Canadian Hydrological Model: Status and Prospects

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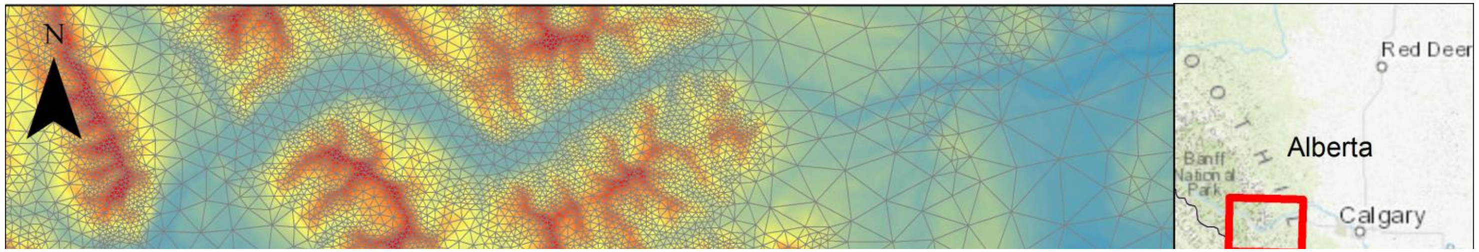
Canadian Hydrological Model (CHM)

- **Unstructured triangular mesh** depending on topography and vegetation complexity

- Flexible structure to test multiple hypothesis, assessment of uncerta
- Incorporation of existing code

- Algorithms for downscaling meteorological data (e.g., from NV

- Accounts for:
  - **slope** and **aspect**; terrain **shad**
  - **gravitational redistribution**
  - **blowing snow (**redistribution + sublimation**)**
  - **snow/canopy interactions**



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Geoscientific Model Development
Discussions
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The Canadian Hydrological Model (CHM): A multi-scale, multi-extent, variable-complexity hydrological model -- Design and overview

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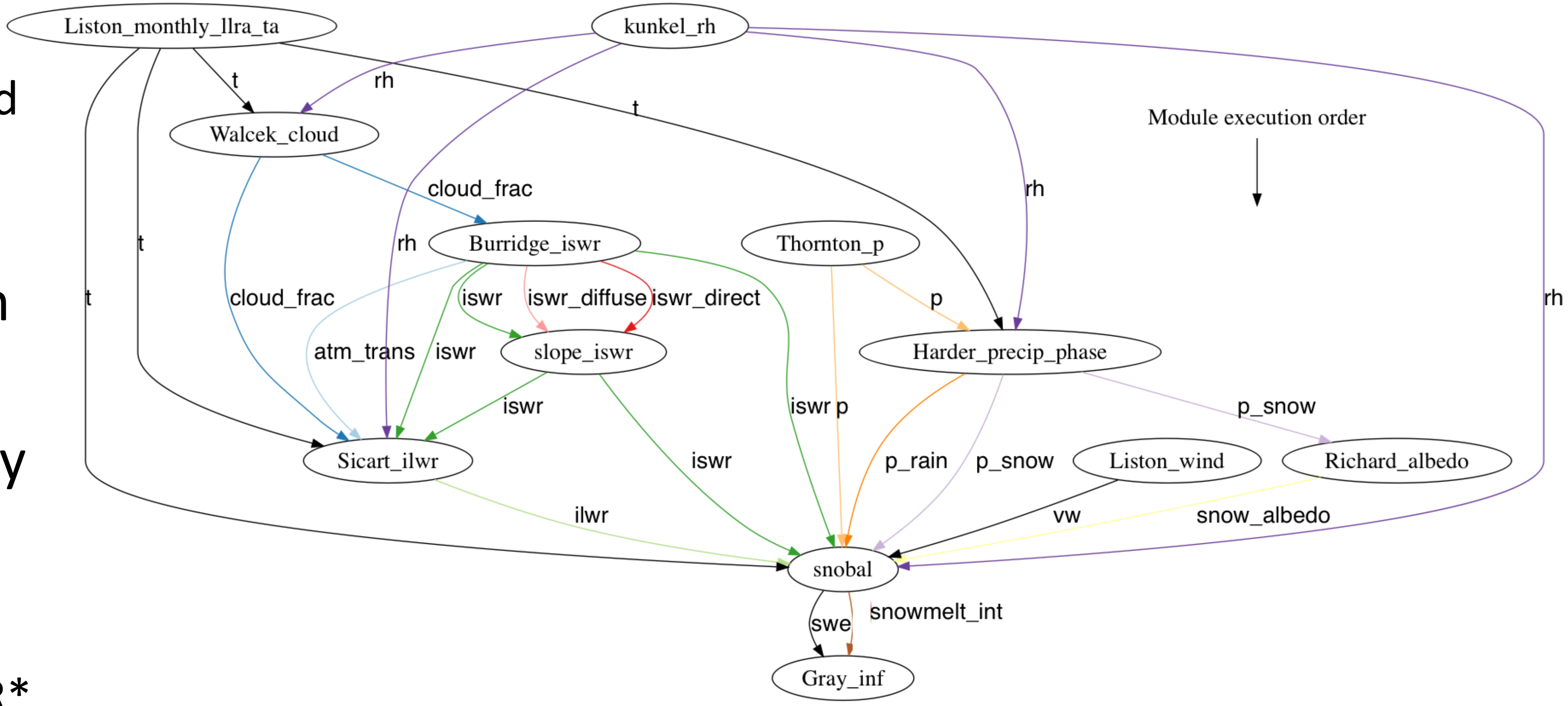
Modular process representation

- **Modules as complex or simple as needed**
  - Mixing empirical and physics-based representations
- Maximizes parallelism
- Incorporation of existing code a priority
- Can call anything that has a C-interface:
  - e.g., Julia, Fortran, R*, Python*, Matlab*



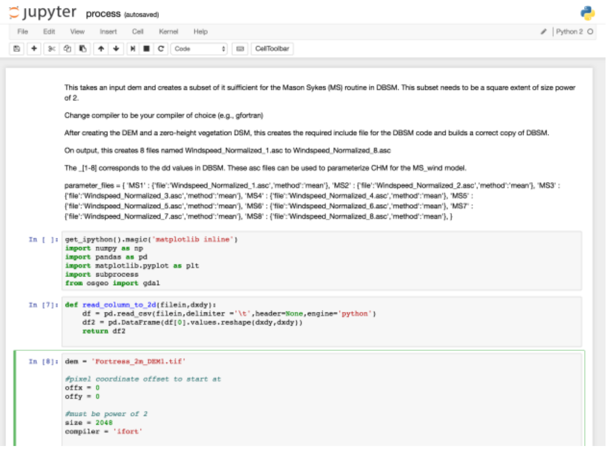
*has implications for parallelism

Process representations

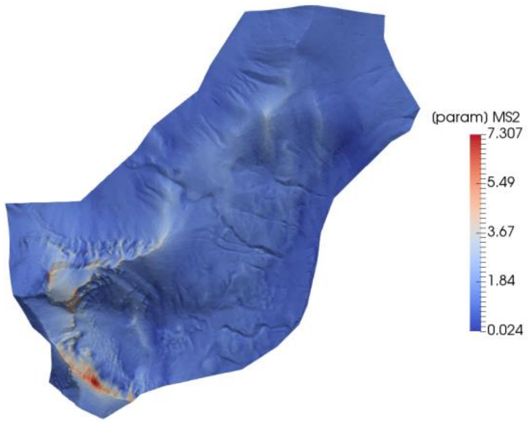
- Air temperature
  - Linear lapse rates (measured, seasonal, constant, neutral stability) (Kunkel, 1989, Dodson et al., 1997)
- Relative humidity
  - Linear lapse rates (measured, seasonal, constant) (Kunkel, 1989)
- Horizontal wind
  - Topographic curvature (Liston, et al., 2006)
  - Mason-Sykes (Mason and Sykes, 1979)
  - WindNinja (Wagenbrenner, et al., 2016)
- Precipitation
  - Elevation based lapse (Thornton, 1997)
- Solar radiation
  - Terrain shadows (Marsh et al., 2011, Dozier and Frew, 1990)
  - Clear sky transmittance (Burridge, 1975)
  - Transmittance from observations
  - Cloud fraction estimates (Walcek, 1994)
- Longwave
  - T, RH based (Sicart et al., 2006)
  - Constant (Marty et al., 2002)
- Canopy
  - Open/forest (exp/log) (Pomeroy et al., 1998; Ellis et al., 2010)
- Snowpack
  - 2-layer Snobal (Marks et al, 1999)
  - Multi-layer Snowpack (Lehning et al., 1999)
  - Various albedo e.g., CLASS (Verseghy 1991)
- Soil
  - Frozen soil infiltration (Gray et al., 2001)
- Precipitation Phase
  - Linear
  - Psychometric (Harder and Pomeroy, 2013)
  - Threshold
- Mass redistribution
  - PBSM3D (Marsh, et al. 2019)
  - Slowslide (Bernhardt, et al. 2012)
- Hydrodynamics
  - FLUXOS (In development)

Mesh generation

- *Mesher* generates the unstructured mesh
  - Reproducible
  - Numerical guarantees on error introduced
  - Handles geospatial conversions and processing
- Mesh generation allows assigning raster values to triangles



Parameterization via *mesher*

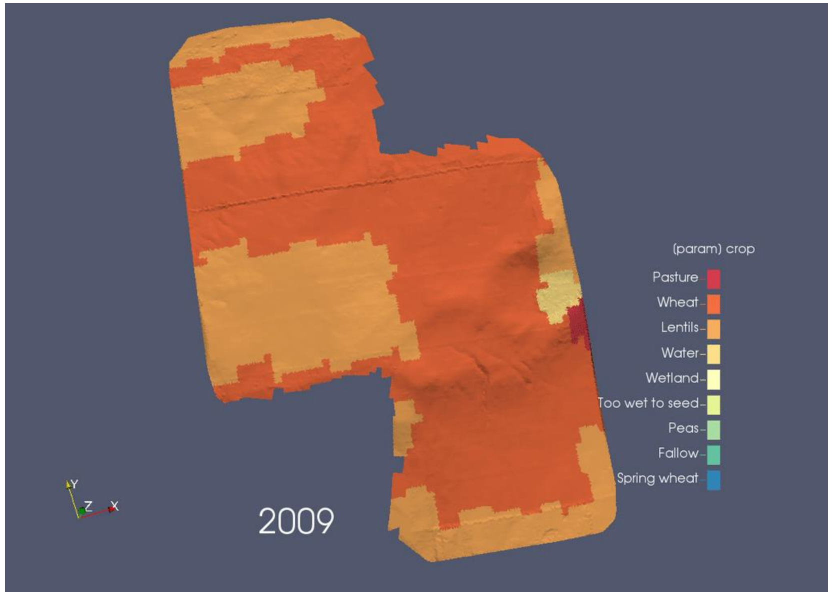



```
//figure out which lookup map we need
int d = int(theta*180.0/M_PI/45.);
if (d == 0) d = 8;

double speedup = face->get_parameter("MS"+std::to_string(d));
W = W*speedup;
```

