Forecasting seasonal snow with million km^2 large-extent snowdrift-permitting simulations

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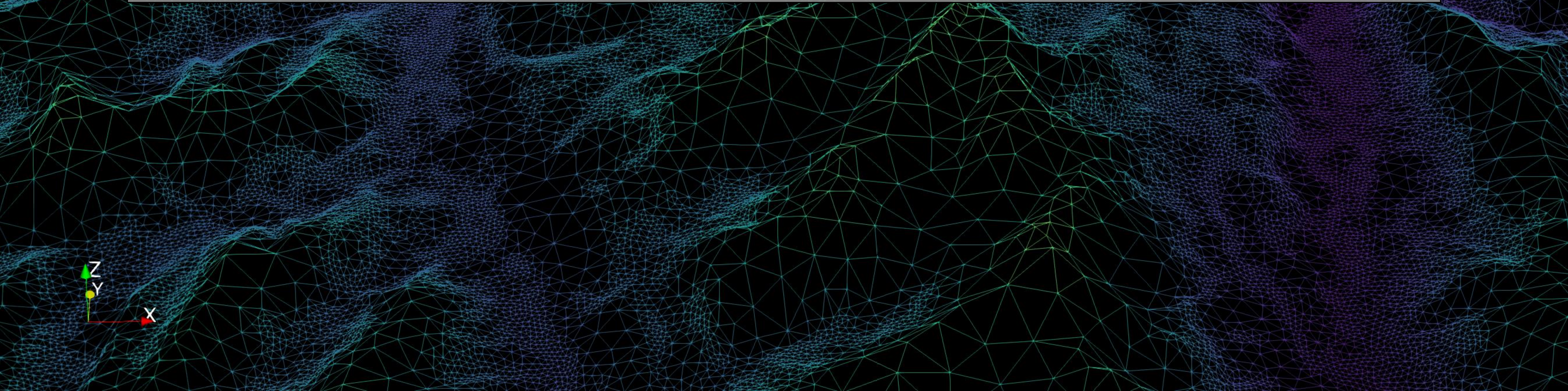


Motivation

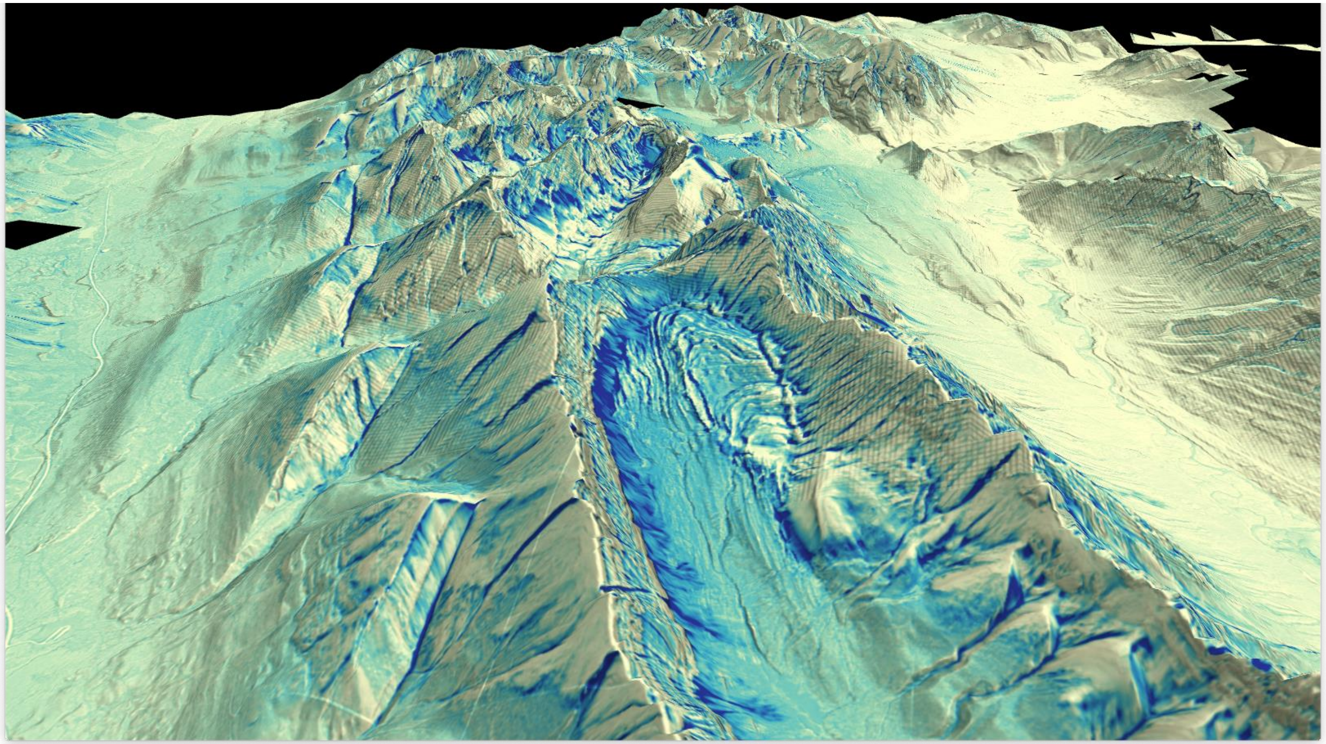
- Improve the predictions of mountain snowpacks to aid in water supply forecasts for local and downstream populations, ecosystems, floods, hydroelectricity, and irrigated agriculture

- A solution is to use multiscale land surface models to simulate winter processes

- 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)

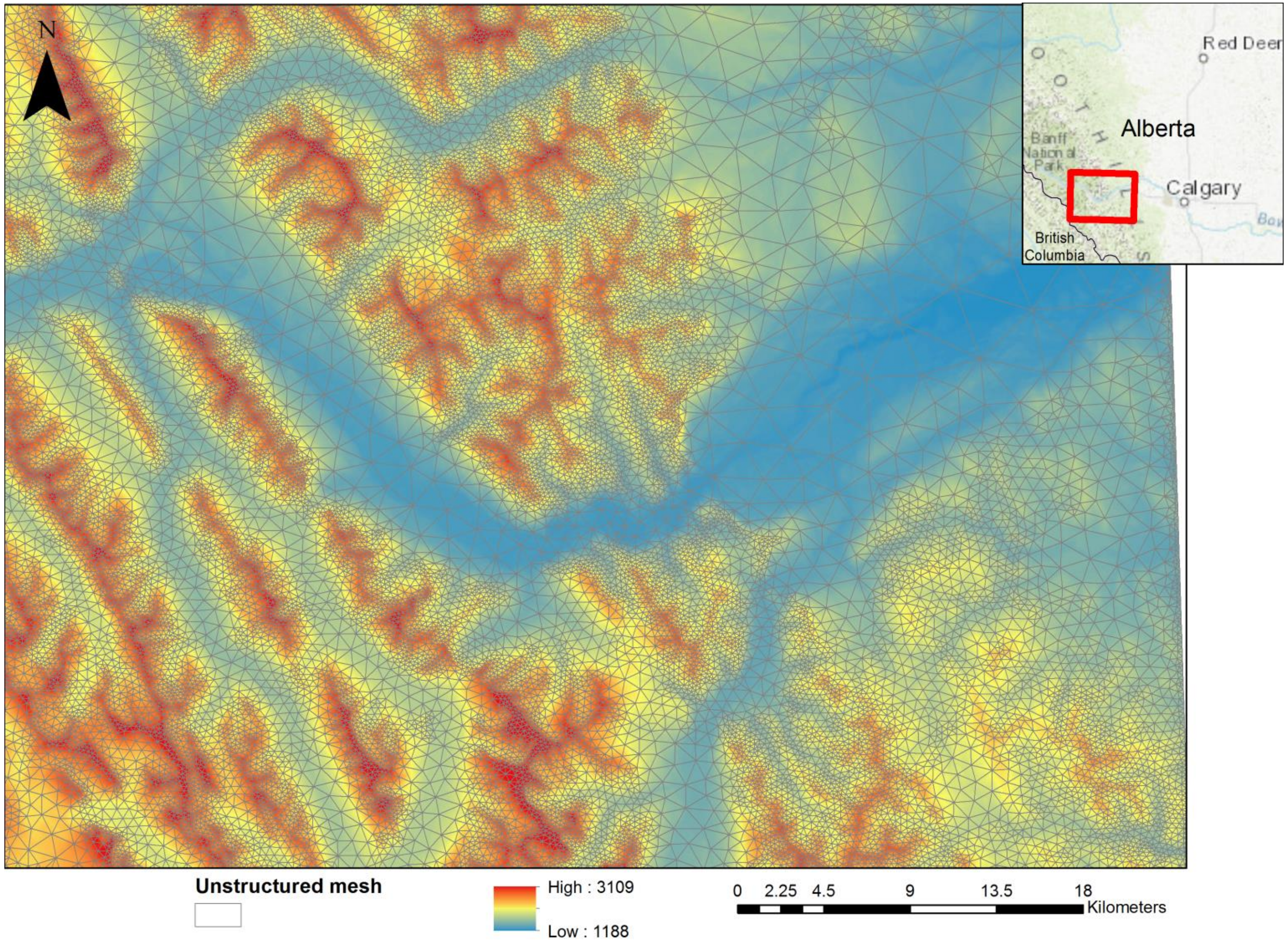
- Estimating spring snowpacks over areas >1M km^2 critical for quantifying late lying snowpacks



