Multi-scale snowdrift-resolving modeling of mountain snowpack evolution

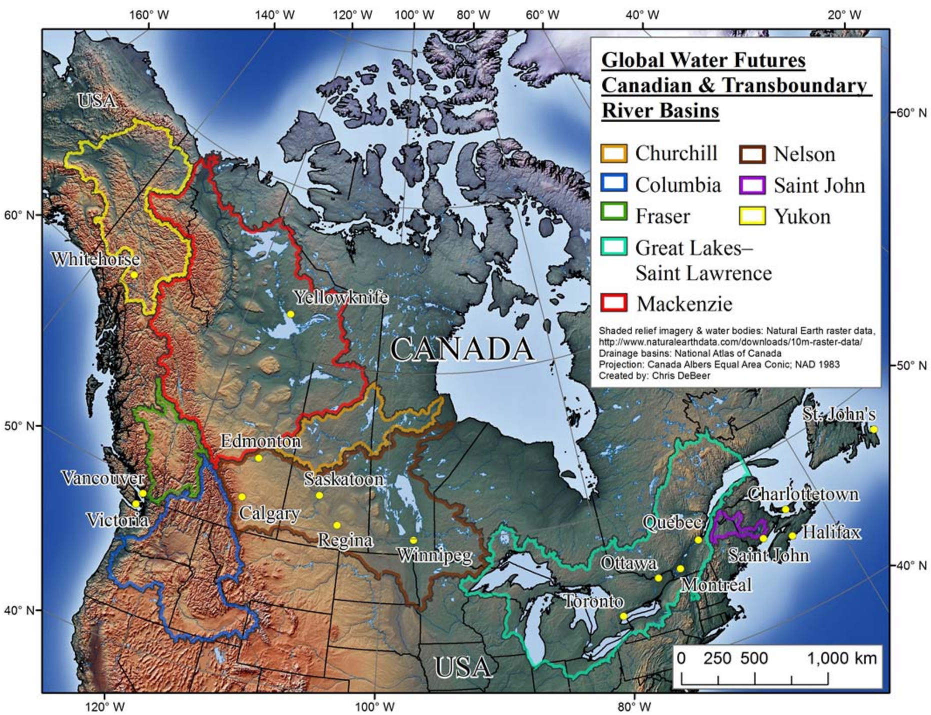
V. Vionnet[1], C. Marsh[1], N. Wayand[1,2], B. Menounos[3], K. Mukherjee[3], J. Shea[1,3], and J. W. Pomeroy[1]

[1] Centre for Hydrology, University of Saskatchewan, Montréal, Canmore & Saskatoon, Canada

[2] Atmospheric Sciences, University of Washington, Seattle, USA

[3] Geography and Natural Resources and Environmental Studies Institute, University of Northern British Columbia, Prince George, Canada

Mountain snow in Canada



➢ Water stored as **snow in the mountains** represents a **key component** of the **hydrological cycle** of many **river basins** in **Canada**

➢ An accurate estimation of snow resources is crucial for **flood forecasting**, **water management**, **irrigation planning**, …

Key questions in mountain snow hydrology:

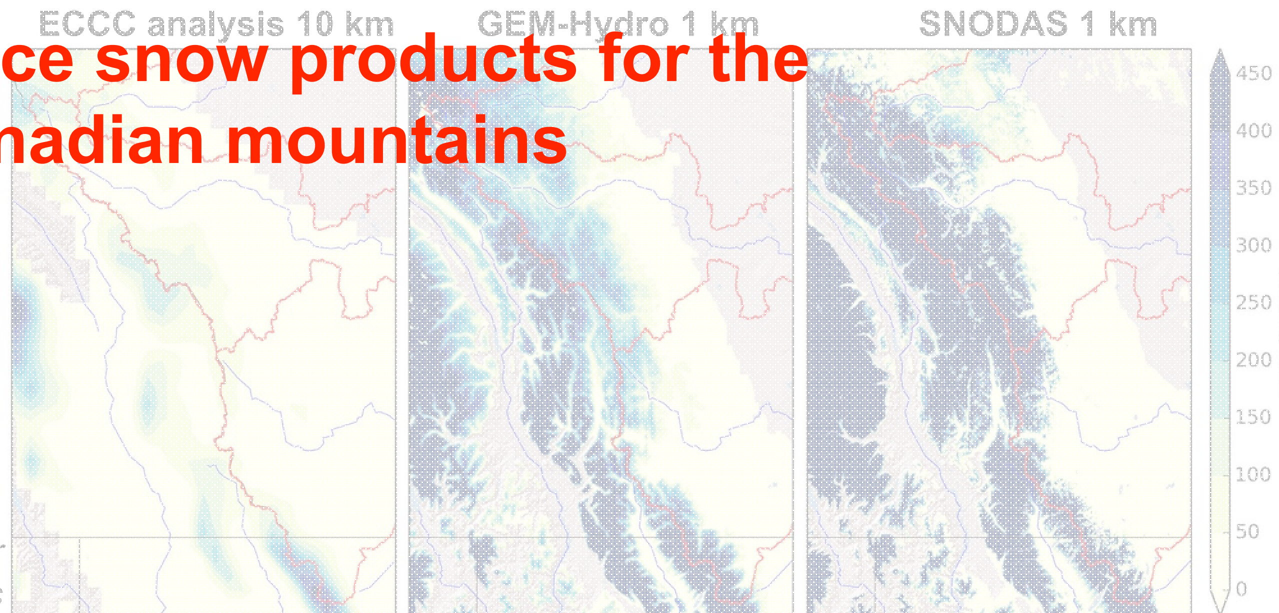
- **How much is there?**
- **How fast does it melt?**

Available gridded snow products

- Several gridded snow products are available across the mountains of Canada:
  - **ECCC snow analysis** at 10 and 2.5 km
  - **US** snow analysis **SNODAS** at 1 km (up to 54 N)
  - Output of **hydrological models** such as **GEM-Hydro, VIC, …**
- Differ in terms of resolution, data assimilation, model and input complexity, …..

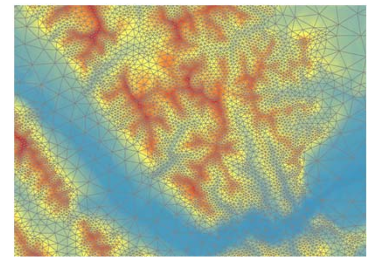
No reference snow products for the Canadian mountains

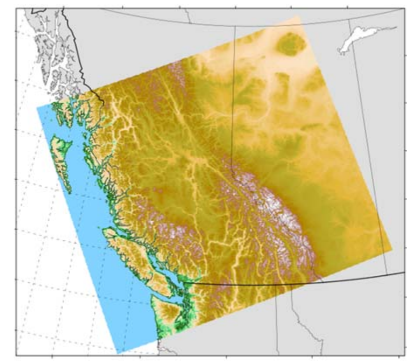
- Example: **snow conditions** during **winter 2013/2013** before the Alberta flood in June 2013
- Large differences between the datasets close to peak SWE
- Impact on SWE estimation at the time of the flood *(Vionnet et al., in discussion, 2019)*



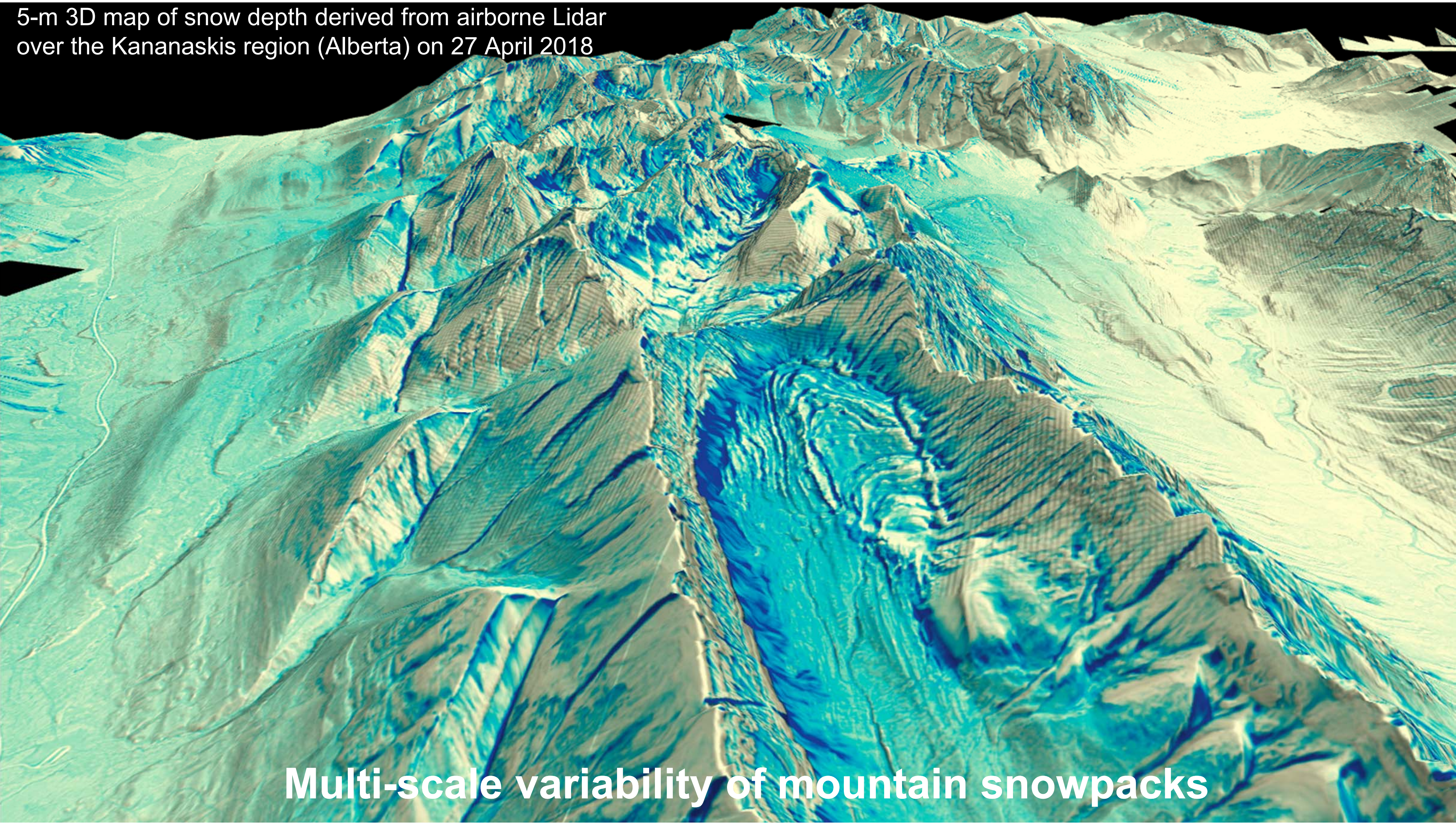
SWE on 1st May 2013 over the upper Bow and Elbow river catchments

