Mountain Snow Hydrology

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Global Mountain Climate and Water Security Challenges

Degradation of water quality – agricultural runoff, industry, sewage

Increasing competition for water resources – transboundary issues.

Increasing risk from extreme events

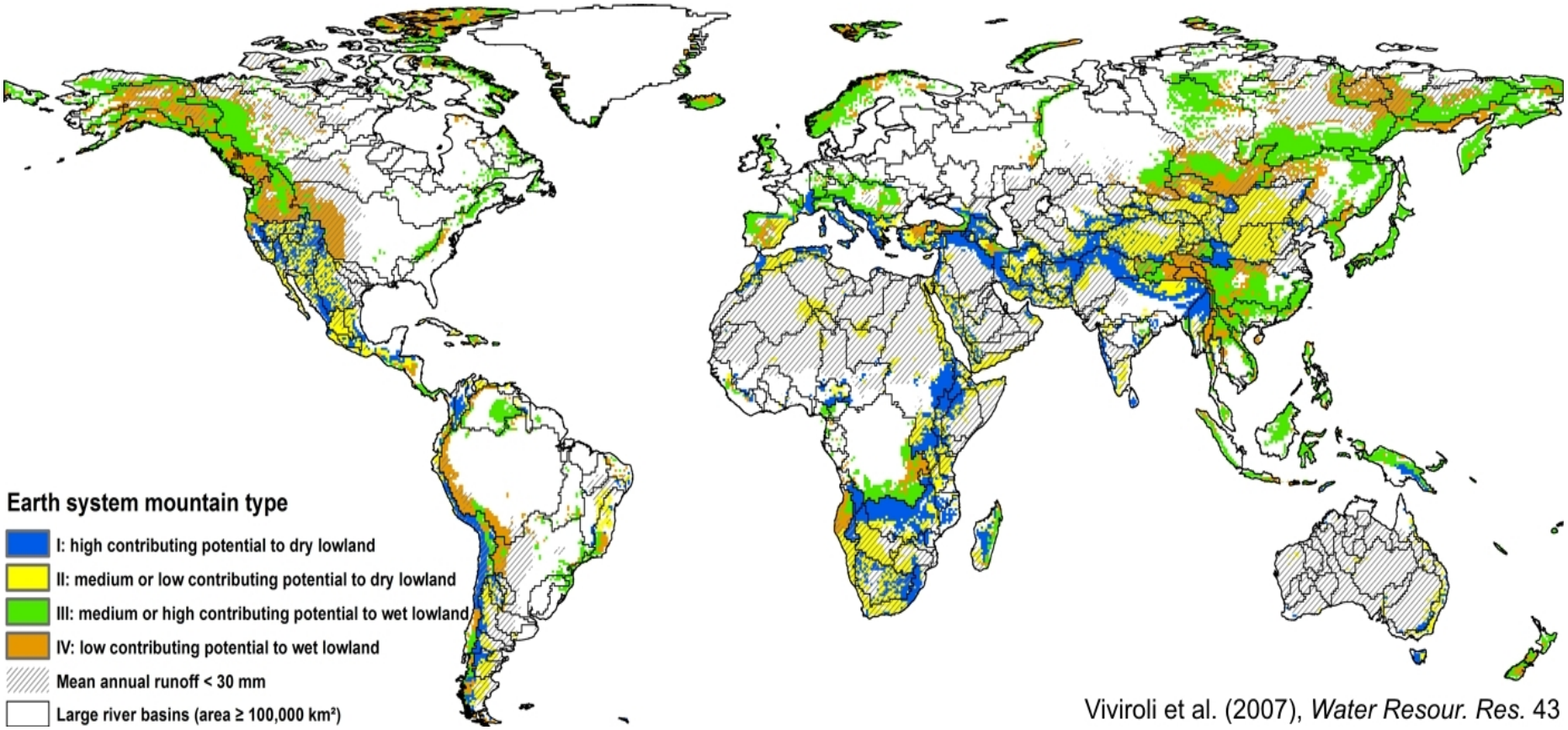
Decoupling of streamflow from snowmelt and glacier melt timing

Unsustainable use of water – food, energy, industry, drinking.

Unprecedented environmental change.

Amplified climate change in high mountains – rapid glacier melt, declining snowpacks, more rainfall.

Mountain Water Services



Viviroli et al. (2007), *Water Resour. Res.* 43

Urgency and Significance of the Study of Mountain Snow Hydrology

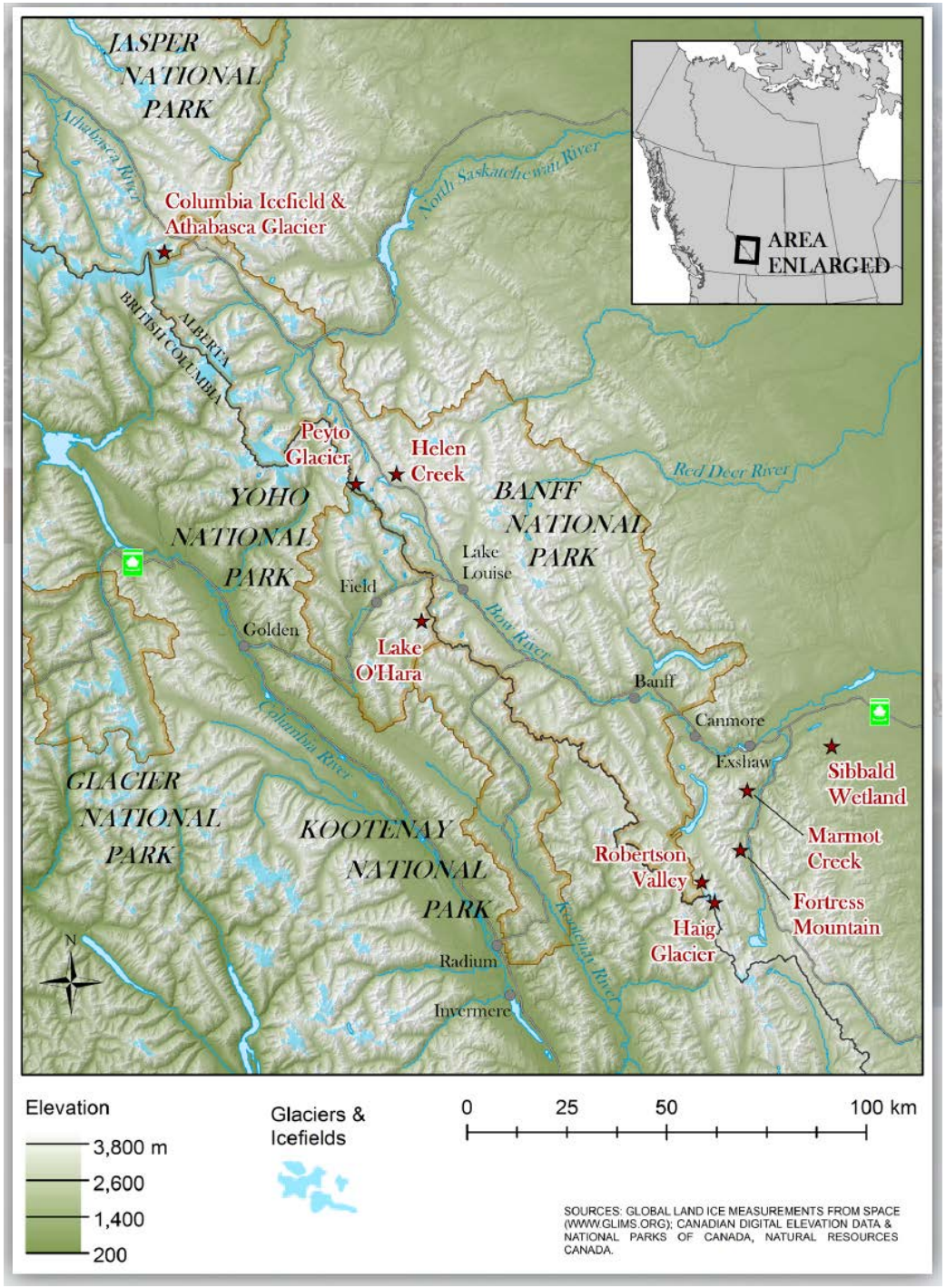
- Melting cryosphere – approaching and passing tipping points.
- Changing ecosystems – treeline and shrub advance into alpine tundra, warmer streams, increasing snow/glacier algae
- Loss of snow and glacier damming effect is challenging current approaches to mountain water management
- High mountain hydrological cycle acceleration is advancing streamflow timing and increasing flood risk
- Sustainability of mountain and downstream communities for water, food and energy security requires better information and predictions.

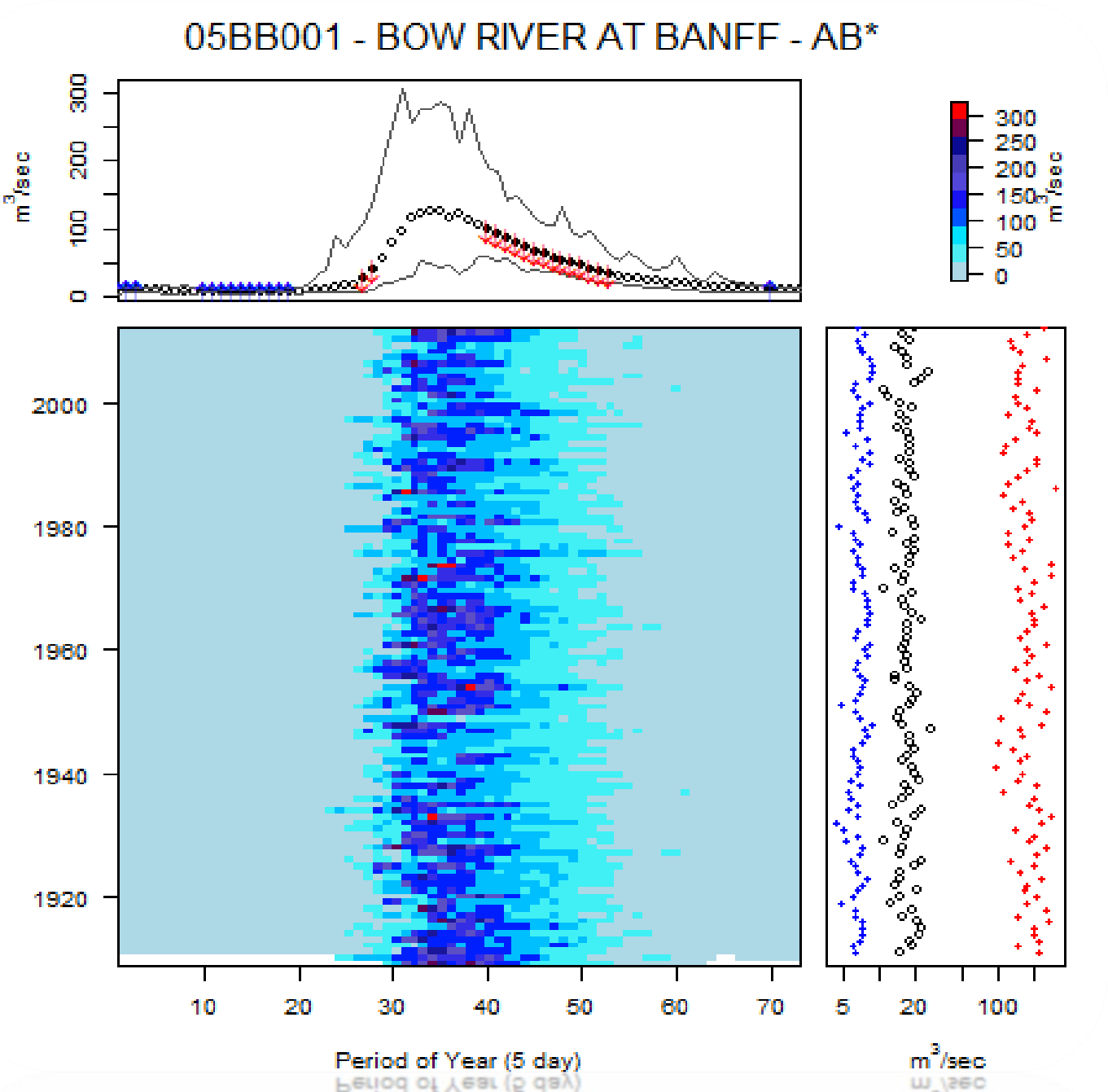
Mountain Snow and Ice are Critical for Canada's Water Resources

https://upload.wikimedia.org/wikipedia/commons/1/15/NorthAmerica-WaterDivides.png

Flood, Drought, Heatwaves and Fire

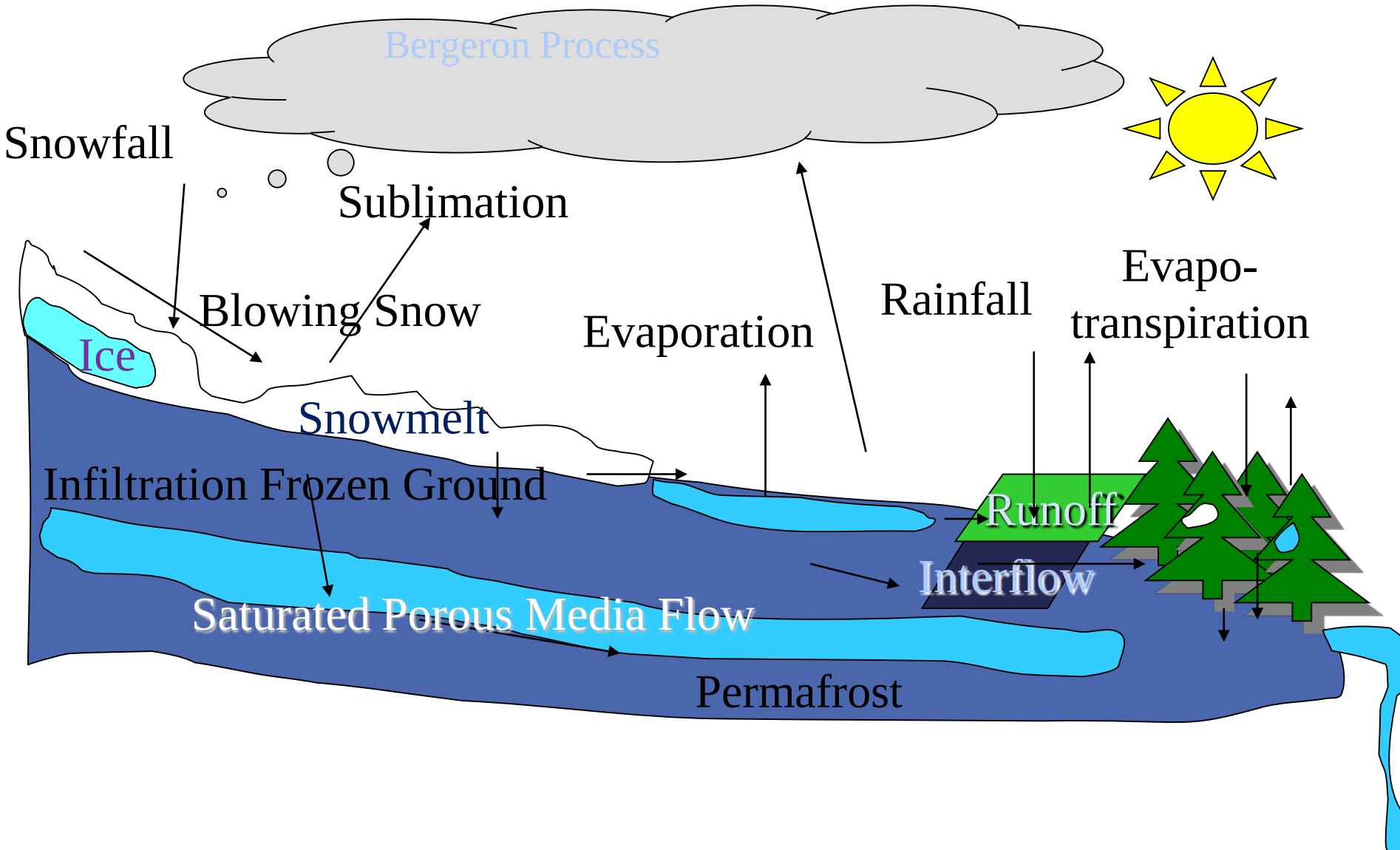
Canadian Rockies Hydrological Observatory and the Bow River Basin



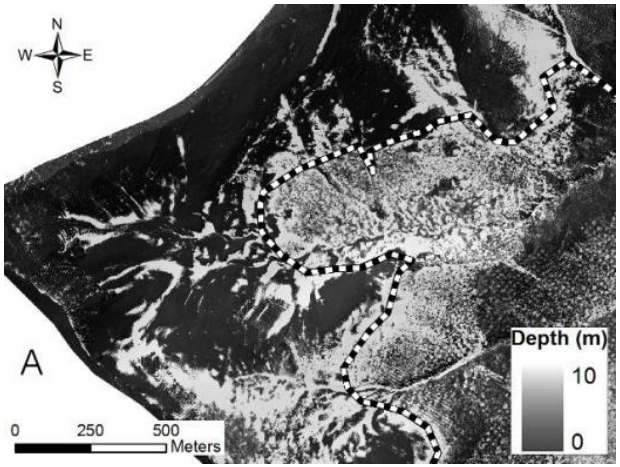

05BB001 - BOW RIVER AT BANFF - AB*
m3/sec
0
100
200
300
300
250
200
150
100
50
0
m3/sec
2000
1980
1960
1940
1920
10
20
30
40
50
60
70
5
20
100
Period of Year (5 day)
m3/sec

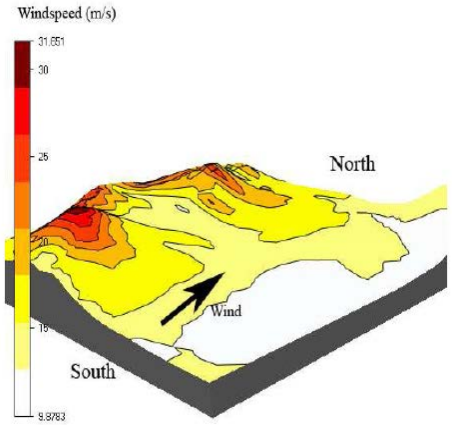
Snow Fed

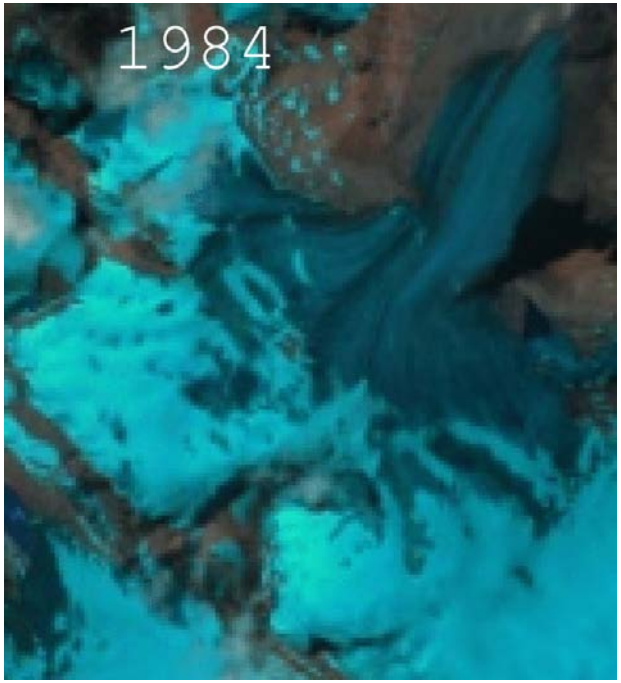
Cold Regions Hydrological Cycle



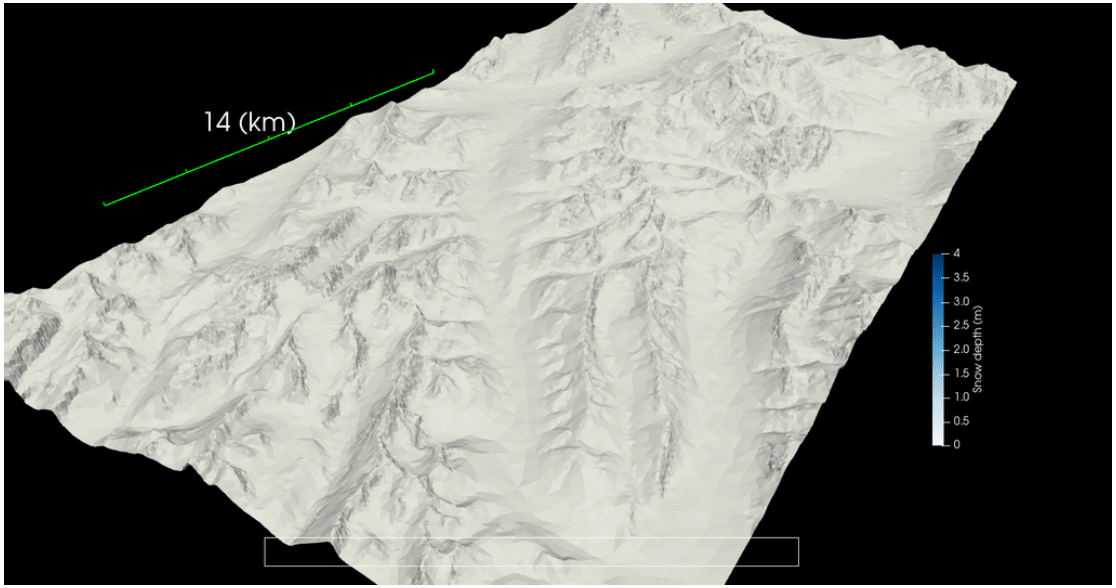
Integrated High Mountain Observations & Predictions