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)

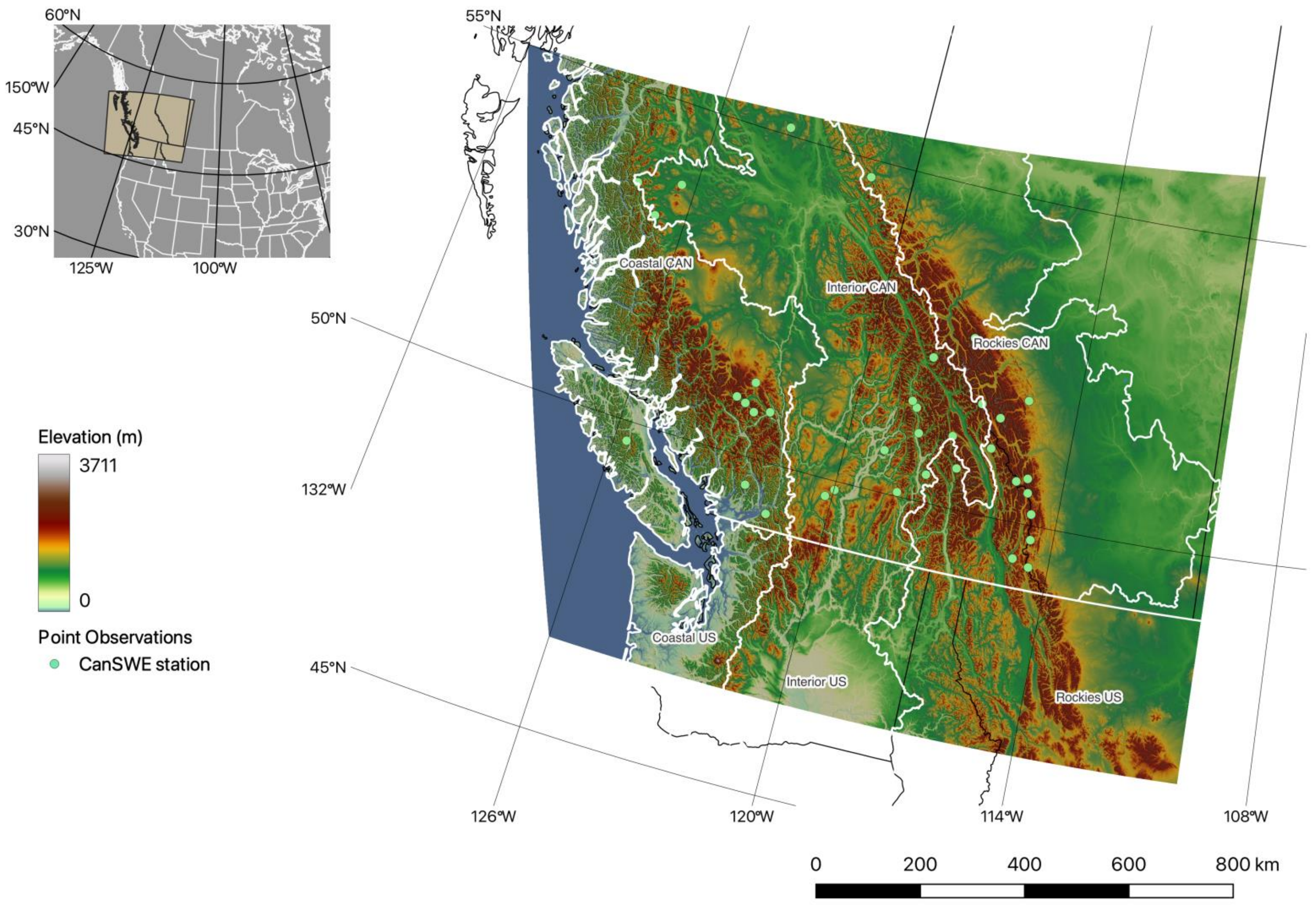
- **Variable resolution triangular mesh** depending on topography, soils, vegetation
- Large decrease in computational and data demands over rectangular gridded models
- Algorithms for downscaling meteorological data
- CHM currently accounts for:
  - **slope** and **aspect**; terrain **shading**
  - **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)

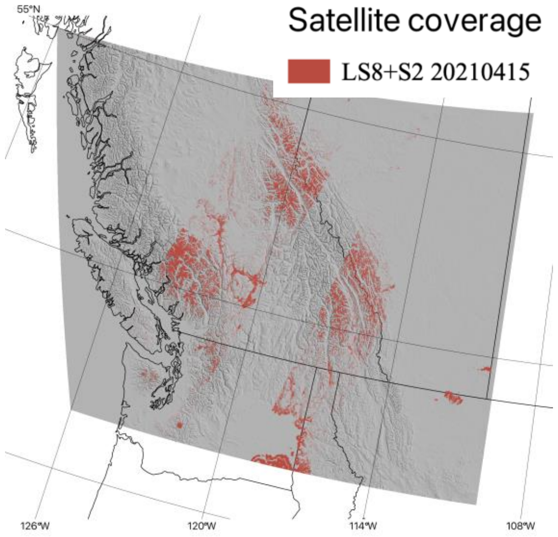
Methodology

- Simulate snowpacks via CHM + HRDPS:
  - avalanching, blowing snow redistribution, canopy interception, shading, sublimation, melt
- HRDPS – ECCC GEM 2-day forecast 2.5 km
- 1.3M km^2 at a snowdrift-permitting resolution
- Falsification with and without snow redistribution (avalanche + blowing snow)
- Multi-scale evaluation using:
  - Landsat8 and Sentinel2 Snow Covered Area (SCA)
  - lidar observed snow depths
  - point observations of snow water equivalent (CanSWE)
- Evaluate falsification at regional scale by aggregating gridded SWE to MERIT basins in each region
  - Basins were binned for outlet elevation and aggregated to the regions shown



