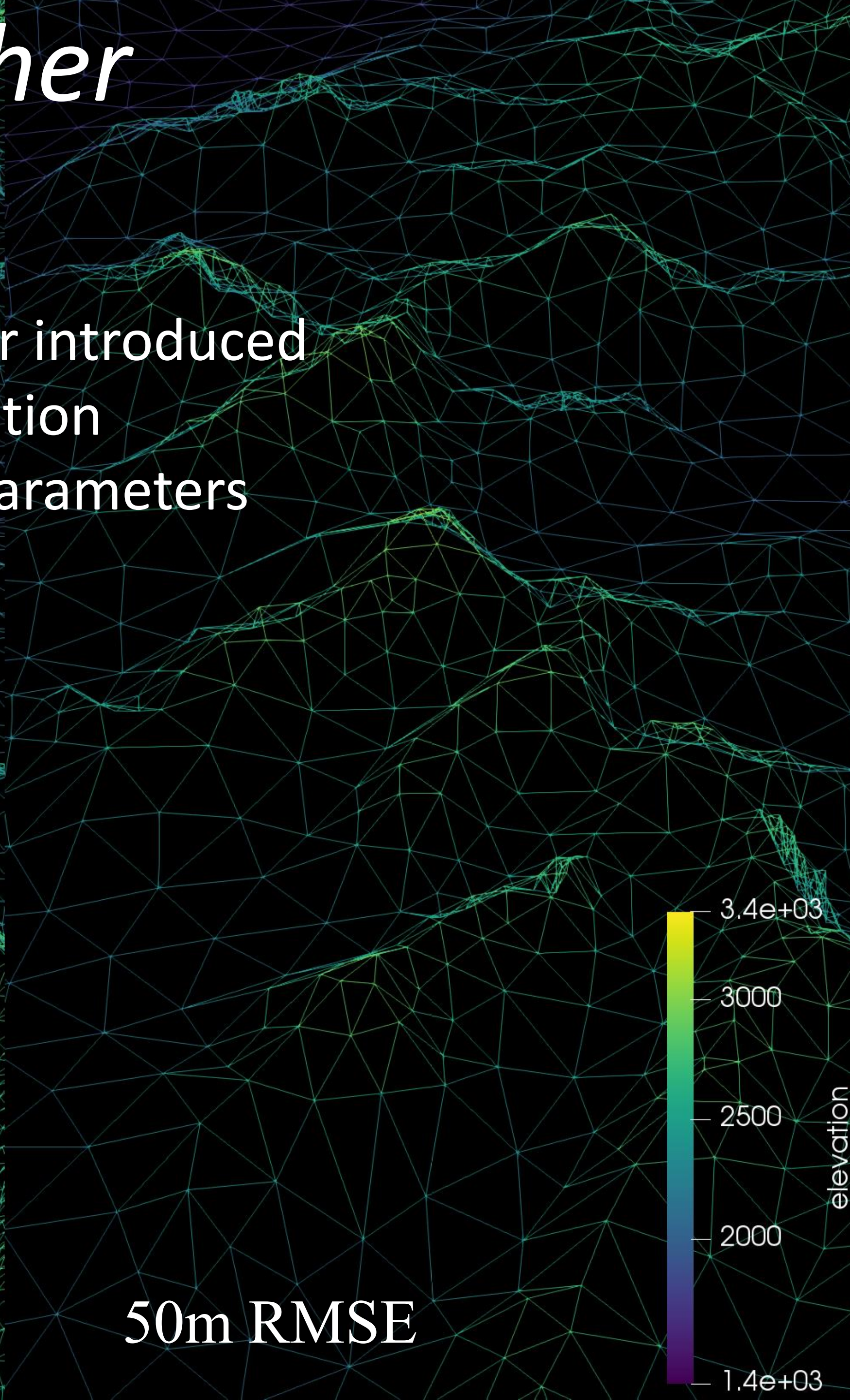


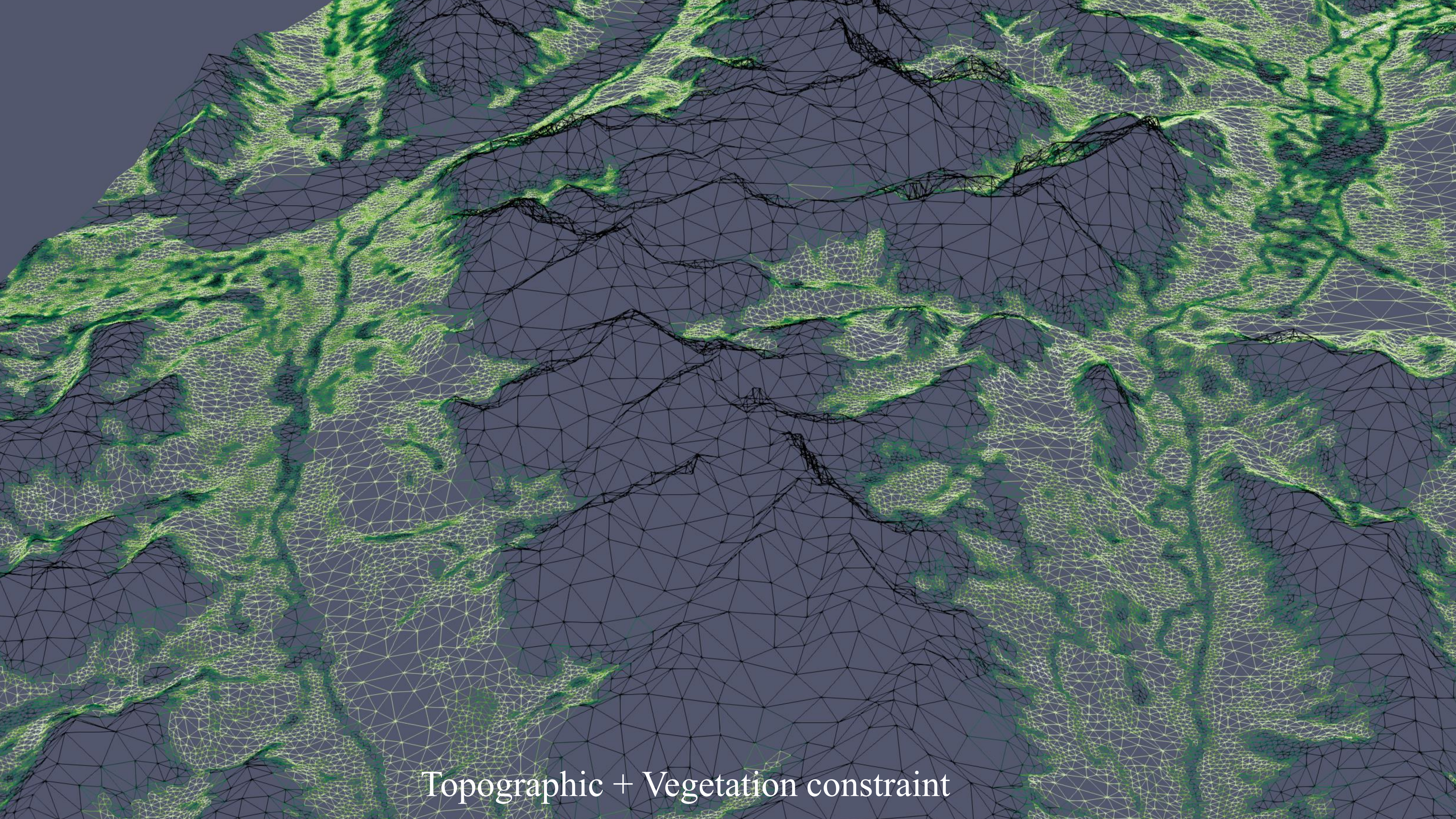
Mesh generator *mesher*

- Reproducible
- Numerical guarantees on error introduced
- Python/C++, Python configuration
- Test uncertainty from mesh/parameters
- Multi-objective








Topographic + Vegetation constraint