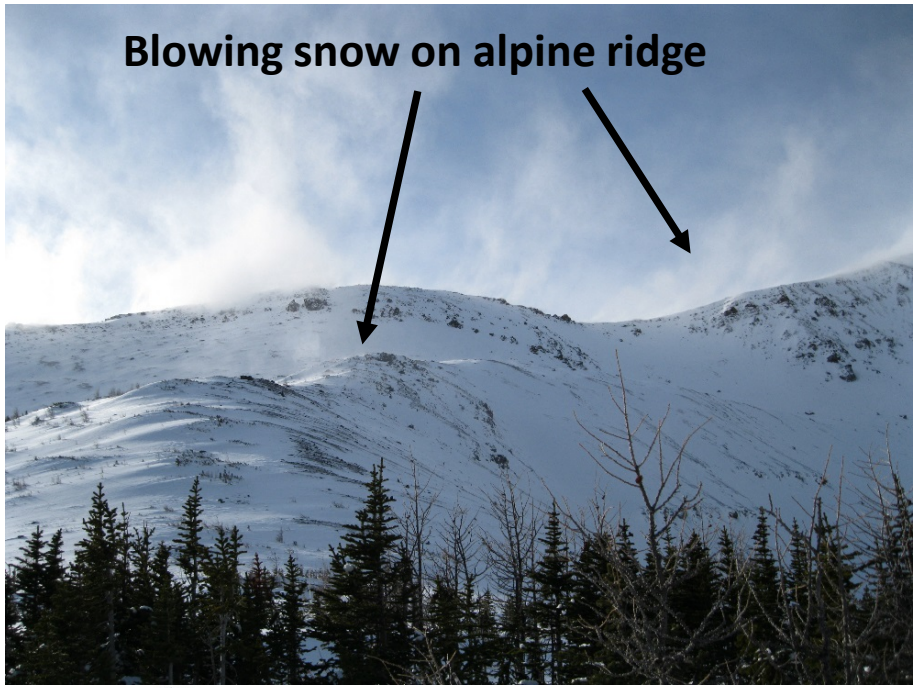




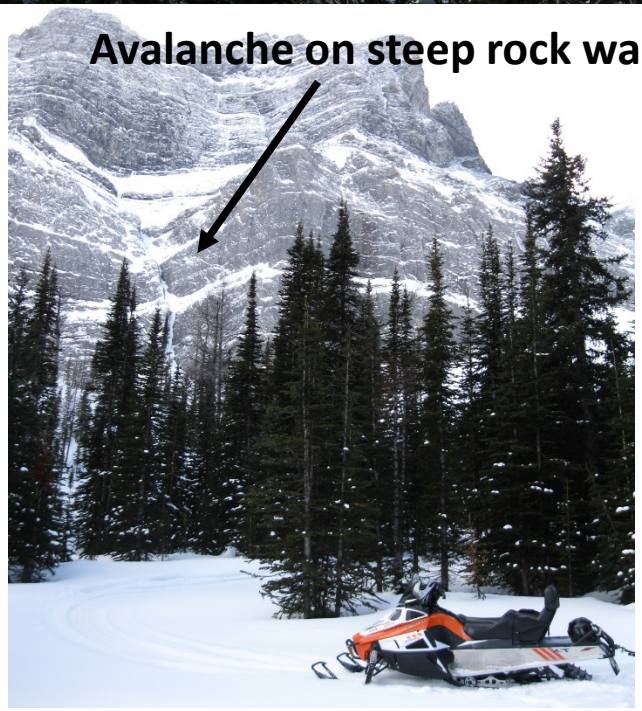


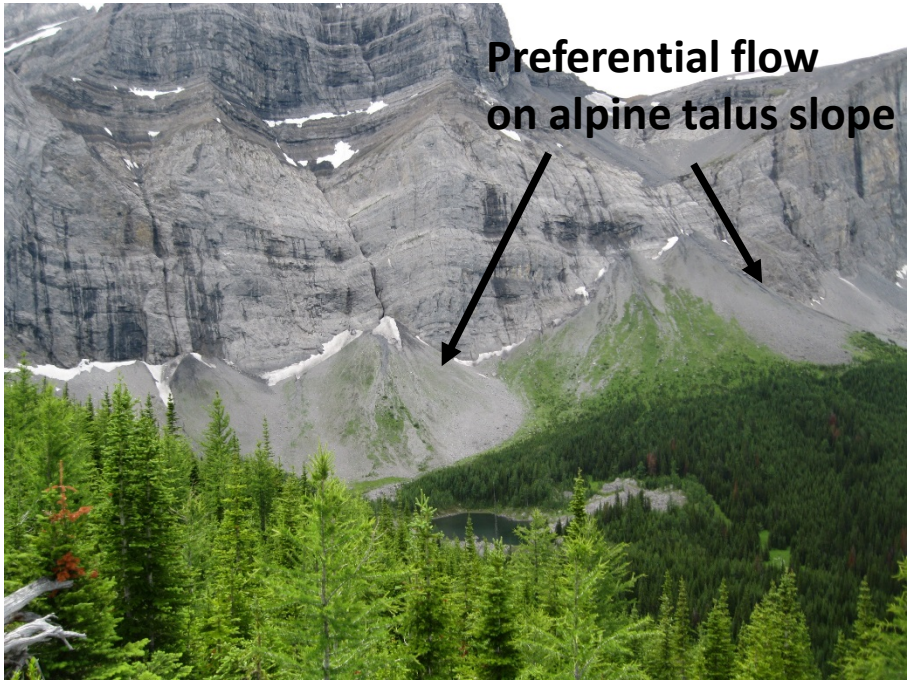
Snow Redistribution and Ablation Model www.snowcast.ca