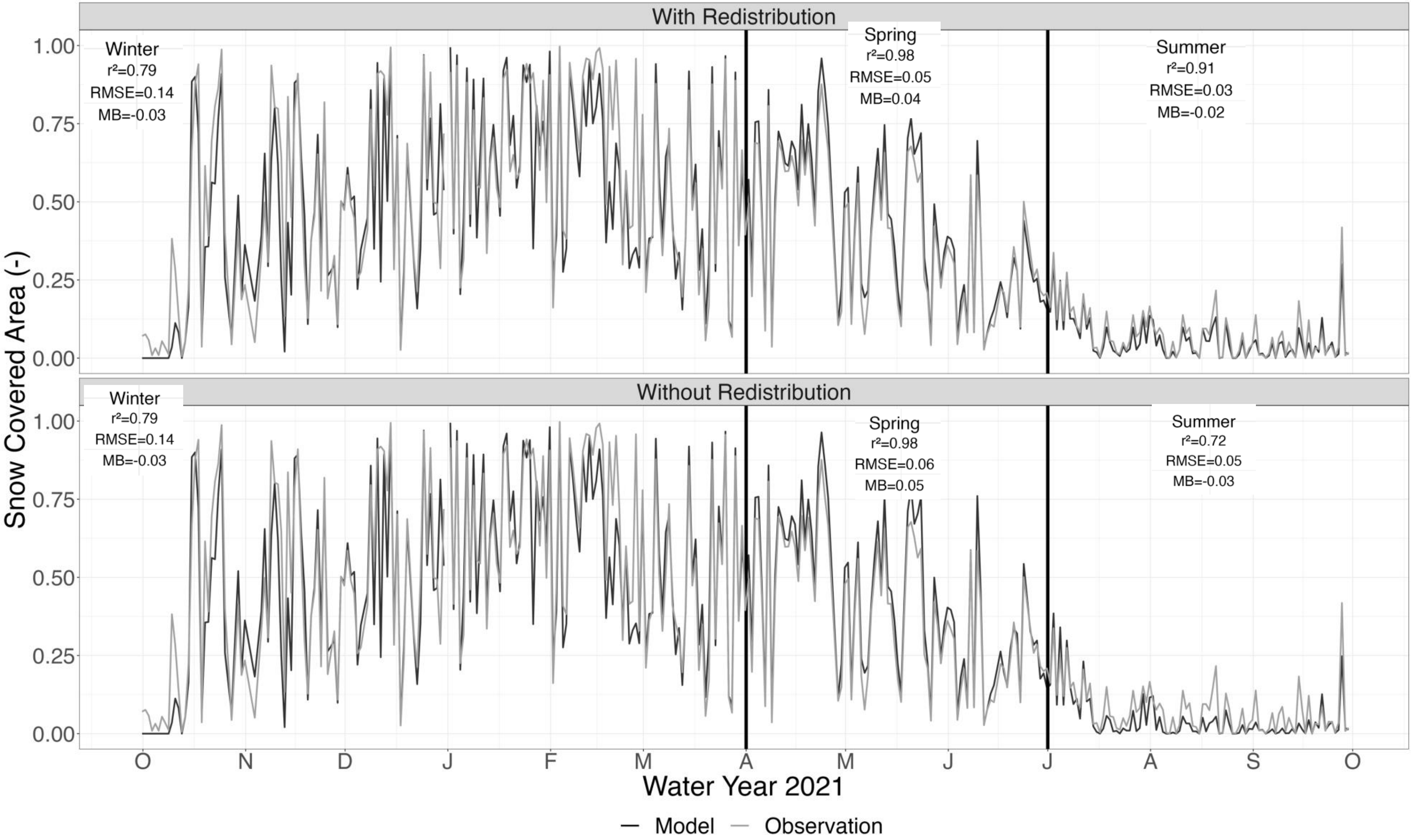
Large Extent Satellite SCA

- Evaluation via SCA is difficult due to the snapshot in space and time of observations



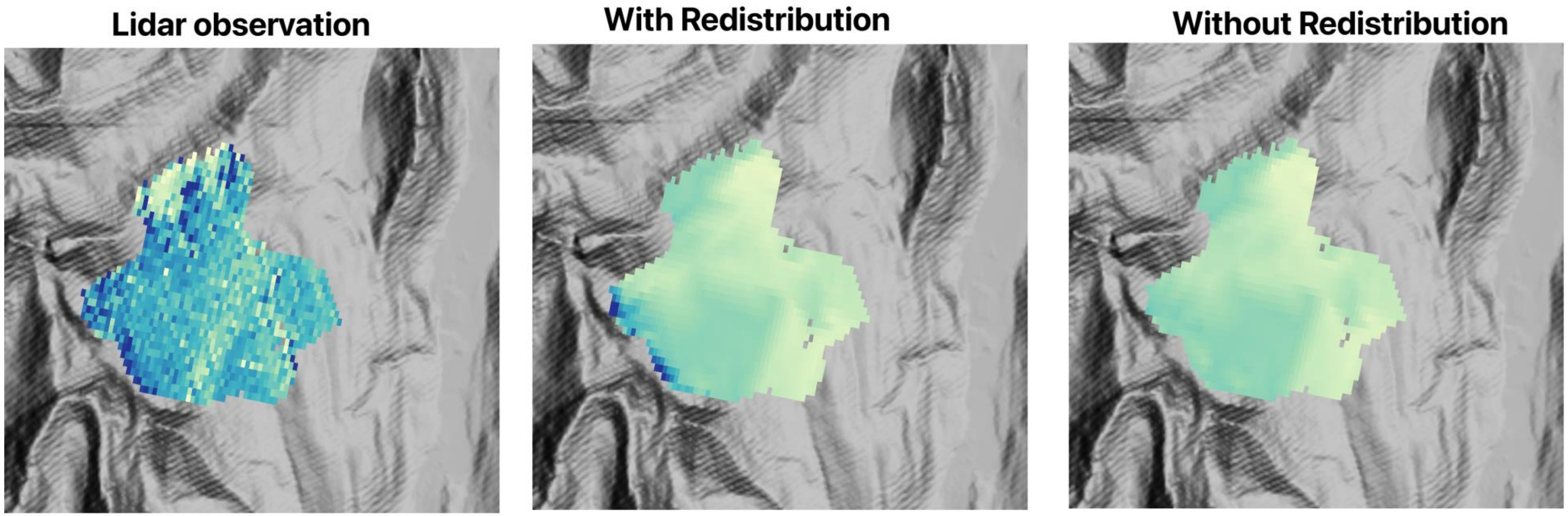
- Evaluating small scale processes like ridgeline redistribution with SCA observations is difficult due the mismatch in spatial resolution

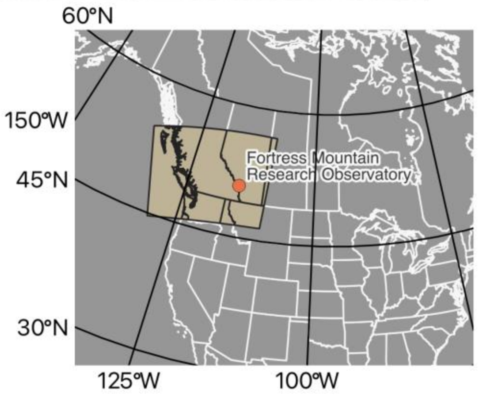
- Mid-winter SCA observations were dominated by regions where snow redistribution did not occur

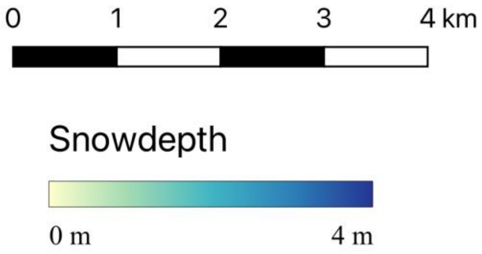


UAV-Lidar Snow depth

- UAV-lidar provides the only high-resolution sub-canopy spatial comparison of snow depth
- Sub-canopy results suggests a low bias in HRDPS precipitation as preferential deposition from the headwall was not captured
- Inclusion of snow redistribution is apparent with avalanche deposits at the headwall
- The complex wind patterns observed at Fortress were not well captured by CHM and require a more accurate wind model