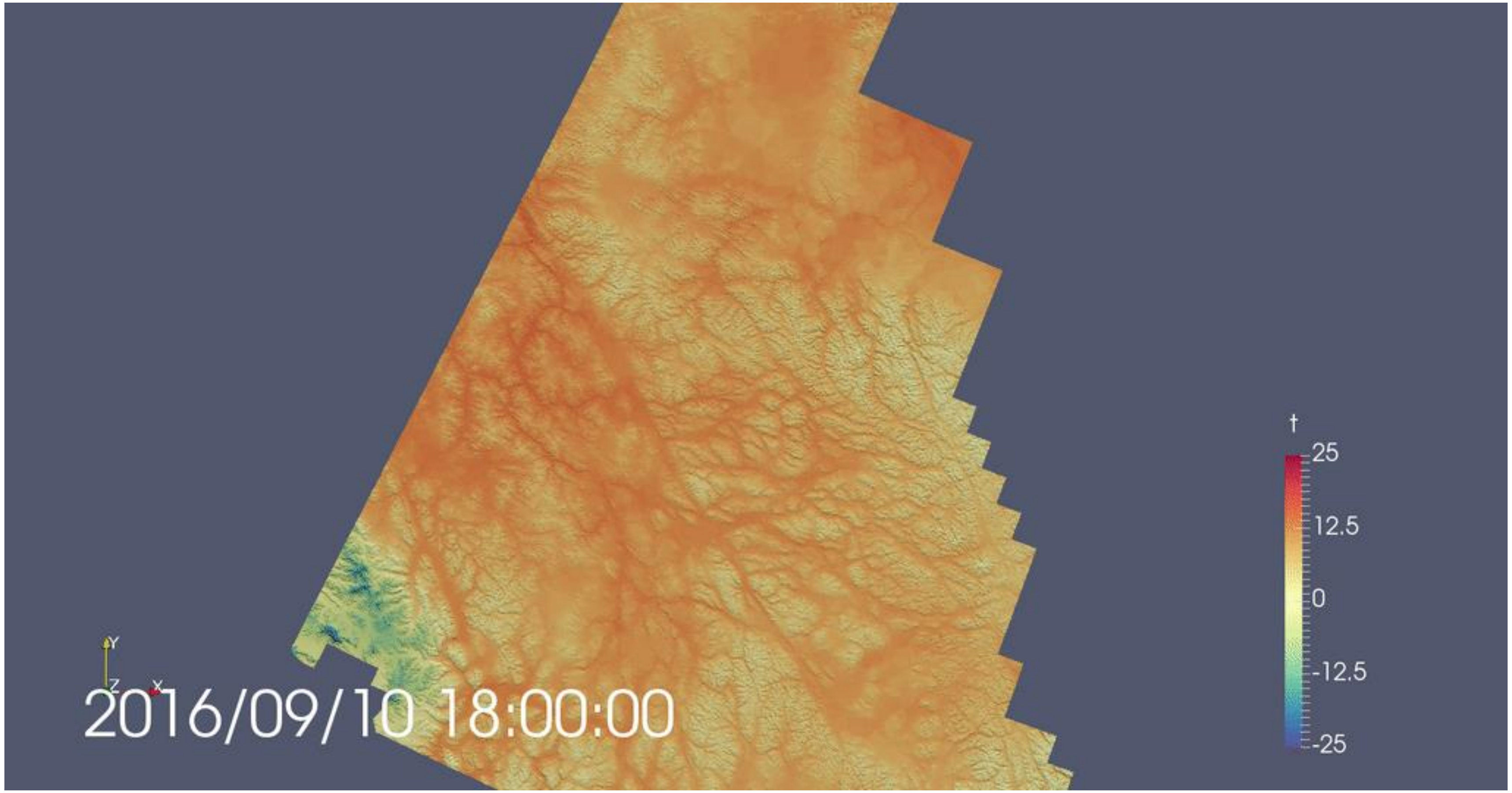
Usage in model

Surface parameters can change during run time



Interpolation & downscaling

- Spatial interpolation
  a) Thin plate spline with tension
  b) Inverse Distance Weighting (IDW)
  c) Nearest neighbour
- Control number of surrounding stations used in interpolation
- Various lapse-rate approaches for downscaling
- NetCDF support for use with NWP outputs

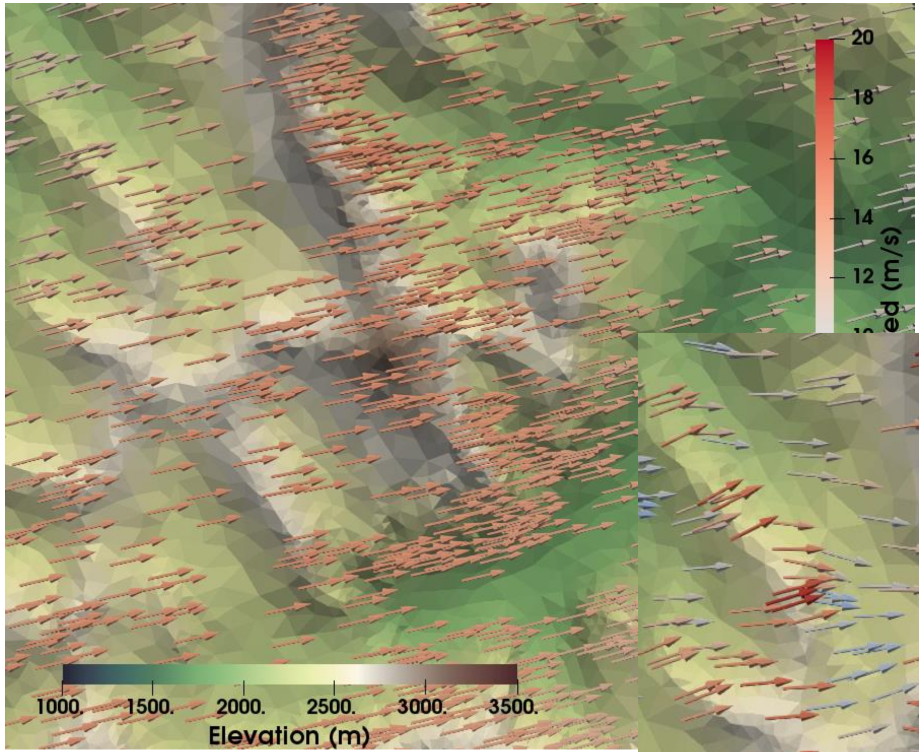


Downscaling 2.5km GEM temperature output
For the Yukon

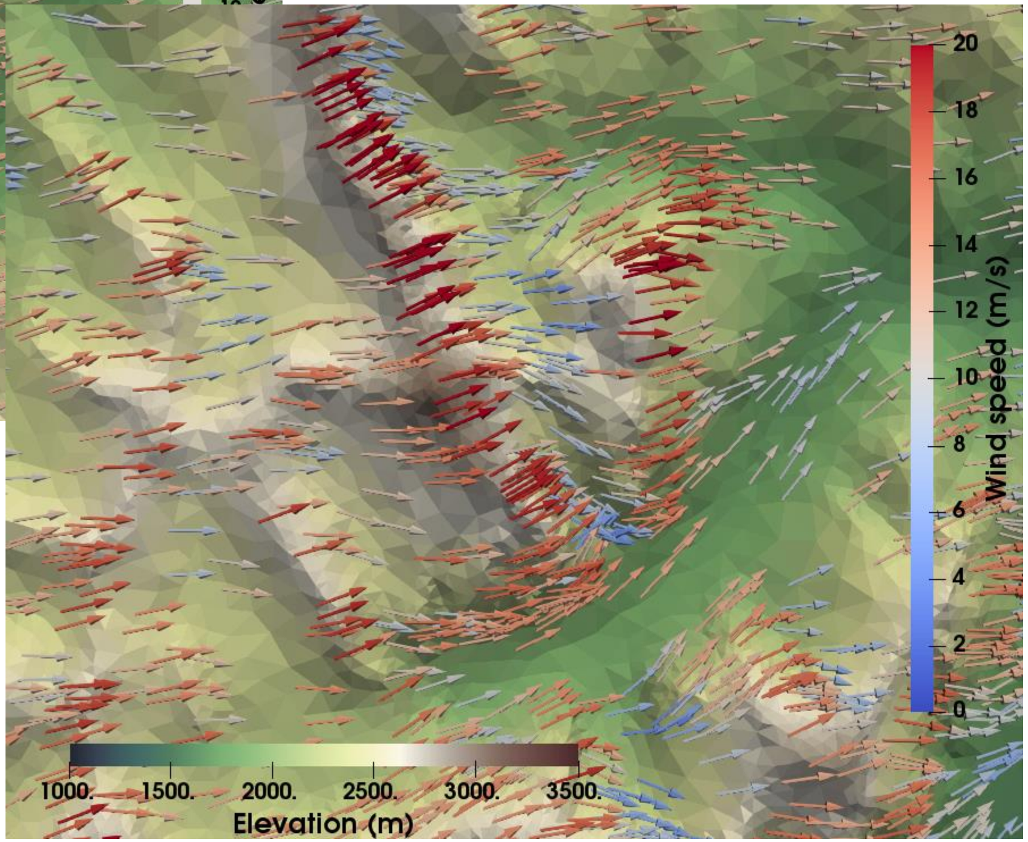
Multiscale blowing snow model (PBSM3D)

- Blowing snow a key component of mass heterogeneity in cold regions
  - “Snow drift resolving scales”
  - 1 m to 150 m resolution
- Up-scaled formulation of the Prairie Blowing Snow Model (PBSM) to a variable resolution mesh
- Includes non-steady fetch effects
- Uses windspeed maps to account for terrain impacts
  - Less computationally expensive than CFD model
  - Better results than terrain-curvature methods
- Applicable to large extents