Blowing snow on alpine ridge

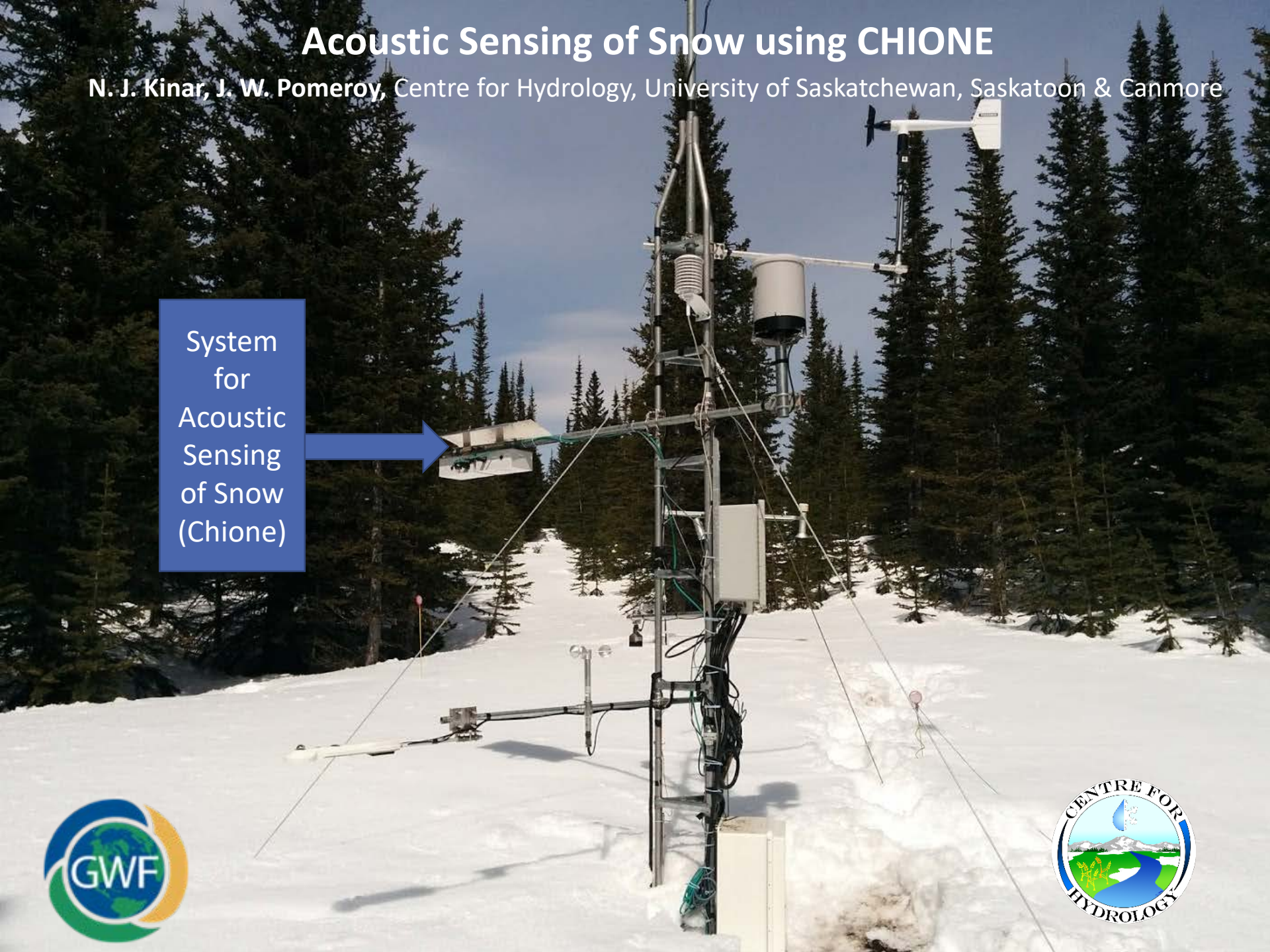

Snow interception
in conifer forest


Avalanche on steep rock wall

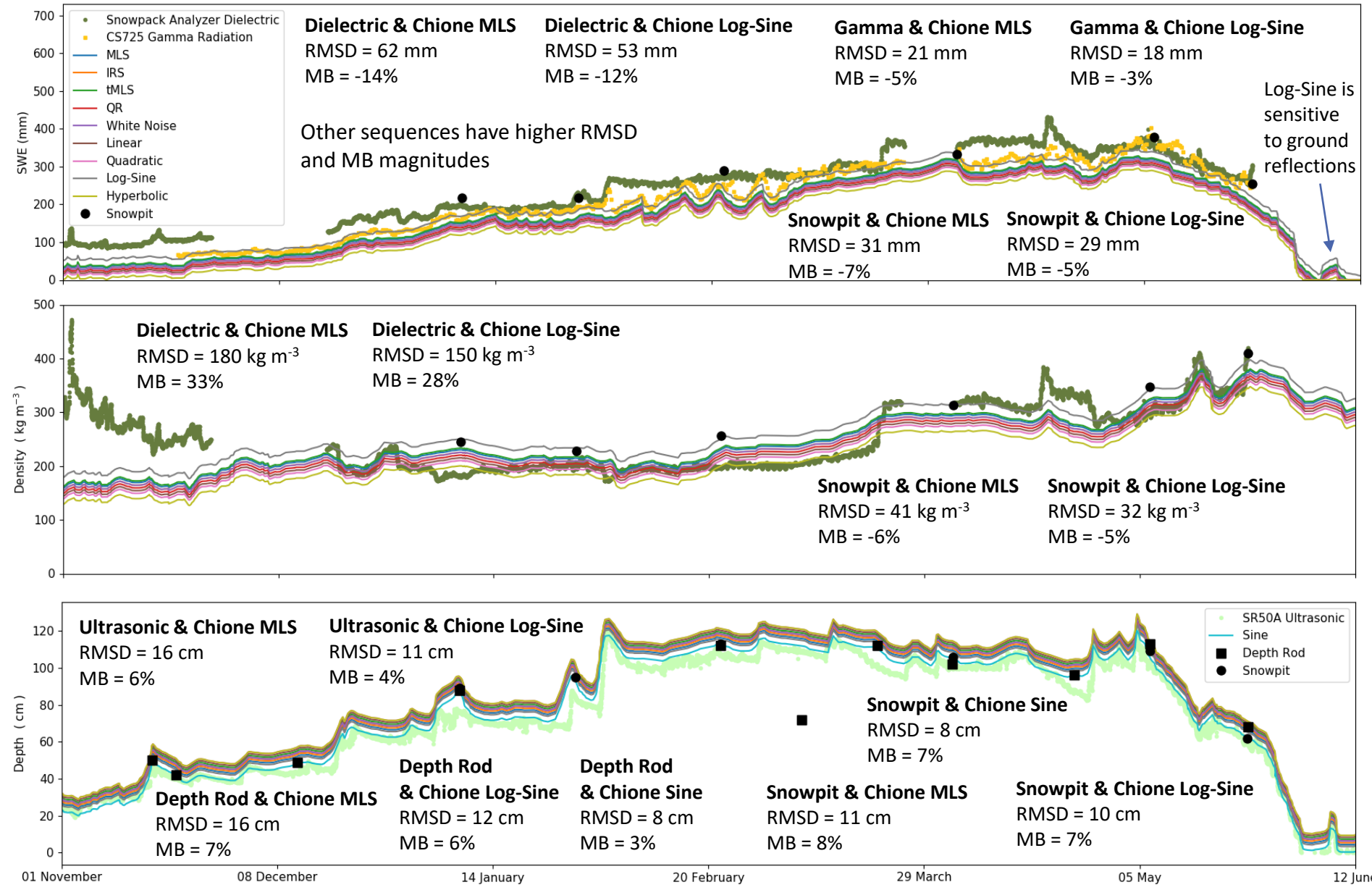

Preferential flow
on alpine talus slope

Acoustic Sensing of Snow using CHIONE

N. J. Kinar, J. W. Pomeroy, Centre for Hydrology, University of Saskatchewan, Saskatoon & Canmore

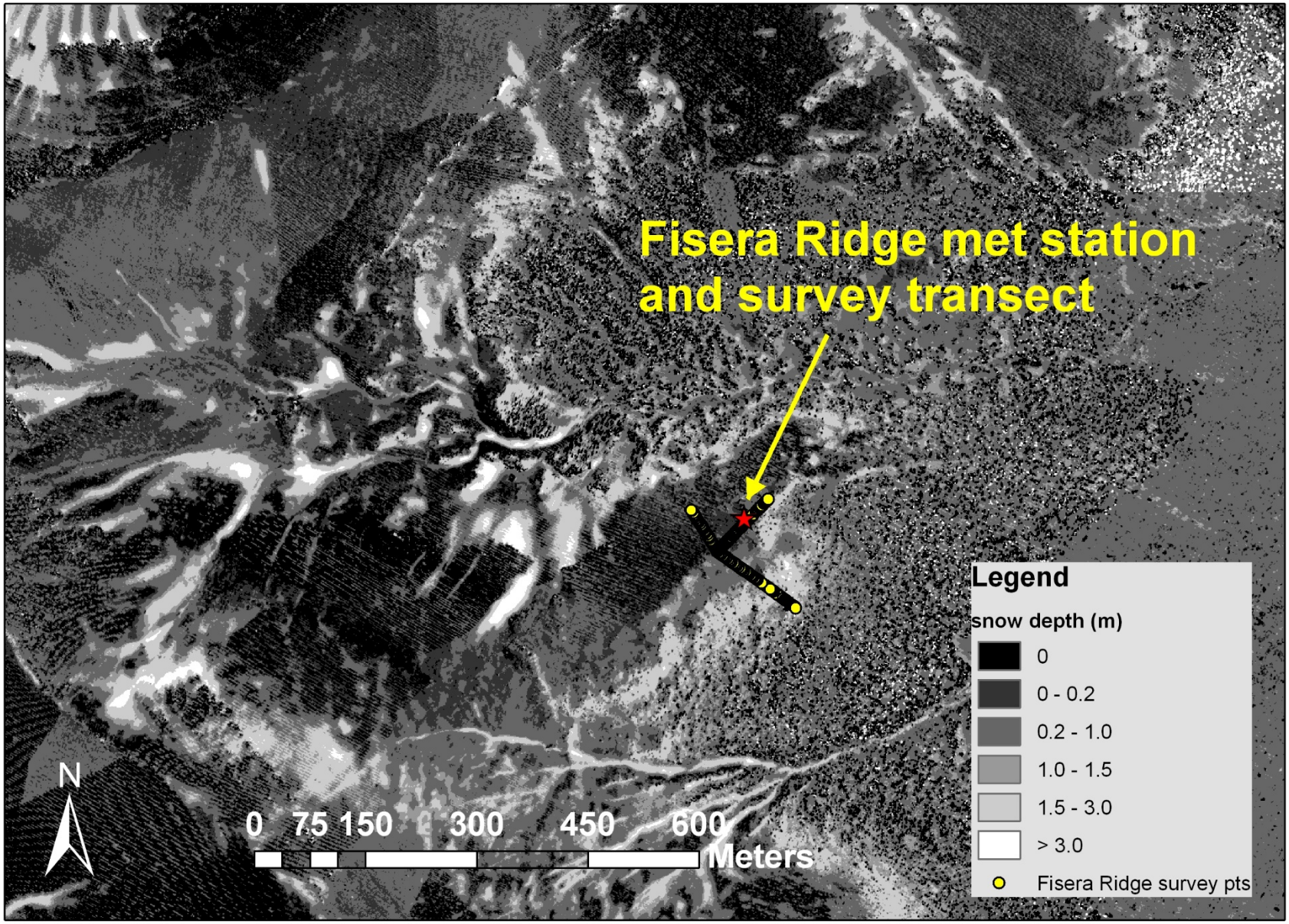


CHIONE – Acoustic Measurement of Snowpacks



RMSD = Root Mean Squared Difference MB = Mean Bias

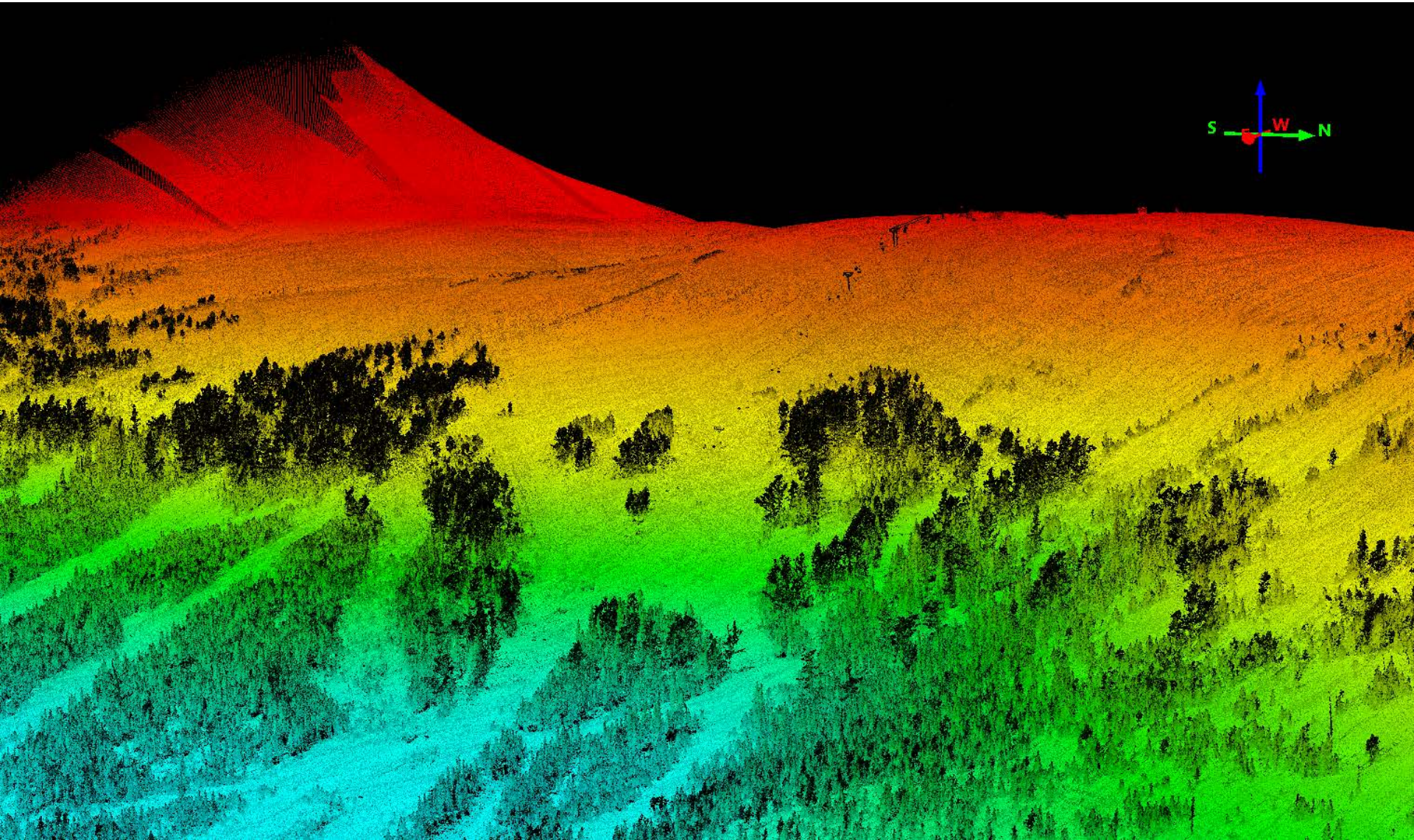
LiDAR Derived Snow Depth Marmot Creek, April 2007



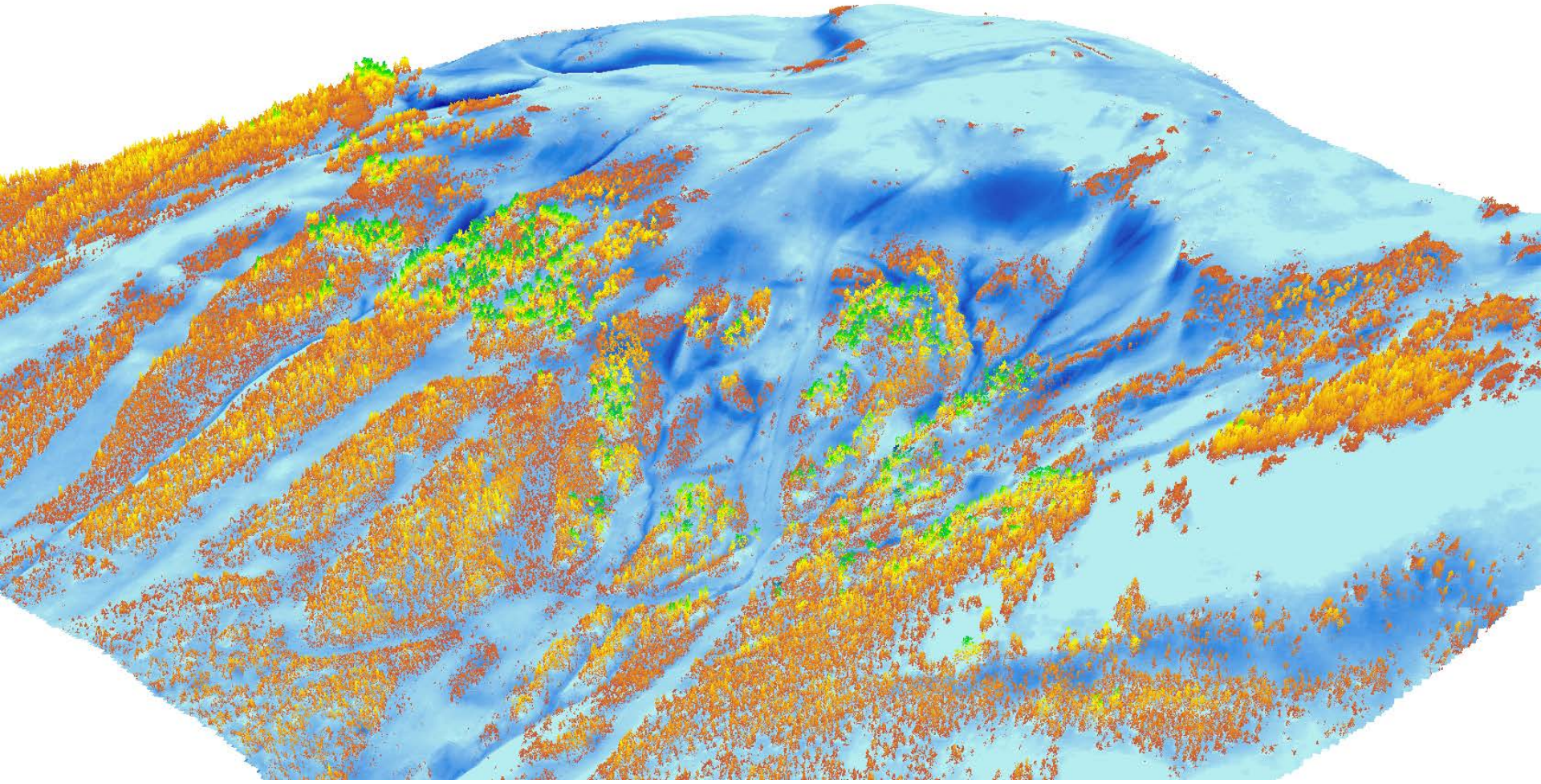
Hopkinson et al., 2009

UAV-borne Remote Sensing in the Canadian Rockies Hydrological Observatory

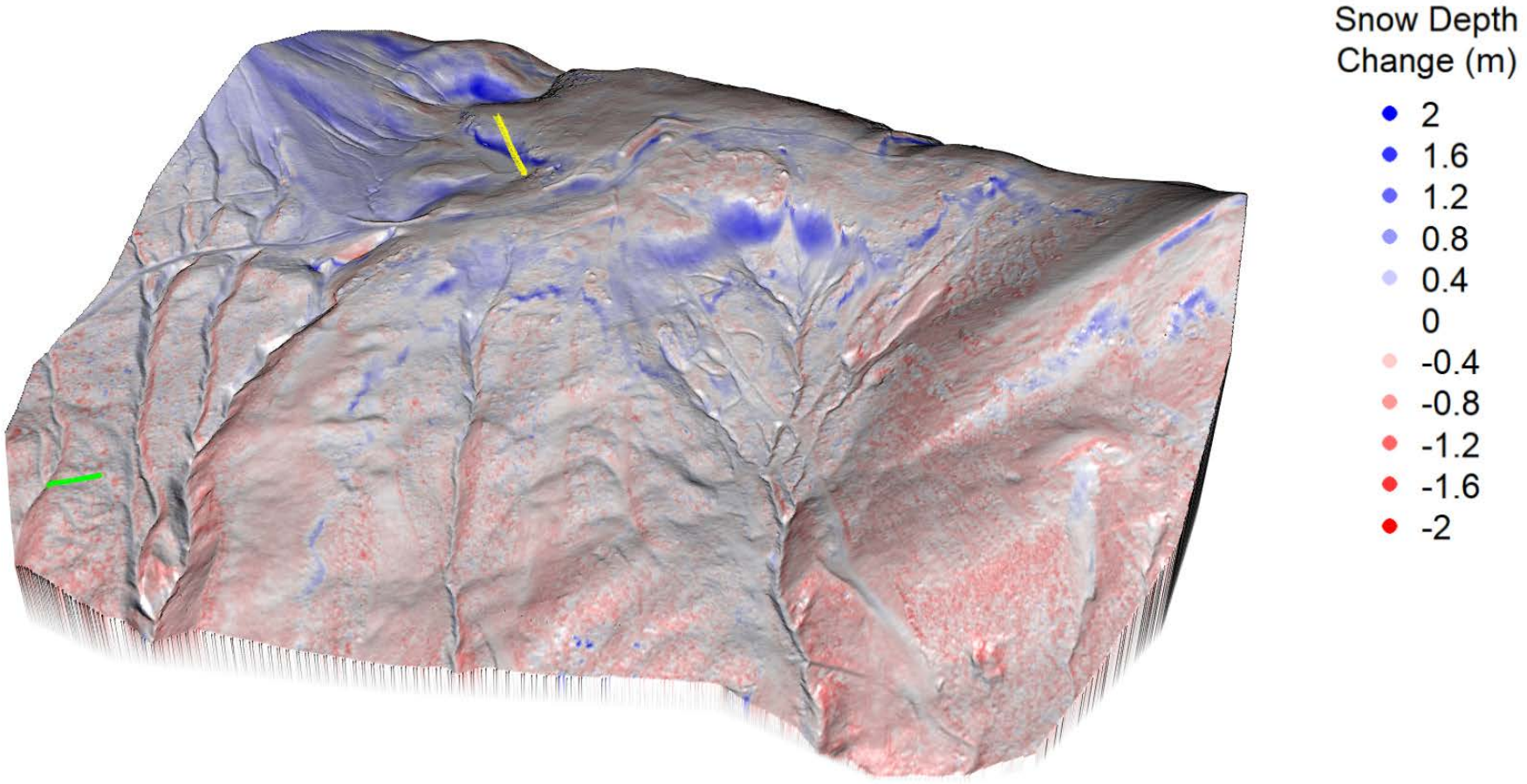
UAV-borne Remote Sensing in the Canadian Rockies Hydrological Observatory



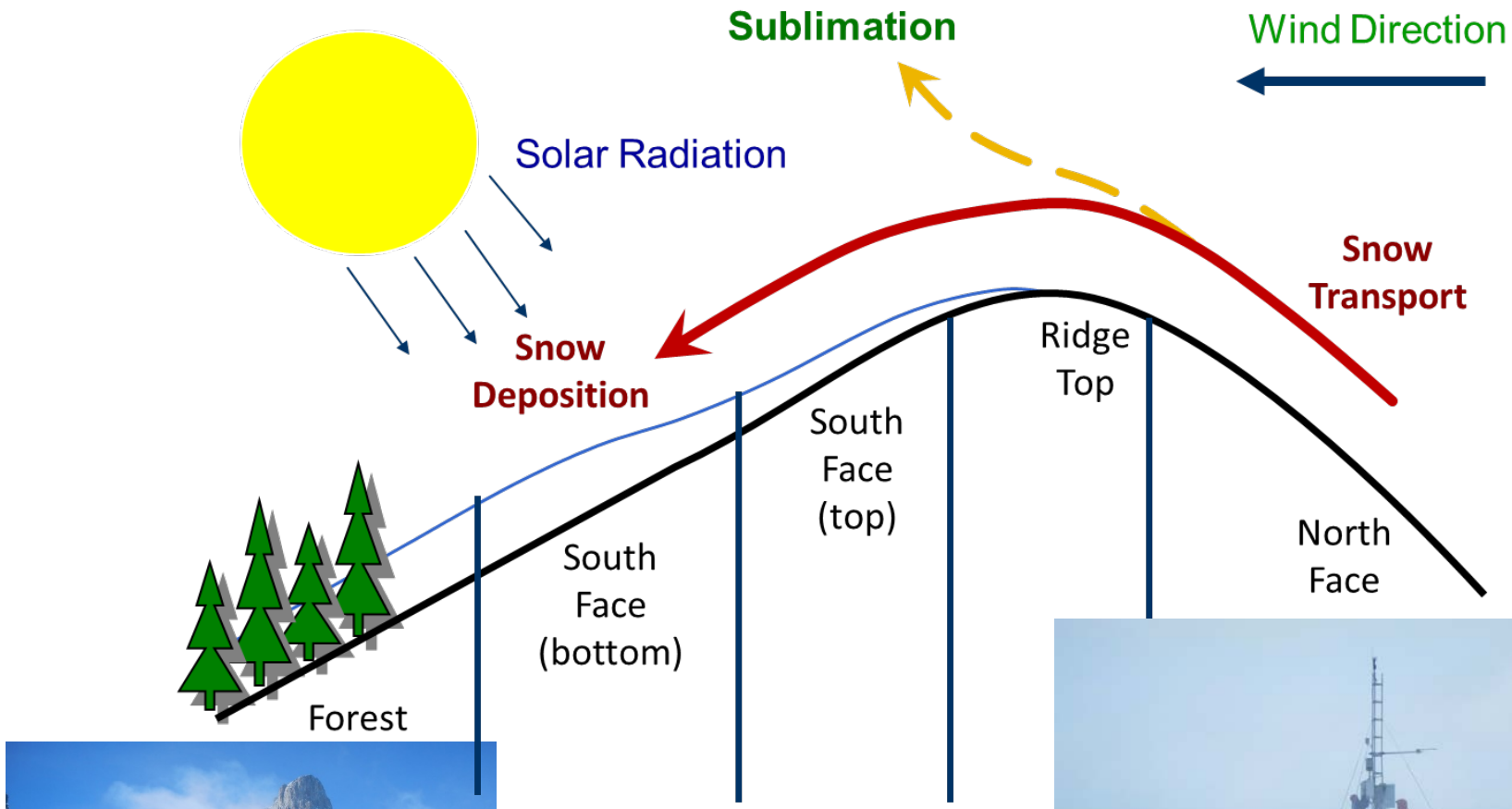
UAV-borne Remote Sensing in the Canadian Rockies Hydrological Observatory



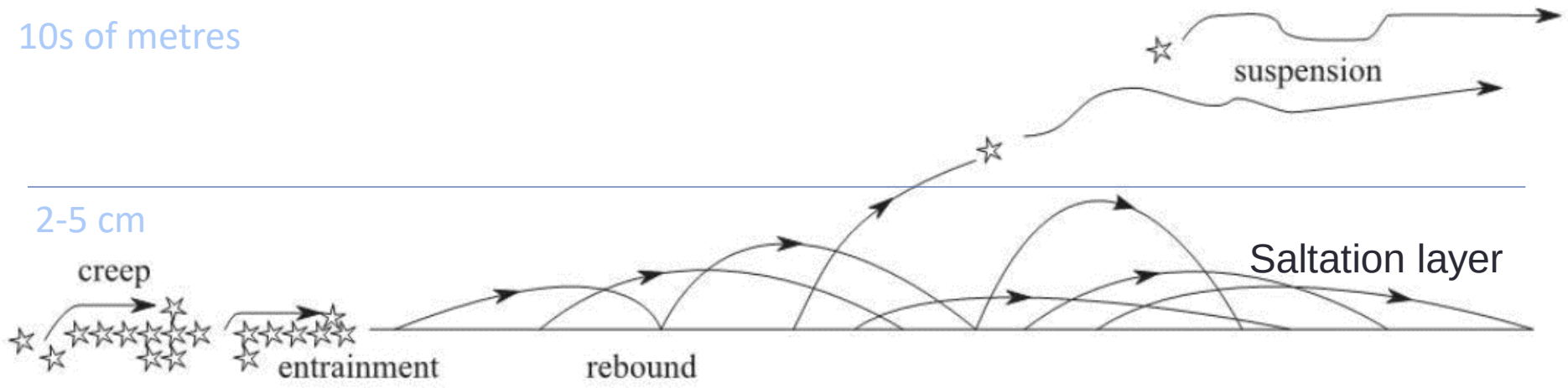
UAV-borne Remote Sensing in the Canadian Rockies Hydrological Observatory



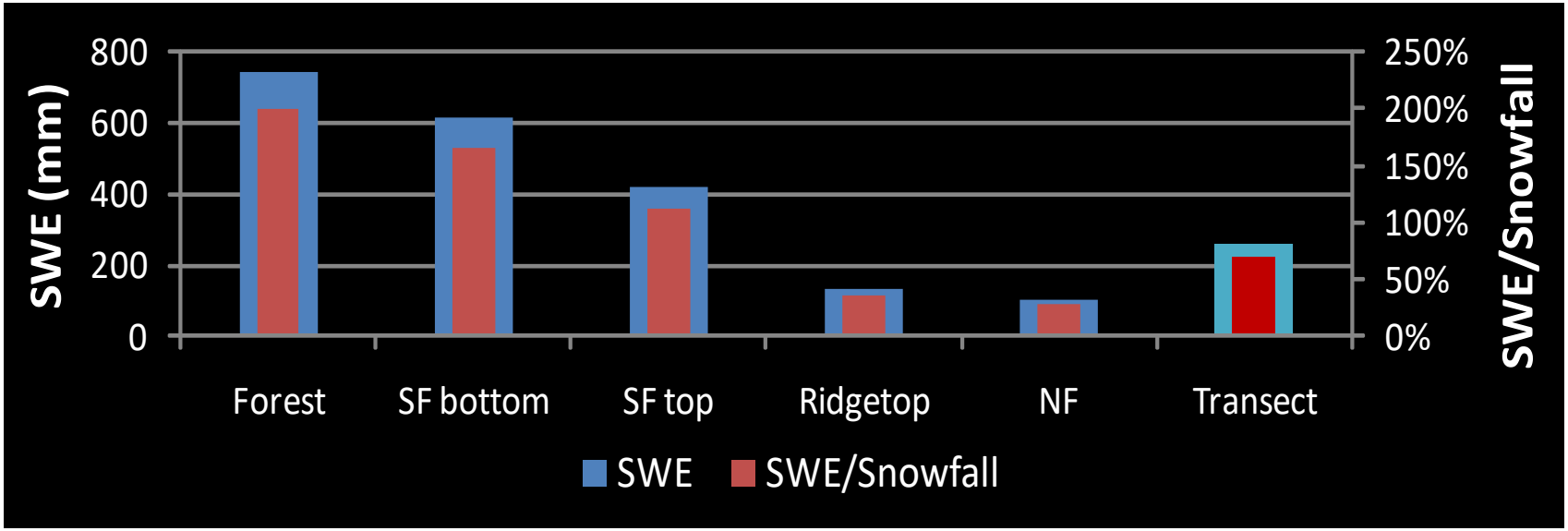
How does snow blow off mountains?