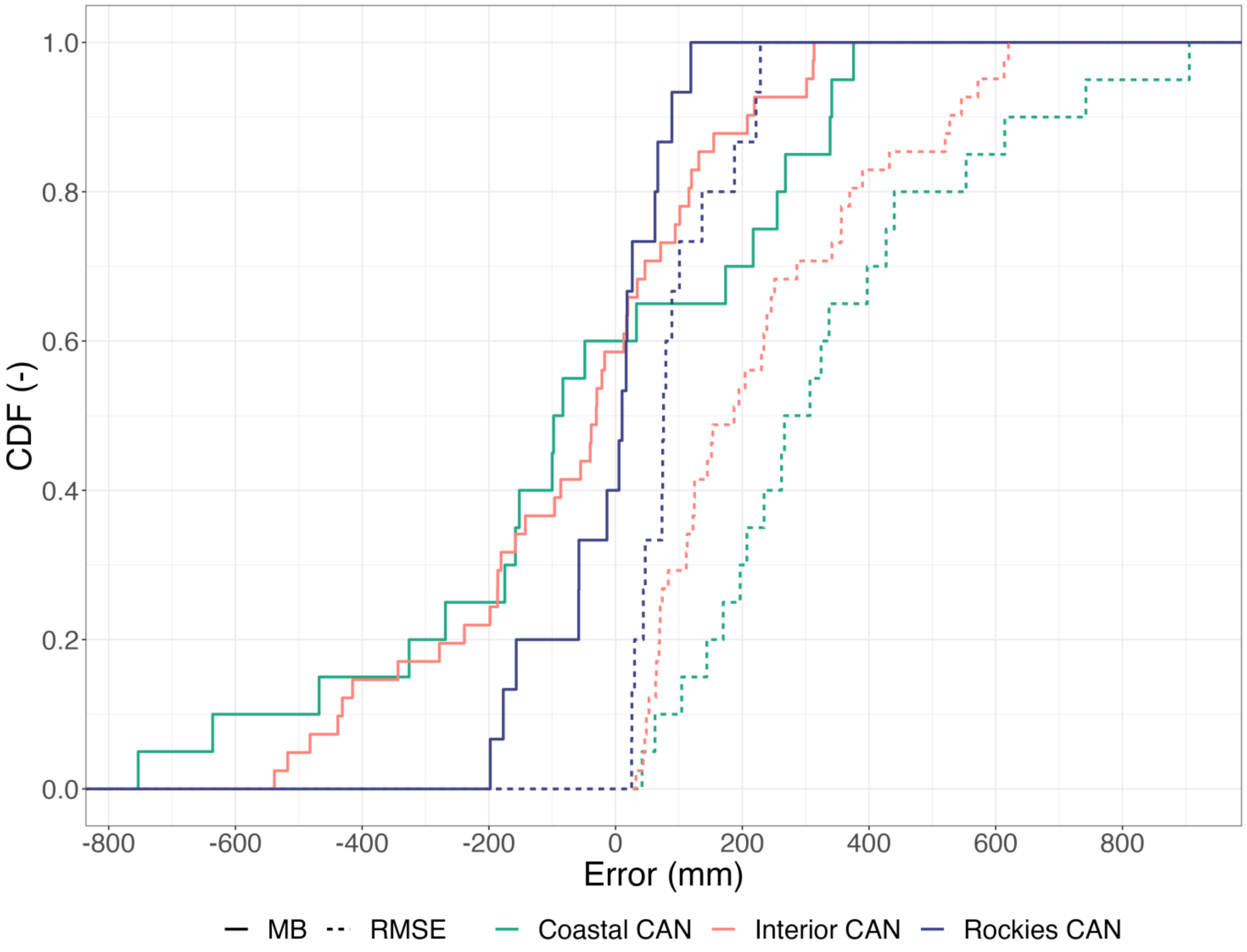




Metric	With-redistribution	Without-redistribution	Lidar
RMSE (m)	1.41	1.44	-
MB (m)	-1.05	-1.12	-
CV (-)	0.61	0.35	0.45

CanSWE

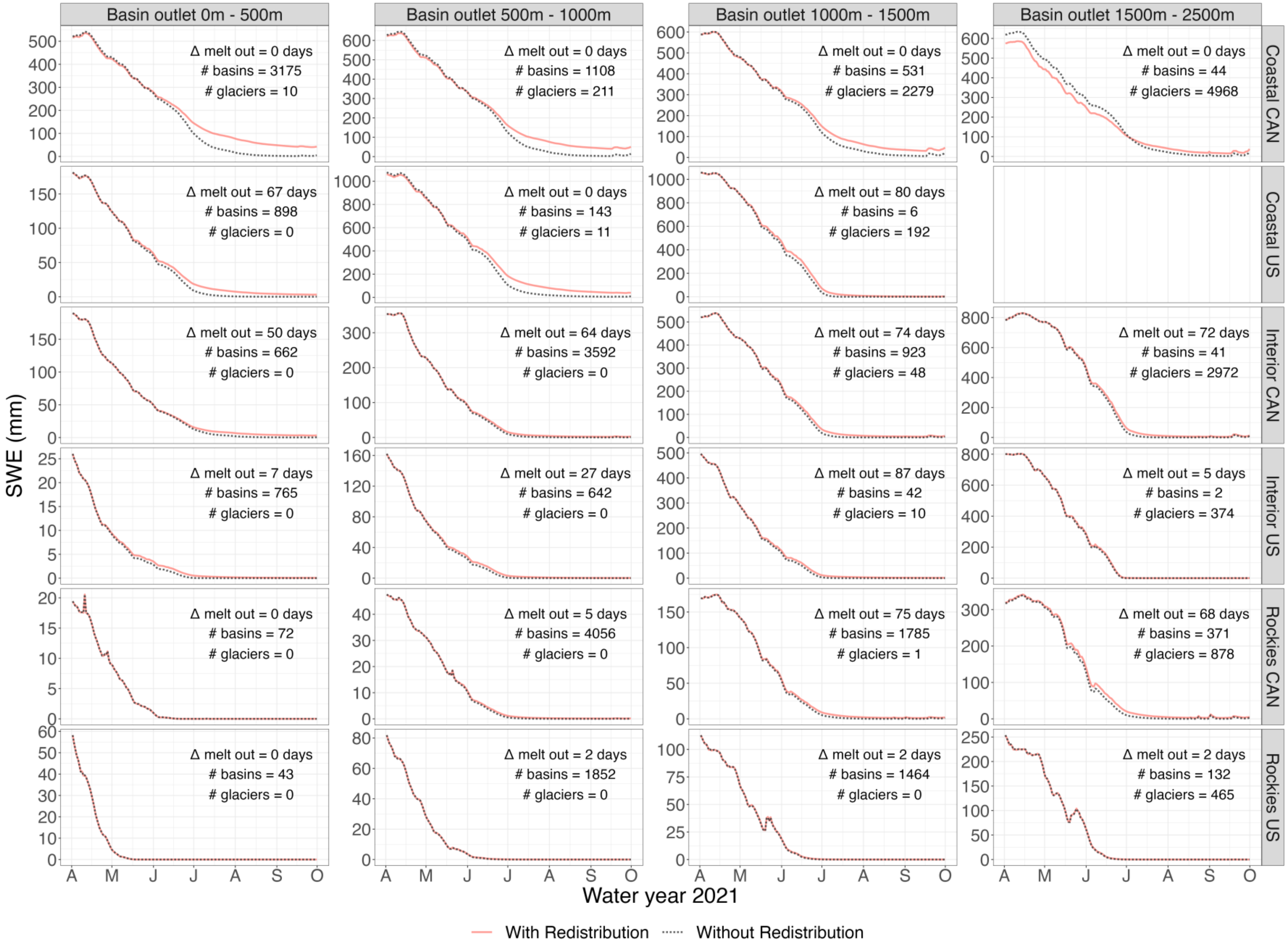
- When compared to the on-the-ground SWE observations of CanSWE, the simulated SWE is dramatically overestimated in the coastal region.
- This regional bias persisted with and without-redistribution, thus eliminating incorrect redistribution as a culprit.
- There is a substantial precipitation bias in GEM - HRDPS in the western coastal portion of the domain (Horton and Haegeli, 2022).