Towards a reference snow product



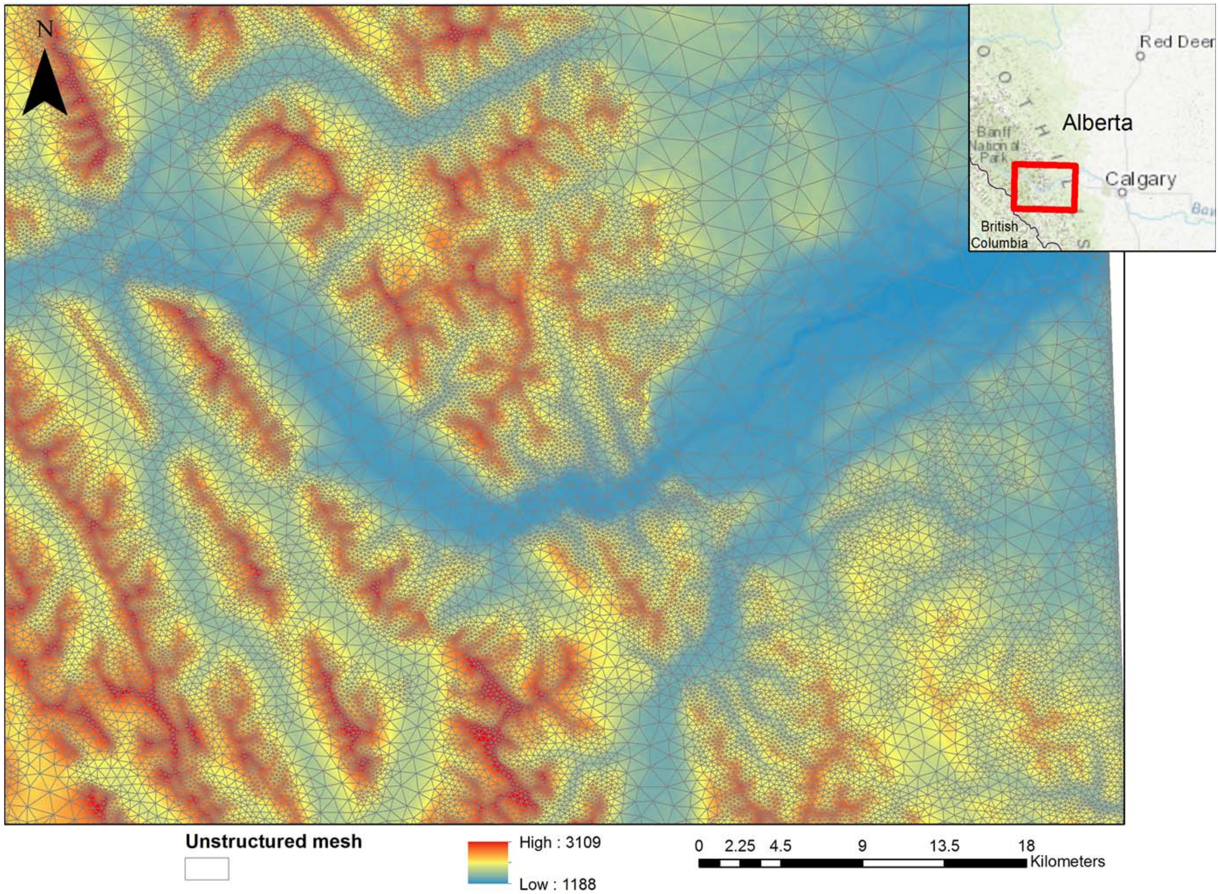


- Capturing the **spatial** and **temporal variability** of snow water resources in mountainous terrain
- Able to **provide input data** to **hydrological models** of varying complexity with different spatial discretisation (distributed, semi-distributed, …)
- Relying on **a physically-based snow model** representing the **main processes** driving snow **accumulation** and **ablation** in mountainous terrain
- Using **atmospheric driving data** at **high temporal** and **spatial** resolution
- Able to **assimilate** the latest products available in **snow remote sensing** (**Lidar**-derived maps of **snow depth**, high-resolution maps of **snow cover** from visible **satellite imagery**, …)

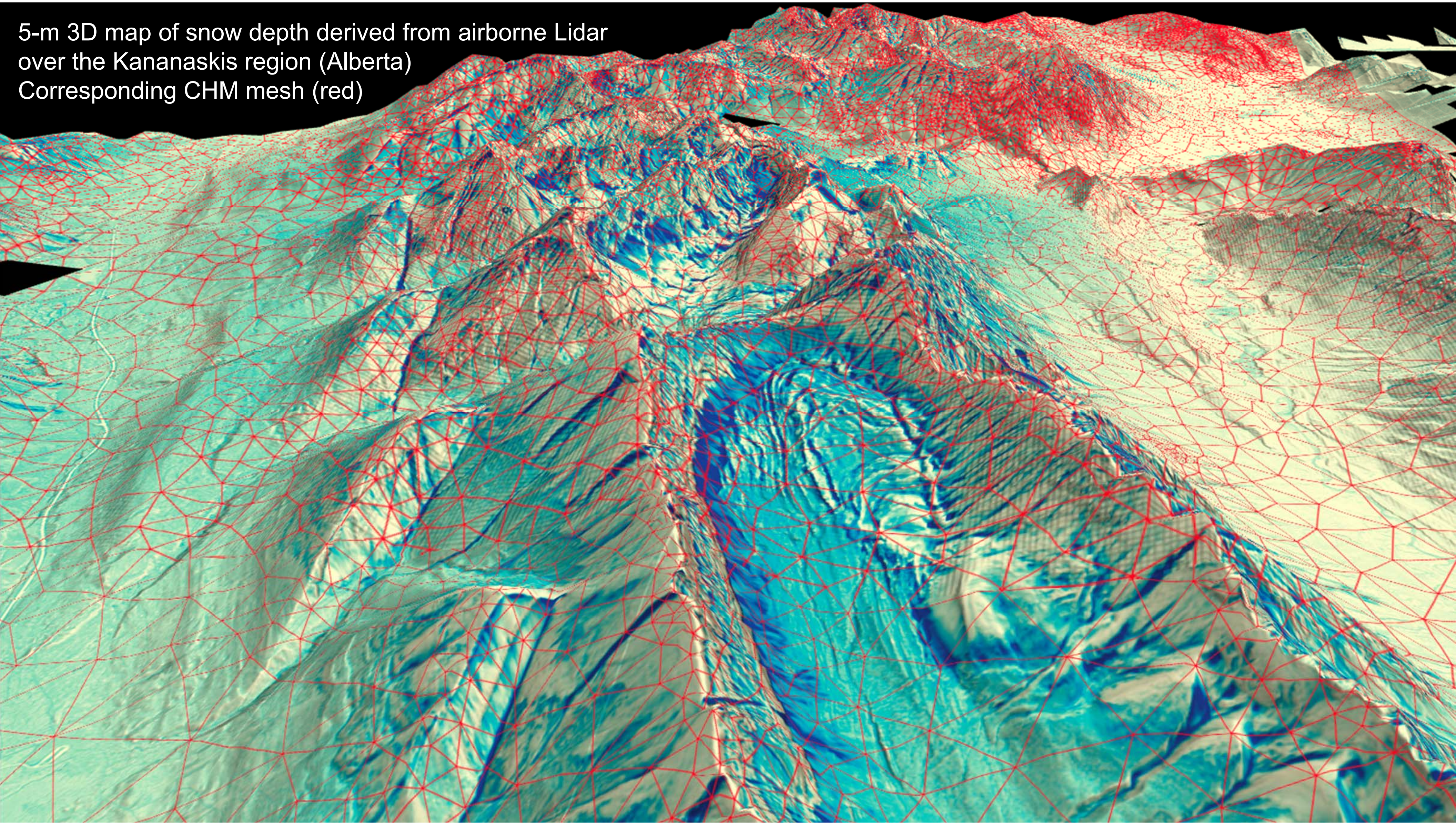

5-m 3D map of snow depth derived from airborne Lidar
over the Kananaskis region (Alberta) on 27 April 2018
Multi-scale variability of mountain snowpacks

Canadian Hydrological Model (CHM)

- **Unstructured triangular mesh** depending on topography and vegetation complexity
- Includes state-of-the-art energy-balance **snowpack schemes**
- Accounts for:
  - **slope** and **aspect**; terrain **shading**
  - **gravitational redistribution**
  - **blowing snow (**redistribution + sublimation**)**
  - **snow/canopy interactions**



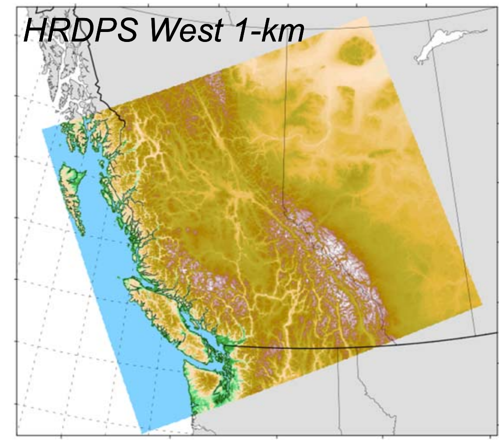
Marsh et al. (2019, in review)


5-m 3D map of snow depth derived from airborne Lidar
over the Kananaskis region (Alberta)
Corresponding CHM mesh (red)

High-resolution driving data

➢ High-resolution atmospheric data are required to drive CHM

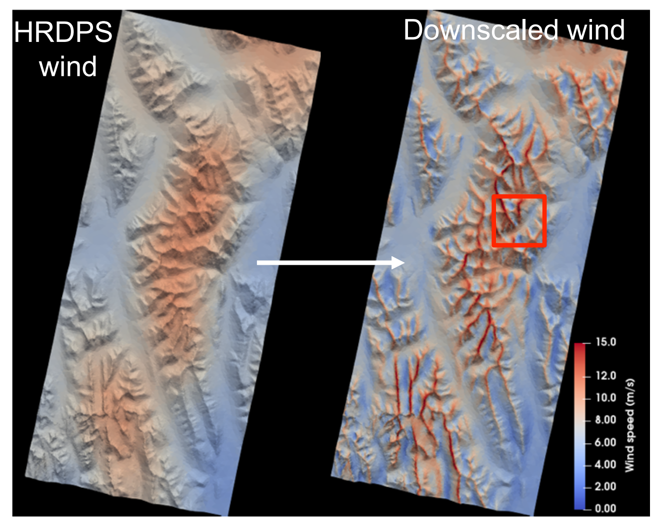
➢ Use of **ECCC high-resolution products**:
  ➢ High Resolution Deterministic Prediction System (**HRPDS**): **2.5 km** over Canada (+ 1-km over Western Canada)
  ➢ Canadian Precipitation Analysis (**CaPA**) at **2.5 km:** combines HRDPS precip. + radar & gauge measurements



Development of **innovative downscaling methods**

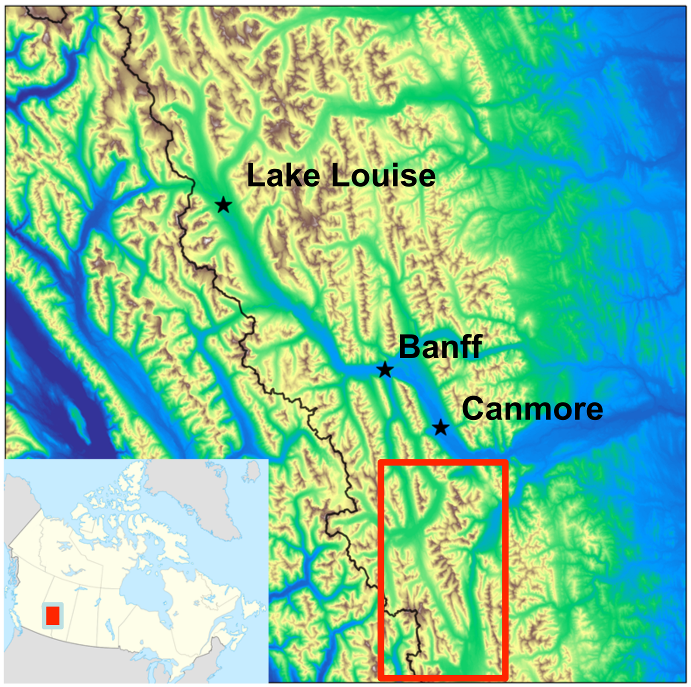
➢ **Wind field**: combination of HRDPS forecast + library of micro-scale wind fields from a diagnostic model

➢ Impact for snow hydrology
  ➢ Redistribution by **blowing and drifting snow**
  ➢ Spatial **variability** of **turbulent fluxes** (in particular during **rain-on-snow** events)



