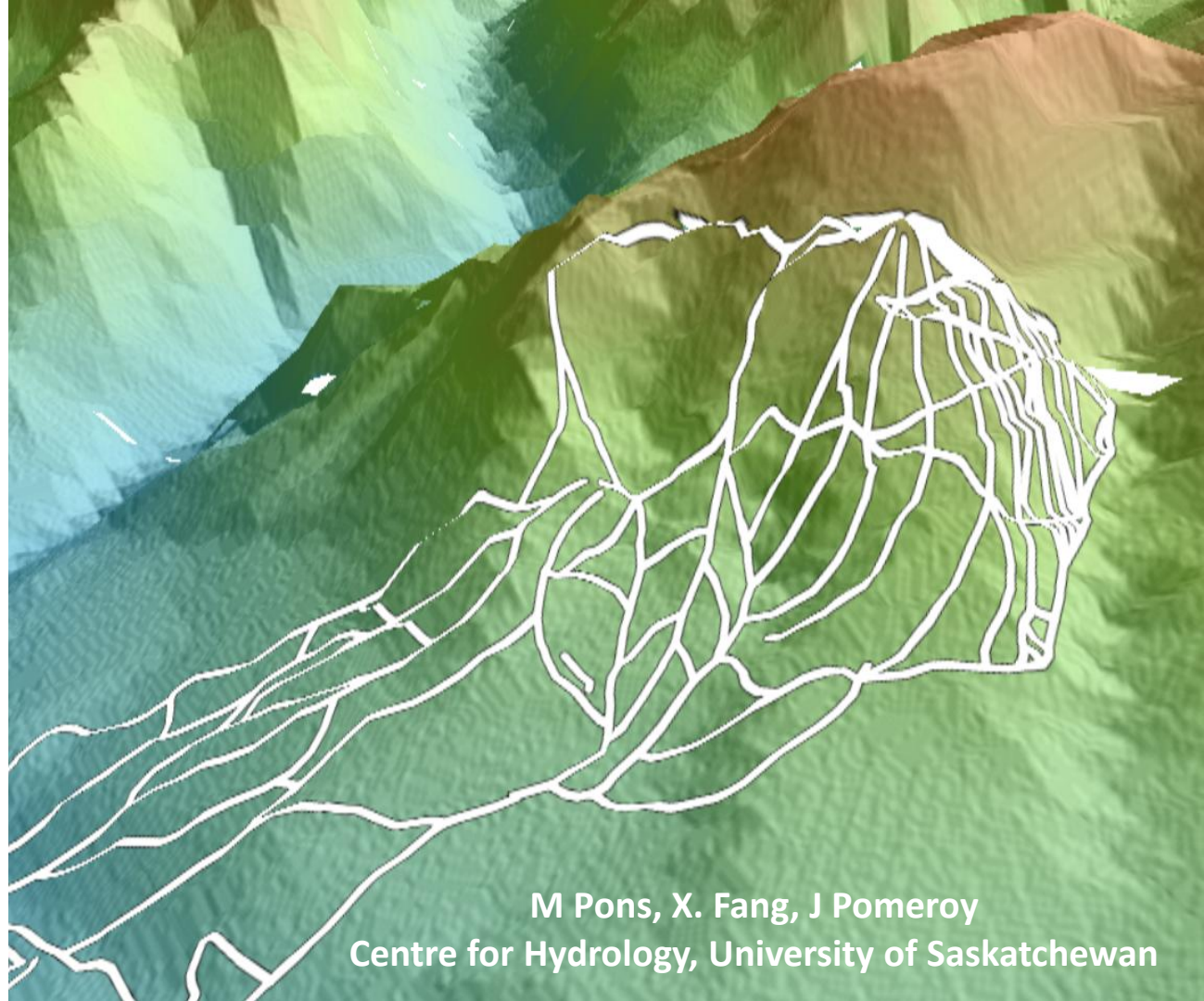


Simulating natural and managed snow and future climate sensitivity at Nakiska Ski Area, Kananaskis Valley