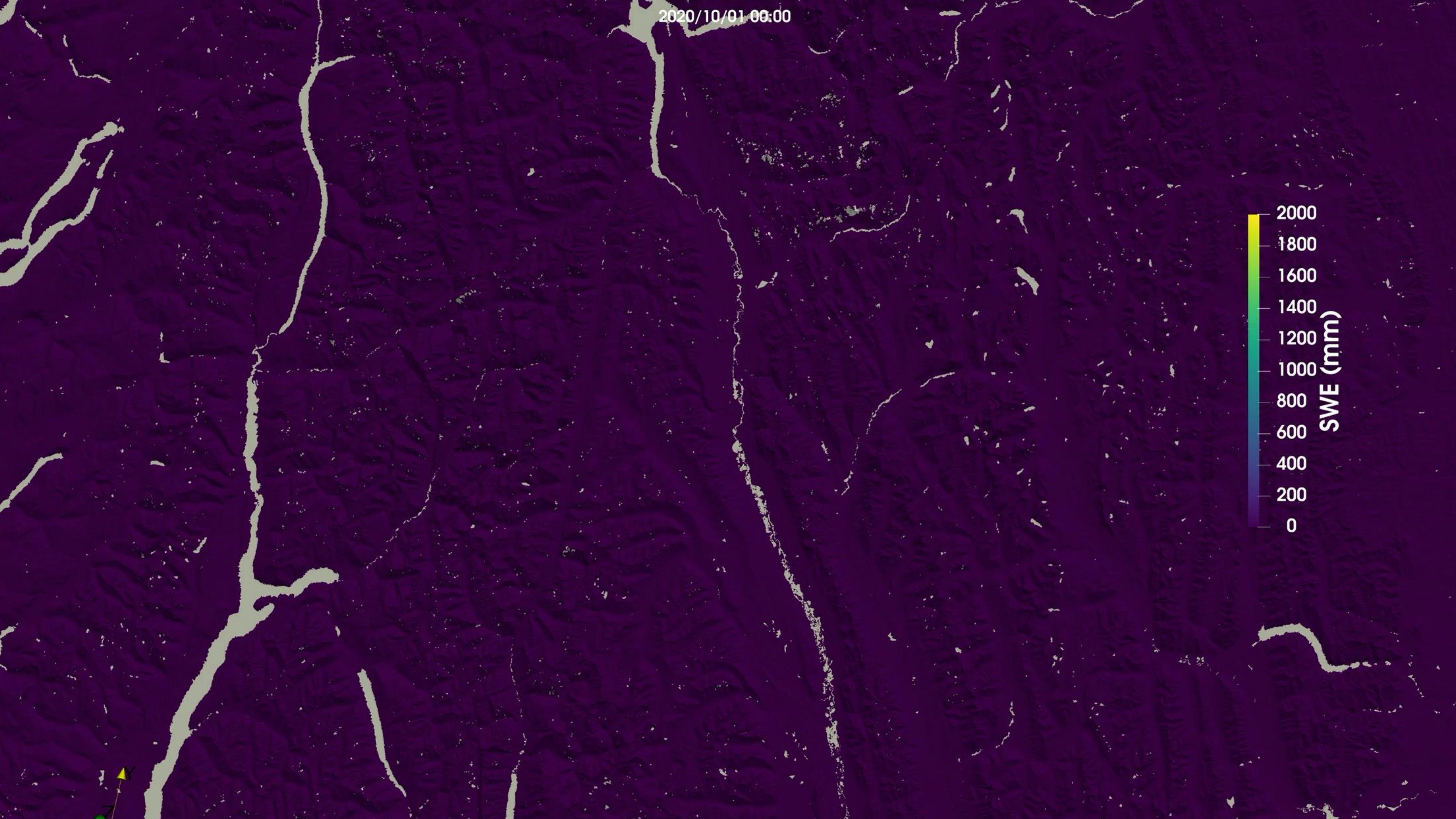


Regional impact of redistribution

- Impact of neglecting redistribution resulted in errors of 100% persisting for one or two months

- The sensitivity to not including redistribution increased in the more continental areas of the domain as well at lower elevations




2020/10/01 00:00
SWE (mm)
2000
1800
1600
1400
1200
1000
800
600
400
200
0

Conclusions

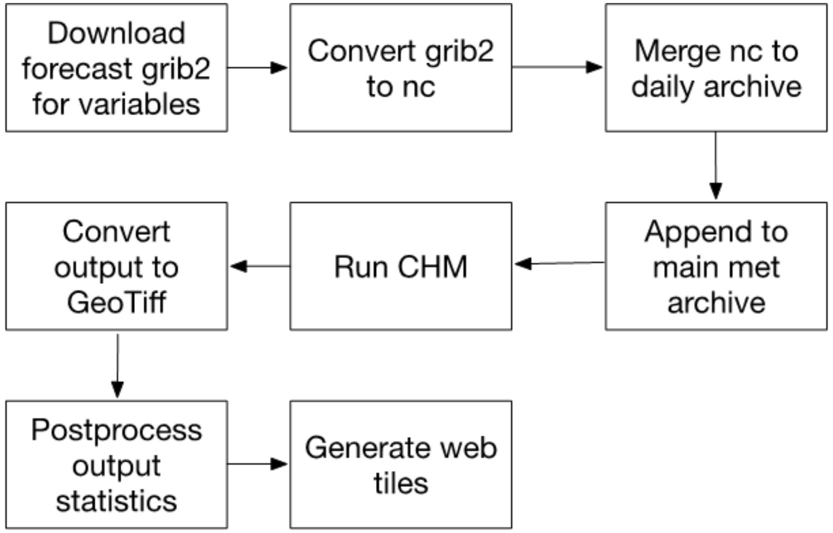
- Including redistribution captured late-lying drifts and avalanche deposits and so had the largest impact on late spring and summer season SWE distributions
- Including redistribution was important for SWE prediction at large-extent, regional scales
- In some regions, neglecting snow redistribution resulted in persistent errors of 100% in SWE prediction