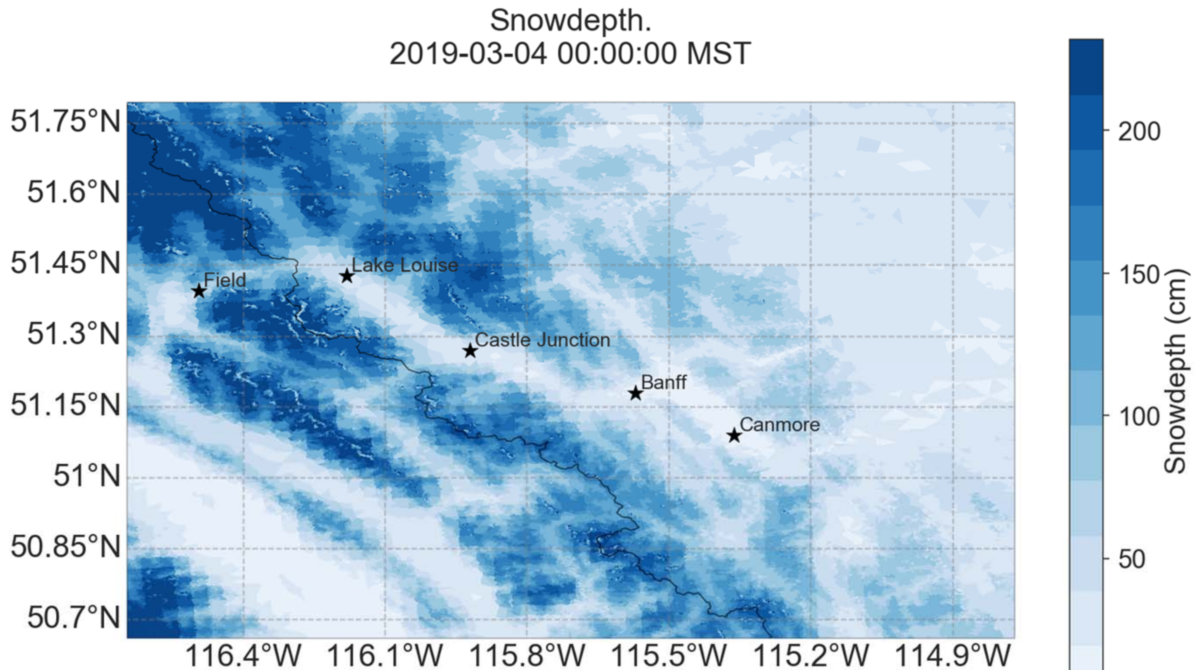
The SnowCast experiment

Developped by N. Wayand and C. Marsh (USask)



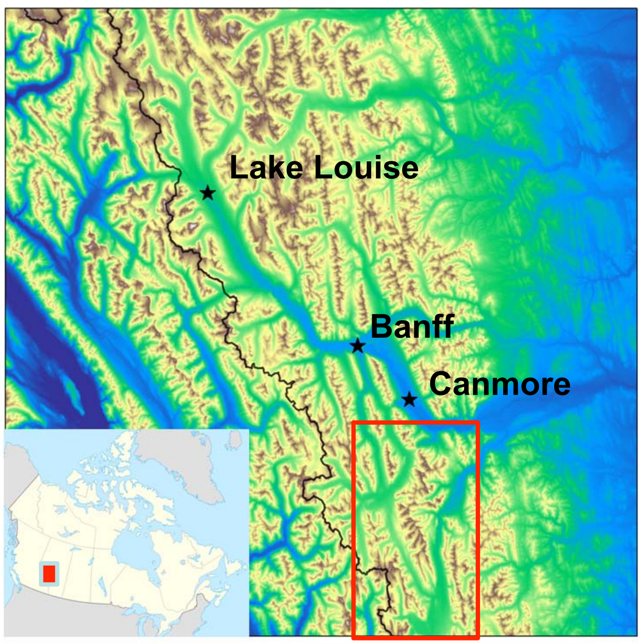
Upper Bow River Basin

- ➢ CHM over the **Upper Bow River basin** (16 000 km^2)
- ➢ **Atmospheric driving data**: **GEM 2.5 km** (High Resolution Deterministic Prediction System) **downscaled** to the CHM mesh
- ➢ **Forecasts** of **SWE**, **snow depth** and **melt runoff** up to **+ 48h**

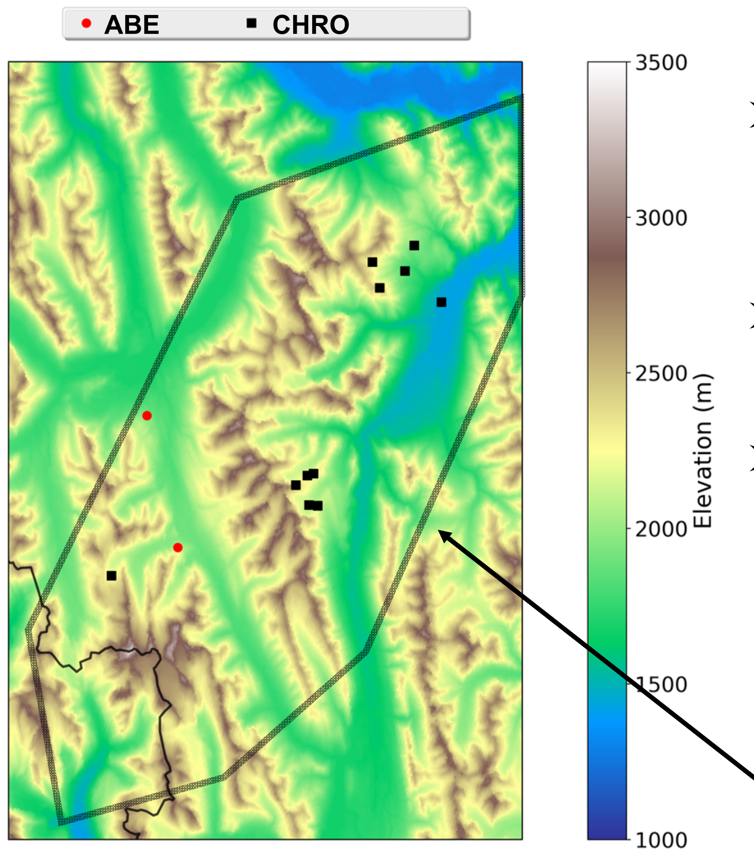


Daily output available at http://www.snowcast.ca

Study area - Kananaskis, Canadian Rockies



Upper Bow River Basin

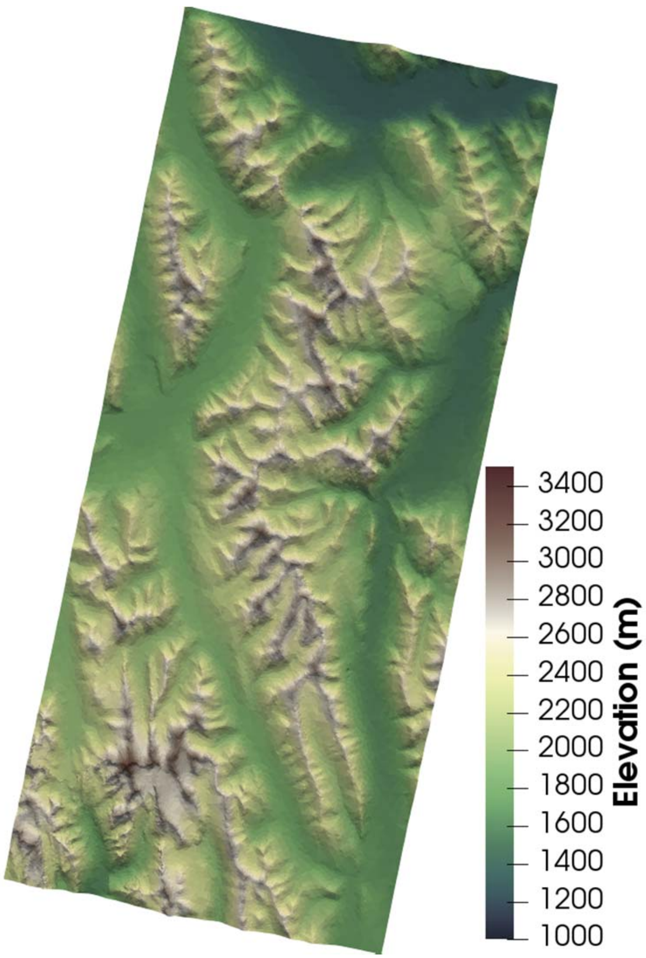


Kananaskis area

- ➢ Canadian Rockies Hydrological Observatory (CRHO)
- ➢ Alberta Environment (ABE) snow courses
- ➢ **Airborne LiDAR** (UNBC Riegl Q 780):

1-m snow depth map
27 April 2018

CHM over the Kananaskis region



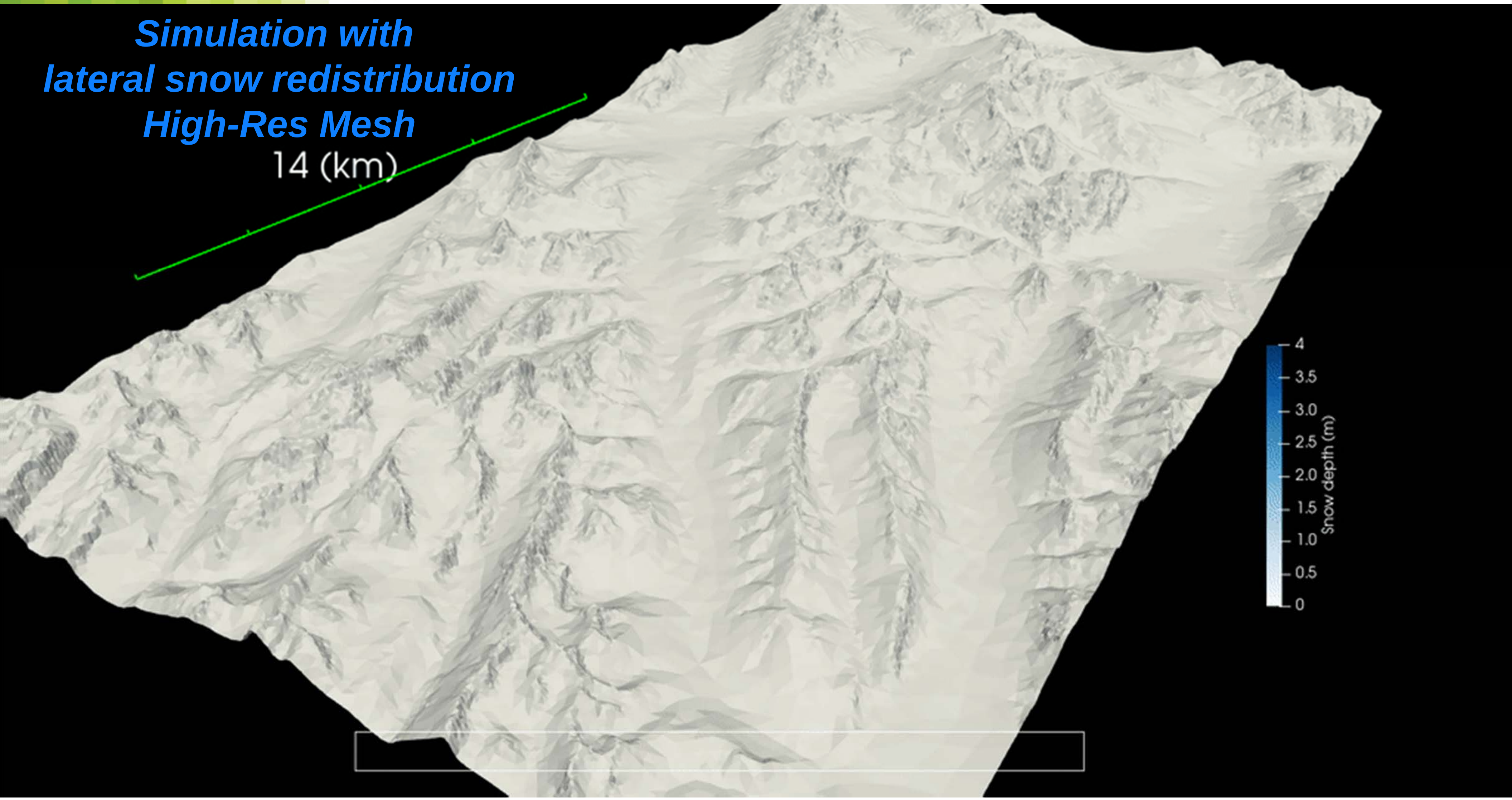
- **Simulation domain:** 1014 km^2 **-** Water year 2017/2018

CHM Mesh	Min. Resolution	Max. Resolution	Triangles
Operational	200 m	2500 m	16200
High Res.	50 m	500 m	97300

- **Atmospheric forcing:**
  - **HRDPS** short-term NWP forecasts at **2.5-km grid spacing**
  - **Downscaling** to the **CHM mesh**
    - **Wind downscaling** relying on pre-computed wind field library from a high-resolution wind model