1. Why model snow dynamics in ski areas?



Significant socioeconomic consequences from climate change



Different snowpack behaviour from a natural snowpack

1. Why model snow dynamics in ski areas?



Snowmaking and grooming highly impact the energy balance of the ski run snowpack

RESEARCH ARTICLE

Sensitivity of Snow at Western US Ski Resorts to Climate Change

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Keywords: climate change | ski resorts | snow | western US

ABSTRACT

The sensitivity of winter recreation to climate change, especially to warming, is widely recognized but few studies report quantitatively on the observed effects of climate change on ski resorts, in part because consistent and available data directly from ski resorts is scarce. Augmenting strictly modelling-based studies, we use both numerical modelling and observation-based estimates of sensitivity in snow depth (HS) and snow water equivalent (SWE) to temperature and precipitation using data from nearby SNOTEL (snow telemetry) and snow course sites for 40 ski resorts in Washington, Idaho, Oregon and California during the ski season. Multiple regression on climate variables then permits statistical projections of future snow depth from projected changes in temperature and precipitation with 20 future climate scenarios (10 global climate models and 2 emissions scenarios, RCP4.5 and RCP8.5). We also use projected future SWE from a hydrology model with climate

Snow

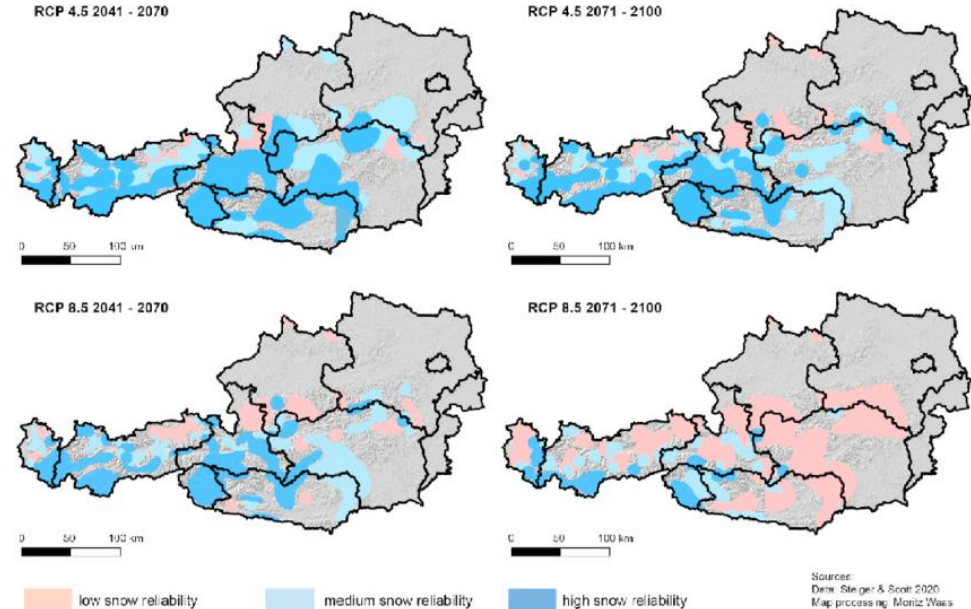
pack

2. Previous approaches

SkiSim – Degree day Snow Model + Snowmaking

*Scott et al. 2012, Steiger et al. 2018,
Knowles et al., 2024*

- Most used approach
- Includes Snowmaking
- No grooming
- Not forcing data intensive – needs observations
- Oversimplistic snowpack dynamics introduce uncertainty and reduce predictive power
- One single point for the full ski area
- Local calibration requires local meteorological observation and snowmelt data