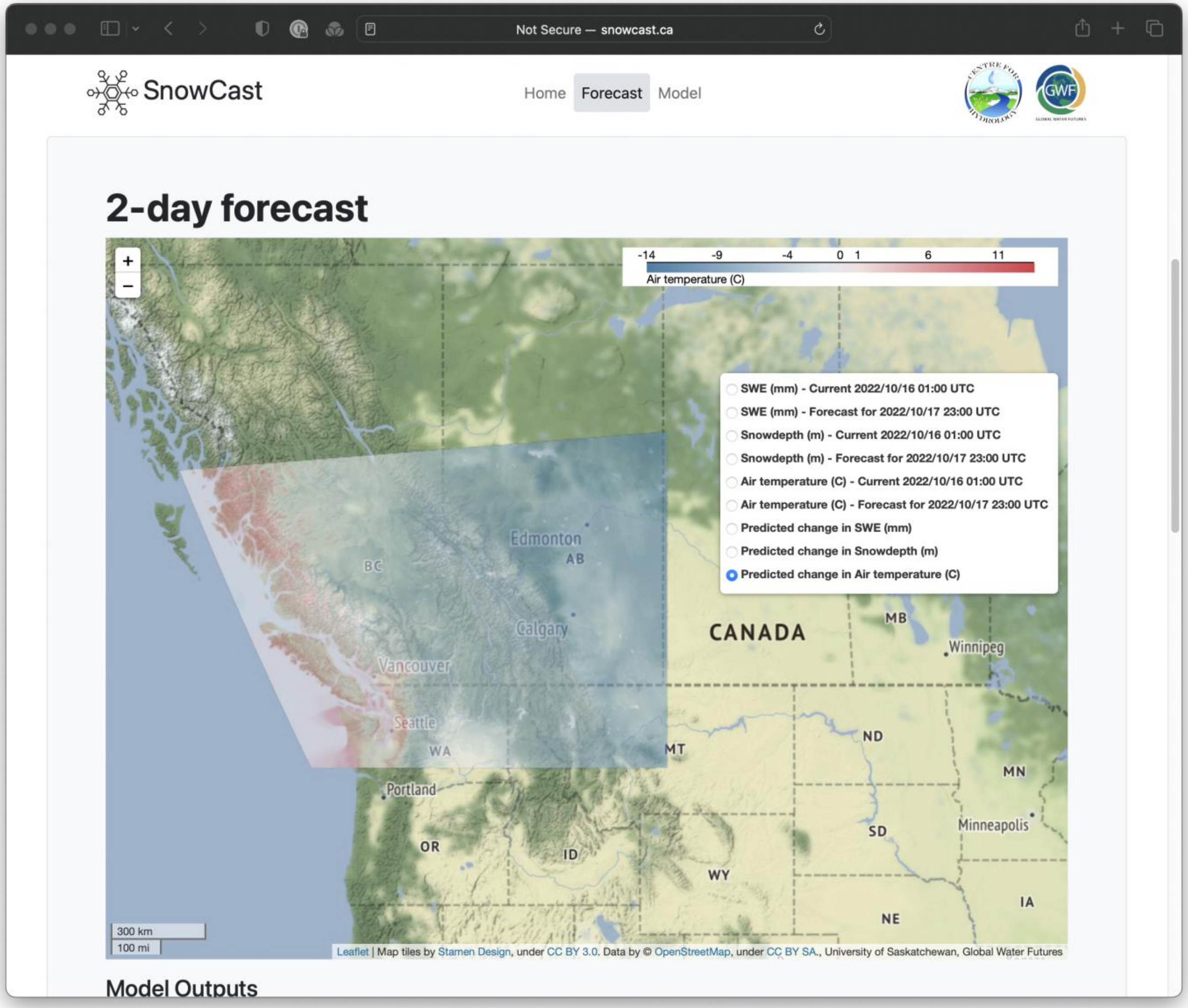
Future research directions

- Pleiades and airborne lidar observations may further quantify model capabilities and limitations
- Need more sophisticated spatial metrics and evaluations
- Investigate the impact of late-lying summer snowpack deposits on mountain runoff generation and sensitivity to climate change
- Apply these methods to INARCH COPE basins