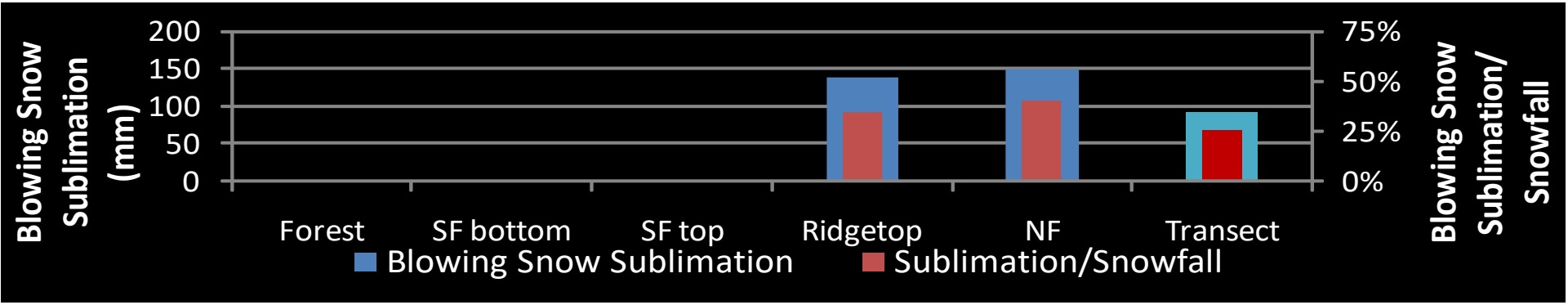


Blowing Snow Mechanism



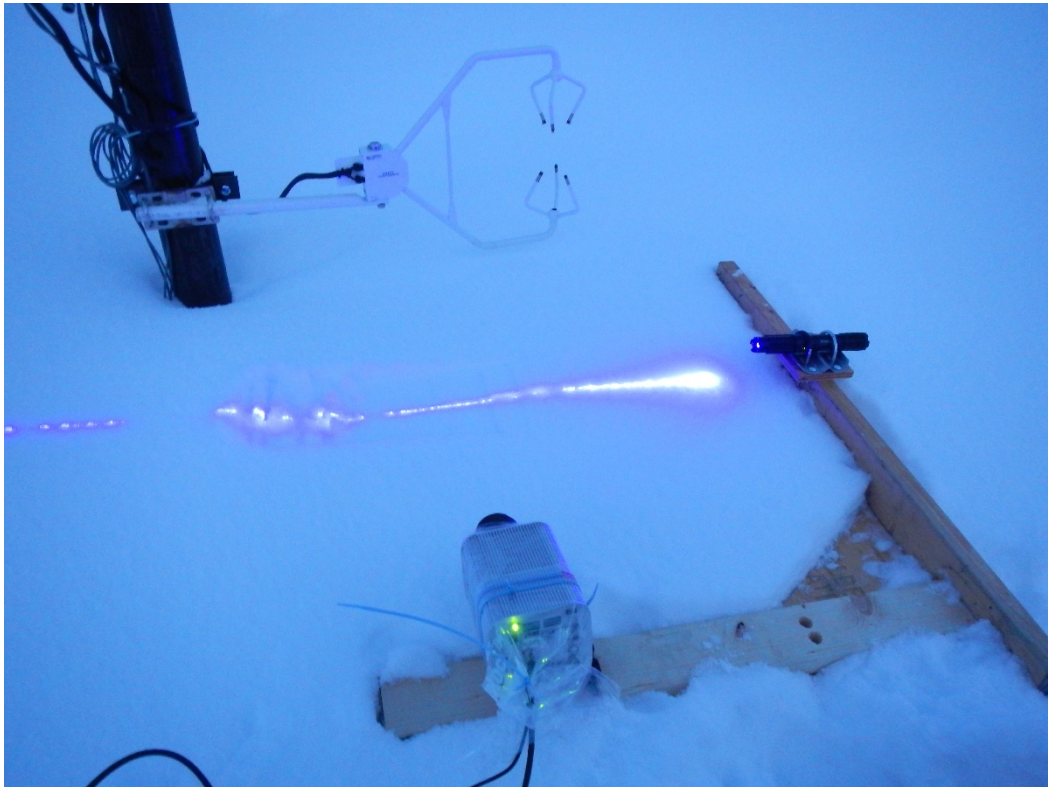
Winter Snow Redistribution and Sublimation

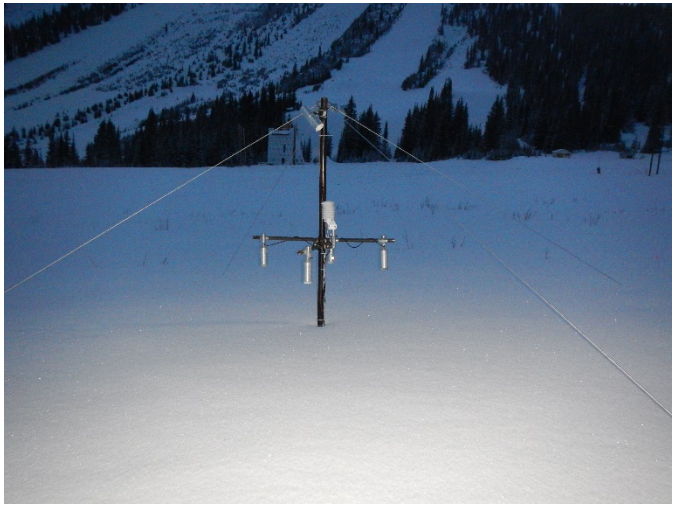




MacDonald, Pomeroy, Pietroniro, 2010

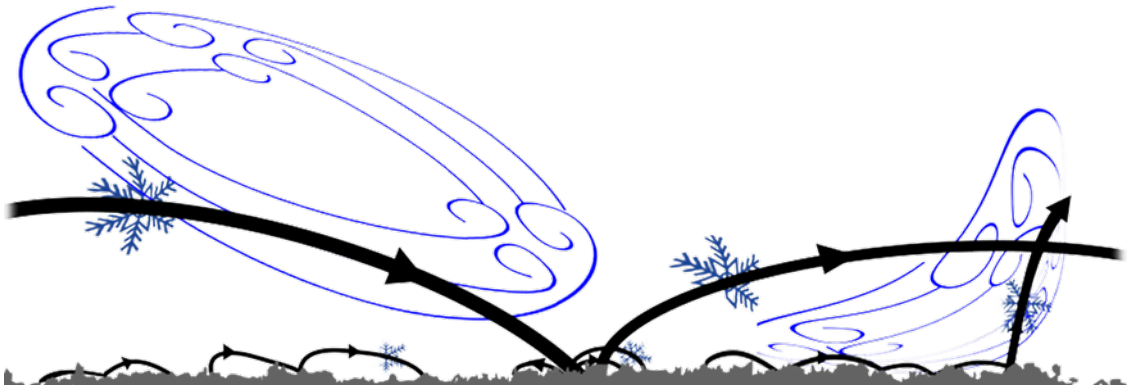
Alpine Blowing Snow Particle Tracking Study





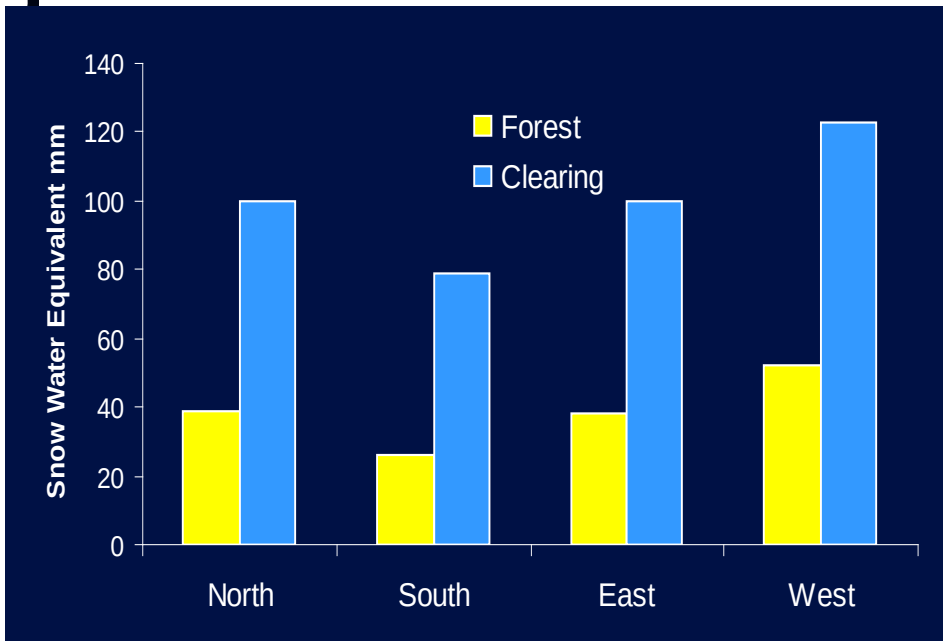
Aksamit and Pomeroy, 2018

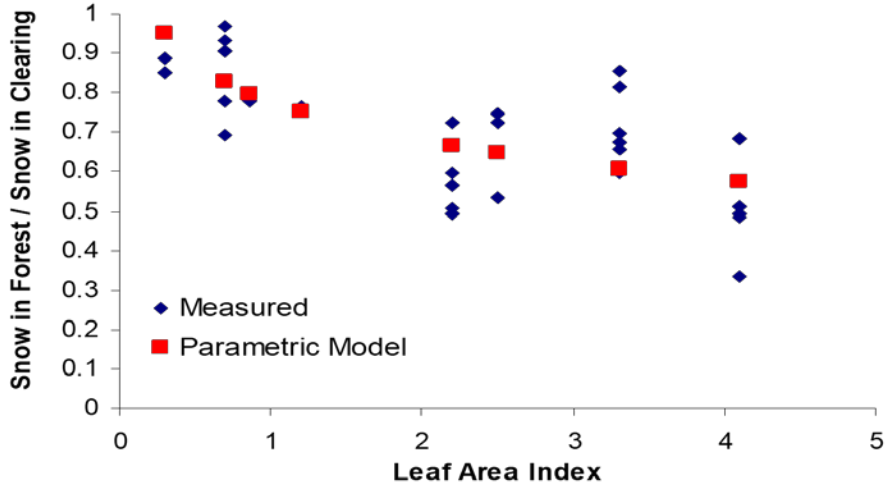
Slow Motion Blowing Snow Particles



Nik Aksamit

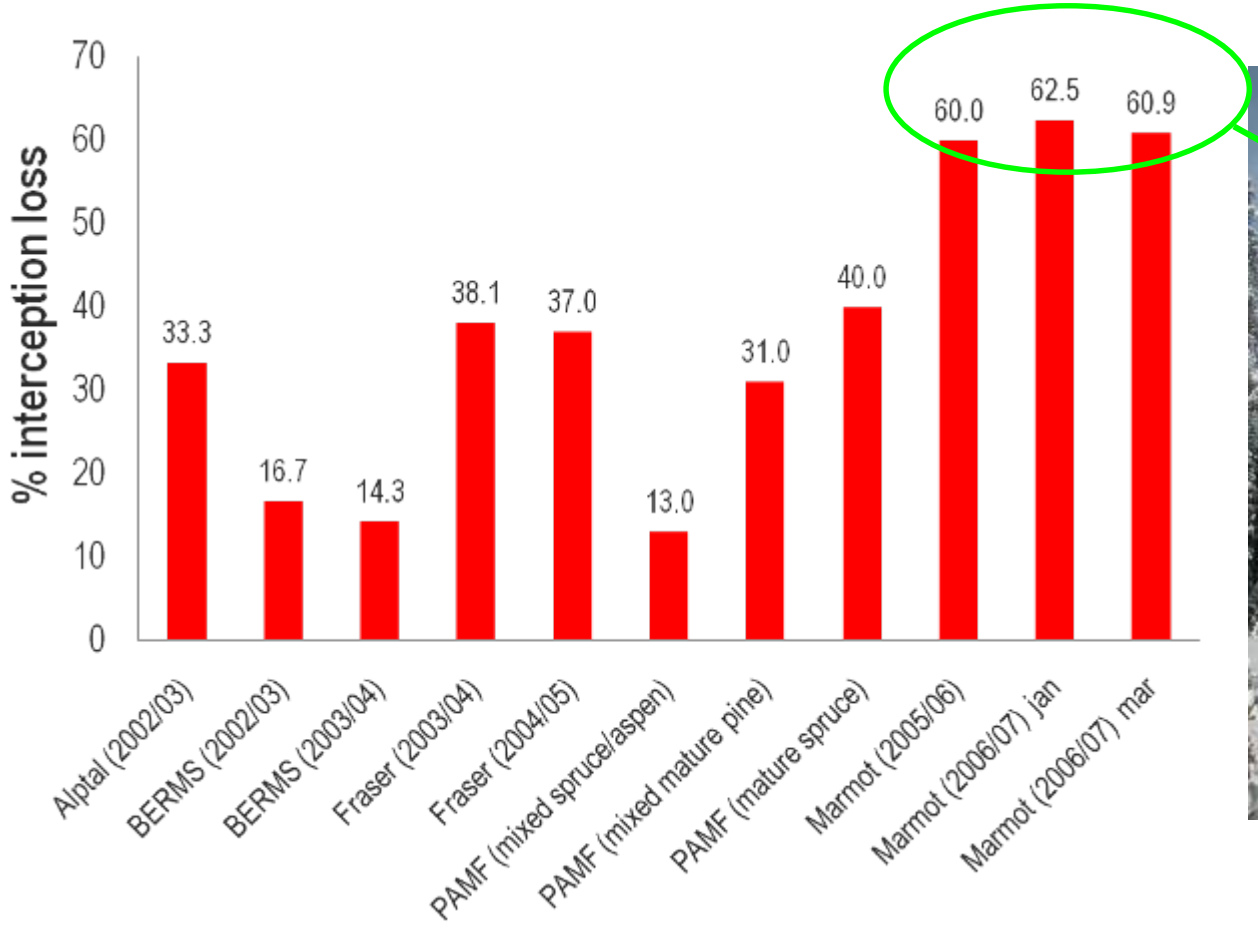
Forest Snow Interception & Sublimation

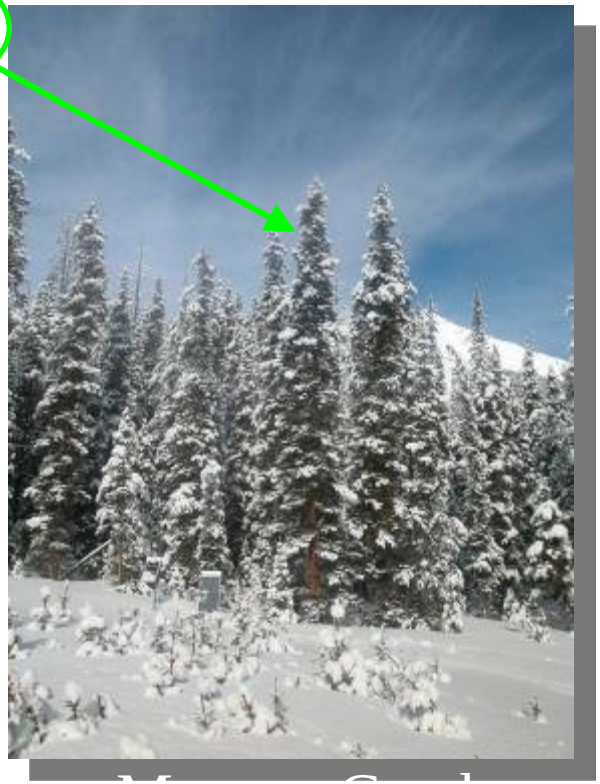




Pomeroy and Schmidt, 1993; Hedstrom & Pomeroy, 1997; Pomeroy et al., 2002; ; Essery et al., 2004; Gelfan et al., 2004; Pomeroy et al., 2008; Ellis et al., 2010