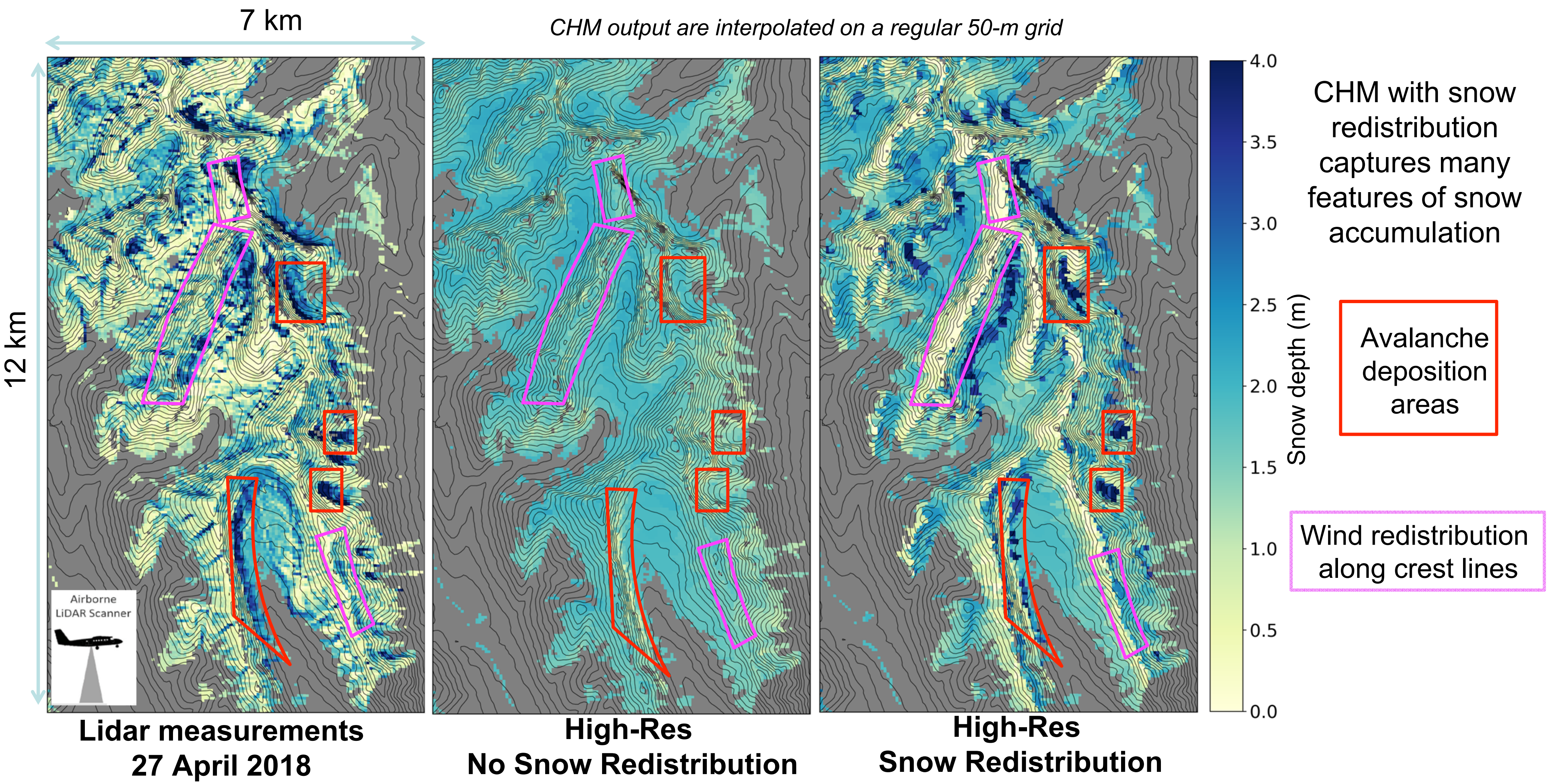
- **2 experiments for each mesh:**
  - No lateral snow redistribution
  - With lateral snow redistribution

Simulation with lateral snow redistribution High-Res Mesh

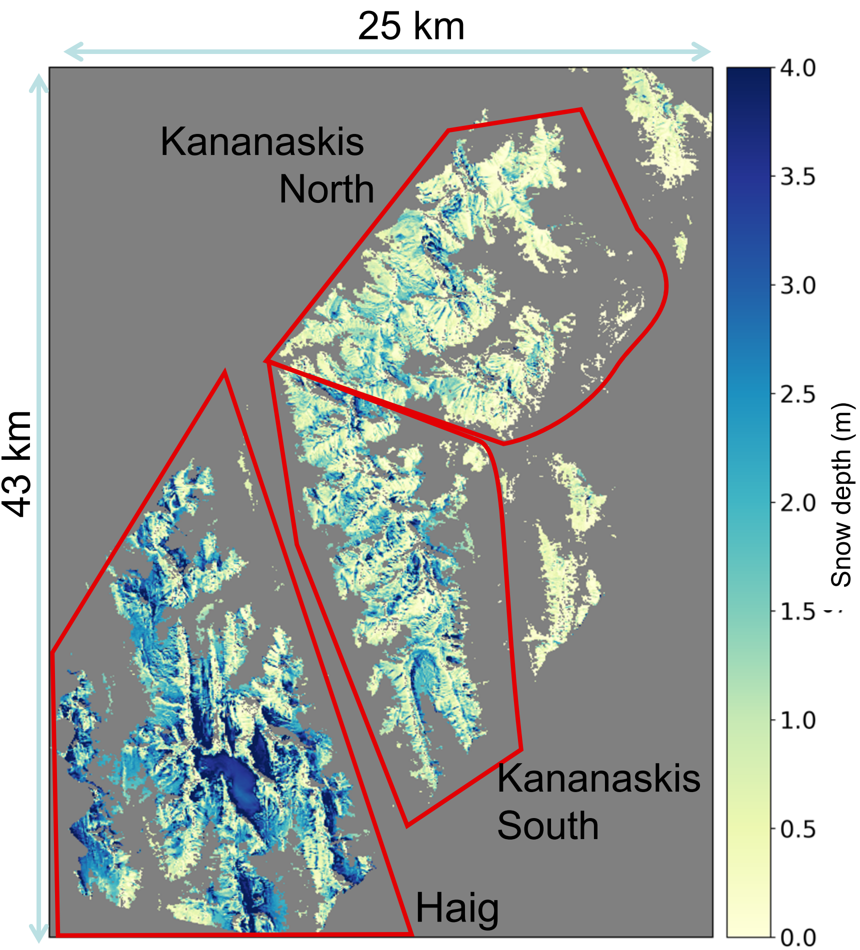


Influence of snow redistribution (High-Res)

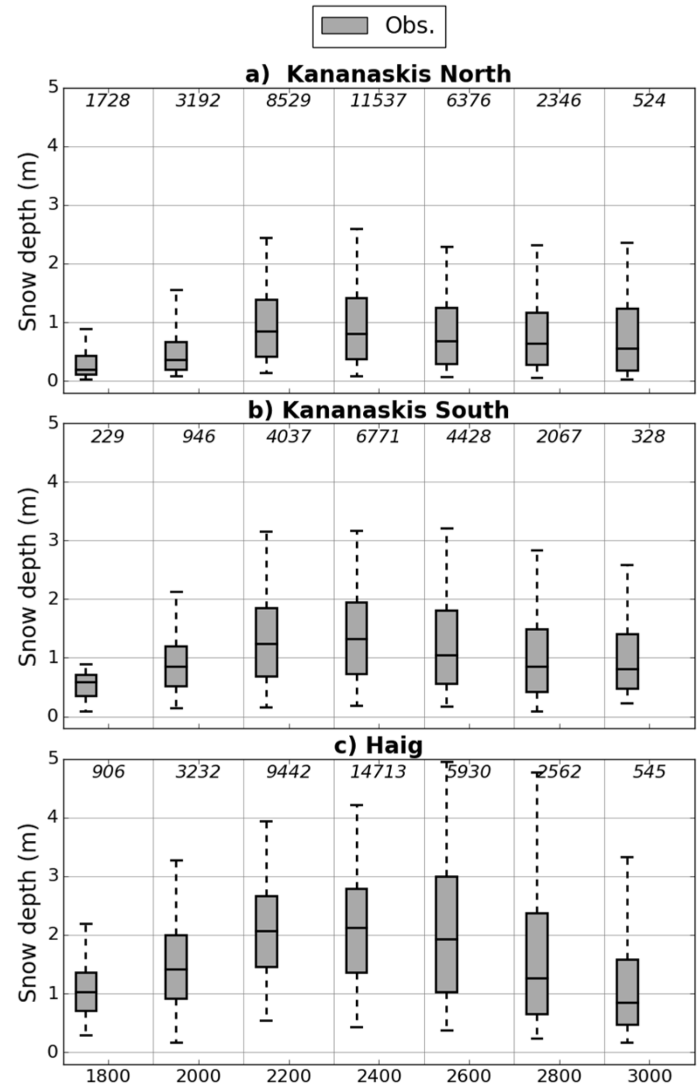
CHM output are interpolated on a regular 50-m grid



Influence of elevation (High-Res)

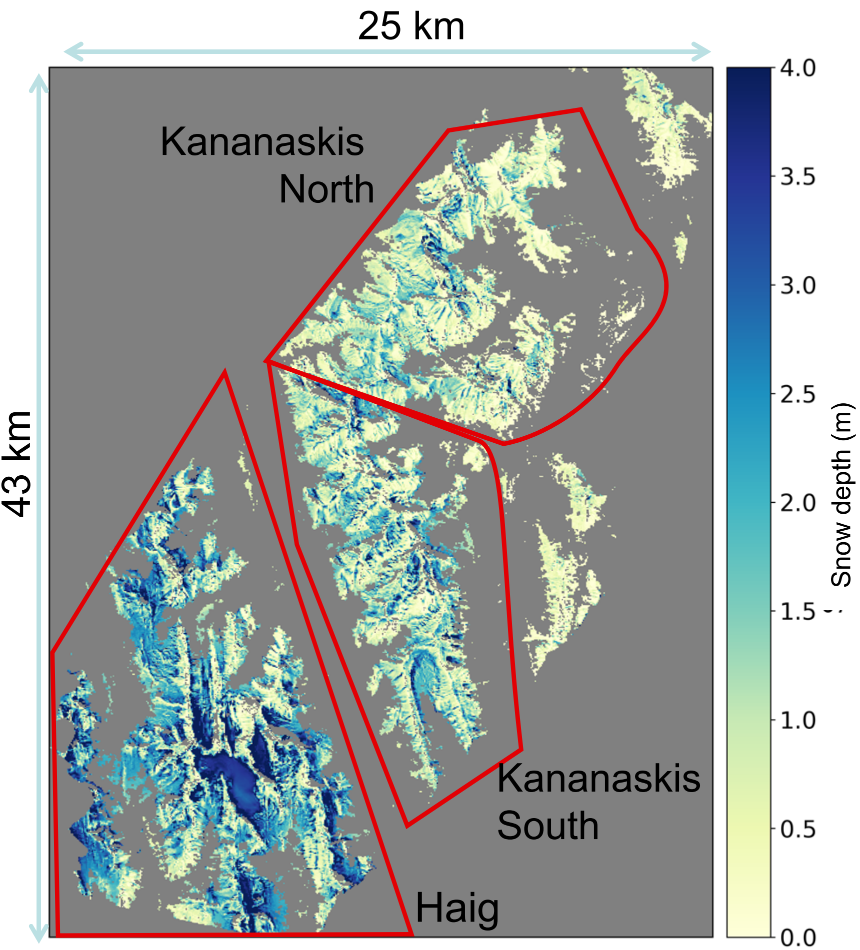


Lidar-derived 50-m map of snow depth (SD) (non-forested areas)