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

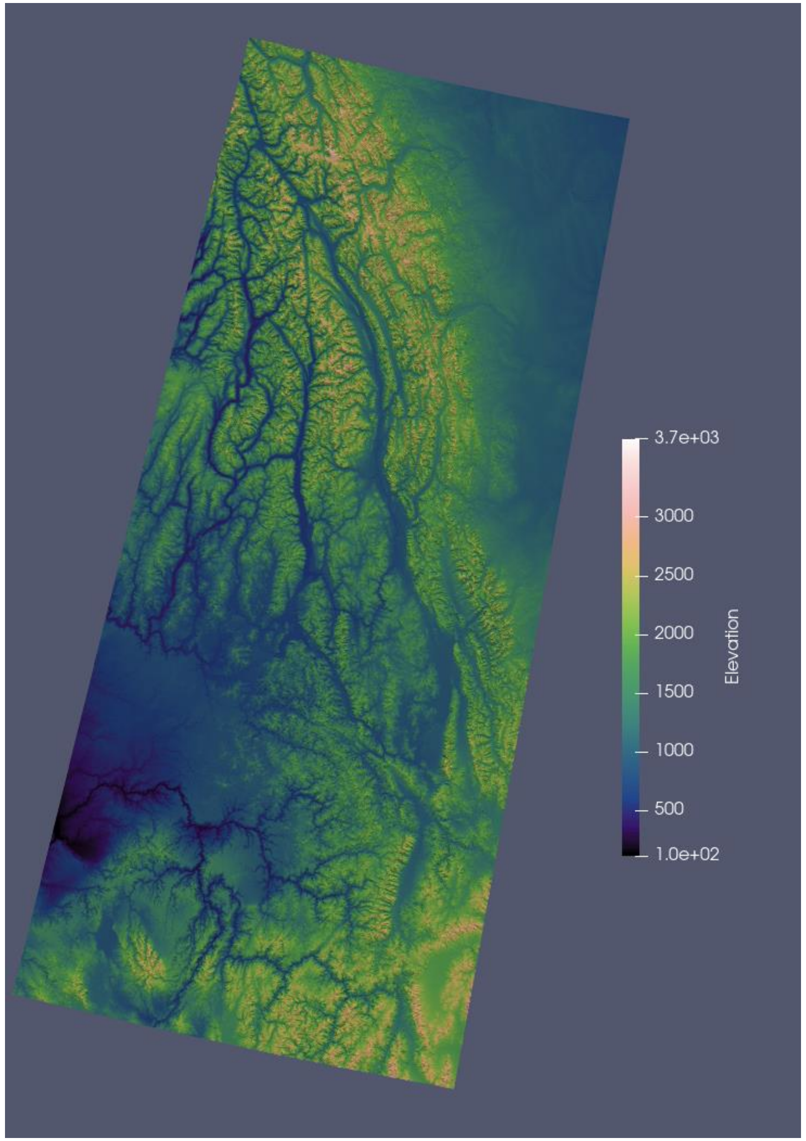


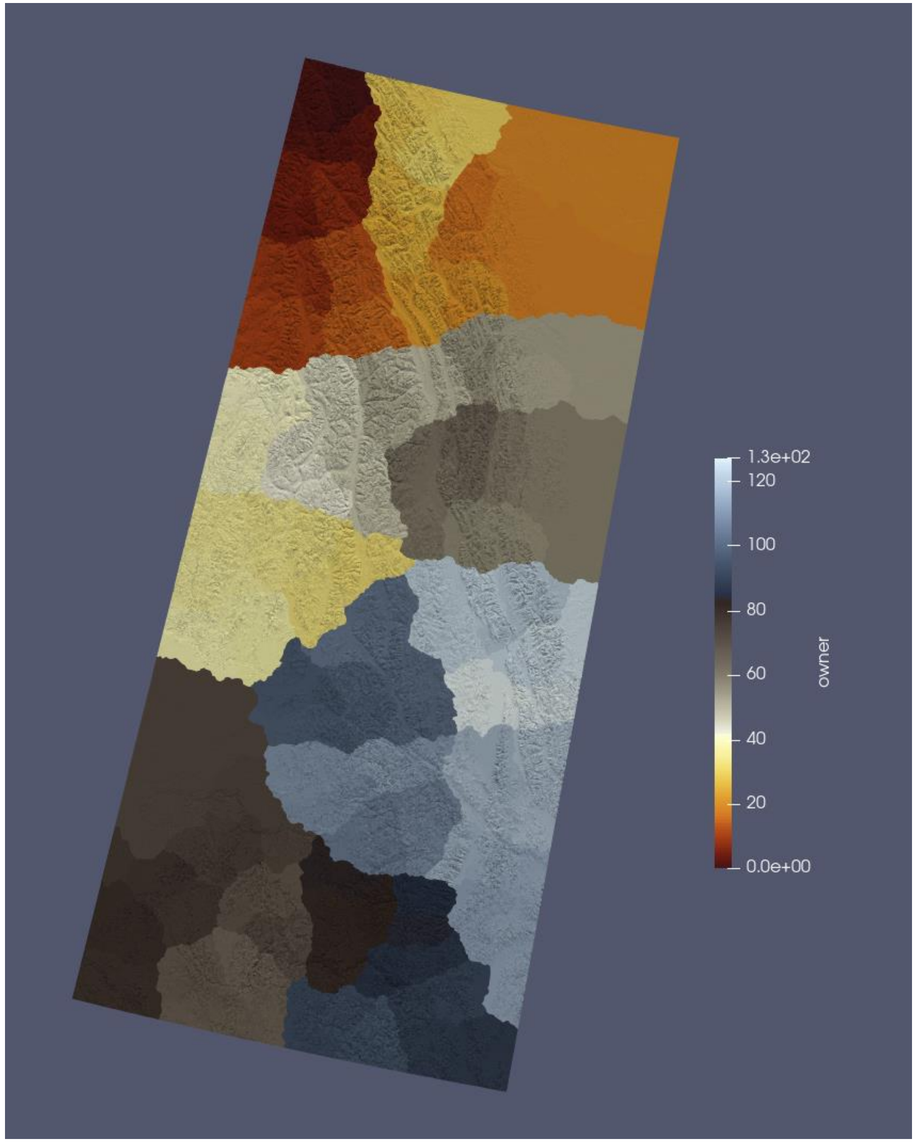


Snowcast.ca

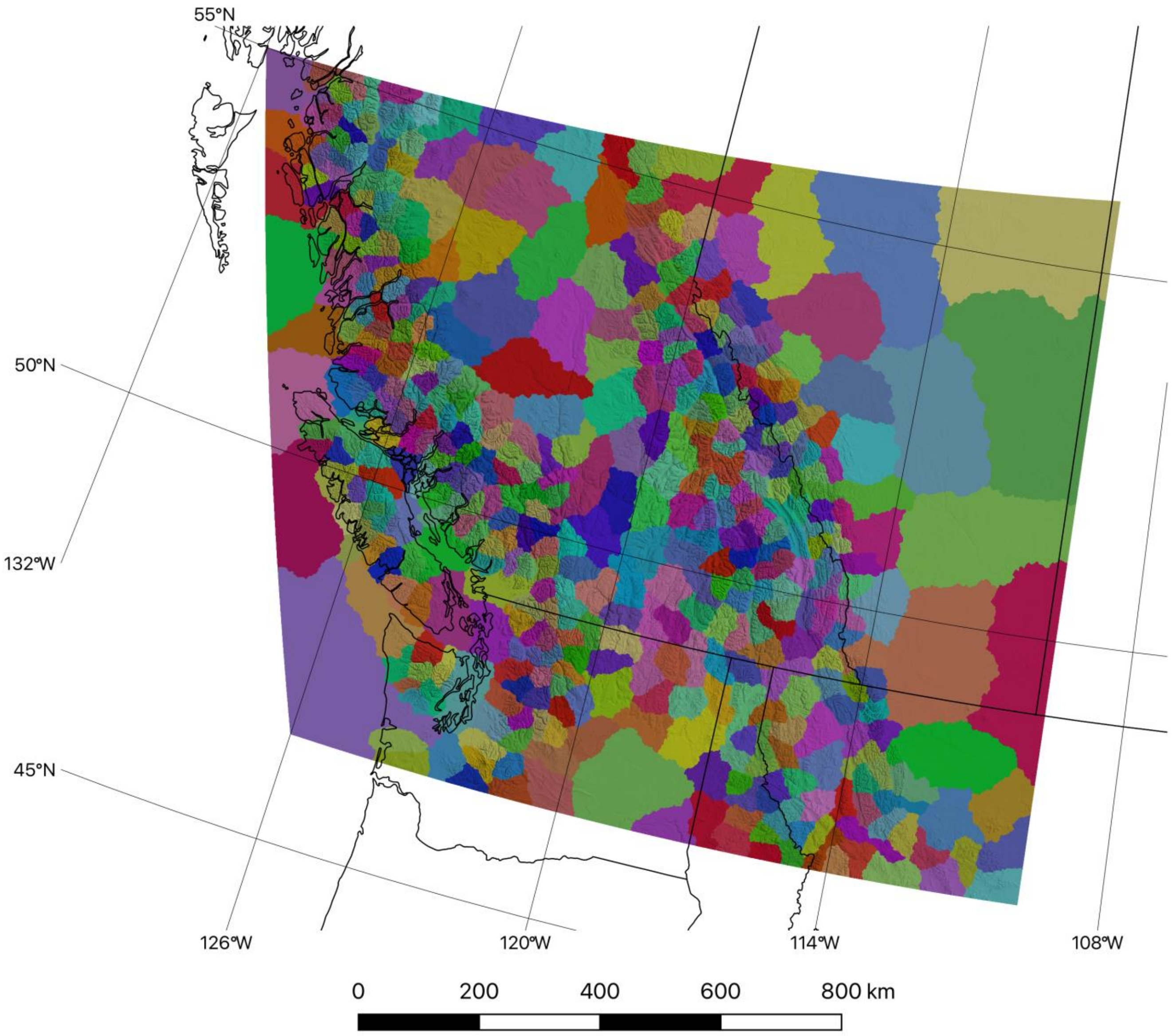
Domain Partitioning

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



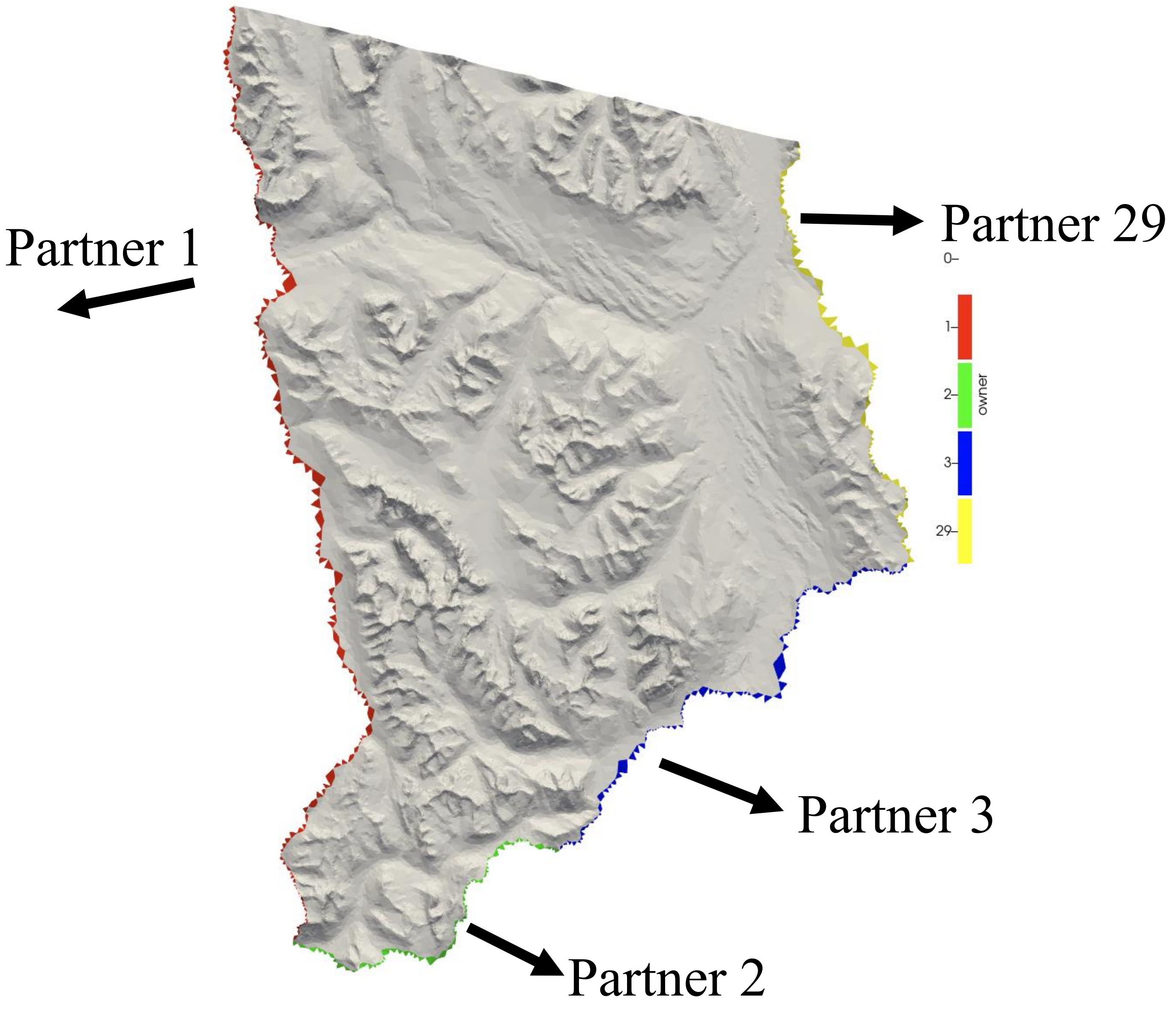


- Massively parallel code via Message Passing Interface (MPI)
- Inclusion of new parallel linear algebra solver Trilinos allows for a global solution to blowing snow
- The SnowSlide avalanche scheme was improved to be MPI aware
- Model outputs are now regridded using the MPI Earth System Modelling Framework (ESMF)
- Domain partitioning uses METIS to minimize MPI communication