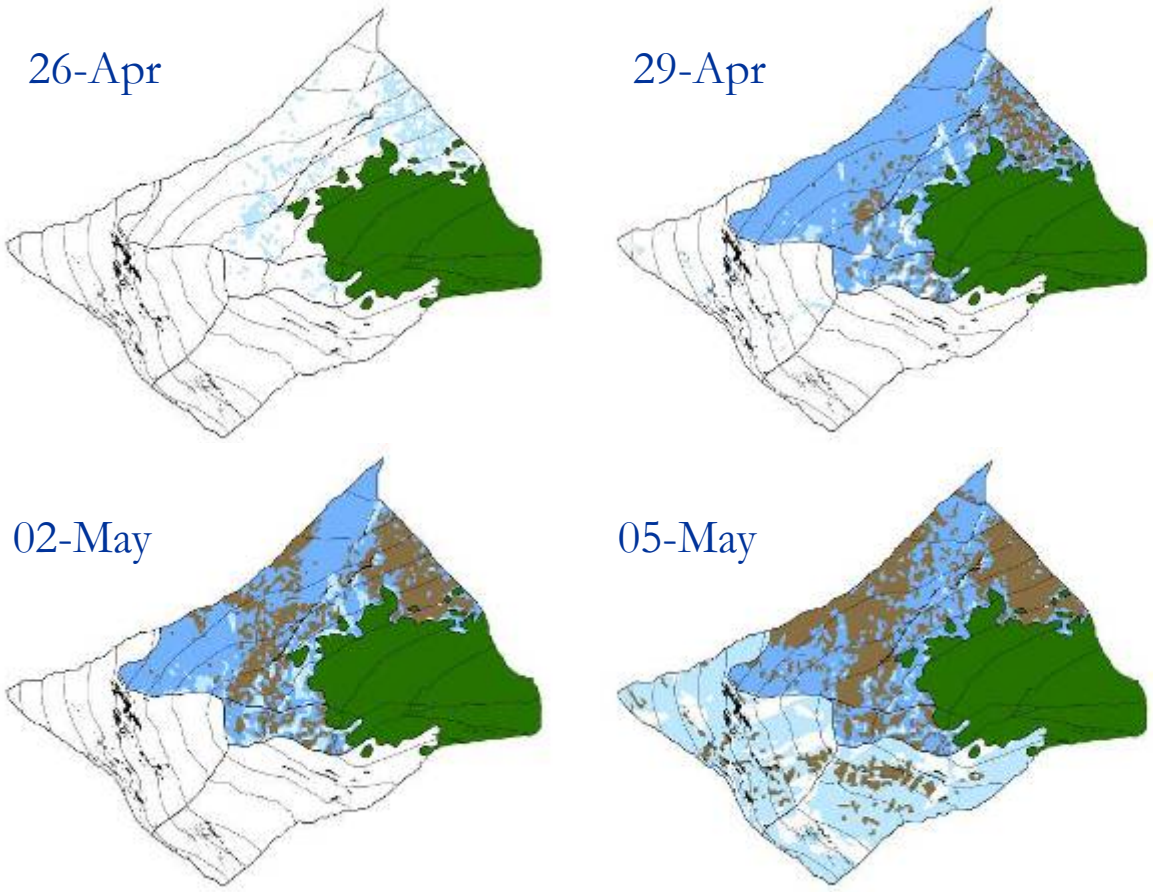
Snow Interception Losses Large

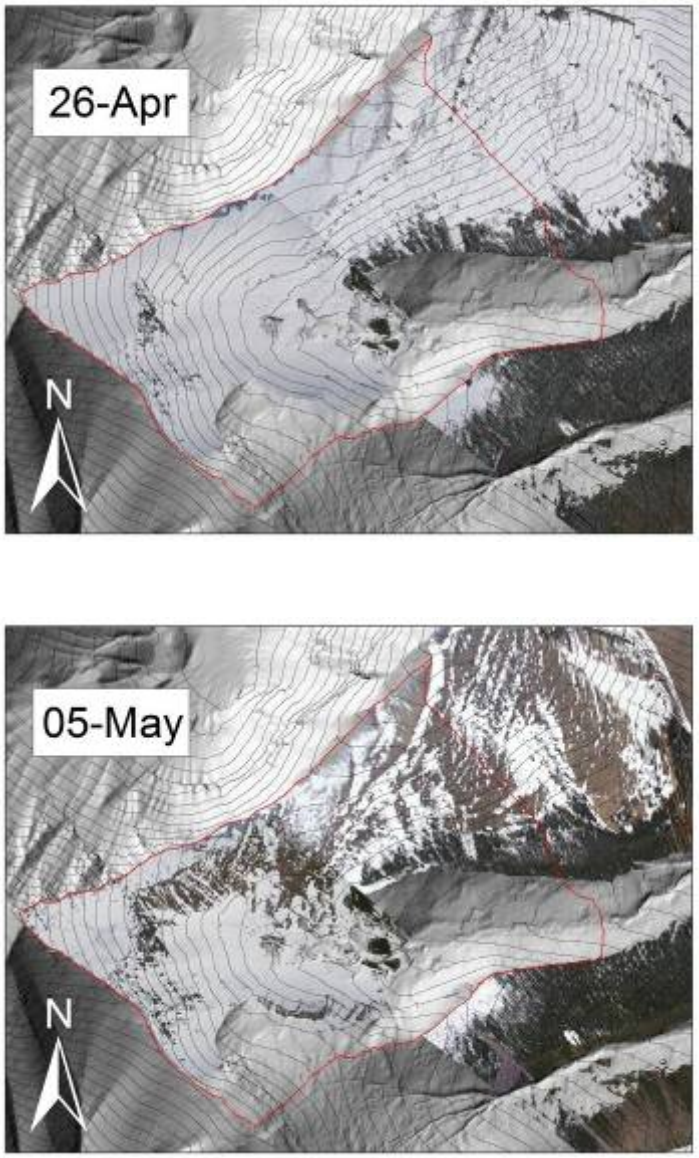




Visualisation of Snowmelt Runoff Intensity

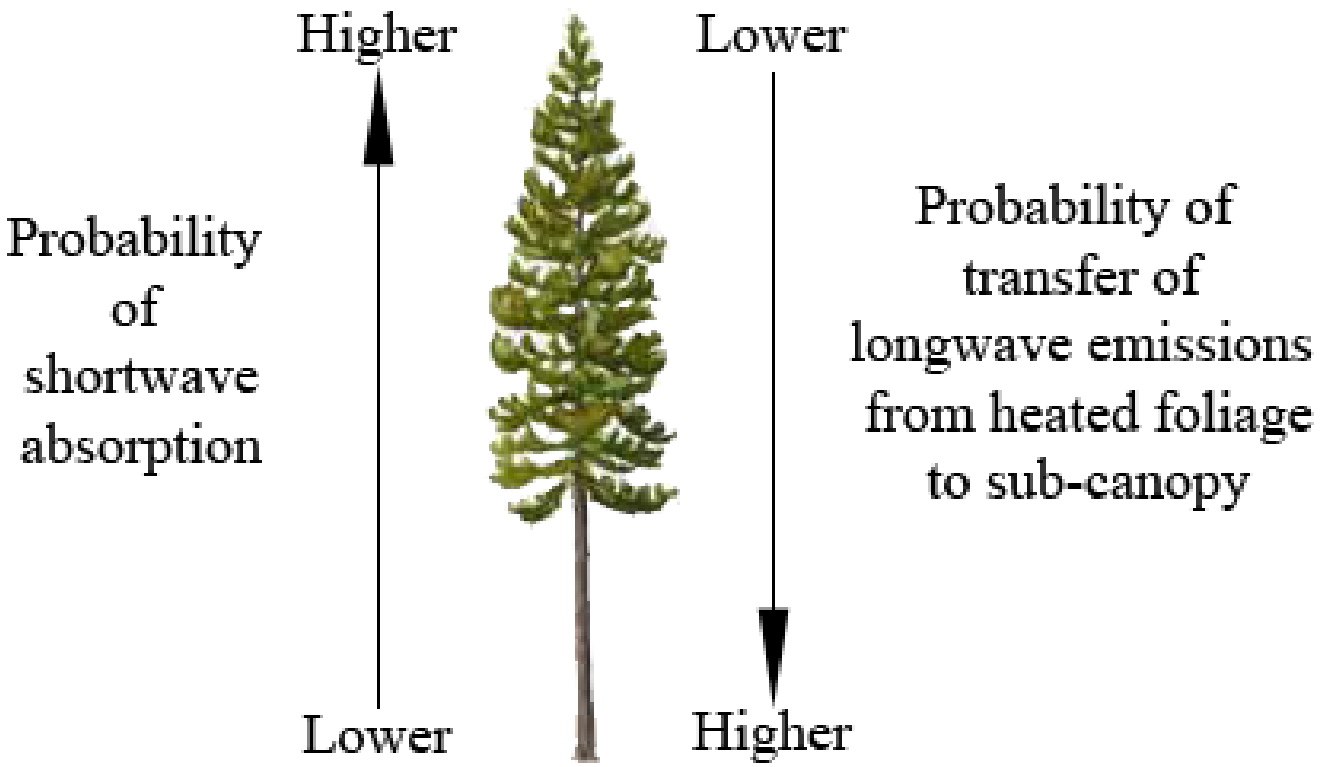
Early Snowmelt Period - 2008





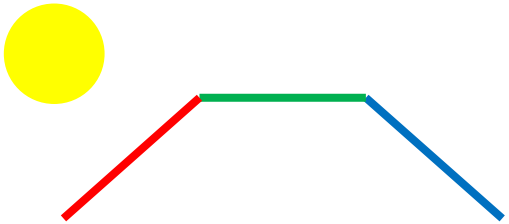
DeBeer and Pomeroy, 2010

Forest Snowmelt

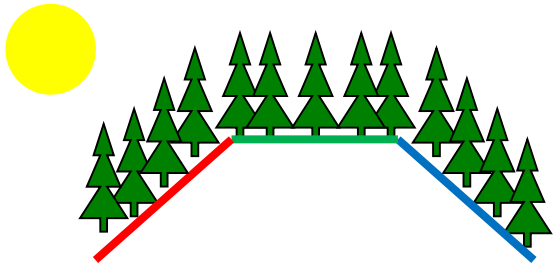


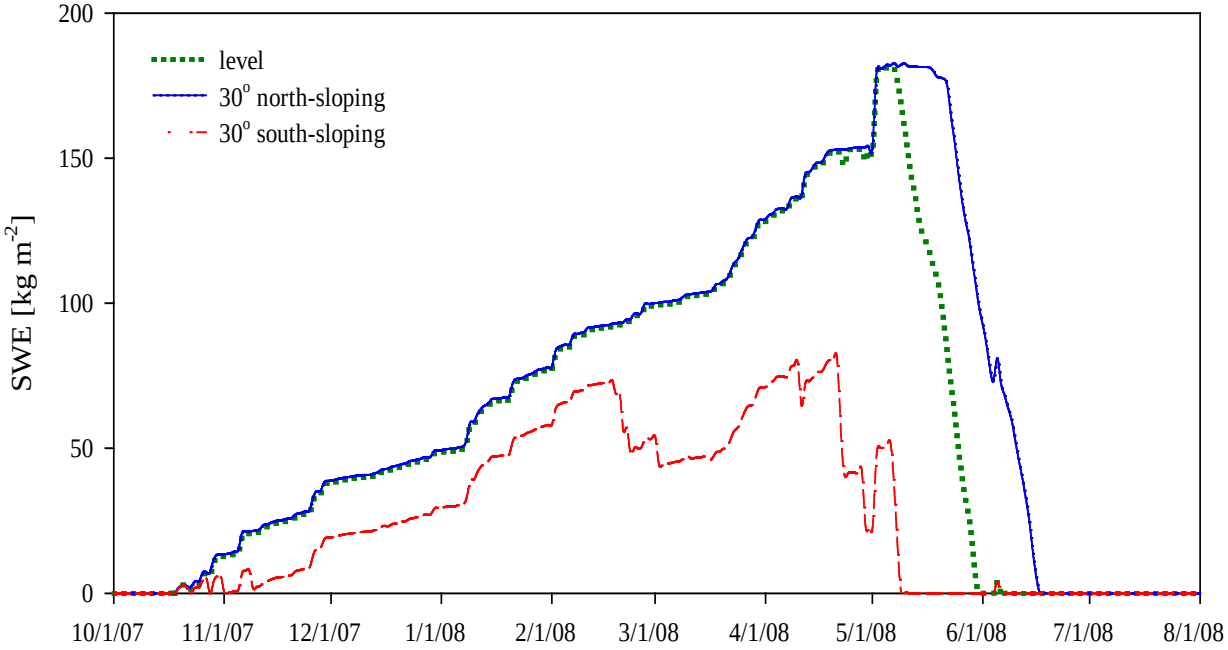
Ellis and Pomeroy, 2007; Ellis et al., 2011

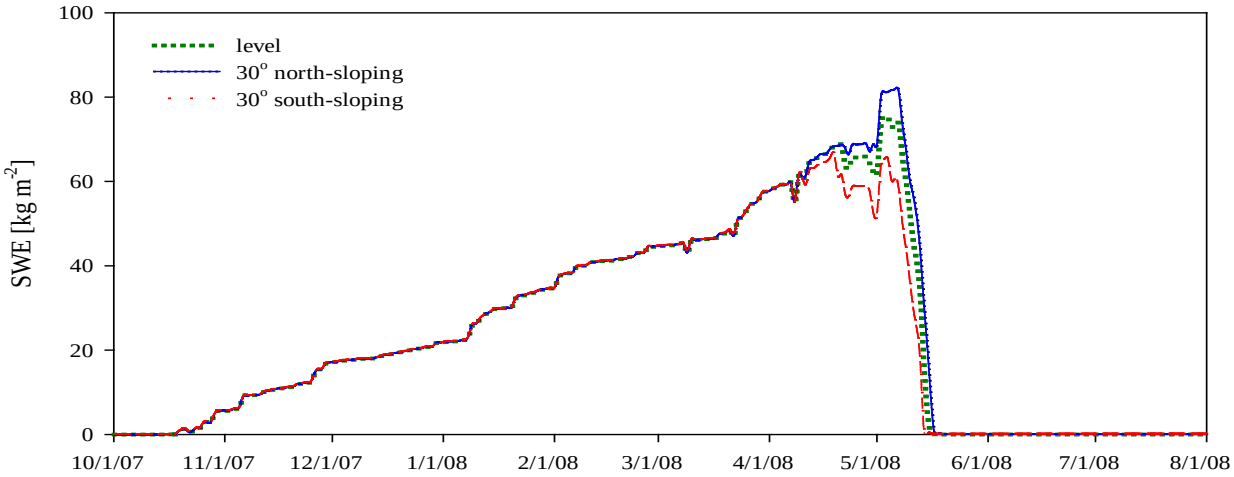
Forest Snow Regime on Slopes



Open slopes highly sensitive to irradiation difference, forests are not

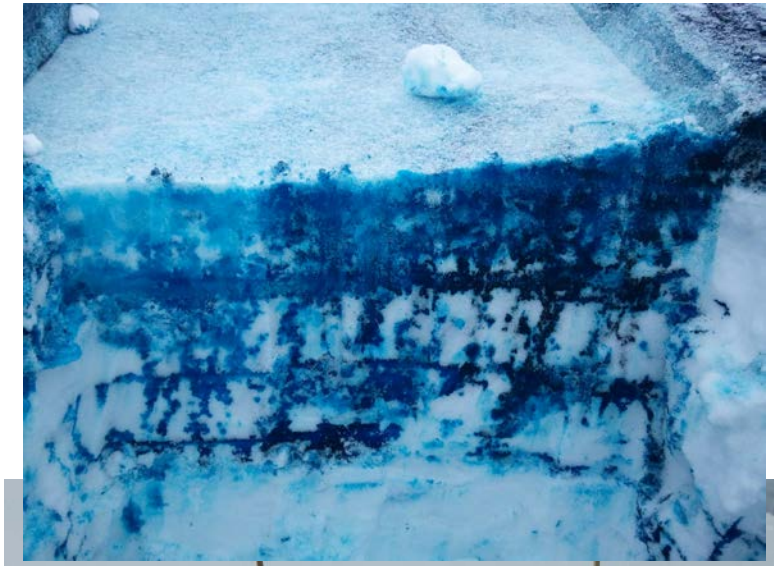


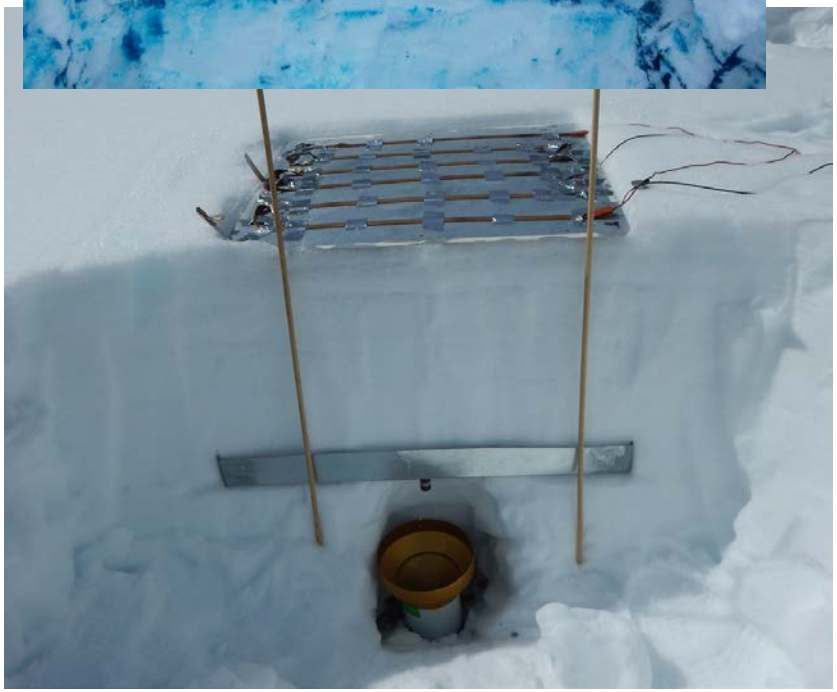




Ellis, Pomeroy, Link, 2013

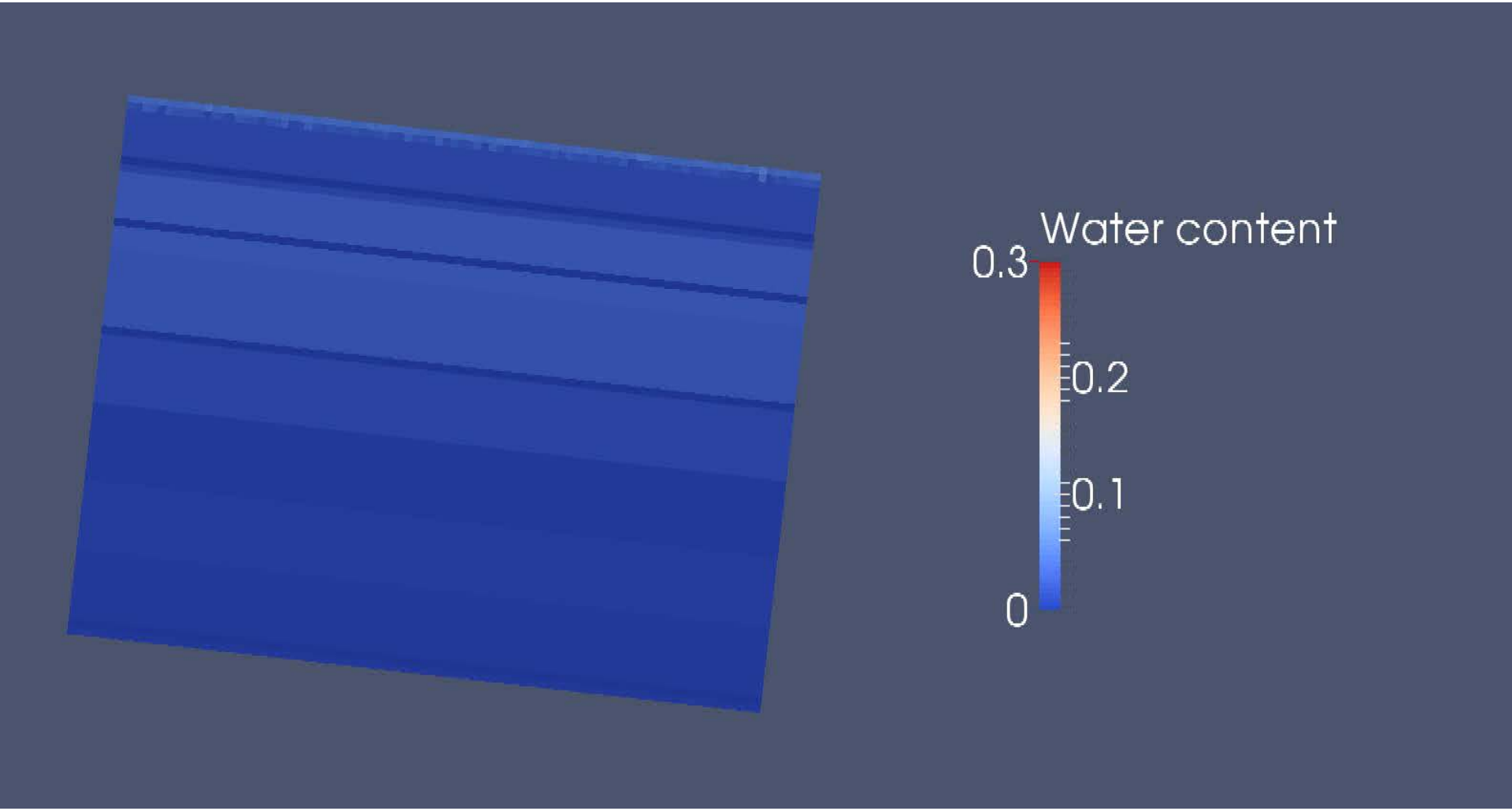
How fast does water flow through snow?