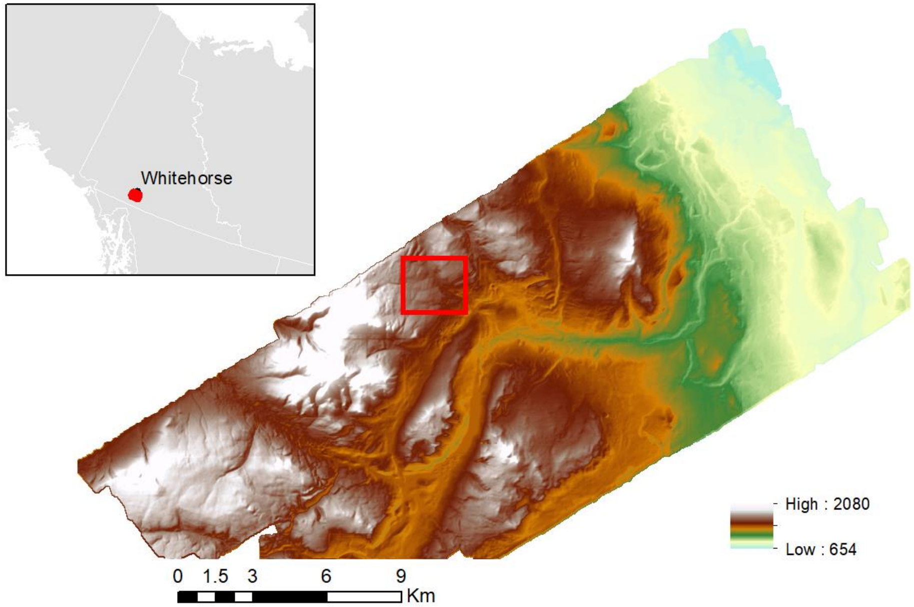
Uncorrected wind field



Corrected wind field

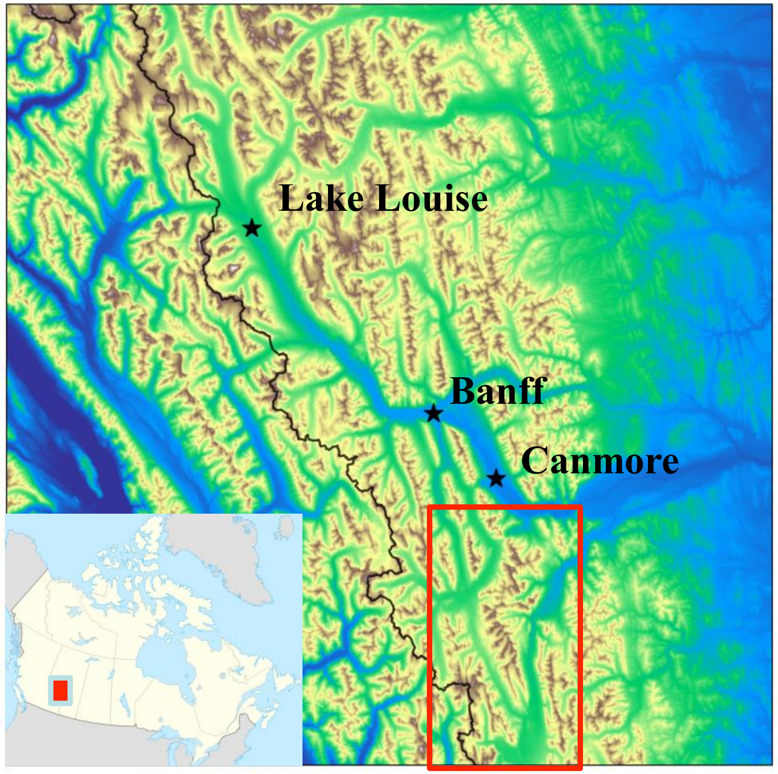


PBSM3D at Granger Basin, Wolf Creek

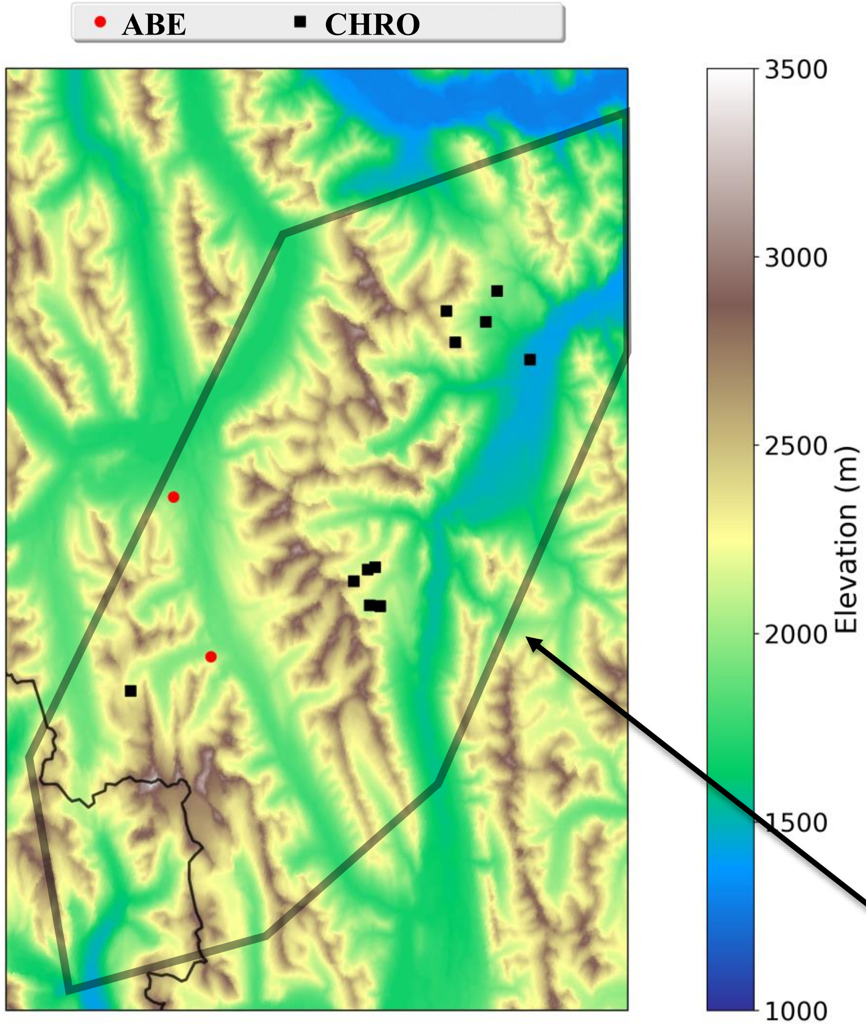


- Inclusion of blowing snow:
  - 13% improvement in RMSE
  - 73% decrease in MBE
  - **Increased CV from 0.04 to 0.4**
    - **Inline with observed values**
- Interannual variability in drift formation was captured
- **Reduced:**
  - **# elements by 62%**
  - **runtime by 44%**

Application to Kananaskis, Canadian Rockies



Upper Bow River Basin



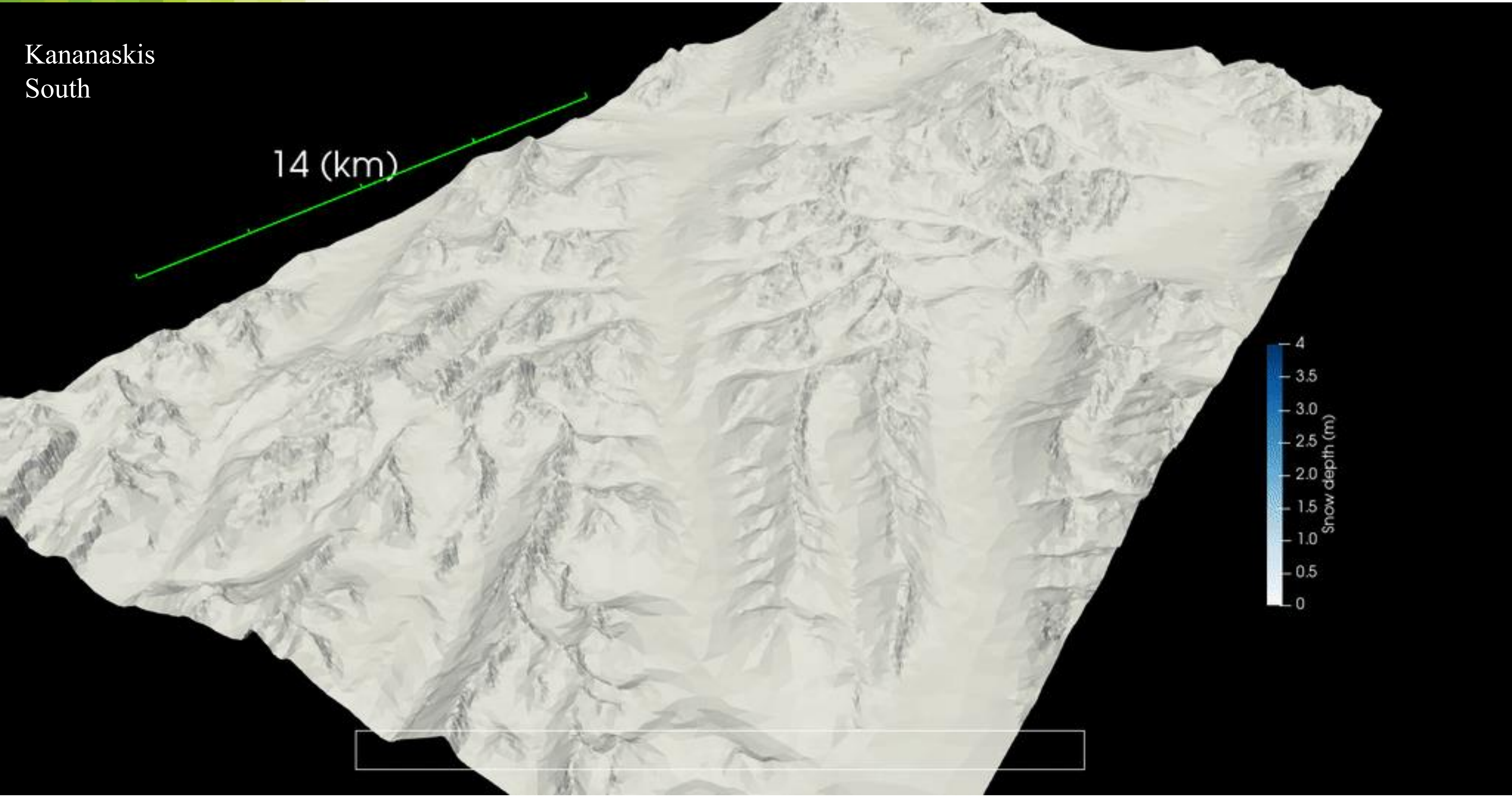
Kananaskis area

- Use GEM HRDPS 2.5km meteorological forcing
- Downscaled to CHM mesh
- **Airborne LiDAR** (UNBC Riegl Q 780):

1-m snow depth map
27 April 2018

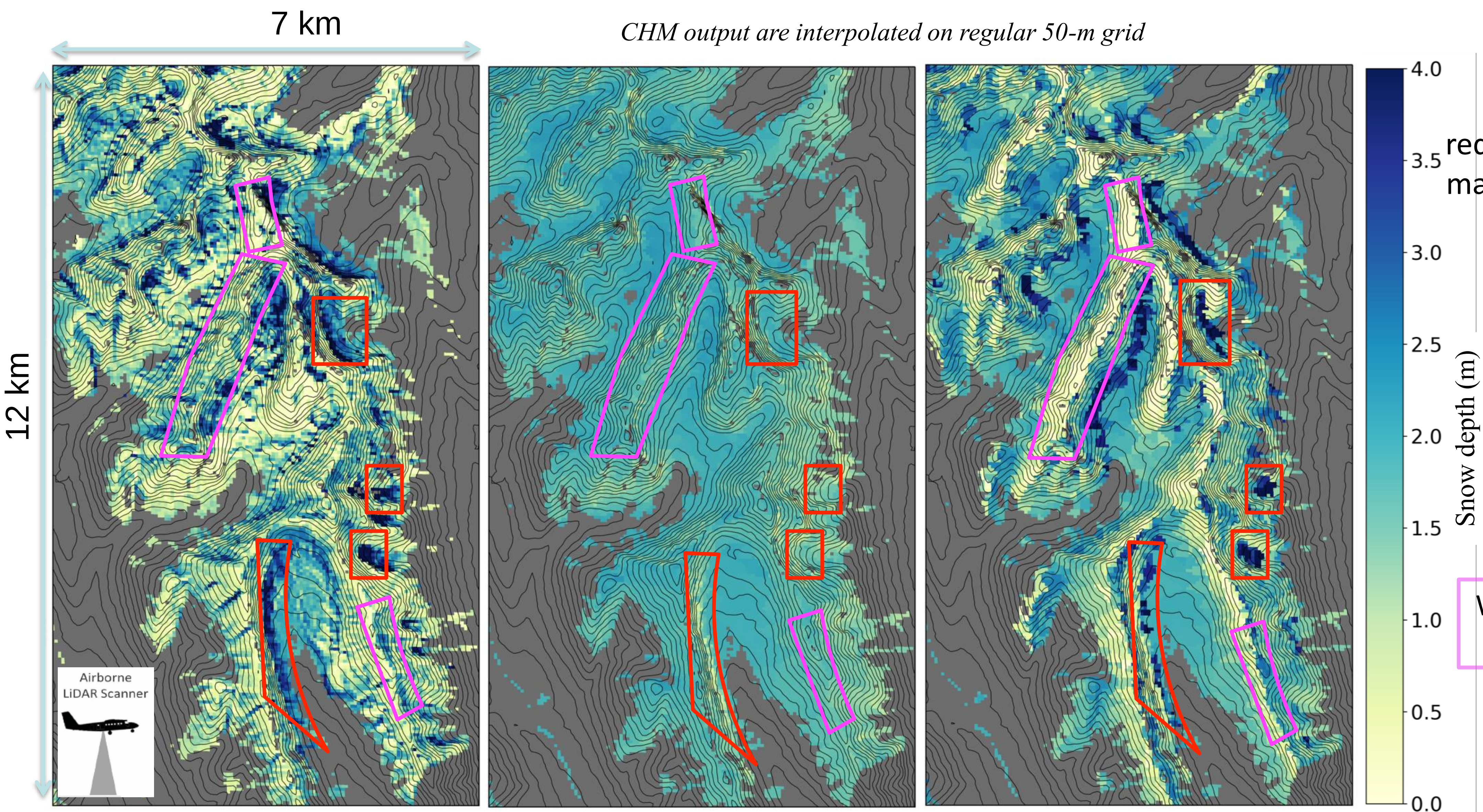
Vionnet, et al., in prep (2019)