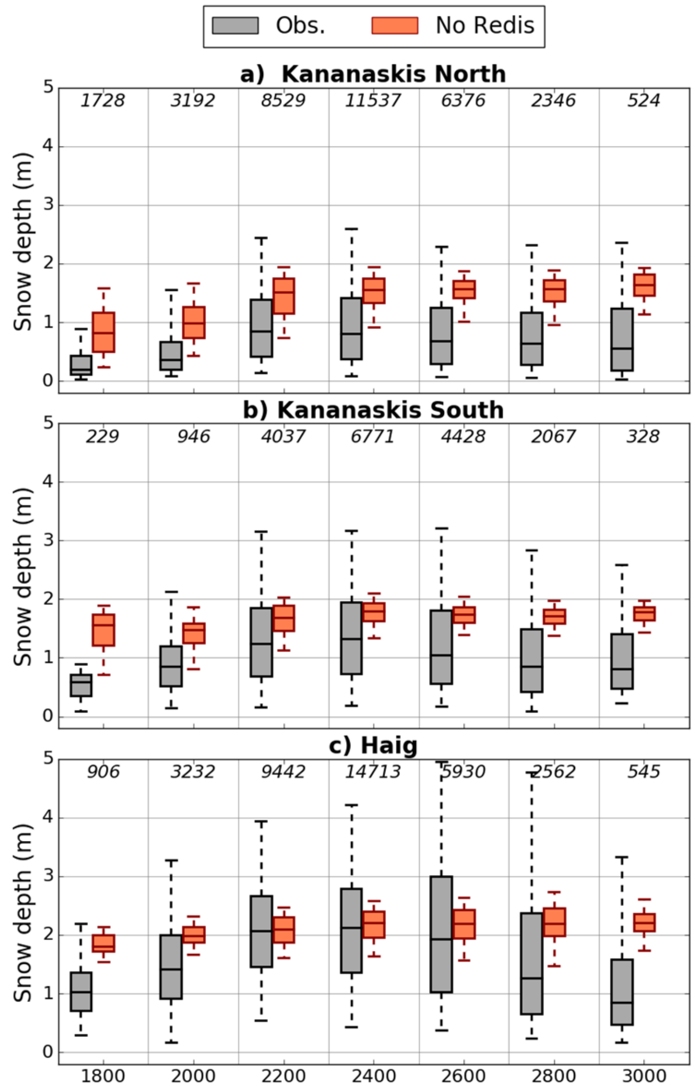


- Decrease in mean snow depth at high elevation

Influence of elevation (High-Res)



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

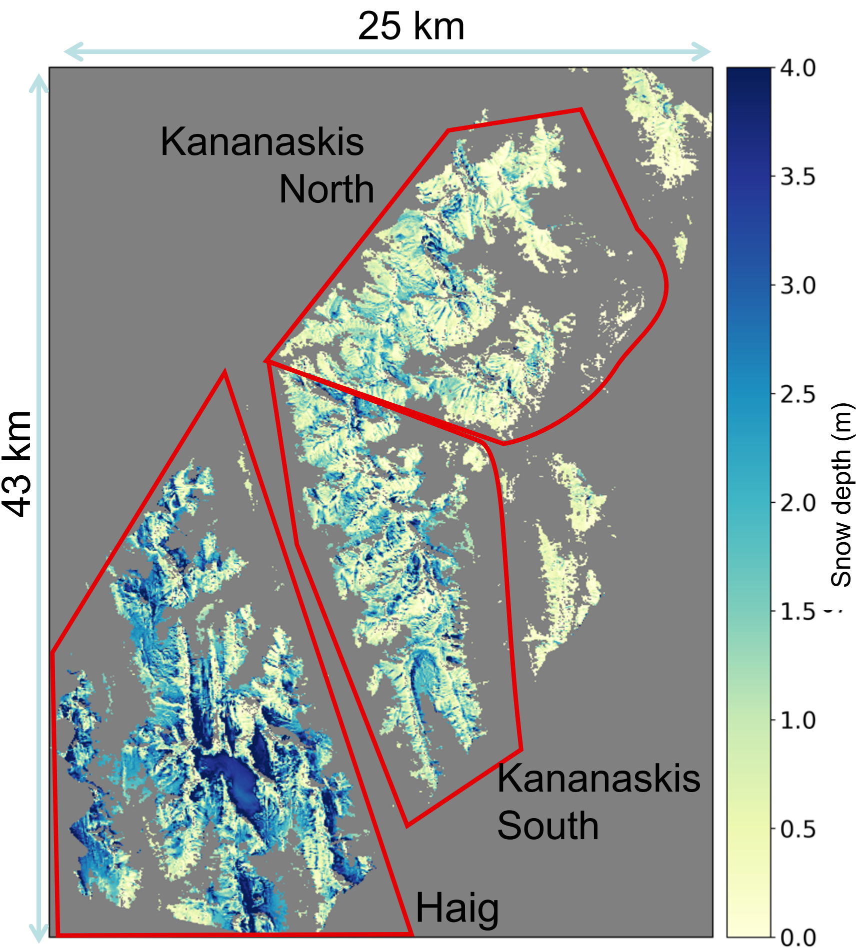


- ➢ Decrease in mean snow depth at high elevation

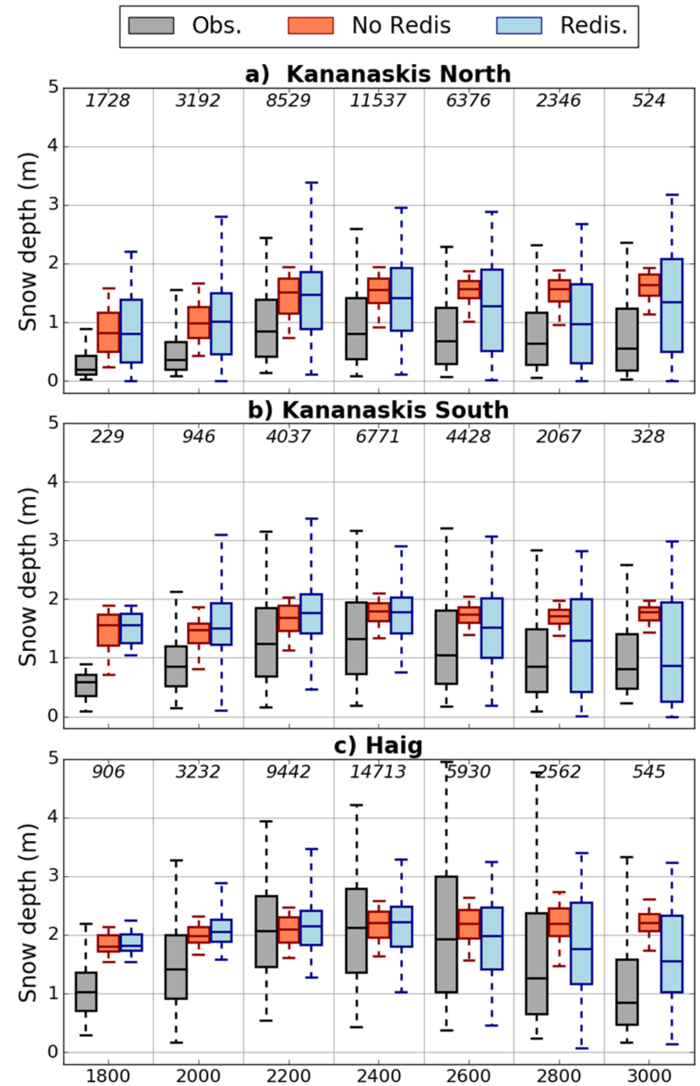
High-Res No-Redis:

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

Influence of elevation (High-Res)



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



- Decrease in mean snow depth at high elevation

High-Res No-Redis:

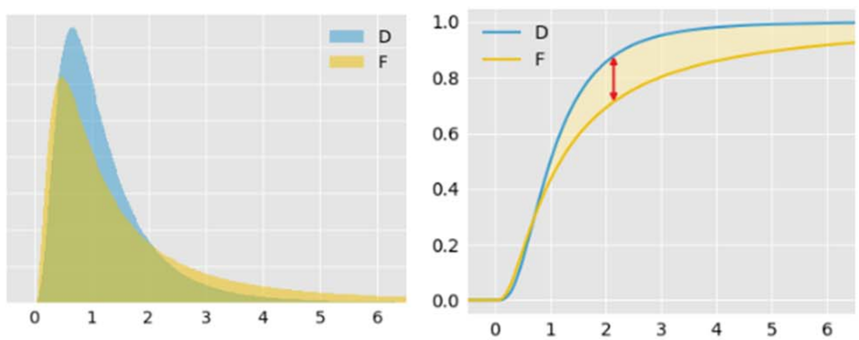
- Does not capture the spatial variability of SD
- No decrease of SD at high-elevation

High-Res Redis captures:

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

Influence of mesh resolution

Distance between distributions

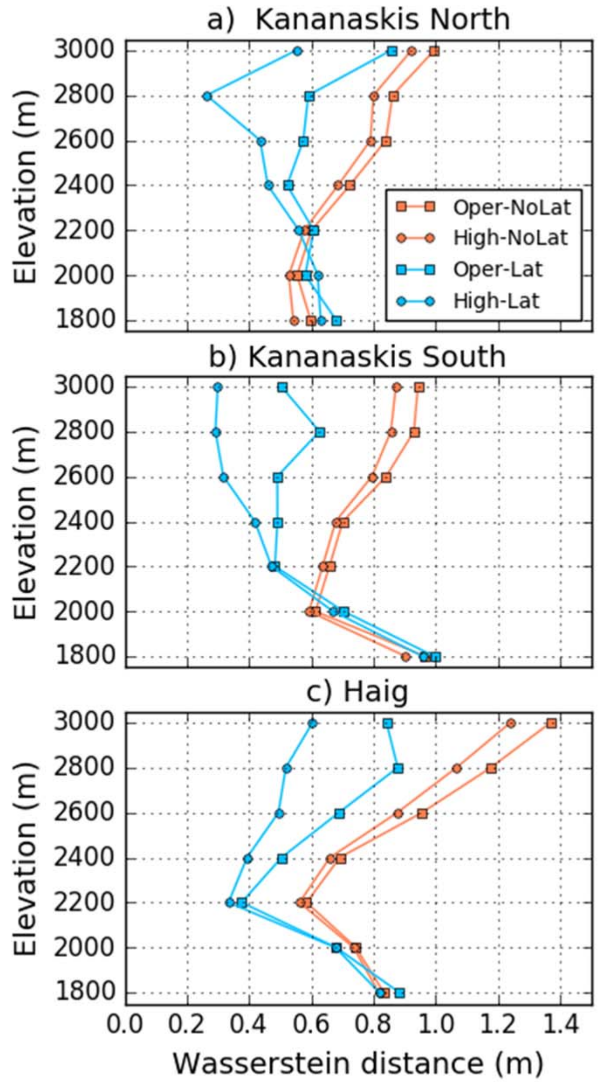


Wasserstein distance between cumulative distribution functions:

$$D_w(D,F) = \int_0^{\infty} |D - F|$$

Perfect match: $D_w = 0$

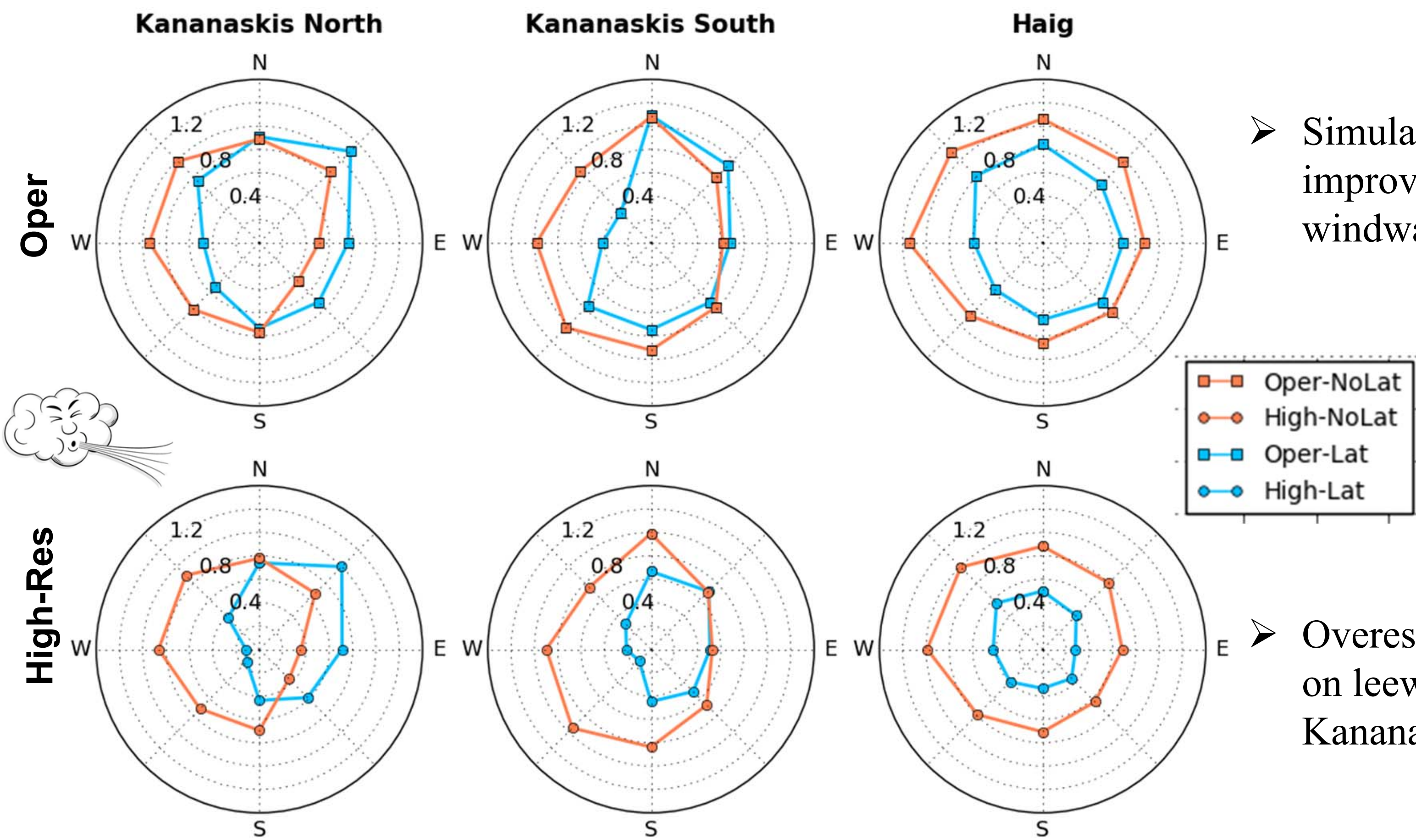
Here: comparison between simulated and observed snow depth distributions