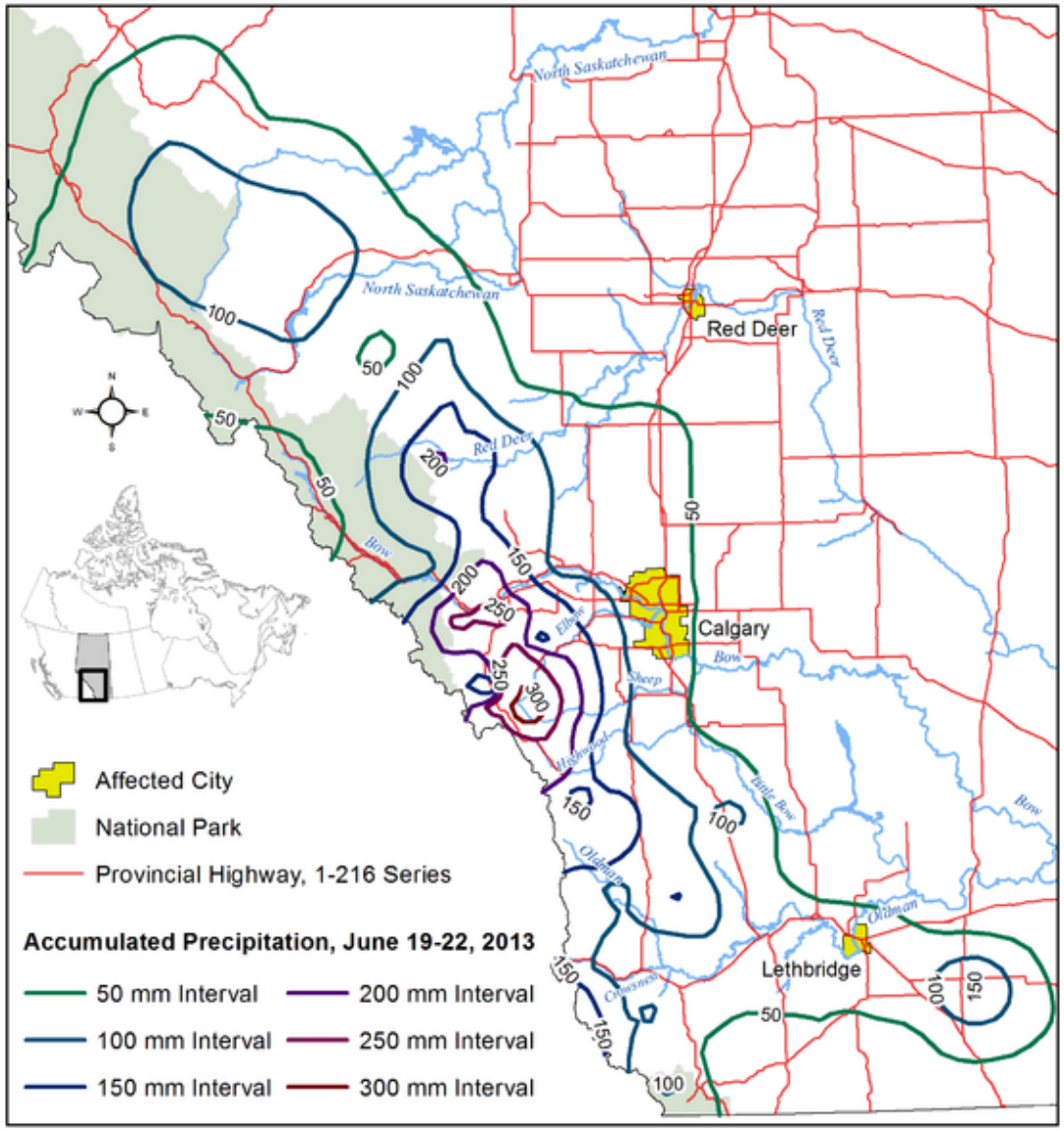


Nicolas Leroux

New Model of Water Flow through Snowpacks



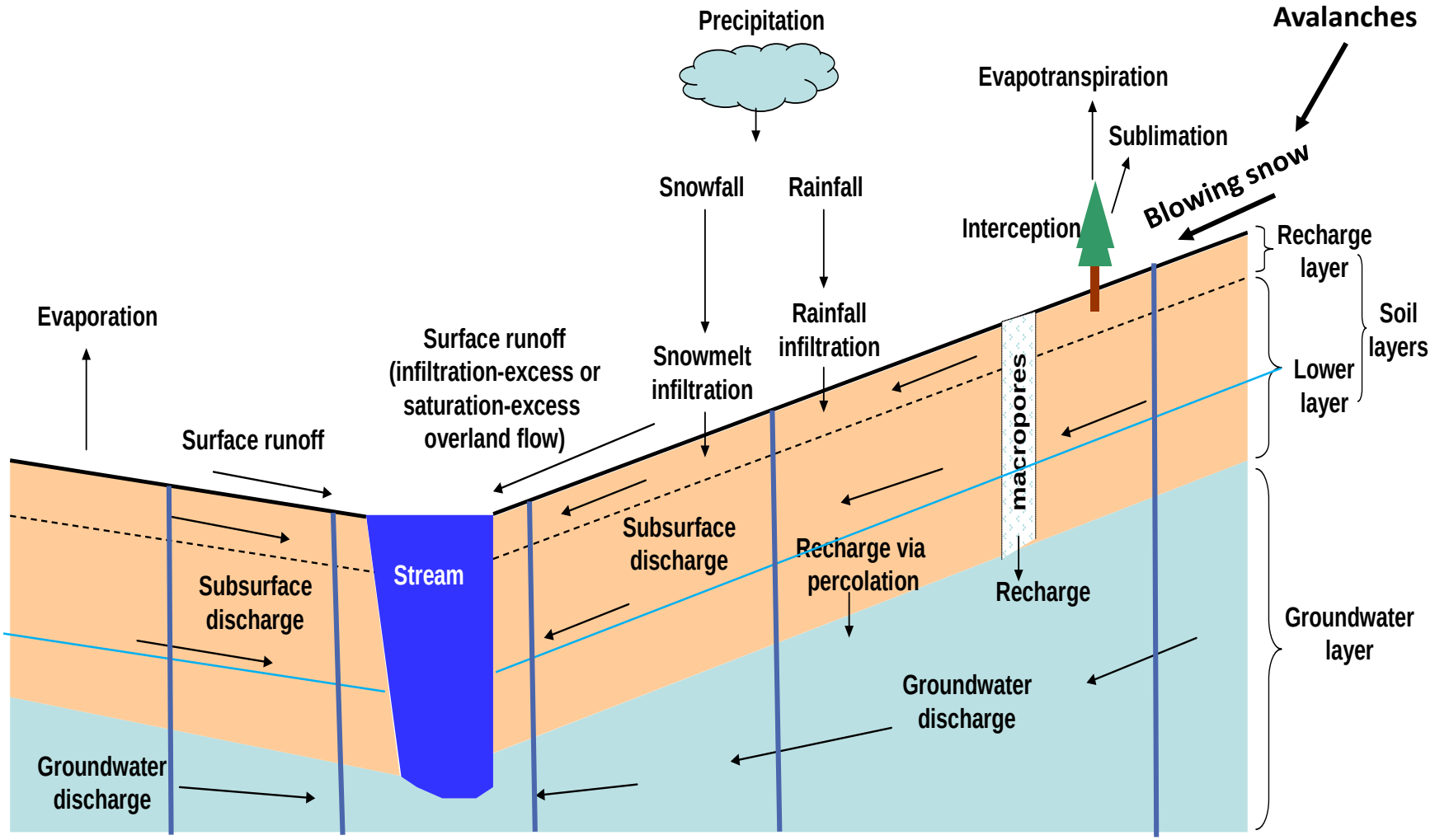
Precipitation during the 2013 Alberta Flood



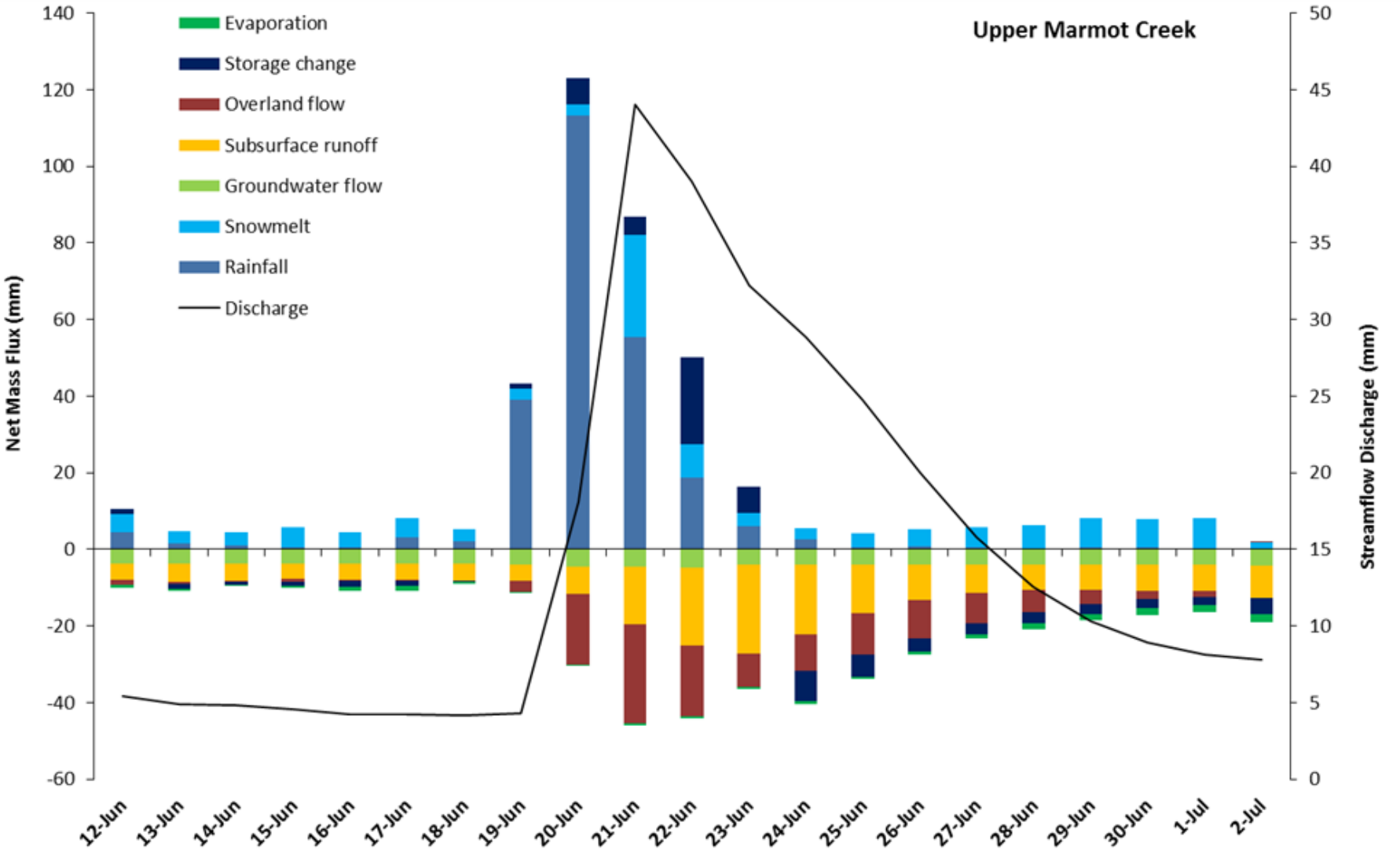
courtesy: Alberta Environment & Parks

Alter-shielded Geonor Precipitation Gauge and Tipping Bucket Rain Gauge Marmot Creek

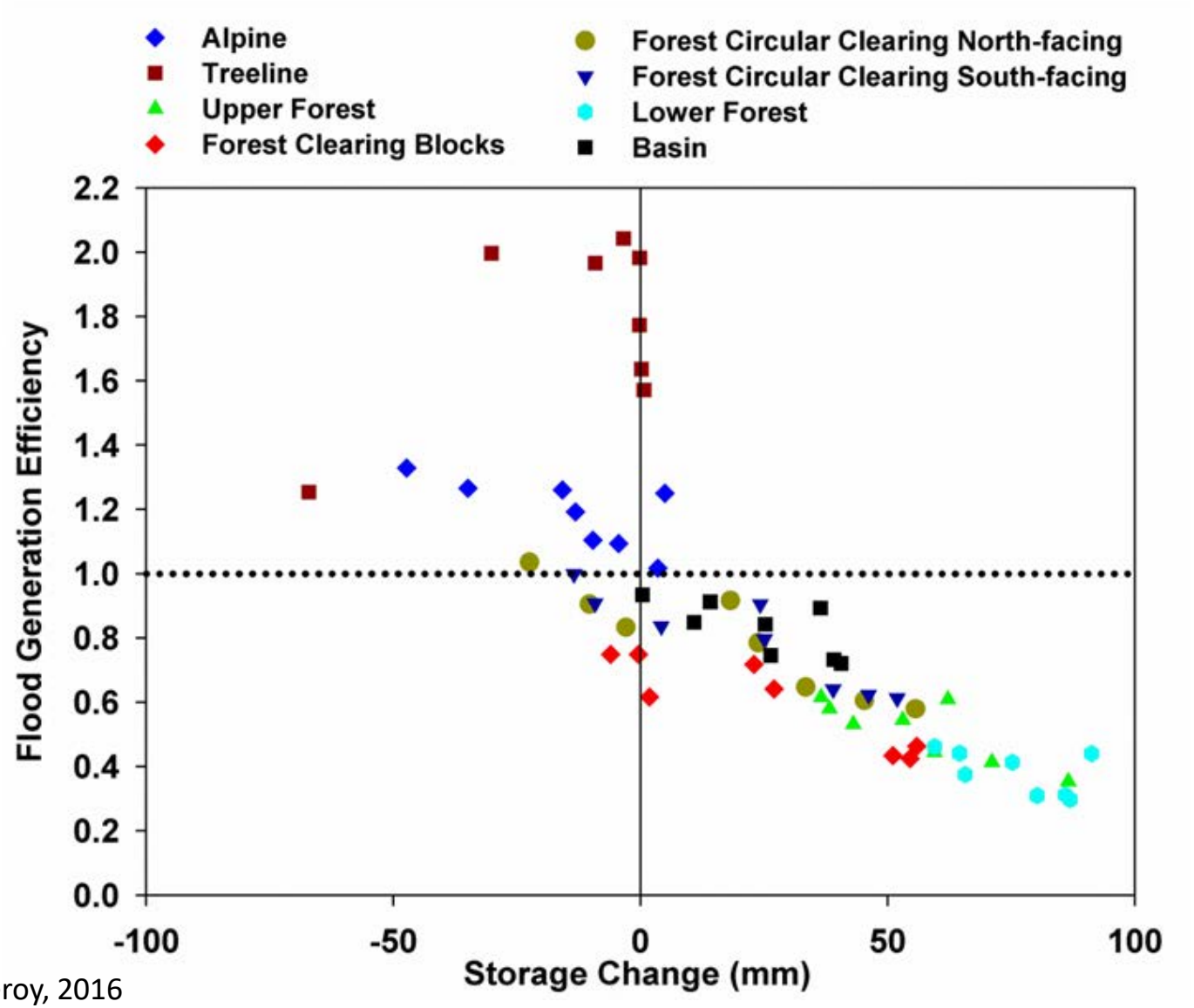
Mountain Hydrology in the Cold Regions Hydrological Model (CRHM)



Rain-on-Snow Processes

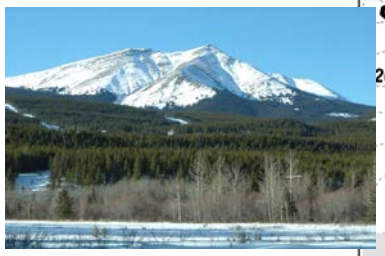


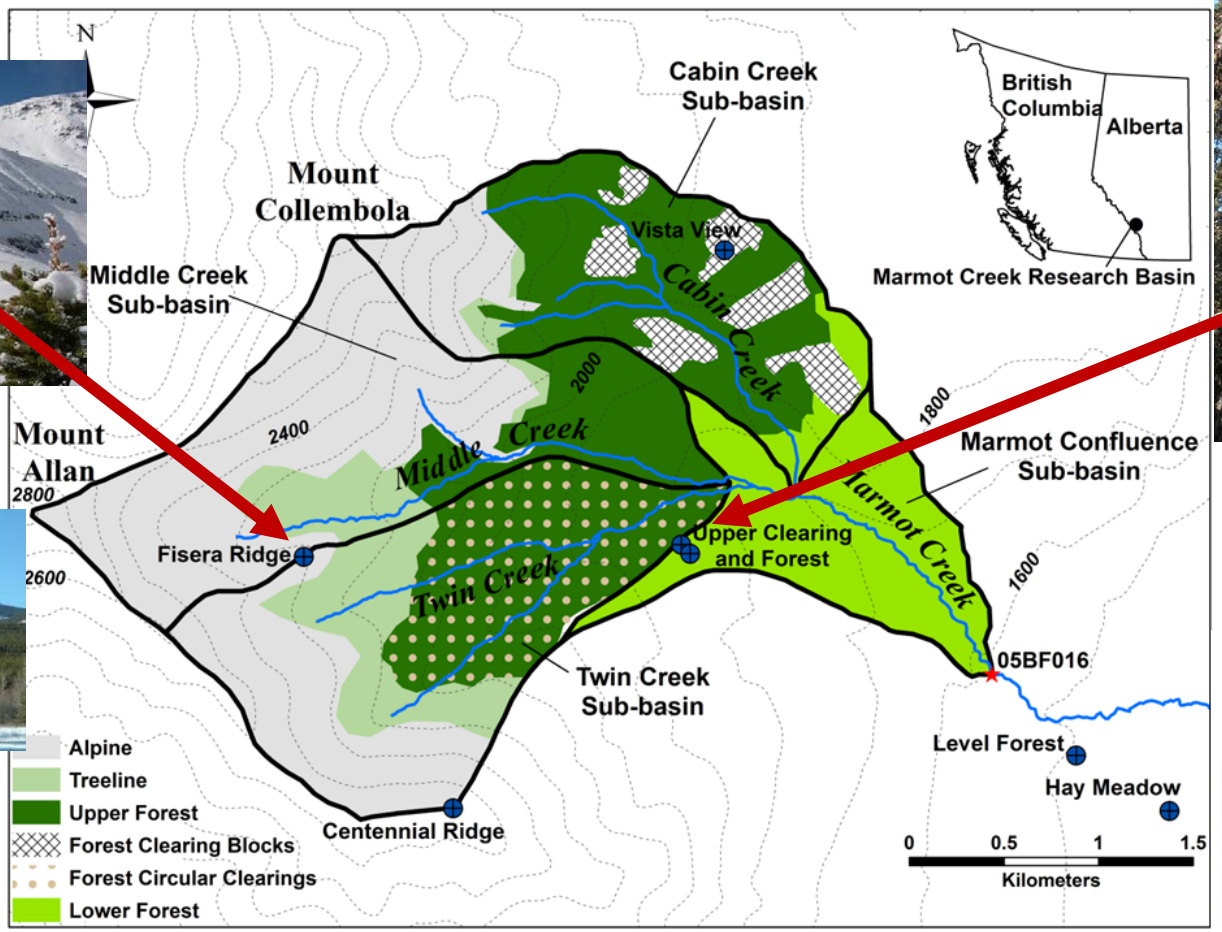
Sub-surface Moisture Storage Dynamics Control Flood Generation in Marmot Creek