Kananaskis South



Influence of snow redistribution

CHM output are interpolated on regular 50-m grid



Lidar measurements 27 April 2018

No Snow Redistribution

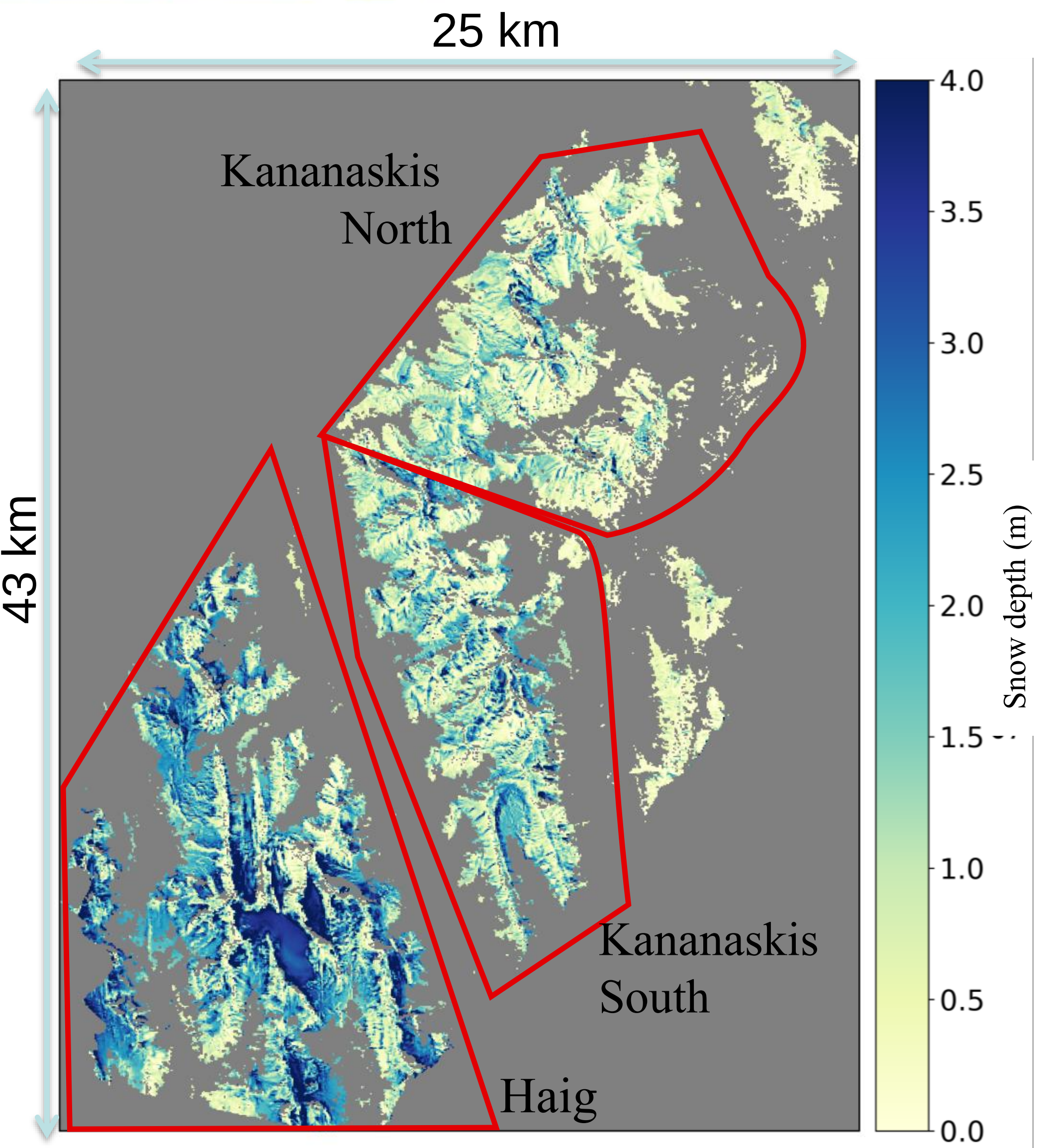
Snow Redistribution

CHM with snow redistribution captures many features of snow accumulation

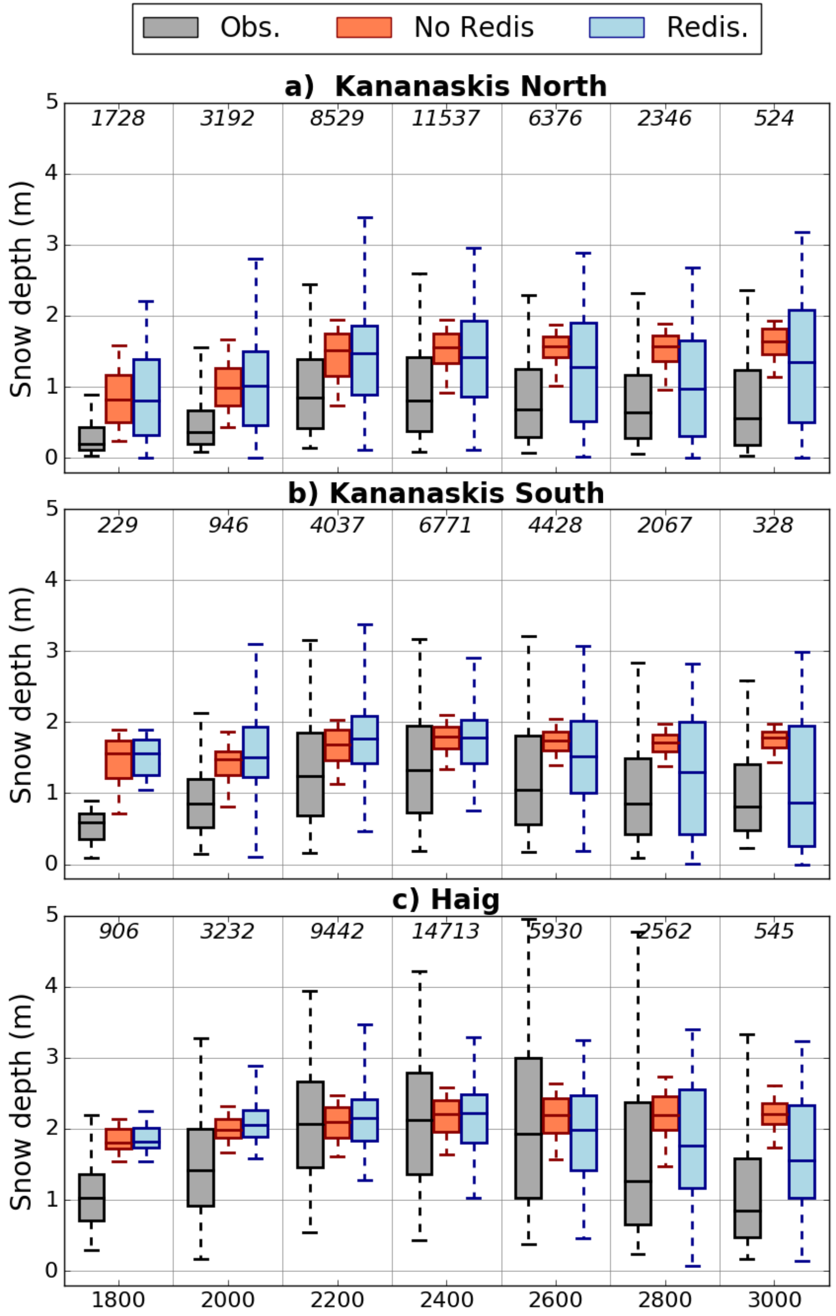
Avalanche deposition areas

Wind redistribution along crest lines

Influence of elevation



Lidar-derived 50-m map of snow depth (SD) (non-forested areas)



- Decrease in mean snow depth at high elevation

No-Redistribution:

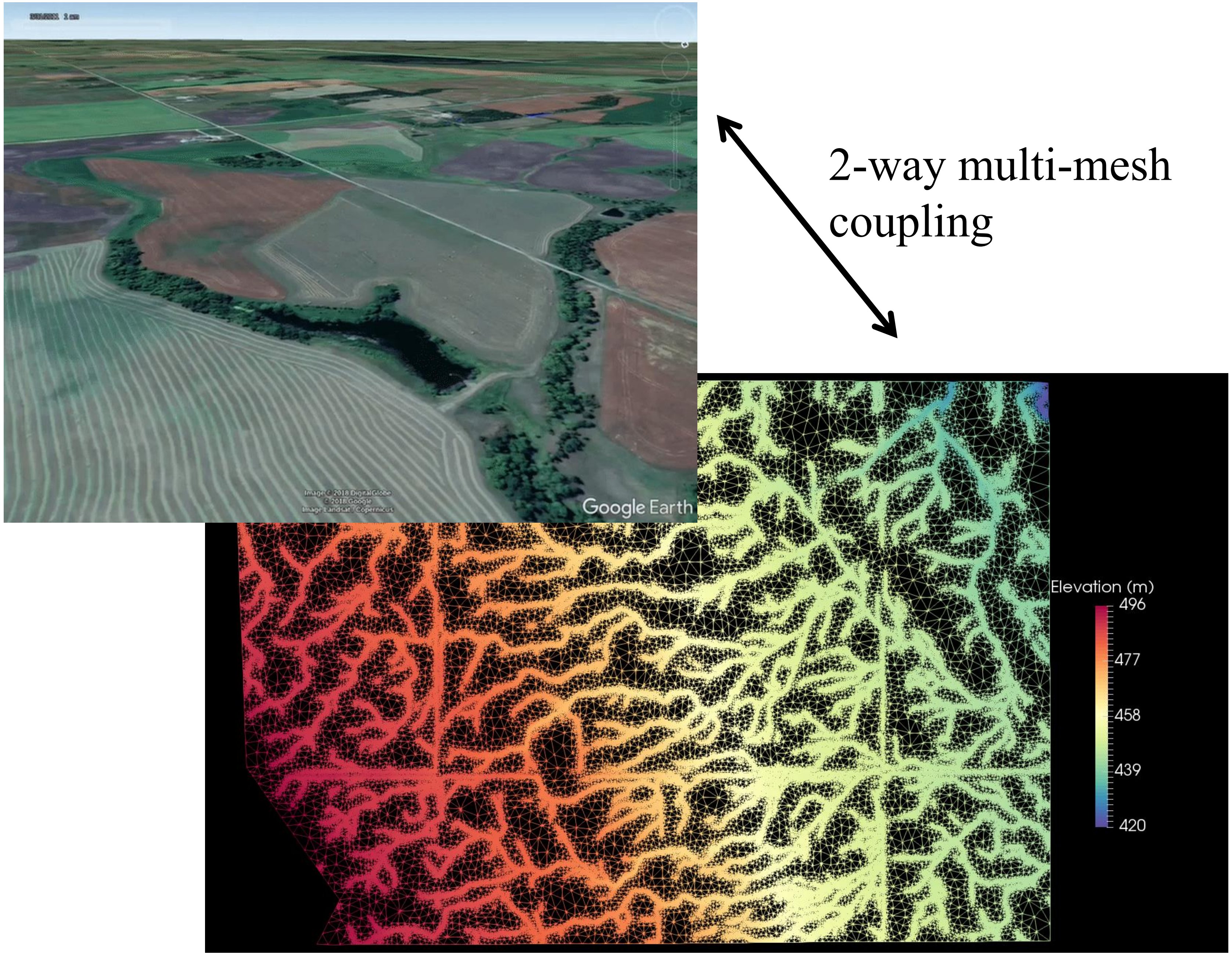
- Does not capture the spatial variability of SD
- No decrease of SD at high-elevation