-Without snow redistribution: *High-Res:* only minor improvements compared to *Oper*

- With snow redistribution: improved results with *High-Res* compared to *Oper* above 2200 m

Model performance around ridges

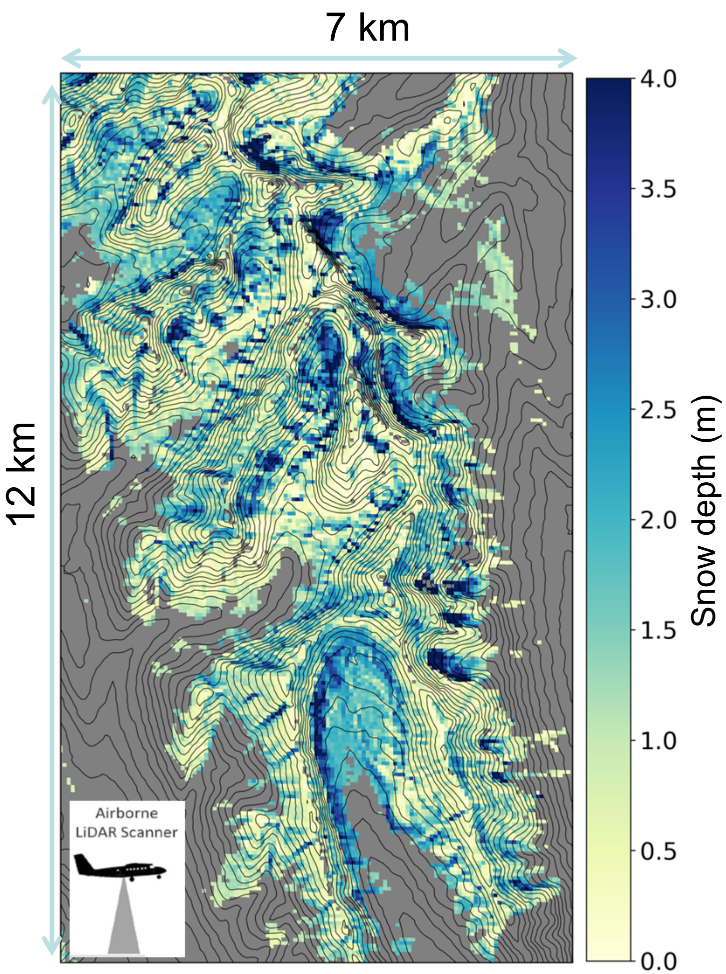


Wasserstein distance (in m) around ridges as a function of slope orientation

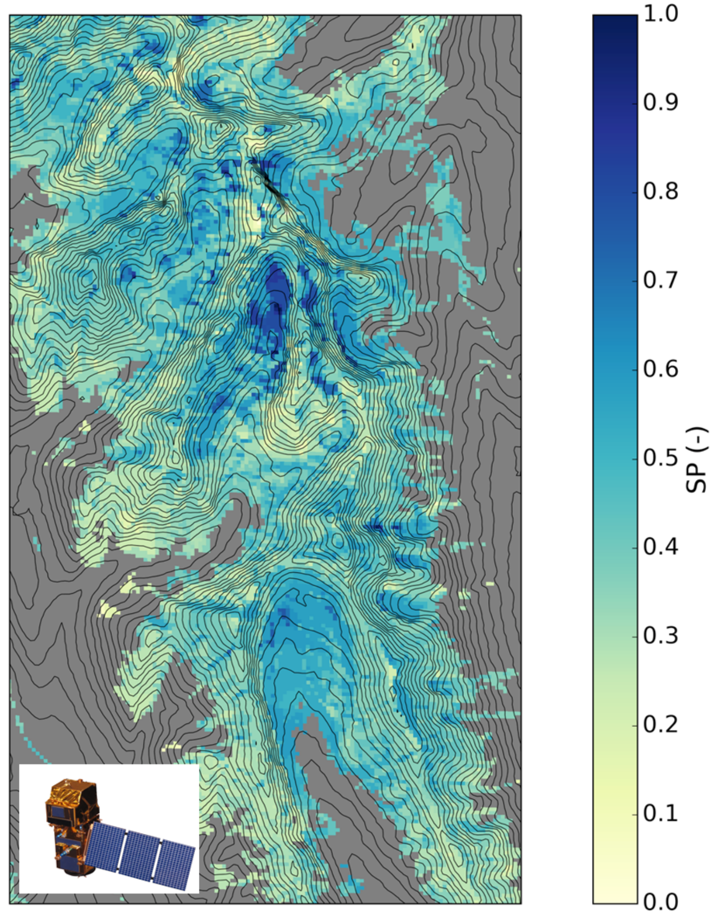
- Simulations with snow redistribution improves SD representation on the windward slopes (SW, W, NW)

- Overestimation of snow accumulation on leeward slopes (SE, E, NE) for Kananaskis North and South

Snow persistence index



Lidar measurements 27 April 2018



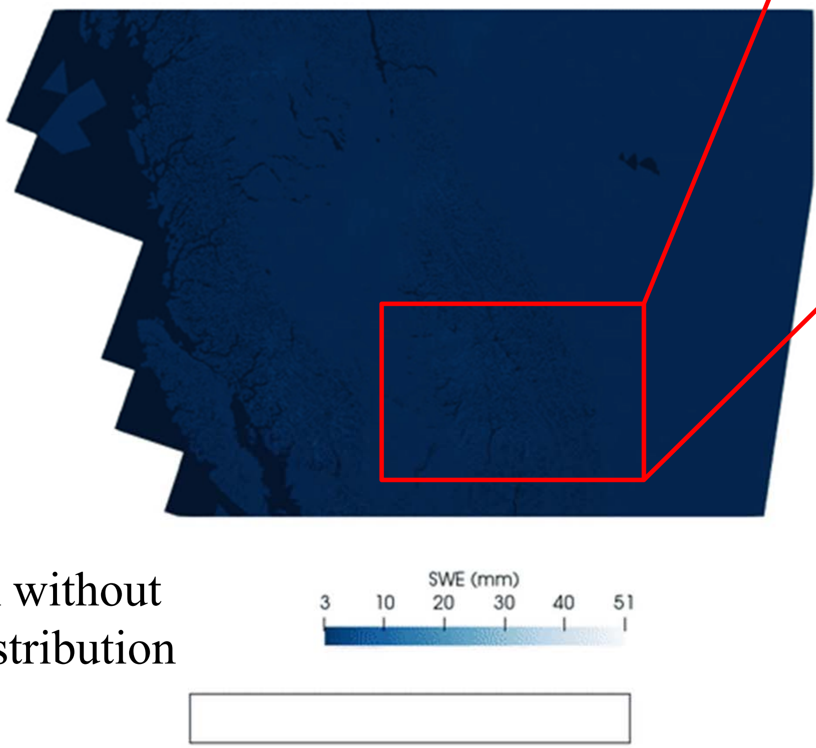
Snow persistence index derived from Sentinel-2

- Snow persistence (SP) index is derived from snow cover maps at 20-m resolution from Sentinel-2
- SP is calculated from snow-covered areas during spring and summer.
- SP variability results from variability in snow accumulation and snowmelt energy
- **Potential** to evaluate **high-resolution snowpack simulation** at **large scale**

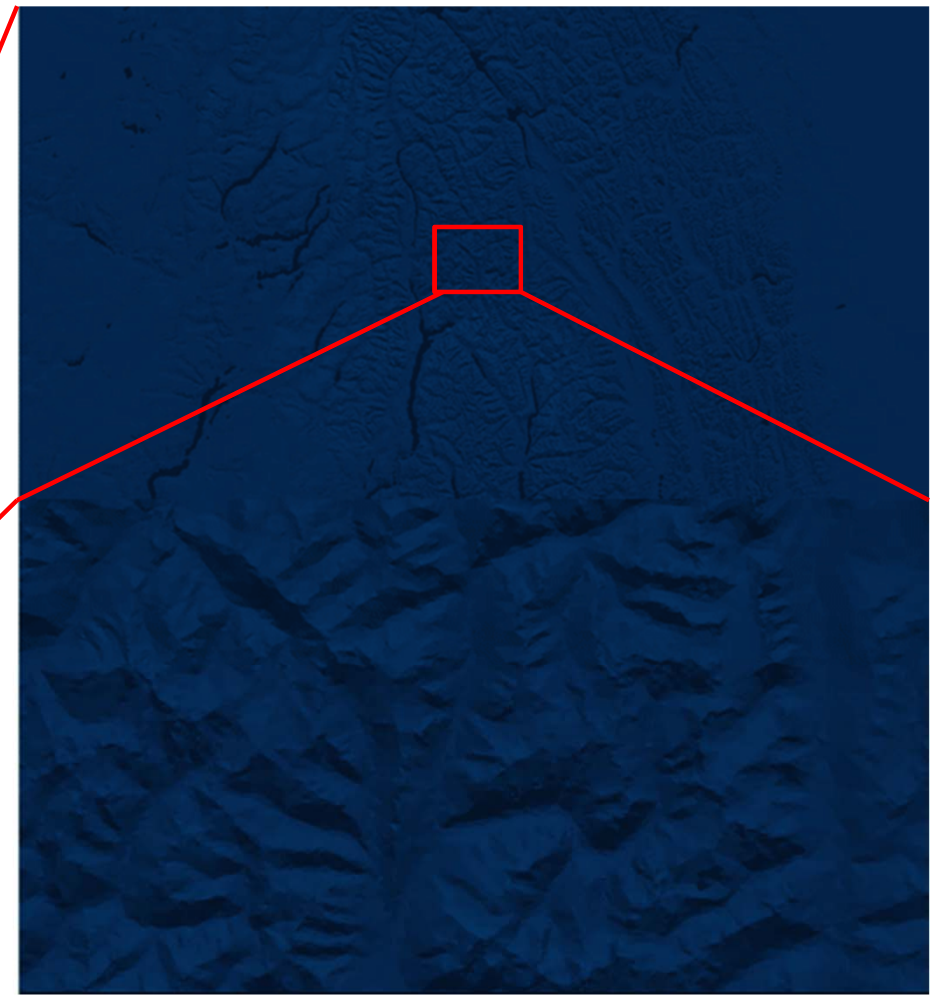
Method of Wayand et al. (2018)
Sentinel images provided by S. Gascoin (CESBIO, France)

CHM over Western Canada

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



Simulation without snow redistribution



Conclusion and perspective

- Development of a **multi-scale snowpack modelling** system in Western Canada
- CHM captures some of the **spatial variability** of mountain **snowpack over 1000s of km^2**
- **Snow redistribution** must be included in **distributed snow modelling** at resolution **below 200 m,** in particular to **avoid unrealistic accumulation** at **high elevation.**
- **Perspectives:**
  - **Improvement** of **CHM** for **alpine environment**
  - **Improvement** of **atmospheric forcing**
  - **Large-scale simulations** across the mountains of BC and AB.