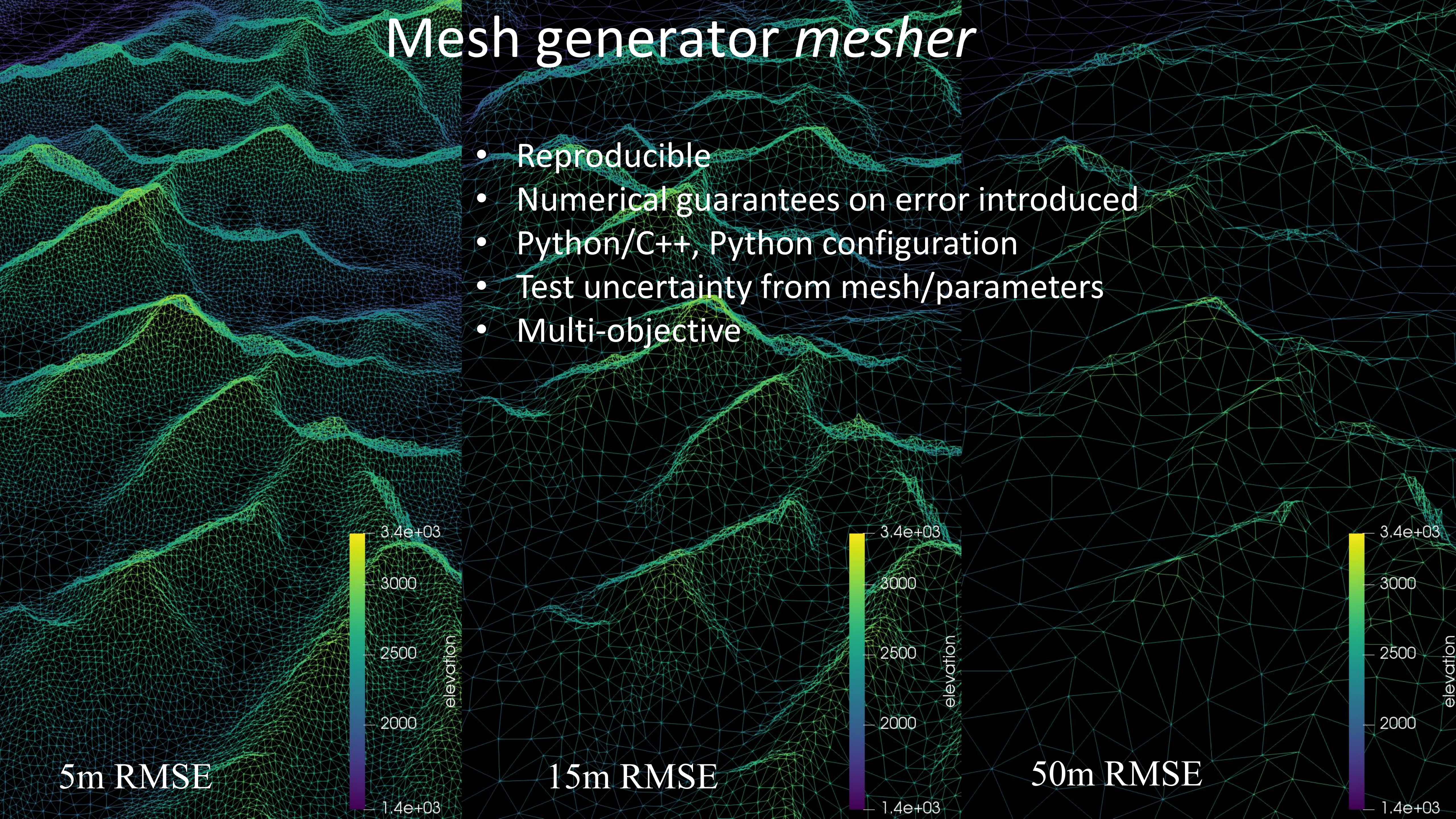
Inter-node communication

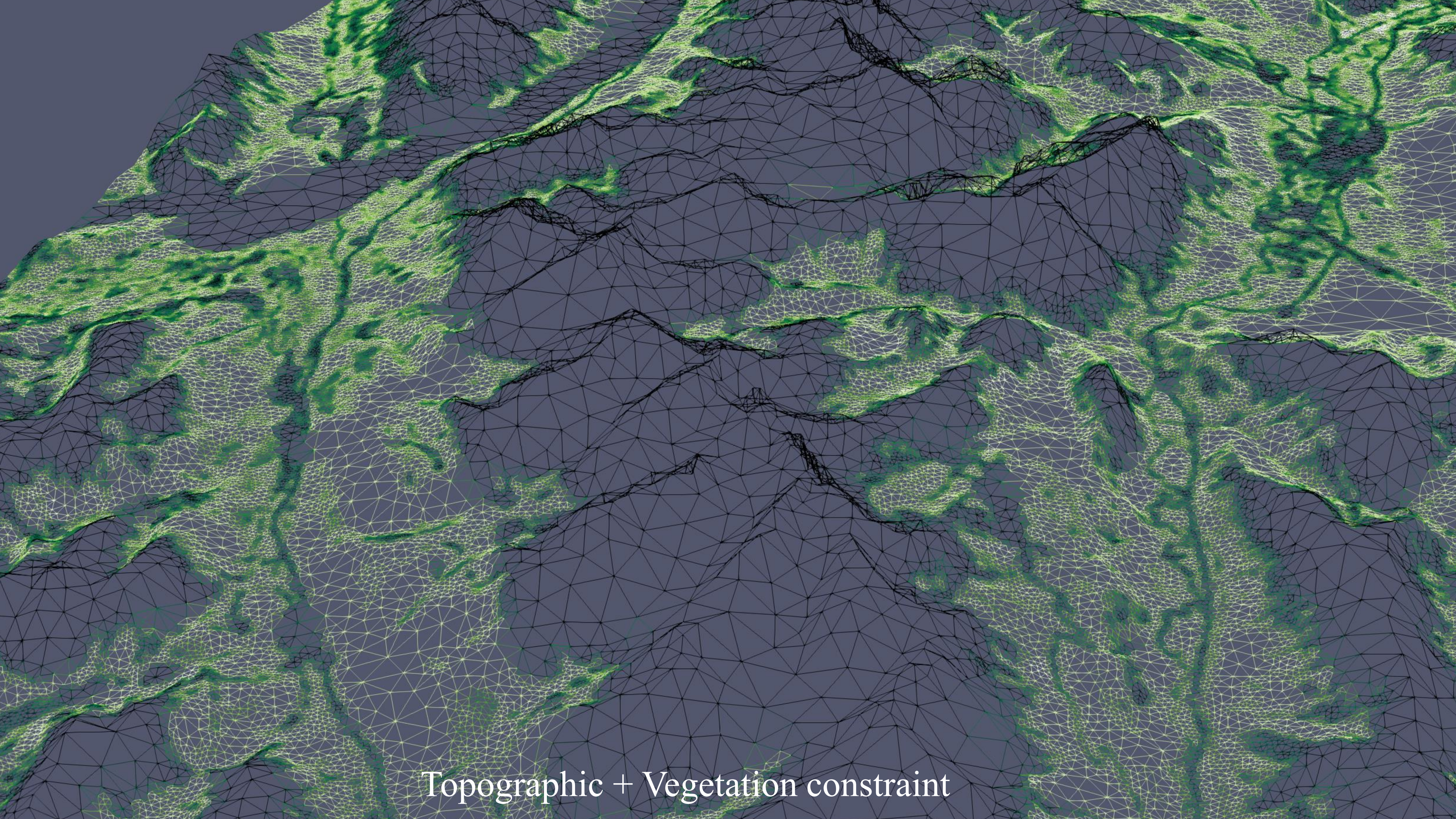
- To transfer a flux between MPI partners
- Coloured triangles are communication partners



Mesh generator *mesher*

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





Topographic + Vegetation constraint

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)