Redistribution captures:

- increased SD variability due to snowdrifts and avalanche deposits
- Snow transport from high-elevation

Hydrodynamics

- Couple CHM with 2D hydrodynamic code FLUXOS (dynamic wave solver)
- Use for snowmelt runoff and nutrient export dynamics
- Challenges:
  - Couple unstructured mesh with internal structured mesh of FLUXOS
  - Migrate FLUXOS to unstructured mesh



High performance computing developments

Multiple compute nodes via MPI

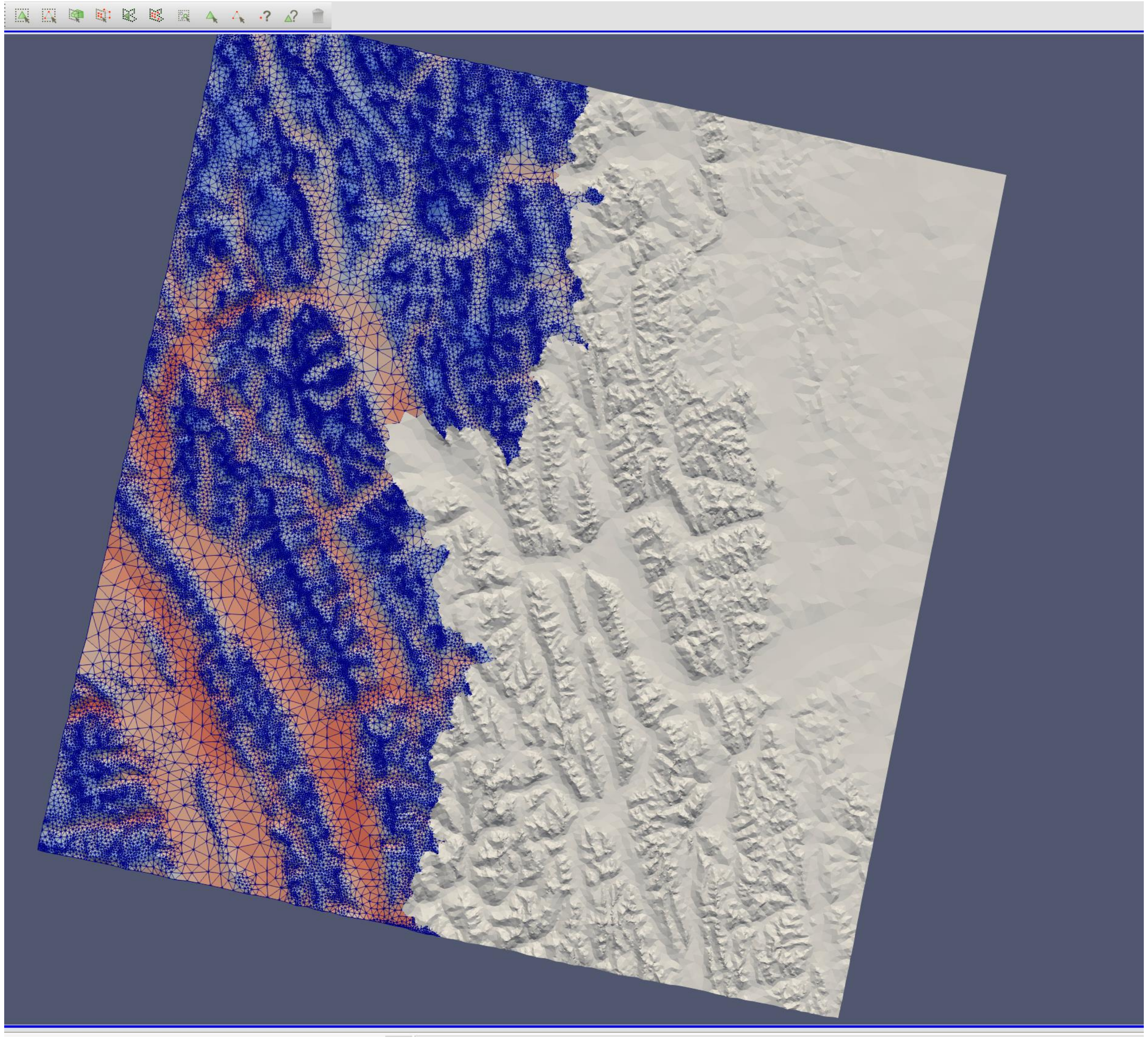
- Currently scaling to 3200 CPUs

Mesh reordering

- Ensures triangles near to each other are on same node
- Improves linear algebra solution time
- Decreases inter-node communications