Thanks you for your attention!
GWF
CENTRE FOR
HYDROLOGY

Wind field downscaling

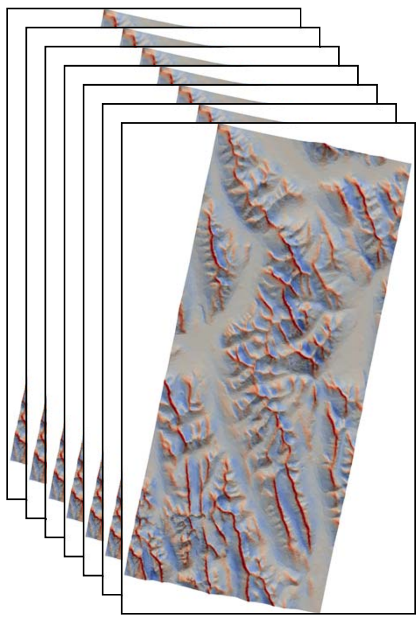
Objective: efficient downscaling method to adjust GEM wind

1. Diagnostic wind model

WindNinja

2 versions: - mass conservation (used here)
- CFD model

- Wind field library
- 50-m resolution
- 24 directions (15°)
- 10 m s^{-1} at 40 m



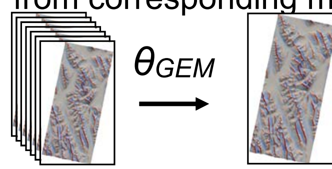
- Stored on CHM mesh:
- Wind components: U,V
- Speed-up factor:

$$f_{WN} = \frac{UV_{WN}}{< UV_{WN} >_{2.5km}}$$

2. Meso to micro downscaling

At each triangle with U_{GEM} and θ_{GEM}:

Select U_{WN}, V_{WN}, f_{WN} from corresponding map



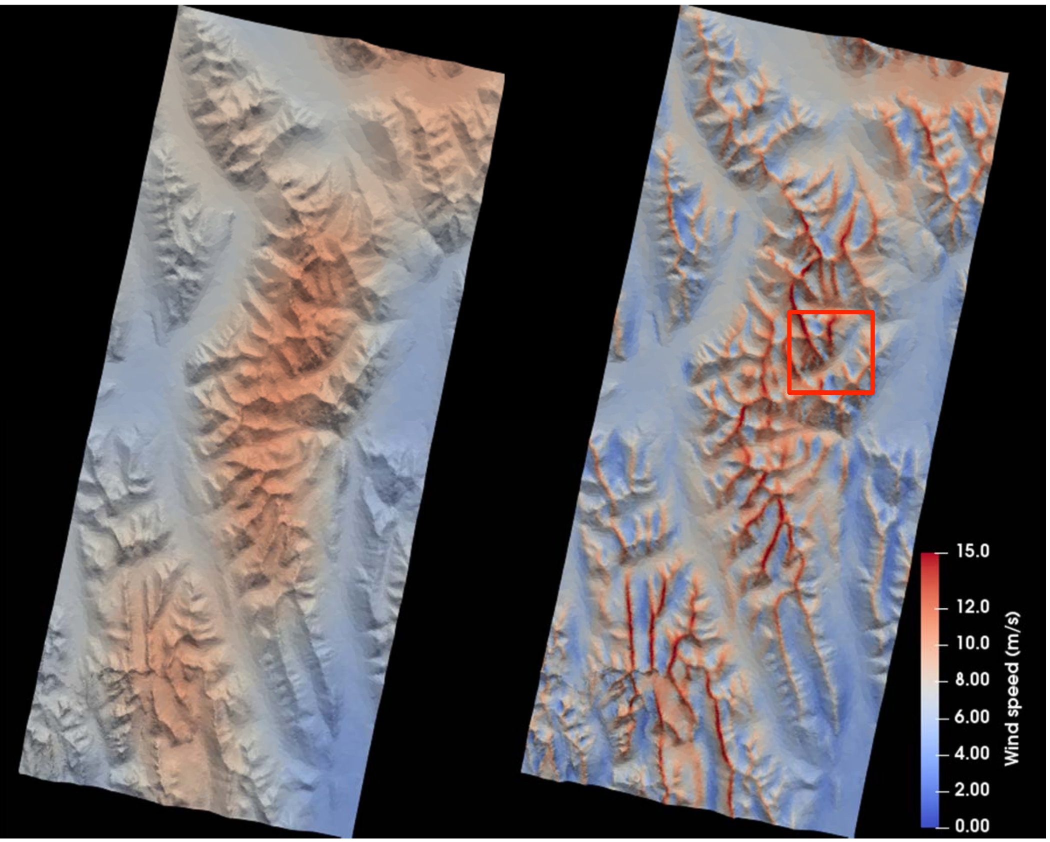
→ Local direction θ_{Down}, from U_{WN} & V_{WN}

→ Local wind speed $U_{down} = f_{WN} U_{GEM}$

Based on Bracons et al. (2017), Marsh et al. (In prep.)

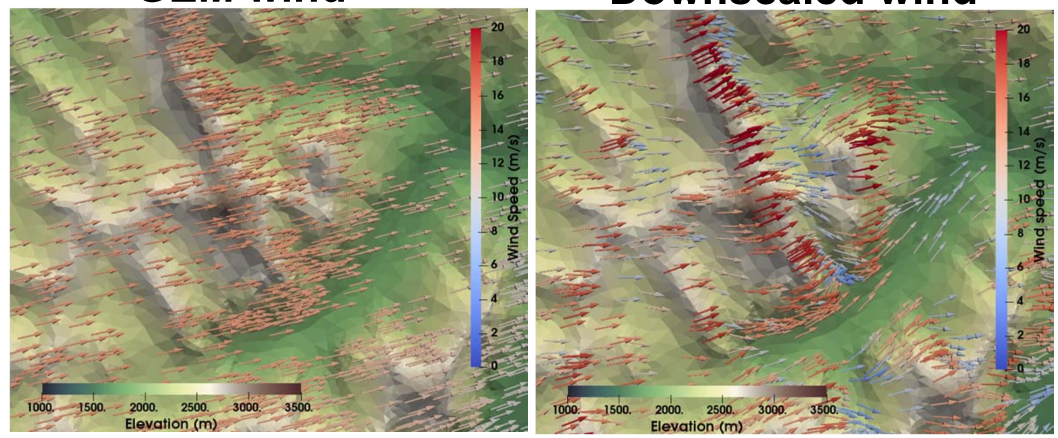
Wind field downscaling: example

GEM wind **Downscaled wind**



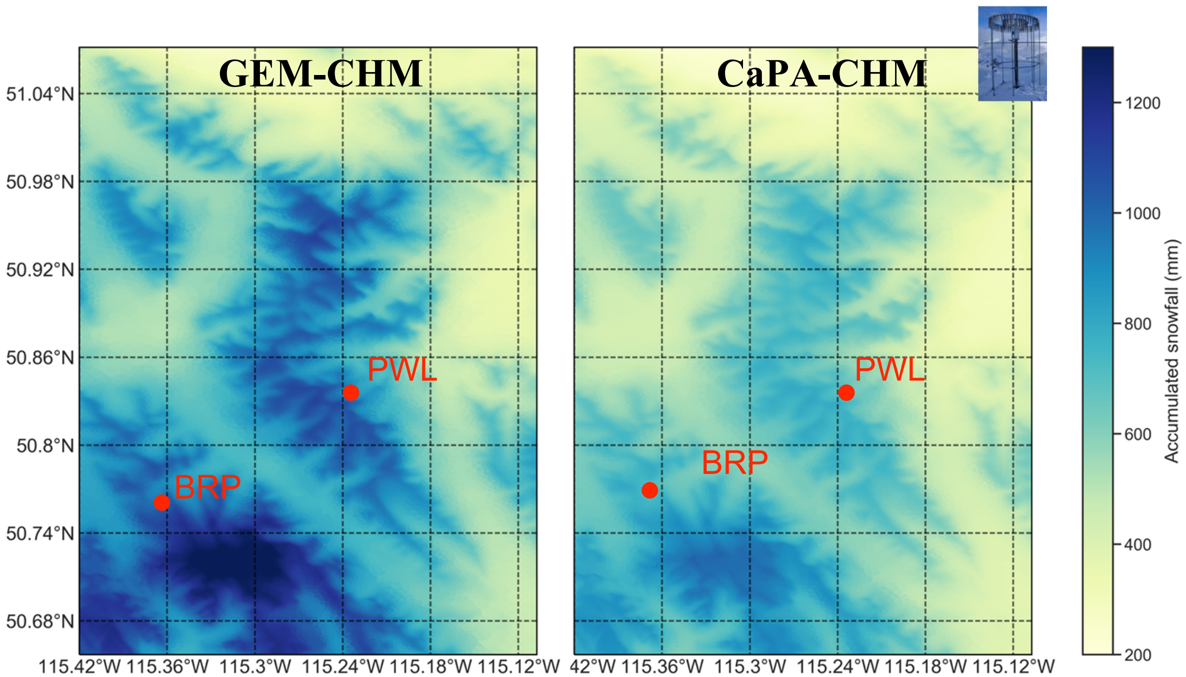
40-m wind speed on 10 Sept. 2018 18 UTC

GEM wind **Downscaled wind**

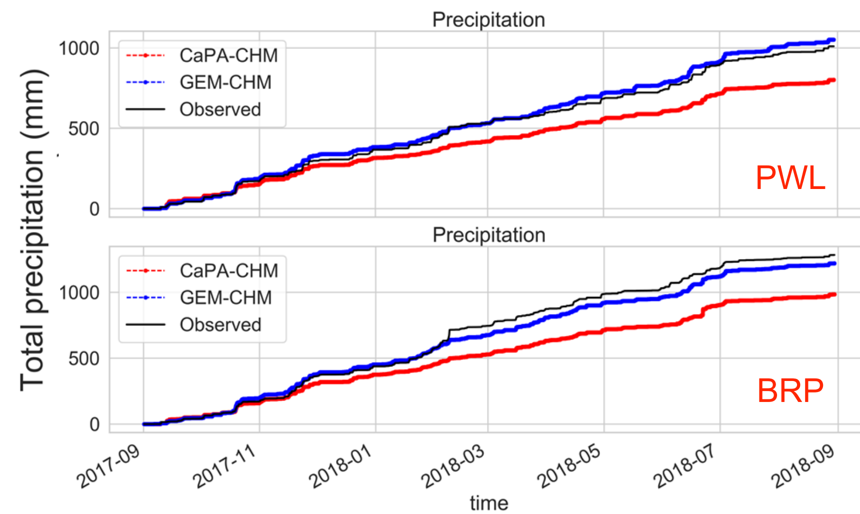


- ➢ **Adjust** local **wind speed and direction**:
  - ➢ Crest speed-up
  - ➢ Valley channelling
- ➢ **Limitation:**
  - ➢ **Leeside** recirculation is **not captured** (limitation of the mass-conserving approach)
  - ➢ Thermal flows are not captured