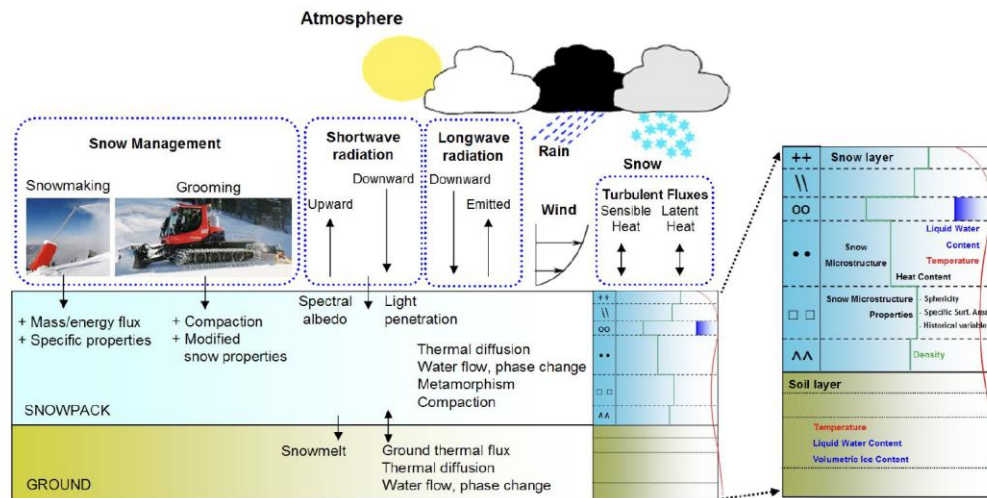


2. Previous approaches

CROCUS-Resort

Spandre et al., 2018

- Multi-layer snow physics model
- Includes snowmaking + grooming
- Numerical Weather Model-based input
- Interpolation to different aspects and elevations
- Forcing data, parameter and computationally intensive
- Requires high resolution forcing data, local parameters and high performance computing to apply

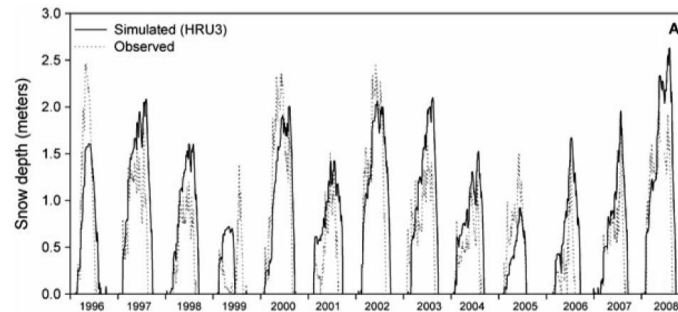
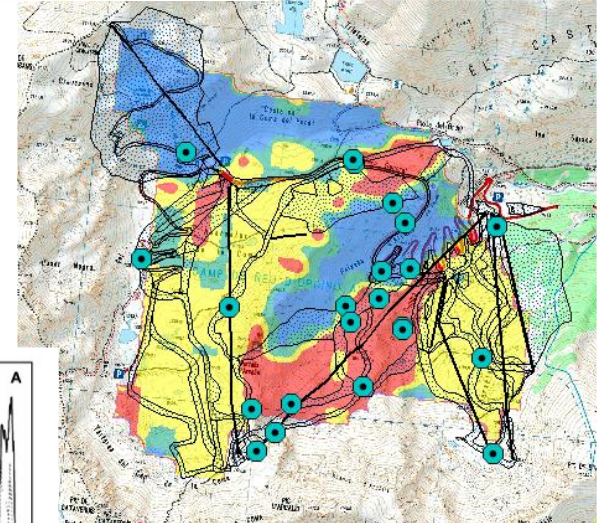
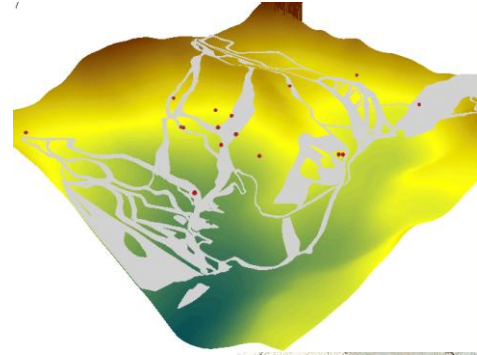