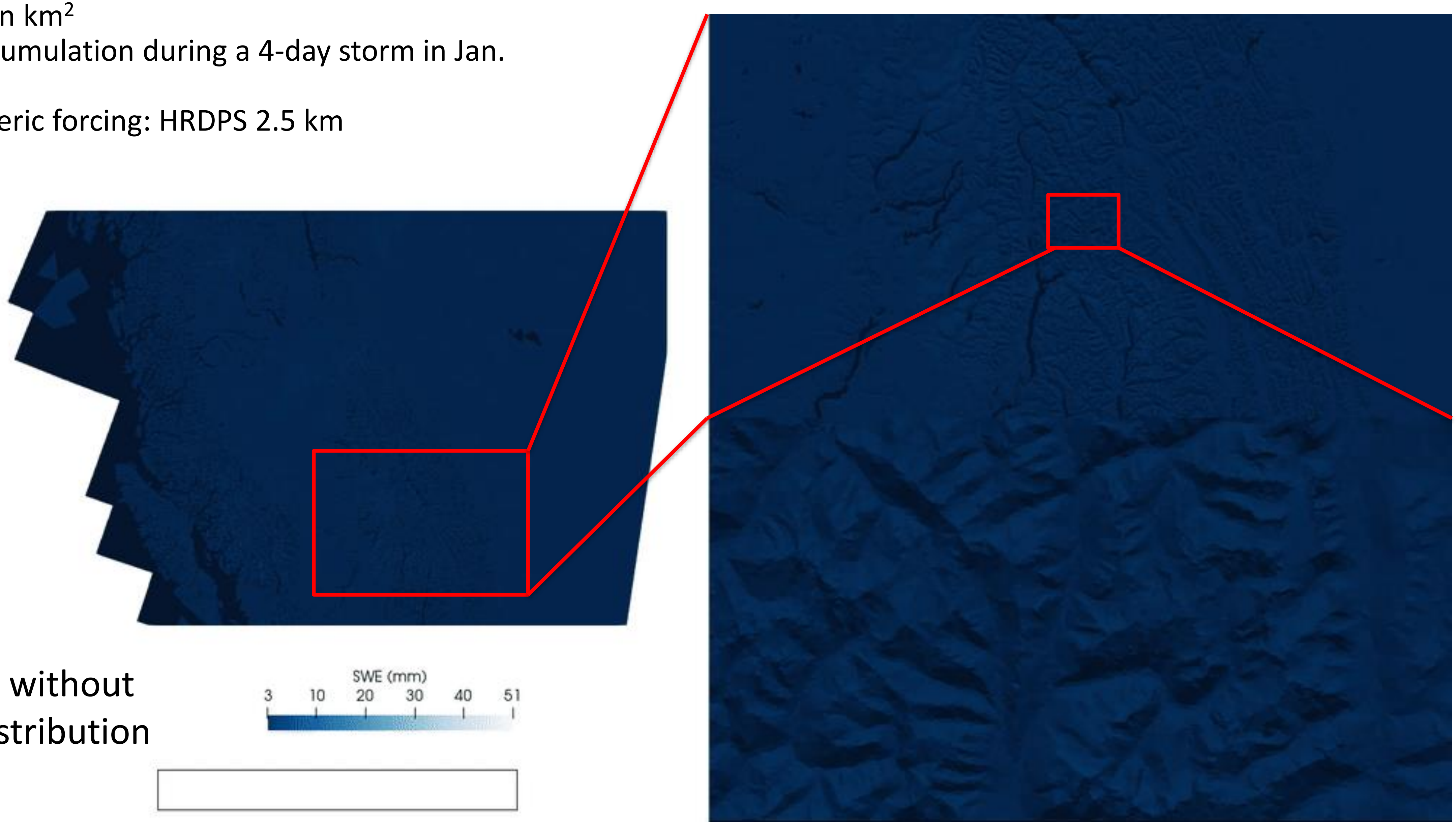
In progress

- Distributed mesh
- Inter-face communications
- Global linear algebra solver



CHM over Western Canada

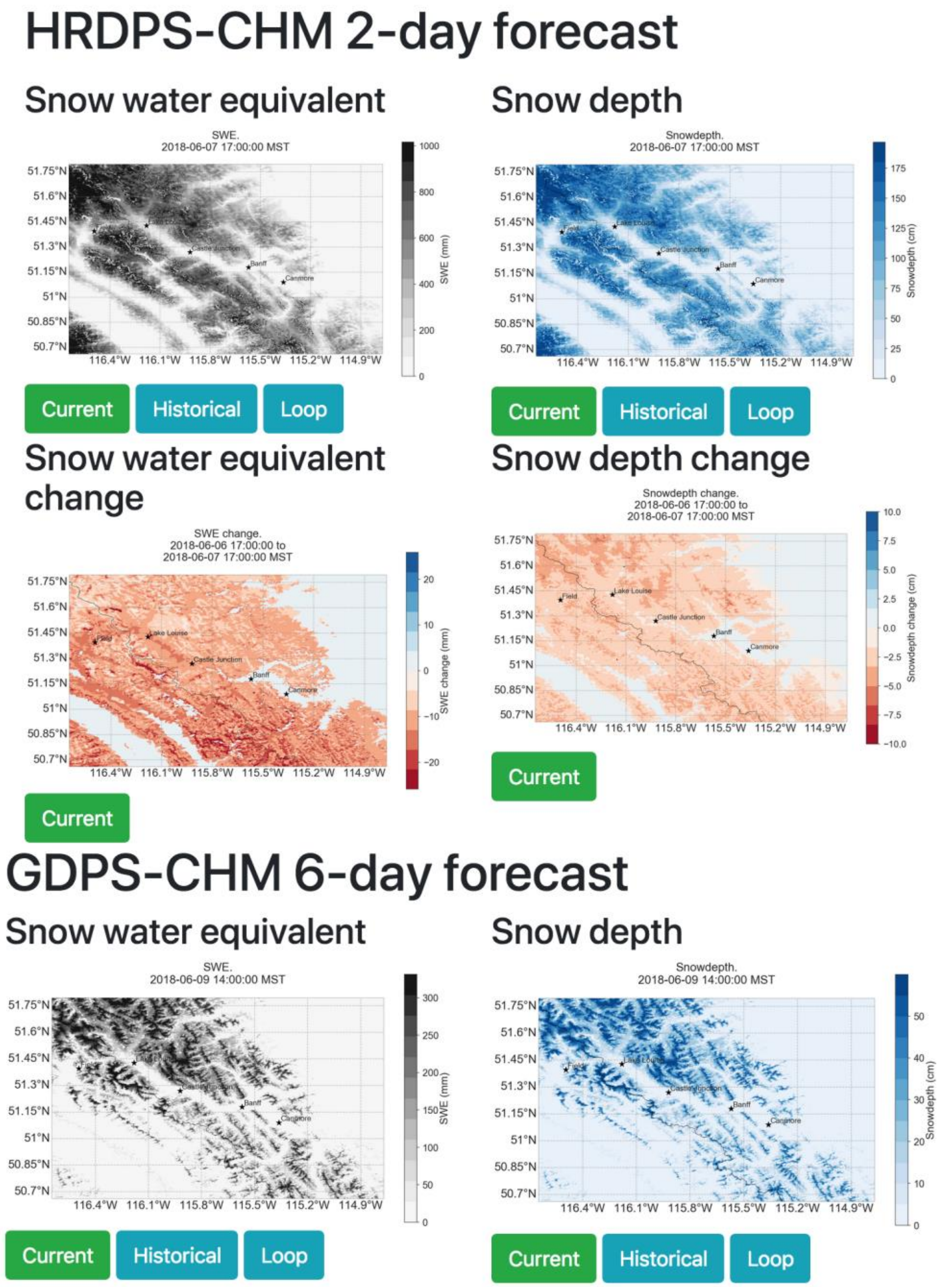
- CHM mesh with a 200 m triangle size near ridges
- 1.3 million km^2
- Snow accumulation during a 4-day storm in Jan. 2018
- Atmospheric forcing: HRDPS 2.5 km



Simulation without snow redistribution

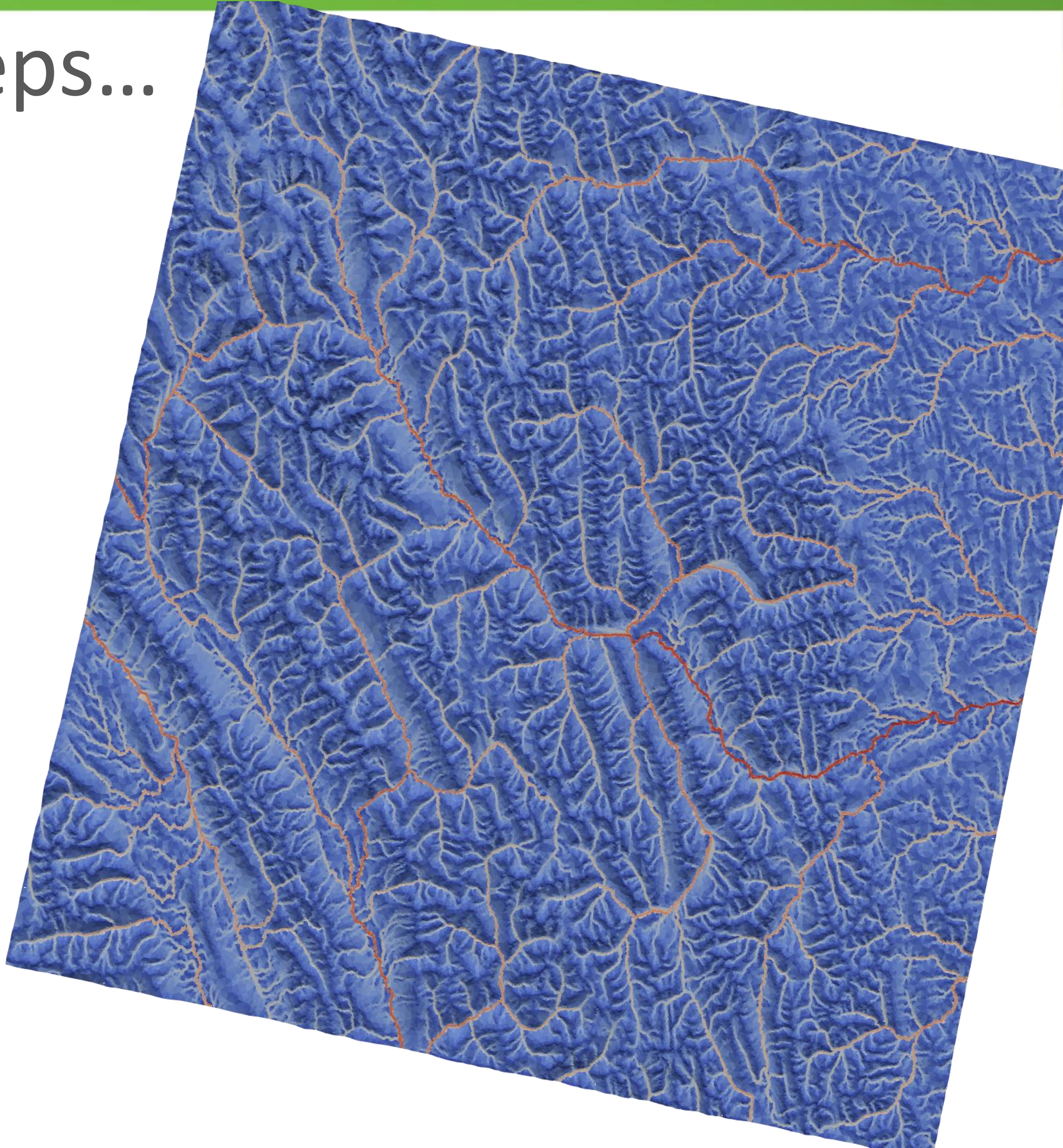
SnowCast

- Daily snowpack forecast
    - +2 and +6 day
    - downscaling of GEM 2.5 km output
- Domain is the Bow Valley near Banff, Alberta
- Provides estimate of current snow depth, density, SWE in the Canadian Rockies
- Potential to provide initial conditions for flood forecast model (assimilation)
- http://www.snowcast.ca/