Importance of precipitation forcing



Total snowfall over water year 2017/2018

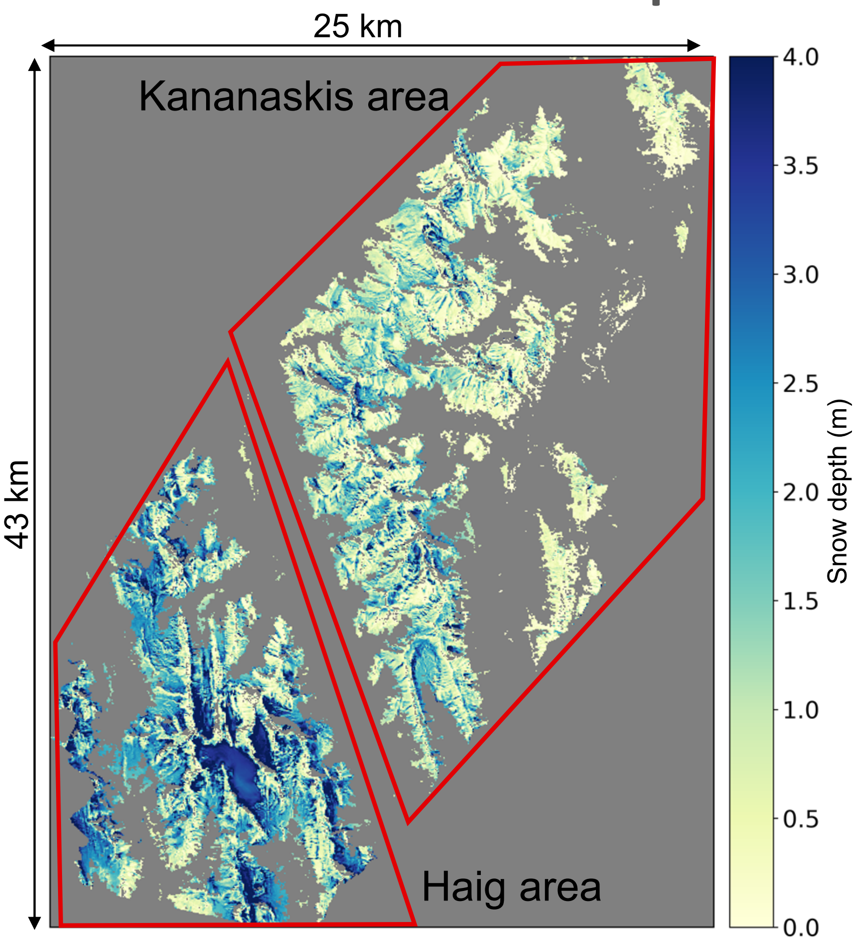


Time series of cumulated precipitation at 2 CRHO stations (not included in CaPA)

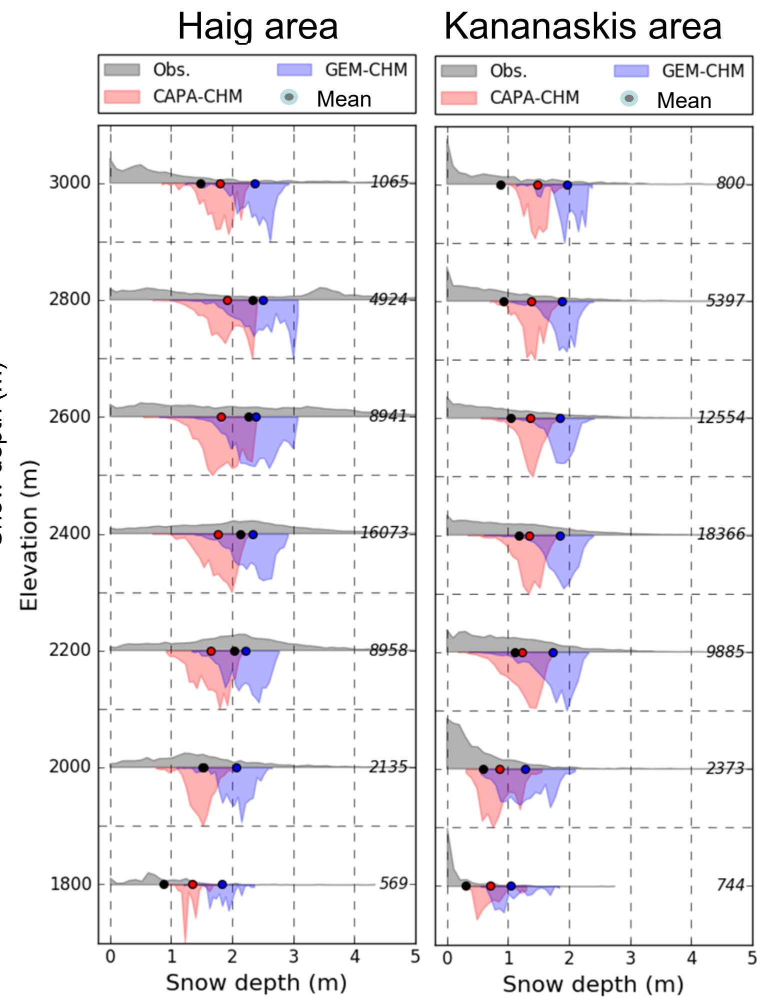
- ➢ Lower seasonal snowfall amount with CaPA-CHM compared to GEM-CHM
- ➢ Only 1 low-elevation station entering CaPA in this region of 1000 km^2

- ➢ Underestimation of total precipitation with CaPA
- ➢ Improved estimation with GEM

Importance of precipitation forcing



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



Snow depth variability per 200-m elevation band

Haig area:

- GEM-CHM in better agreement than CAPA-CHM
- But: persistent overestimation at low and high altitude

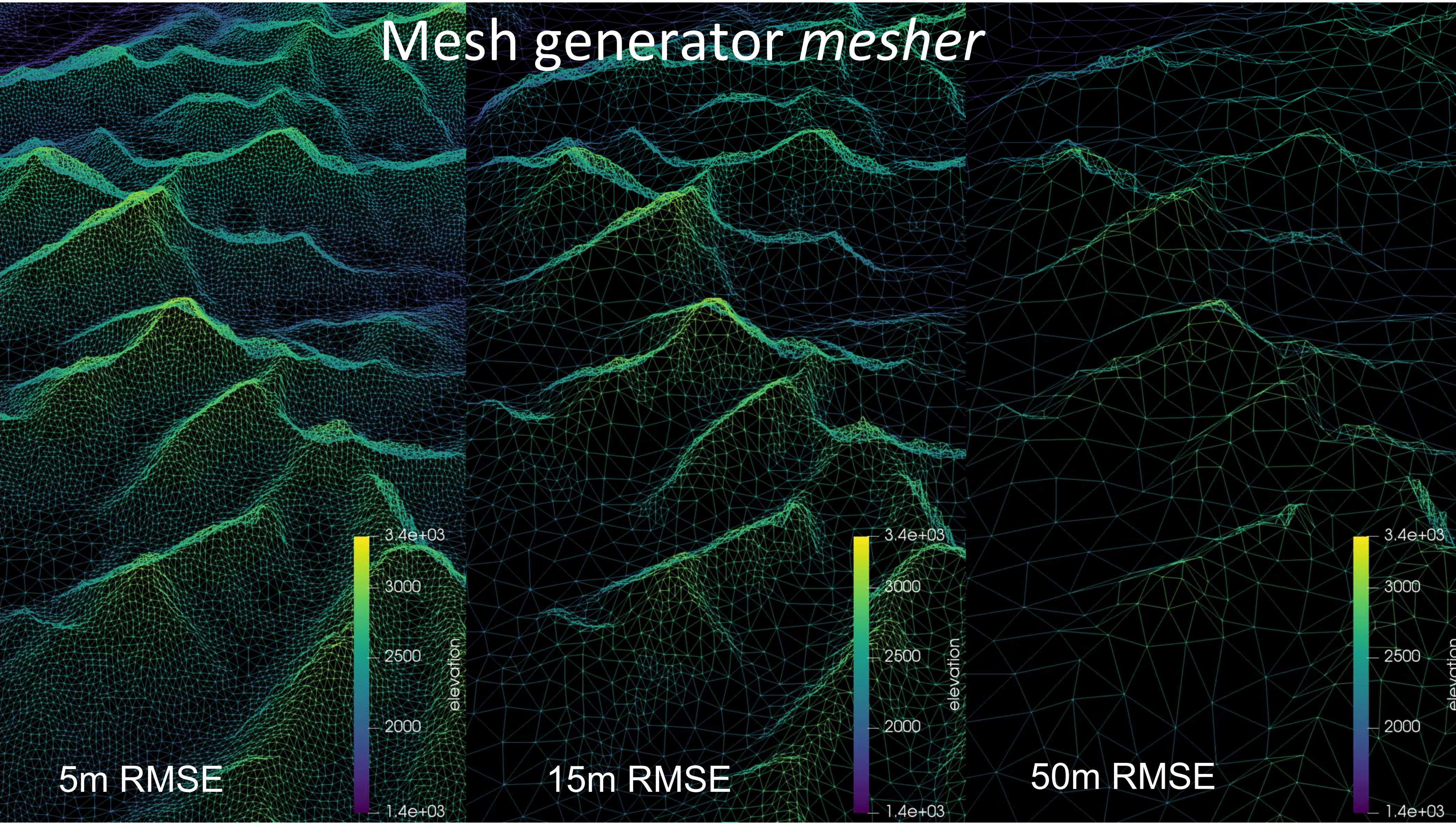
Kananaskis area:

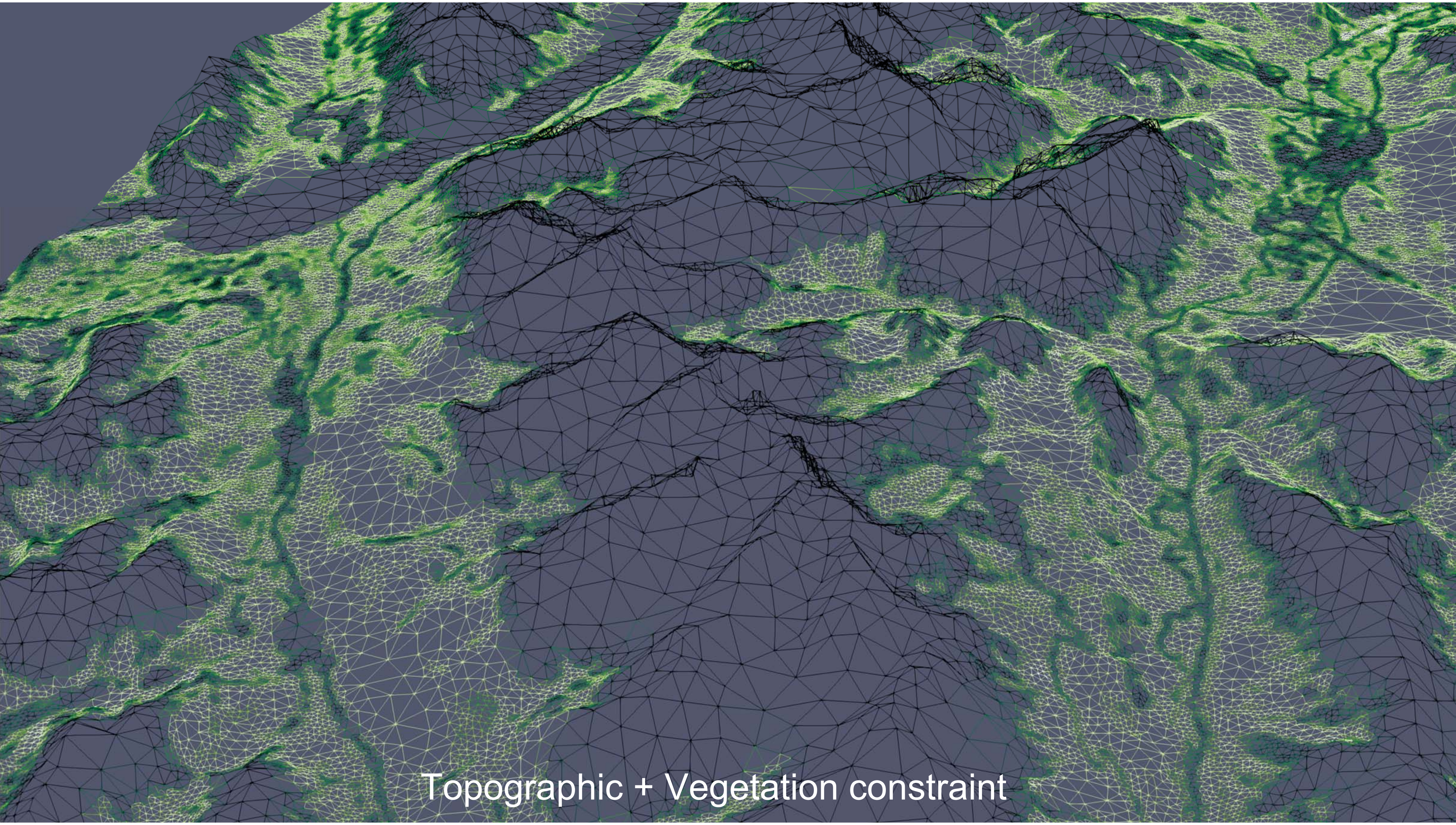
- GEM-CHM: general overestimation of SD
- CAPA-CHM: improved estimation of SD but persistent overestimation at low and high altitude

Bias in SD are not only associated with errors in precipitation input

None of the simulations captures the spatial variability

Mesh generator *mesher*




Topographic + Vegetation constraint