2. Previous approaches

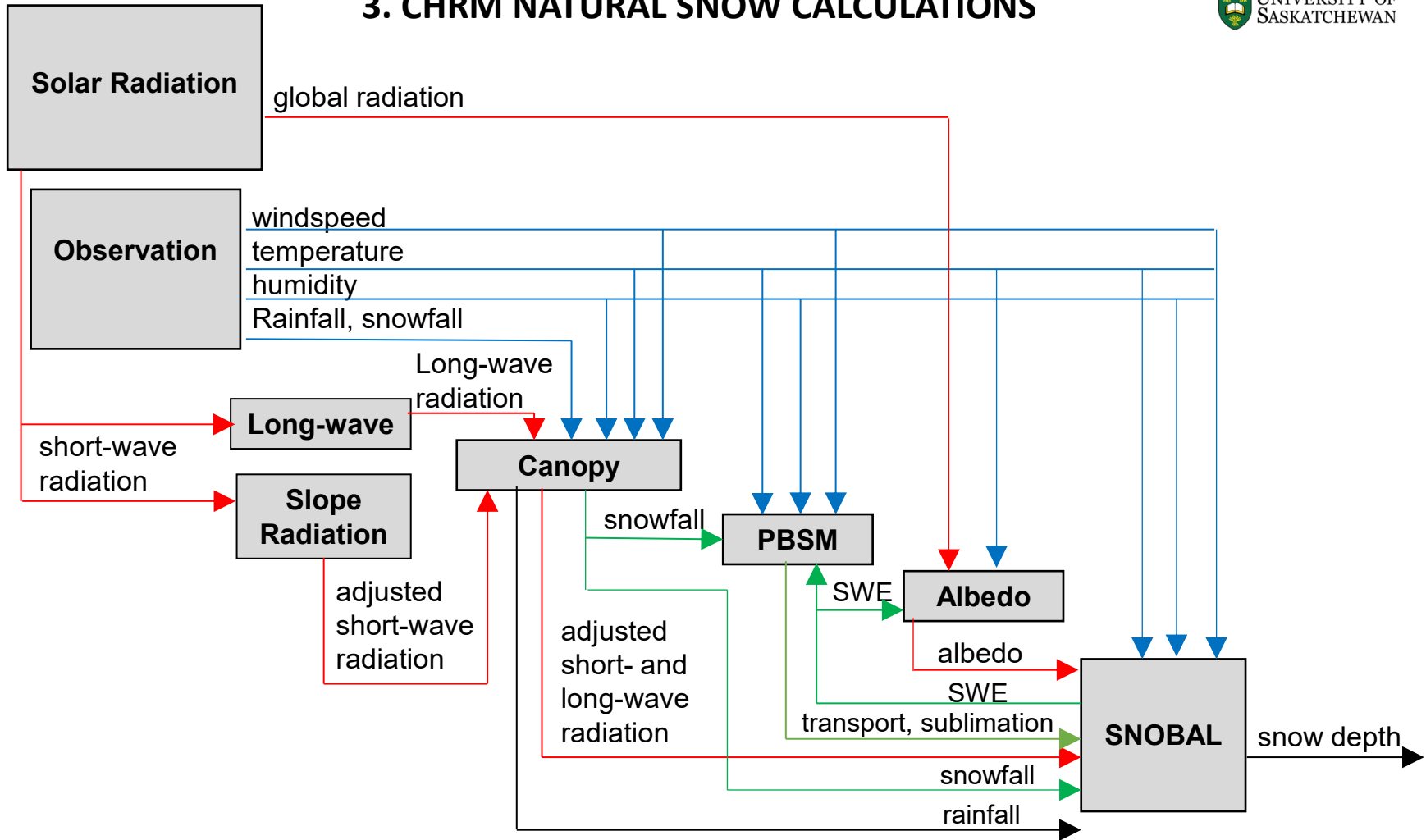
CHRM + External Snowmaking Module

Pons, López-Moreno et al., 2014

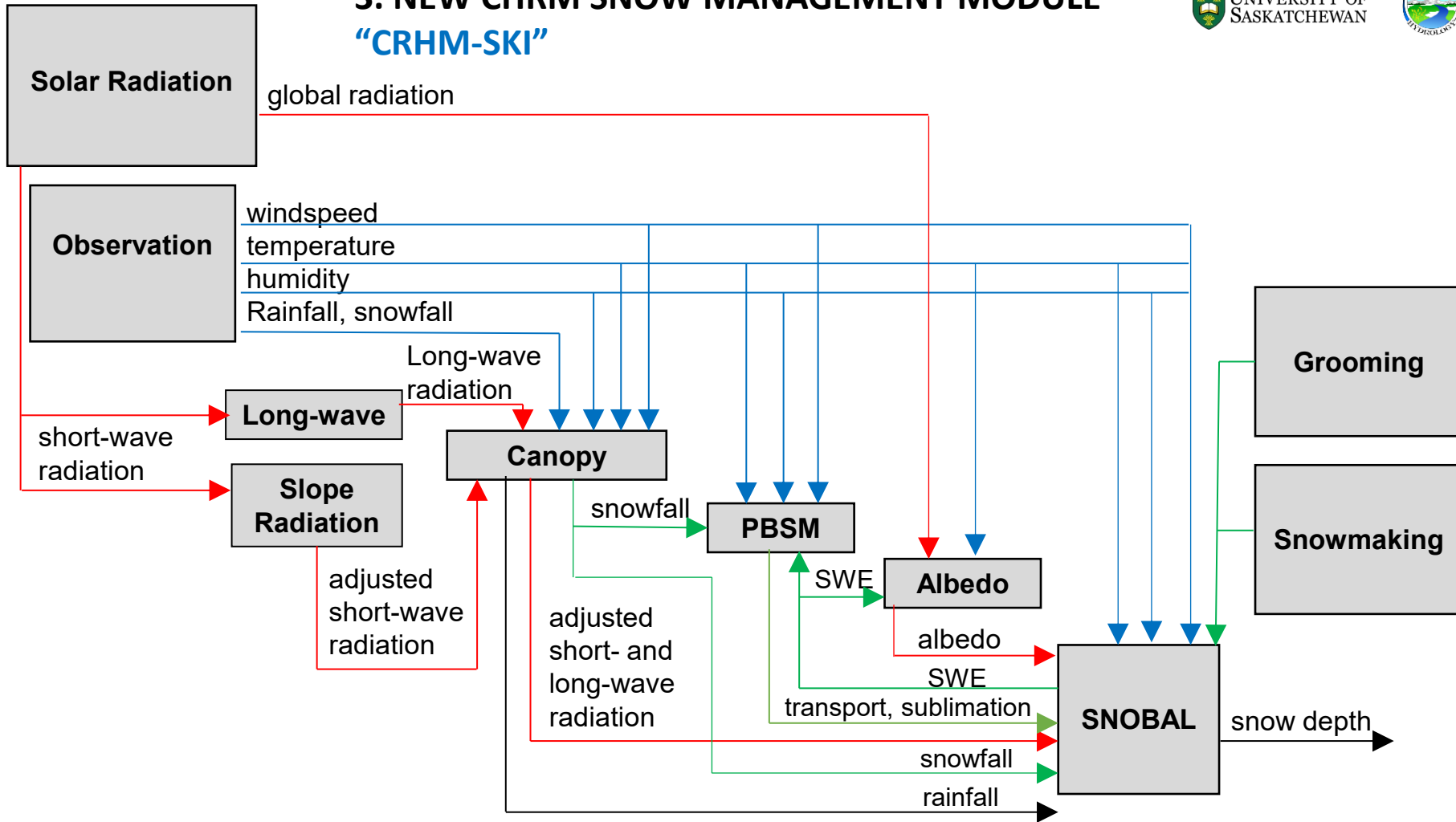
- Includes snowmaking / no grooming
- Observation-based input
- One way forcing – uncoupled approach
- Interpolation different aspects and elevations
- Easy to apply