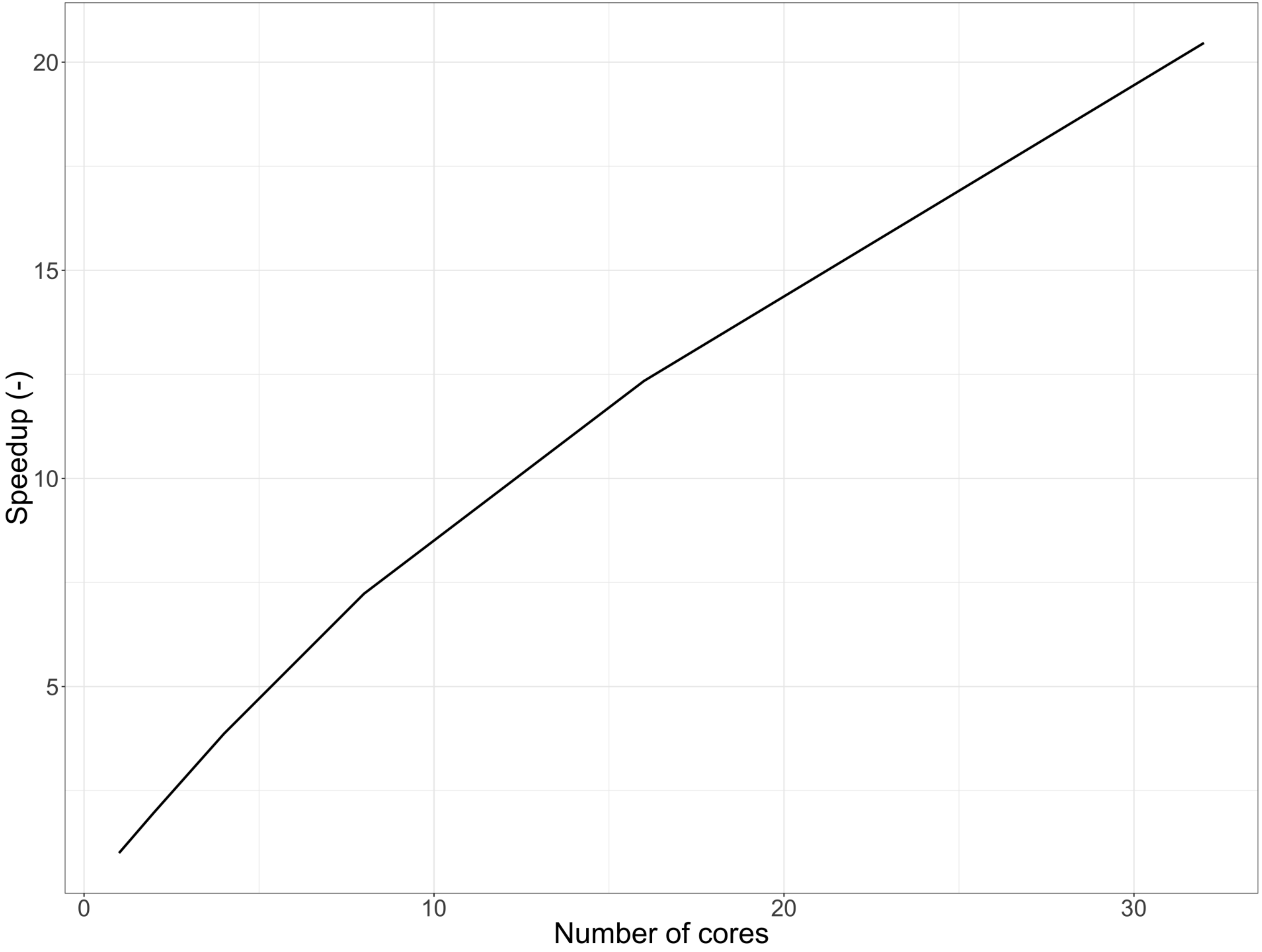
Next steps…

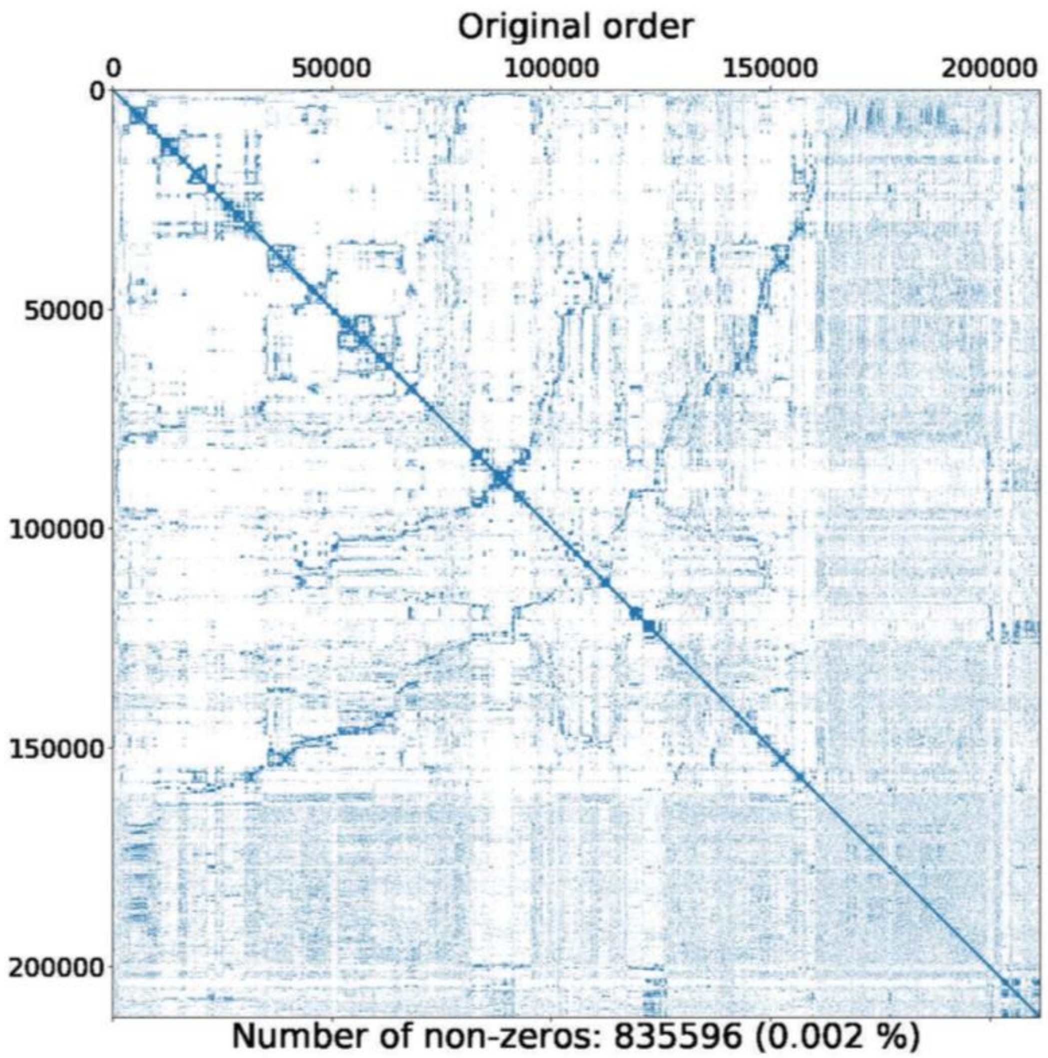
- Evapotranspiration, wetlands, soils, groundwater
- Routing
- Snowdrift resolving simulation over Canadian Cordillera
- Sub-grid variability
- Warranted model complexity across large extents
  a) E.g., use prairie specific models in the prairies
- SnowCast
  - Enable blowing snow
  - Improve visualization
  - Data access

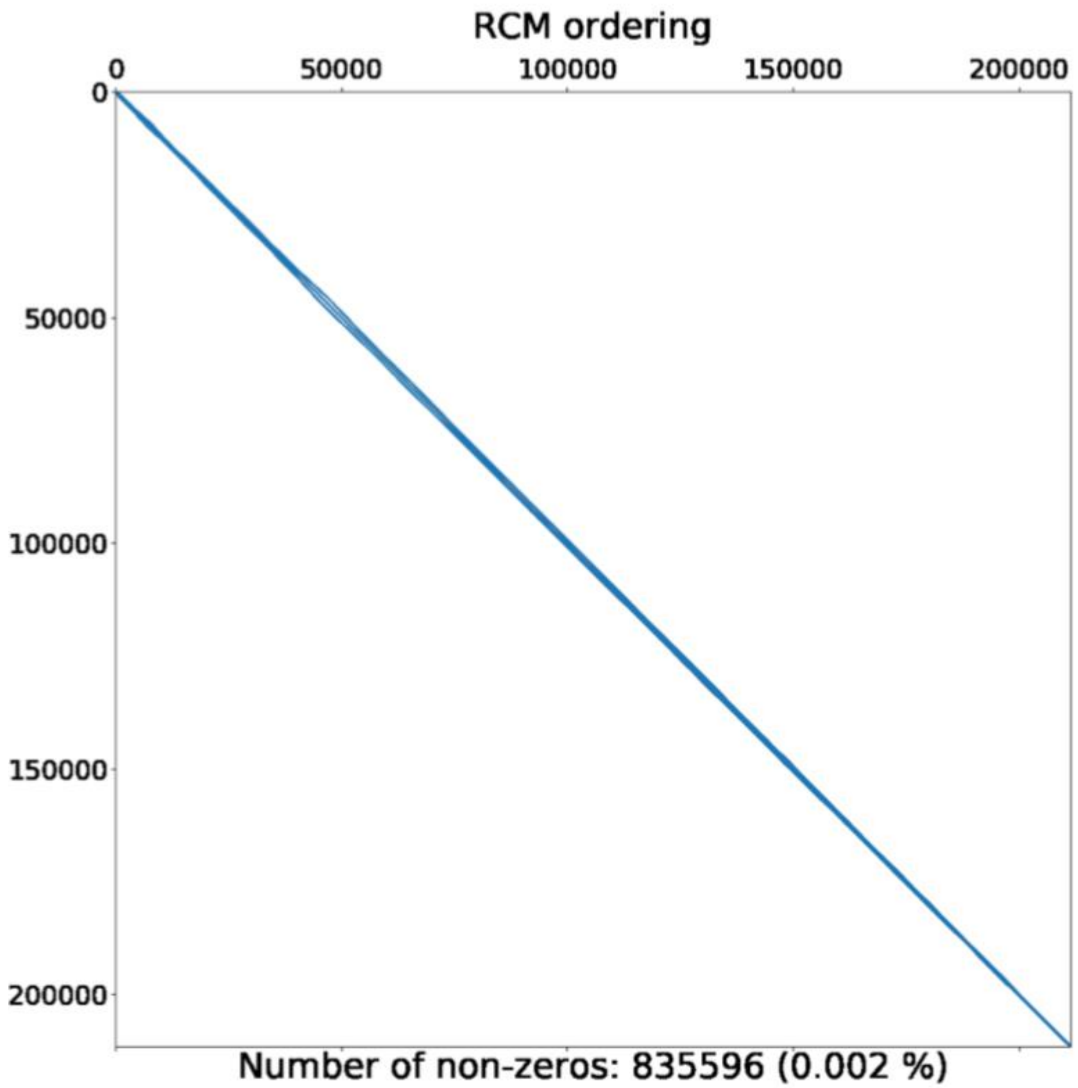


Conclusions

- CHM allows for efficient multi-scale process representation
- Blowing snow and avalanching required for correct spatial and temporal variability in snow mass
- Developments:
  - HPC work has enabled large-extent application at nearly snow-drift resolving scales
  - Large extent SWE simulations for 1.3M km^2
- Next steps:
  - Snow-drift resolving simulation over Western Canadian Cordillera
  - Inclusion of more hydrological processes (e.g., evapotranspiration, routing, soils, FLUXOS)
  - Ongoing code optimizations to support MPI changes to enable larger extents


Speedup (-)
20
15
10
5
0
10
20
30
Number of cores


Original order
0
50000
100000
150000
200000
0
50000
100000
150000
200000
Number of non-zeros: 835596 (0.002 %)


RCM ordering
0
50000
100000
150000
200000
0
50000
100000
150000
200000
Number of non-zeros: 835596 (0.002 %)

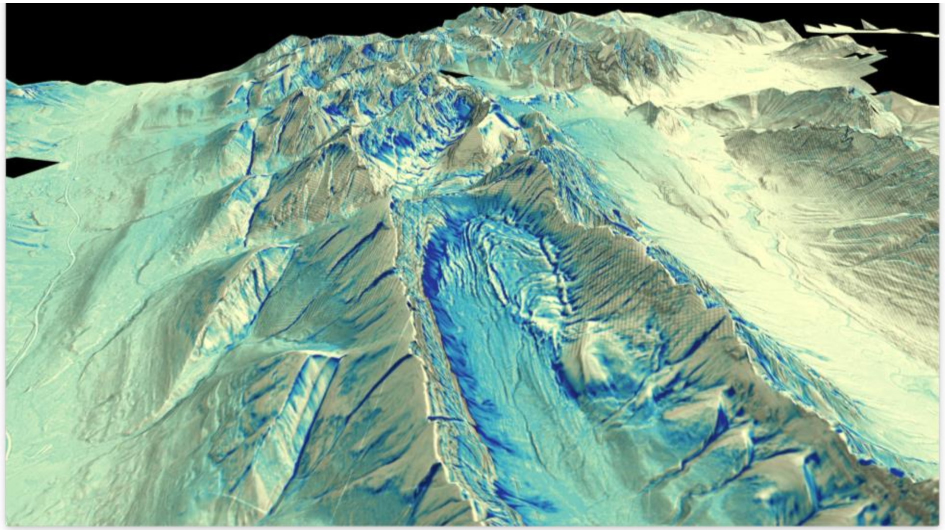
Variability and heterogeneity

- Cold regions have substantial spatial and temporal variability in mass and energy

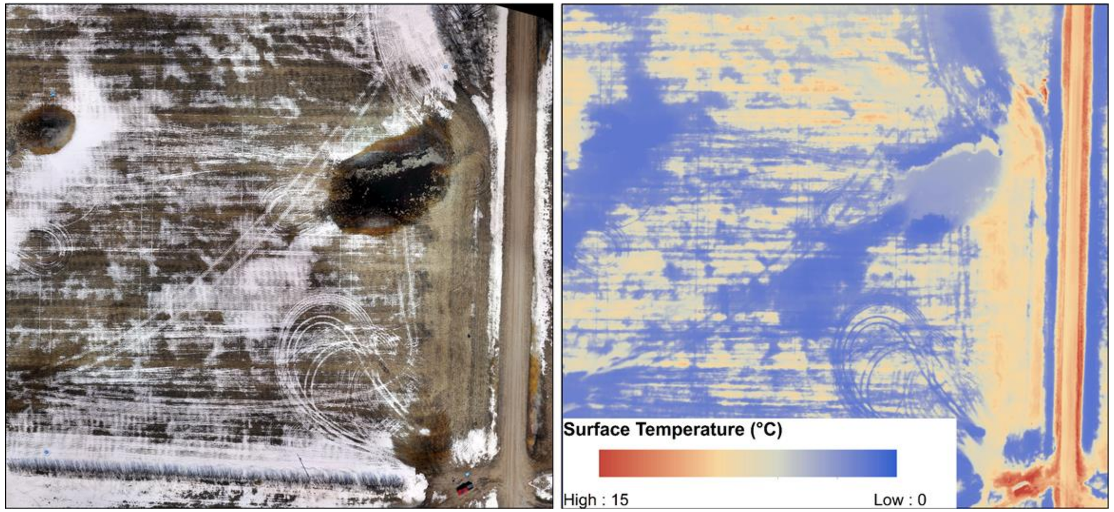
- Results in **heterogeneity in runoff generation**
  - Water stored as **snow in the mountains** represents a **key component** of the **hydrological cycle** of many **river basins** in **Canada**
  - **Flood forecasting,** water management
  - Prairie **snowmelt runoff nutrient transport**