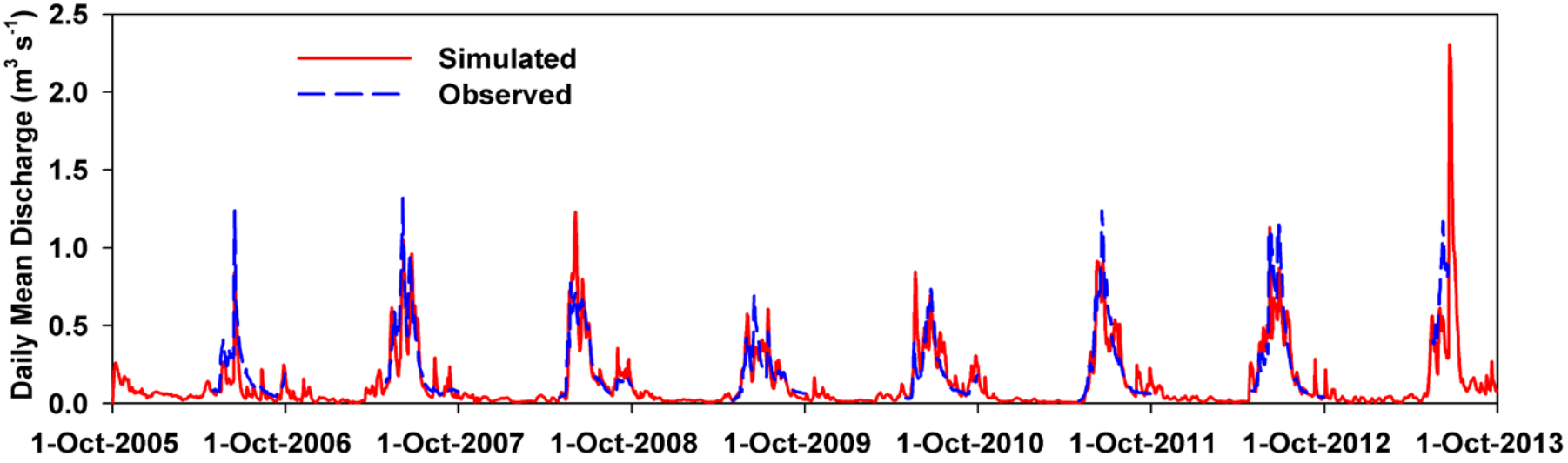
Fang and Pomeroy, 2016

Marmot Creek Research Basin, Canadian Rockies





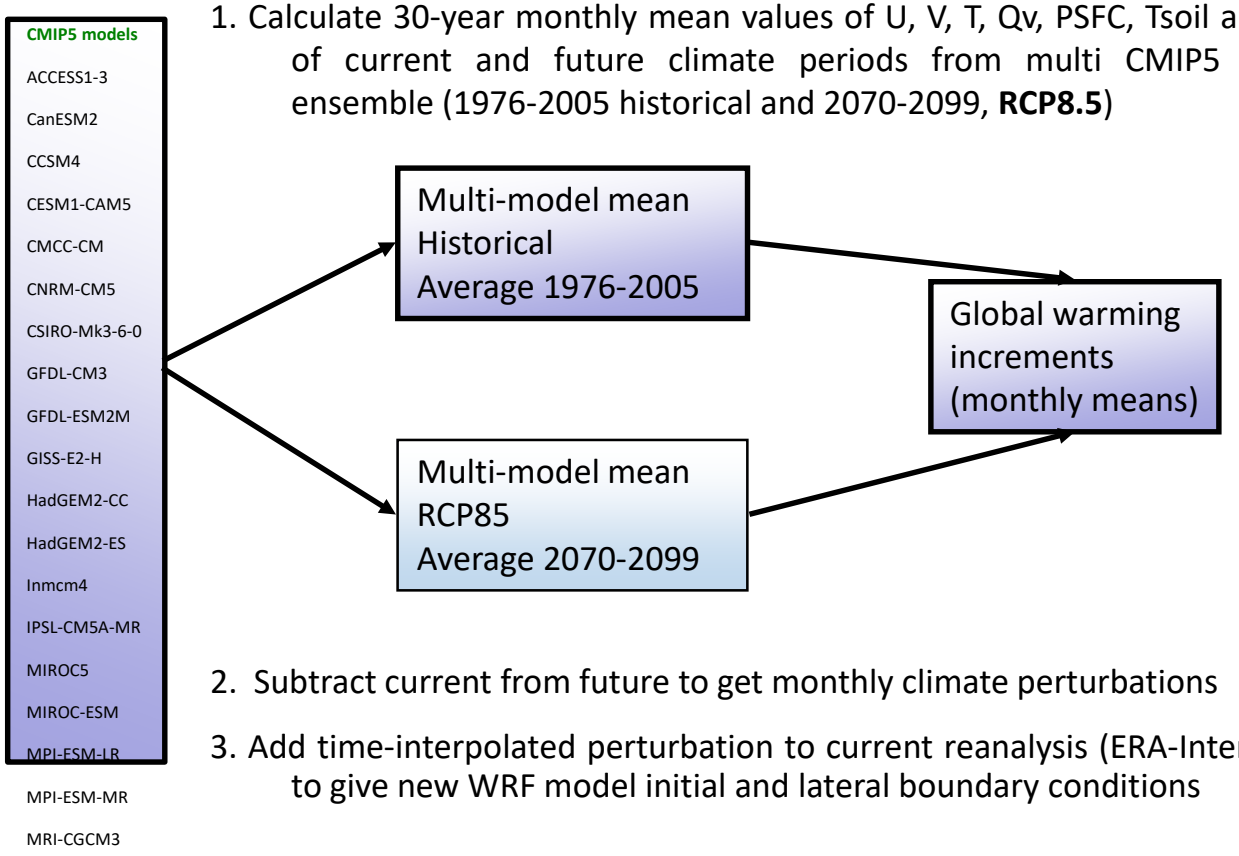
CRHM Simulation of Streamflow



	NSE	RMSD	NRMSD	MB
2006	0.63	0.117	0.60	-0.39
2007	0.77	0.141	0.47	-0.09
2008	0.63	0.134	0.50	0.11
2009	0.61	0.093	0.47	-0.01
2010	0.50	0.131	0.64	0.22
2011	0.77	0.136	0.48	-0.02
2012	0.75	0.164	0.52	-0.08
All seasons	0.71	0.133	0.52	-0.03

No calibration of parameters

Pseudo-Global-Warming 2070-2099



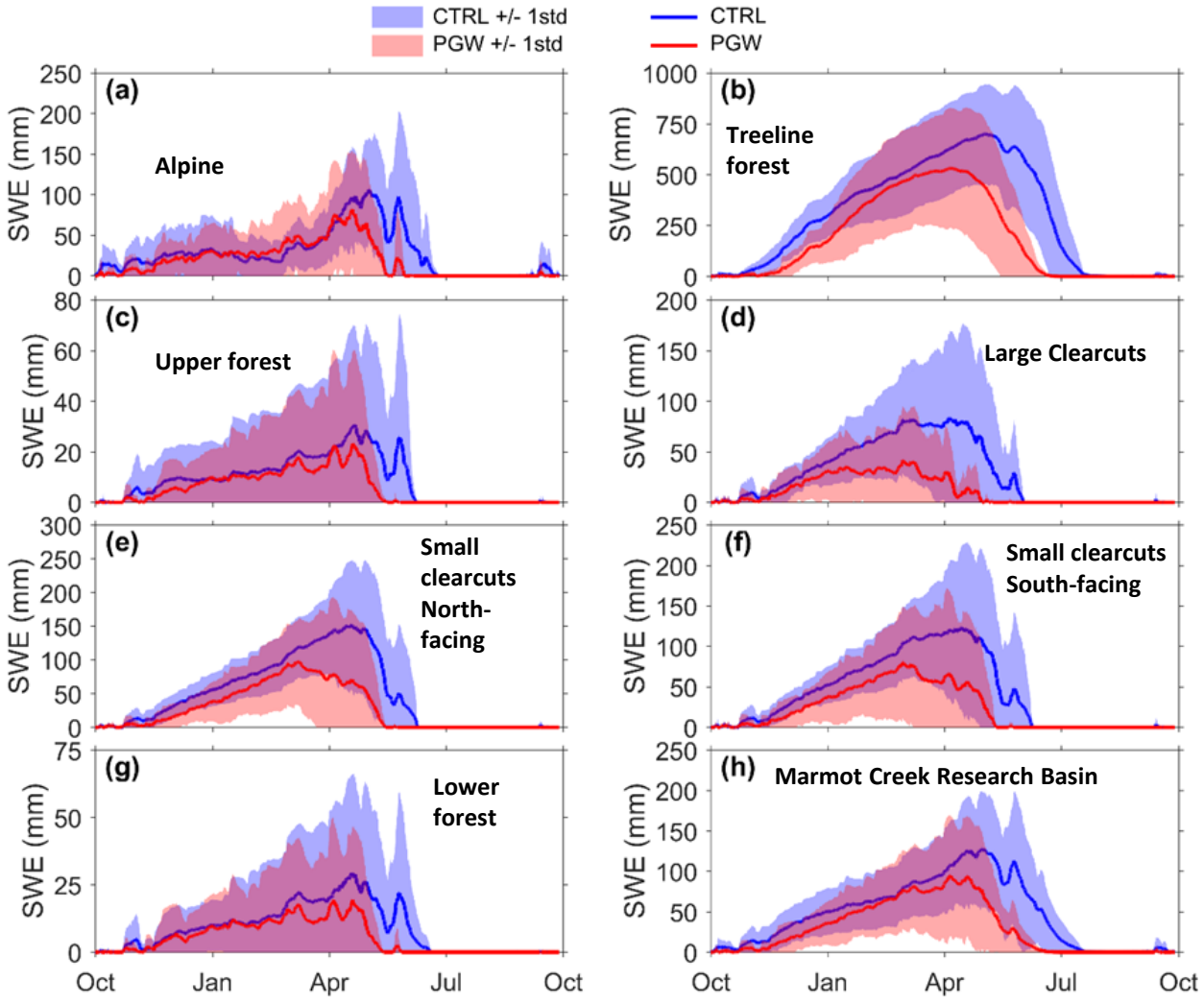
1. Calculate 30-year monthly mean values of U, V, T, Qv, PSFC, Tsoil and SST of current and future climate periods from multi CMIP5 model ensemble (1976-2005 historical and 2070-2099, **RCP8.5**)

2. Subtract current from future to get monthly climate perturbations

3. Add time-interpolated perturbation to current reanalysis (ERA-Interim, 6-hourly) to give new WRF model initial and lateral boundary conditions

Future Marmot Creek Snowpack - less snow, earlier melt

WRF at 4 km bias corrected Pseudo Global Warming

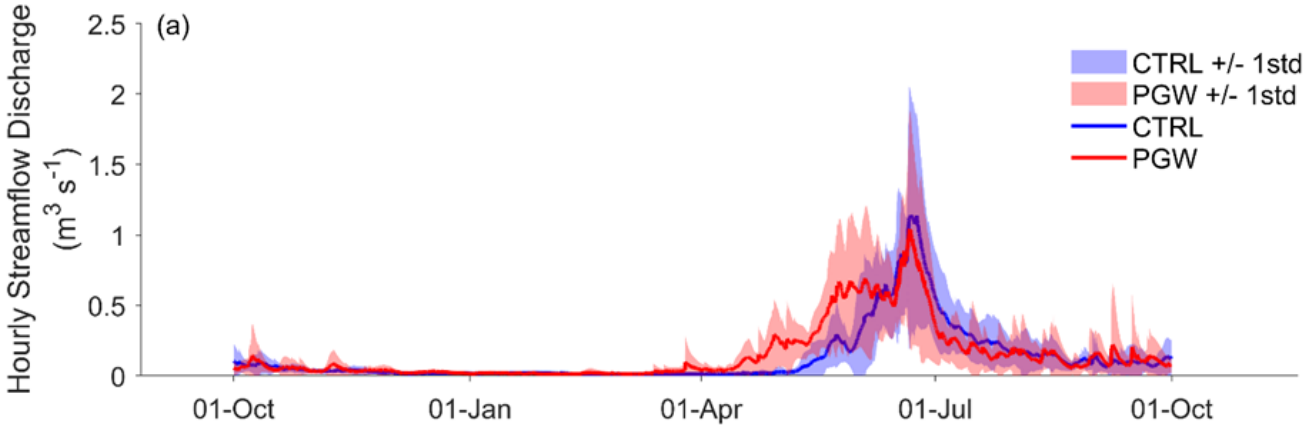


+4.7 °C Temp.
+16% Precip.

-84 mm snowmelt volume

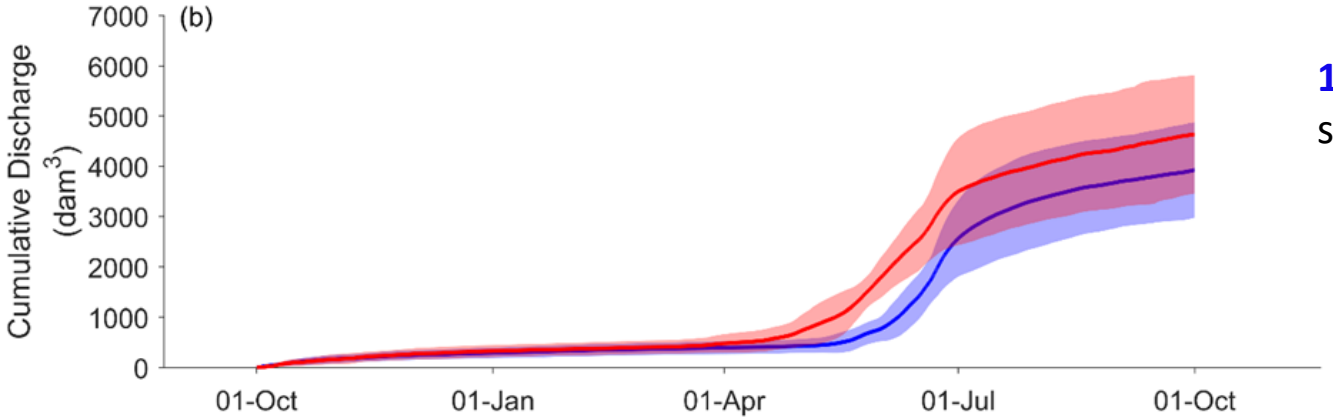
Fang and Pomeroy, 2020

Future Marmot Creek Streamflow –
greater, earlier discharge



+45 day advance in spring freshet

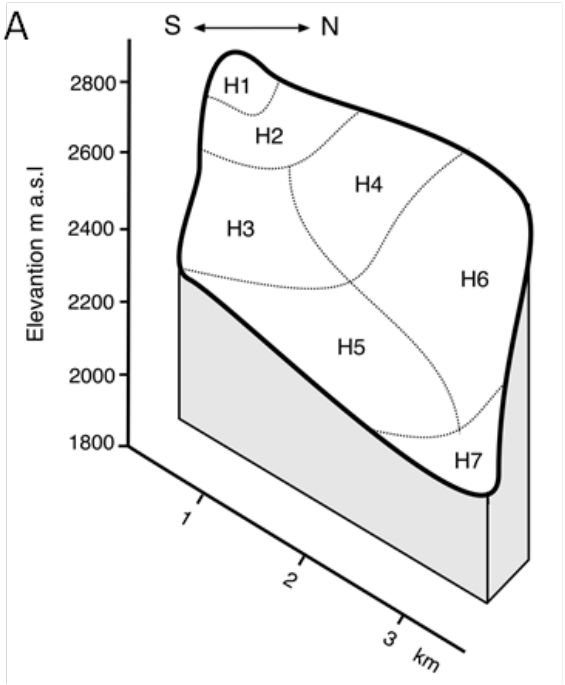
+4.7 °C Temp.
+16% Precip.