- Heterogeneity motivates the use of distributed models and physically-based models

- However, traditional approaches may:
  - over-represent the landscape
  - increase computational costs
  - increase required number of parameters
- Or, lumped approximations may fail

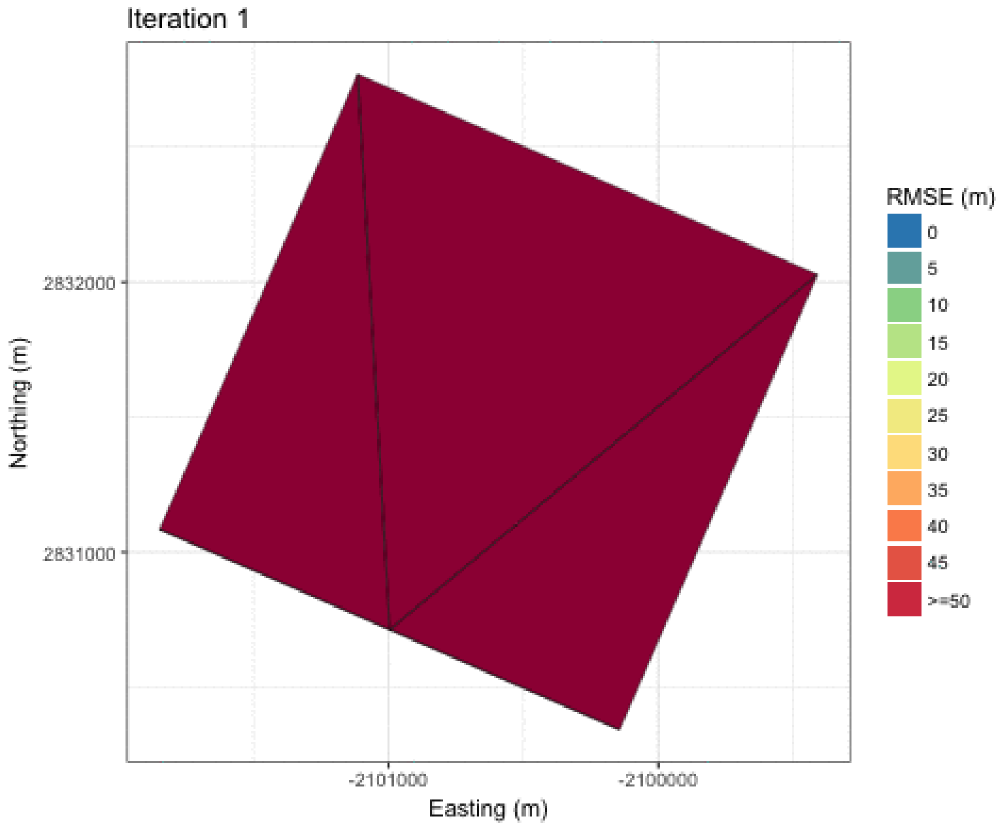


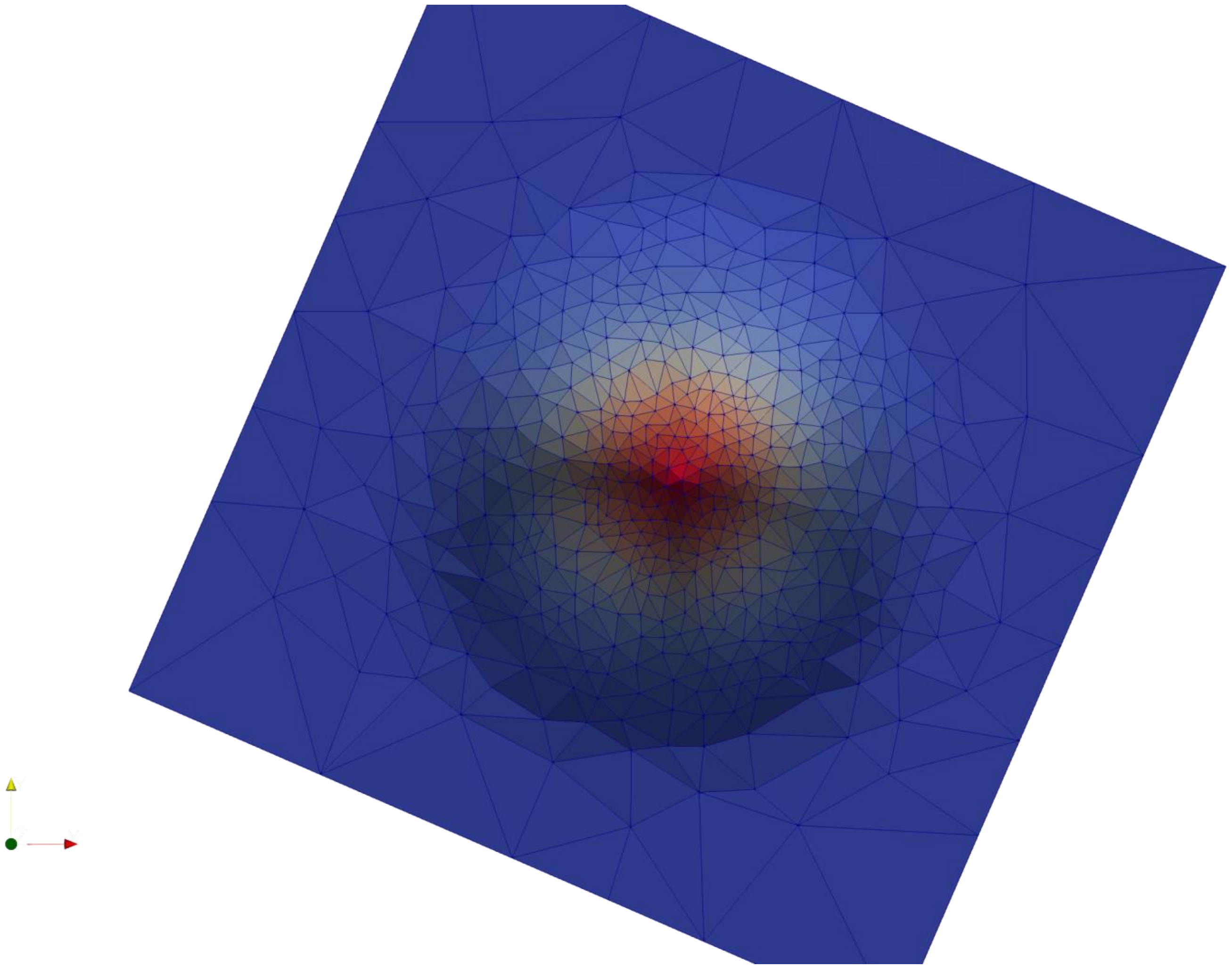
5-m 3D map of snow depth derived from airborne Lidar over the Kananaskis region (Alberta) on 27 April 2018



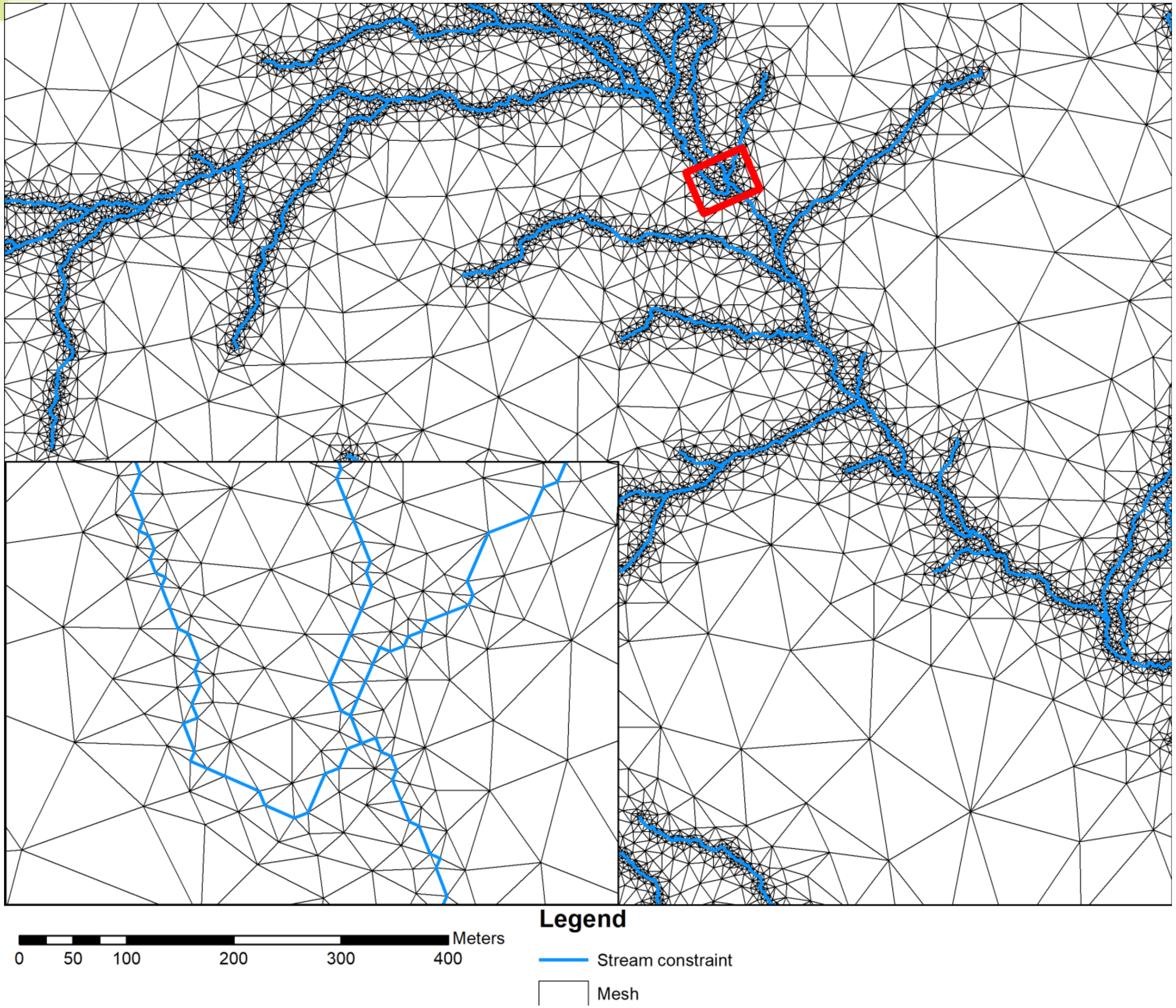
Prairie surface variability (Phillip Harder)

Mesher





https://github.com/Chrismarsh/mesher



0
50
100
200
300
400
Meters
Legend
Stream constraint
Mesh