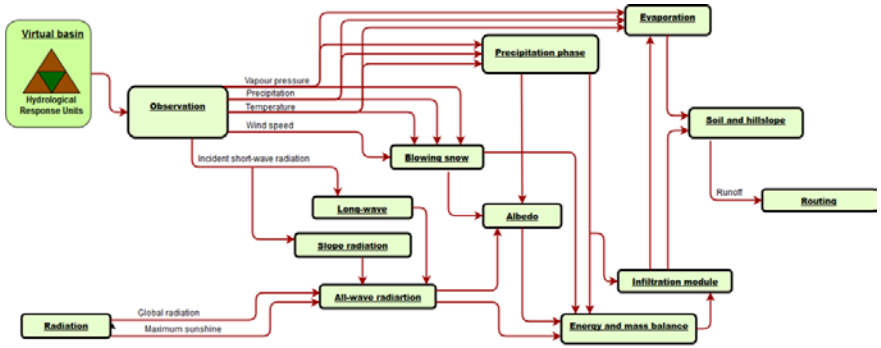


18% increase in streamflow discharge

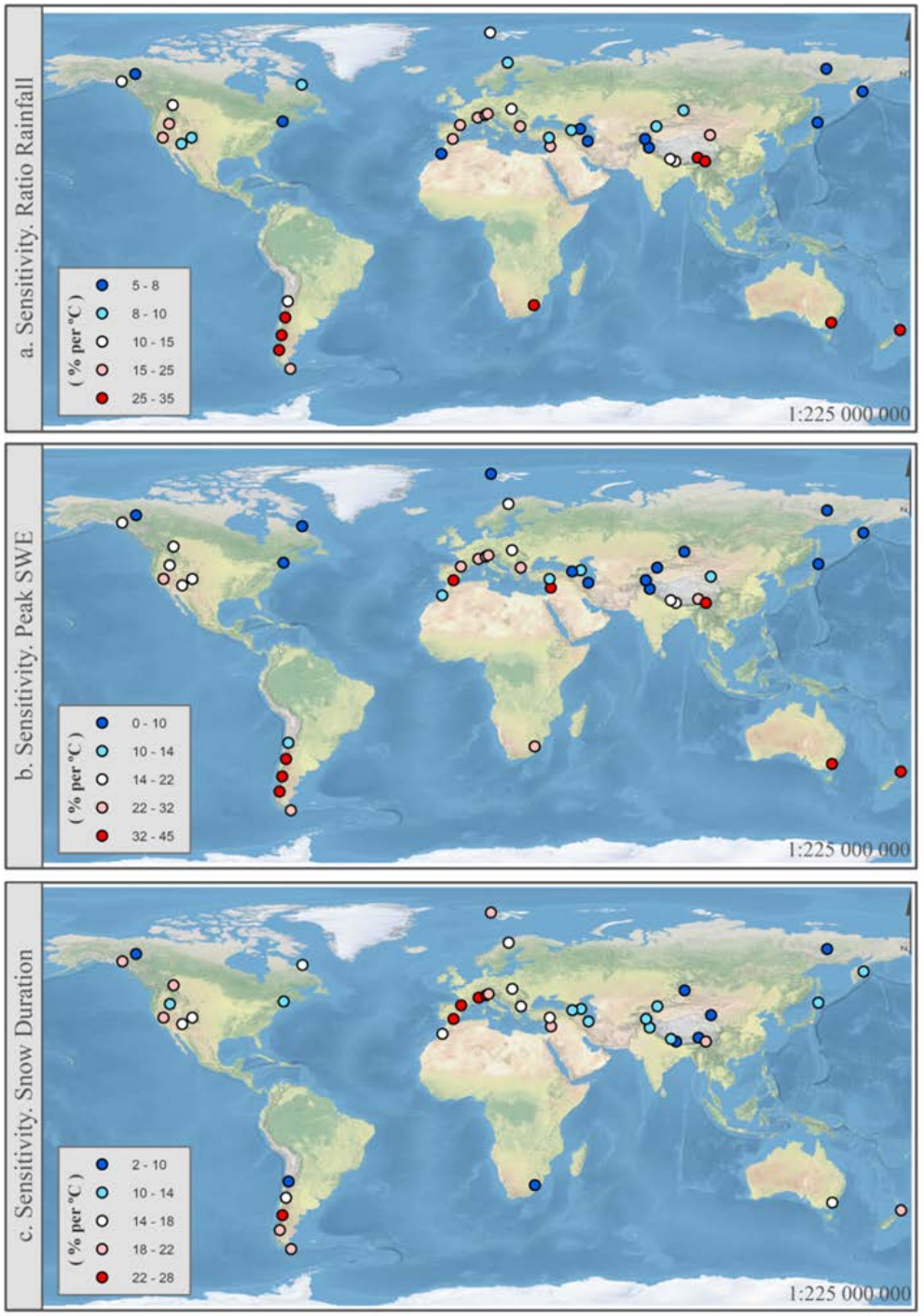
Fang and Pomeroy, 2020

Virtual Basin CRHM for Alpine Hydrology Climate Sensitivity Assessment



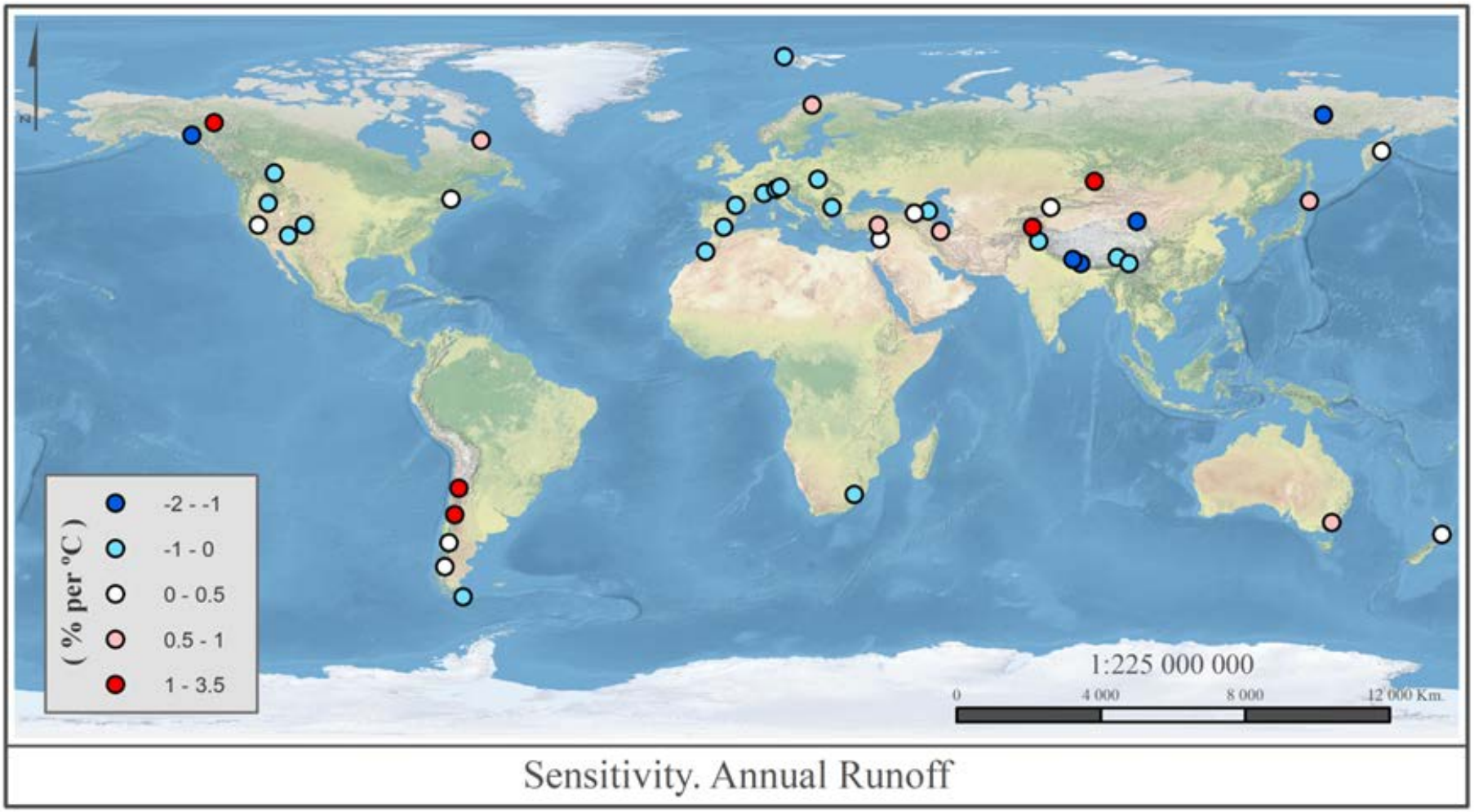


Lopez Moreno et al., 2020 ERL



Virtual Basin CRHM for Alpine Hydrology Climate Sensitivity Assessment

-hydrological sensitivity is lower than snowpack sensitivity to warming

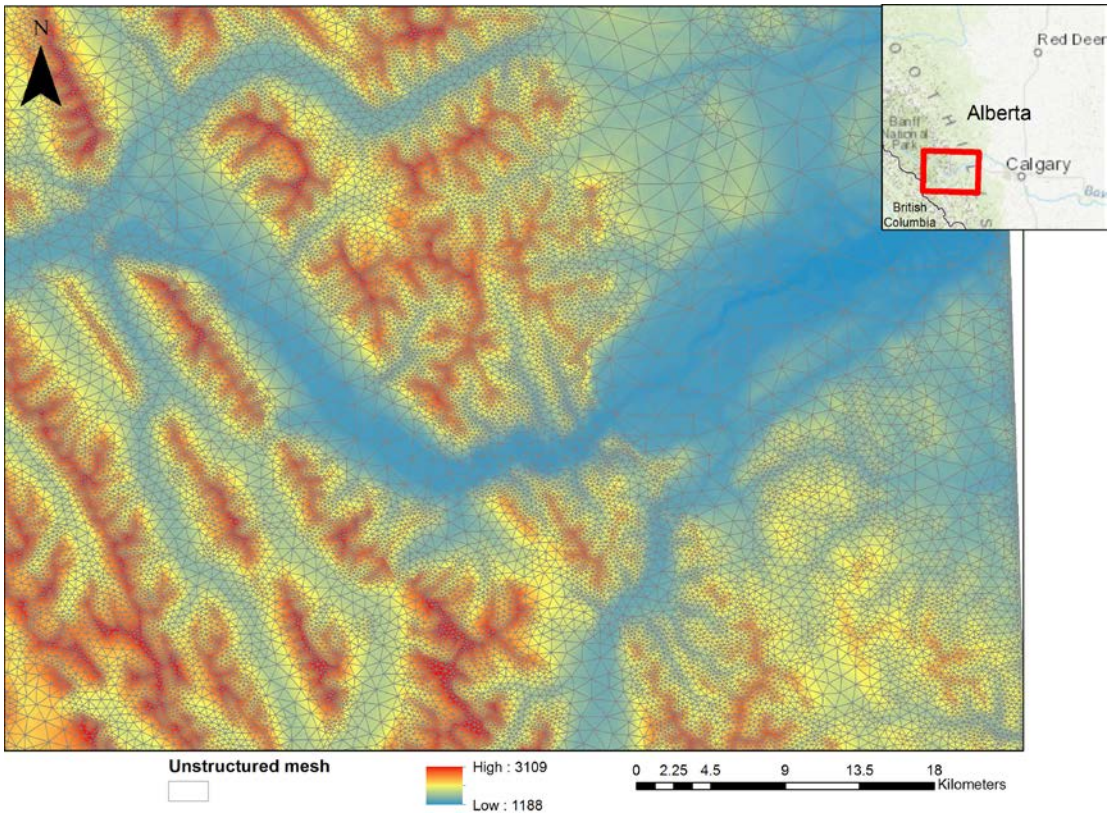


Sensitivity. Annual Runoff

Lopez Moreno et al., 2020 ERL

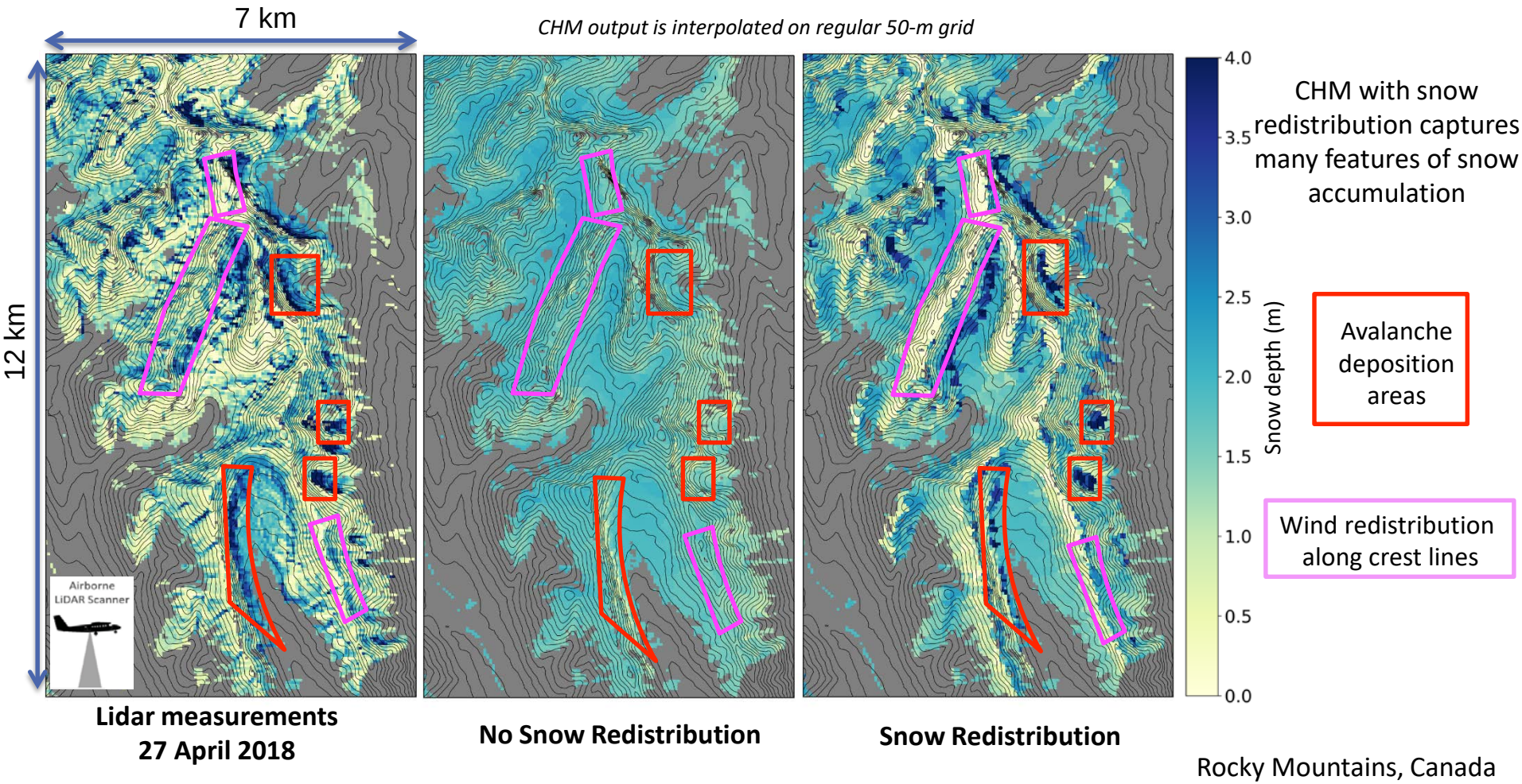
Canadian Hydrological Model (CHM)

- **Variable resolution triangular mesh depending on topography, soils, vegetation**
- **Large decrease in computational and data demands over rectangular gridded models**
- CHM includes algorithms for downscaling meteorological data from stations and weather models.
- CHM currently accounts for:
  - **slope** and **aspect**; terrain **shading**
  - **gravitational redistribution**
  - **blowing snow (**redistribution + sublimation**)**
  - **snow/canopy interactions**
  - **energy balance** snowmelt
- **Globally applicable using existing datasets**



Marsh et al. (2020)

Influence of snow redistribution in high mountains

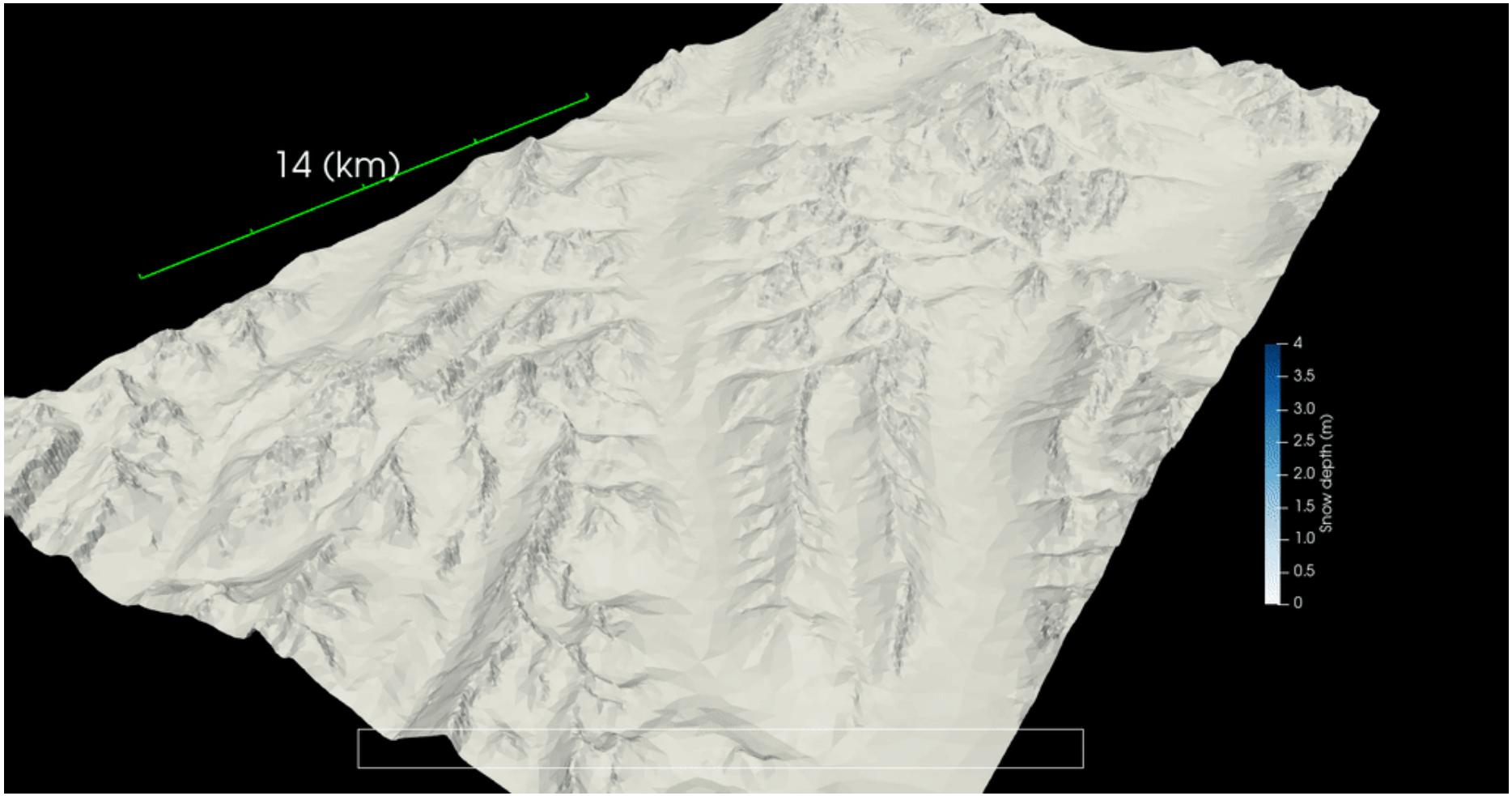


Vionnet et al., 2020

GLOBAL WATER FUTURES
SOLUTIONS TO WATER THREATS IN AN ERA OF GLOBAL CHANGE

GEM-Canadian Hydrological Model - Snow Forecast in the Canadian Rockies

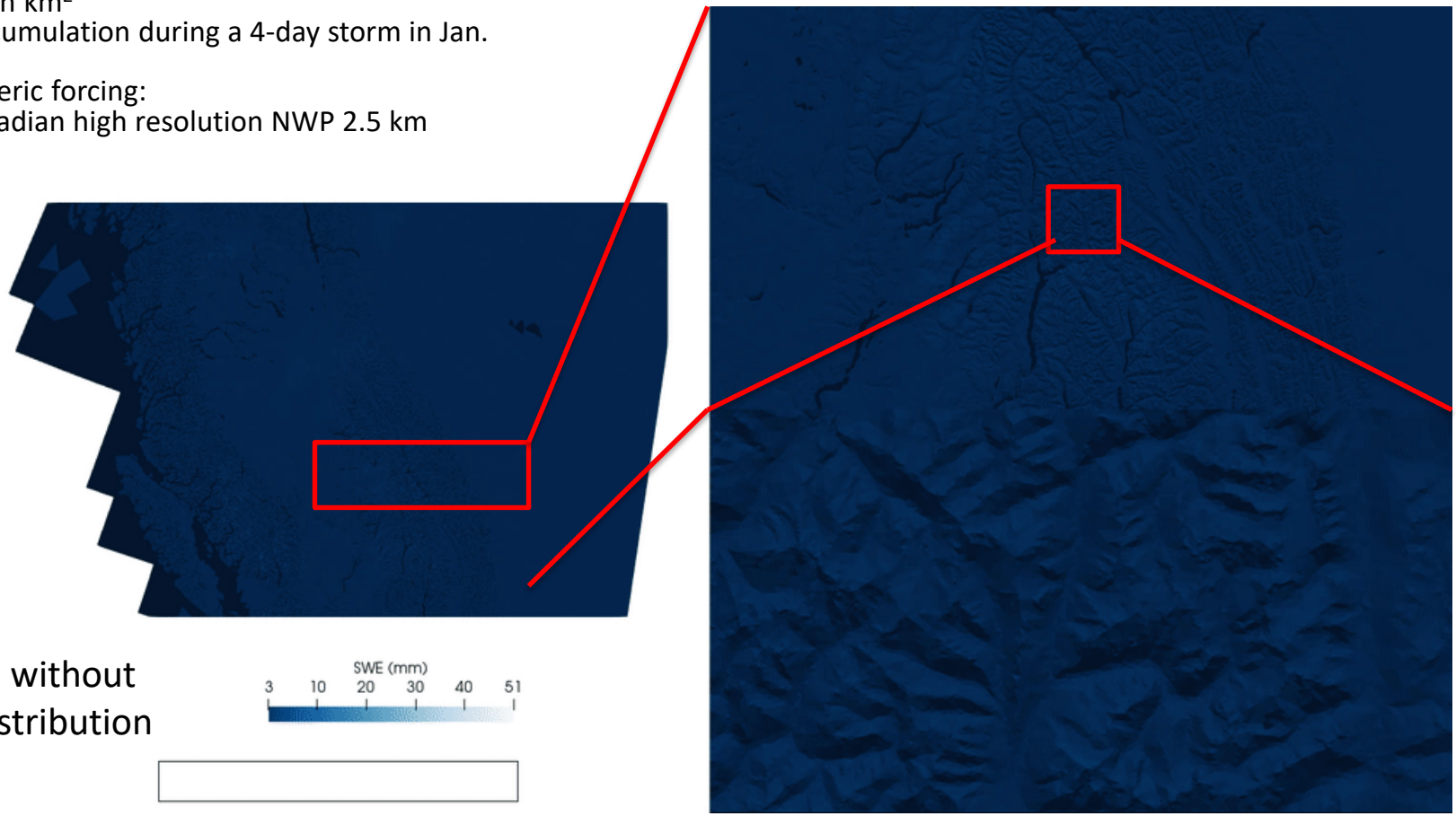
www.snowcast.ca



C Marsh

CHM over Western Canada

- Snowdrift resolving scales near ridges
- 1.3 million km^2
- Snow accumulation during a 4-day storm in Jan. 2018
- Atmospheric forcing:
  - Canadian high resolution NWP 2.5 km



Simulation without snow redistribution

Marsh 2020

Concluding Thoughts

- Snow hydrology provides water for much of the world and is greatly threatened by climate warming
- Snow processes control hydrology
  - Blowing snow – redistribution and sublimation
  - Canopy snow interception and sublimation
  - Snowmelt – energetics control on slopes
  - Flow through snow and flow along and beneath hillslopes
- Coupled mass and energy fluxes and states mean that snow hydrology can be/should be predicted using physical principles
  - Regularity of snowmelt and large storage signals mean that it is amenable to physics based snow hydrology predictive approaches
- Climate warming causing
  - less snow redistribution,
  - less sublimation loss,
  - earlier snowmelt,
  - changes in melt rates,
  - decoupling of mountain streamflow hydrographs from the snow regime
  - Mountain hydrology is becoming more influenced by rainfall-runoff and is becoming less reliable.

www.usask.ca/hydrology

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Just a few of them named here!