3. CHRM NATURAL SNOW CALCULATIONS



3. NEW CHRM SNOW MANAGEMENT MODULE "CRHM-SKI"



3. CHRM-SKI

SNOWMAKING PRODUCTION

Season: October 1 – April 15

Activation Conditions:

- Air temperature $T_w < -2^{\circ}\text{C}$
- Available snow depth $z_s < 0.6\text{ m}$
(target threshold)

TechnoAlpin Production Rates:

- $T_w < -6.0^{\circ}\text{C} \rightarrow 0.050\text{ m/h (max)}$
- $-6.0 < T_w \leq -4.0^{\circ}\text{C} \rightarrow 0.035\text{ m/h}$
- $-4.0 < T_w \leq -2.5^{\circ}\text{C} \rightarrow 0.020\text{ m/h}$
- $-2.5 < T_w \leq -2.0^{\circ}\text{C} \rightarrow 0.005\text{ m/h}$

Snow Properties:

- Initial density: 450 kg/m^3
- Added to bare ground or existing snowpack layers



GROOMING COMPACTION

Season: October 1 – April 15

Daily: Hour 20:00 (once per day)

Activation Conditions:

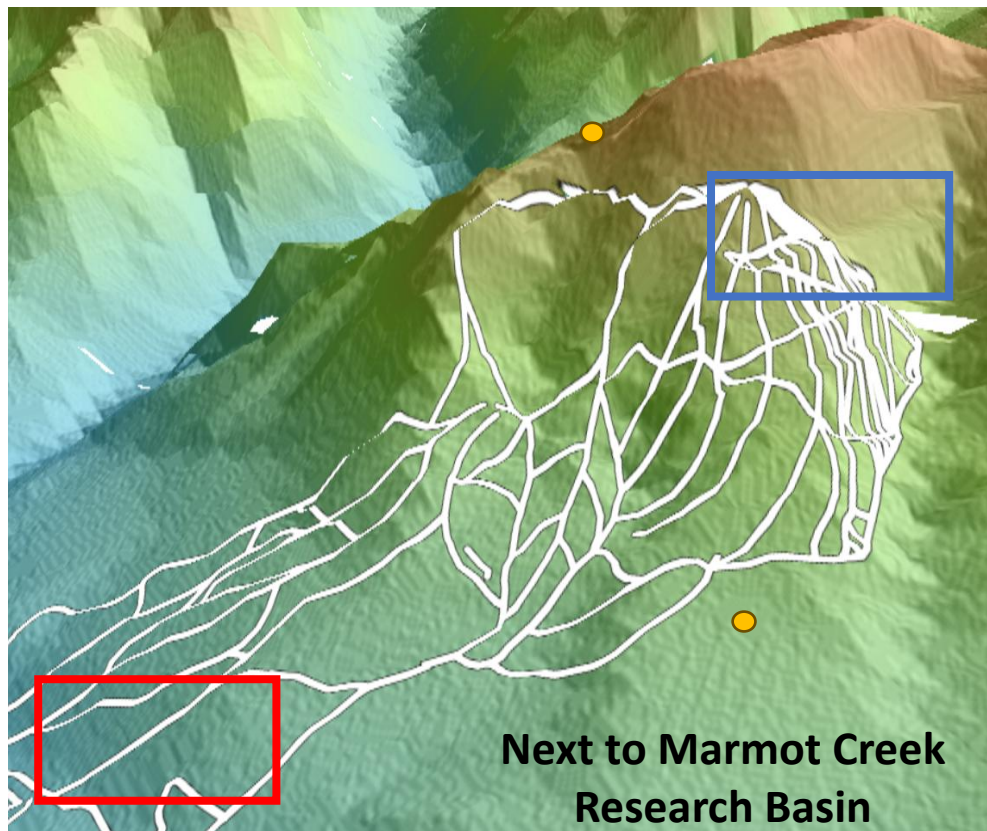
- Snow cover present
- Snow density $\rho < 450\text{ kg/m}^3$
(below target)

Compaction Mechanism:

- Increases density gradually
- Target density: 450 kg/m^3
(based on snow profile obs)



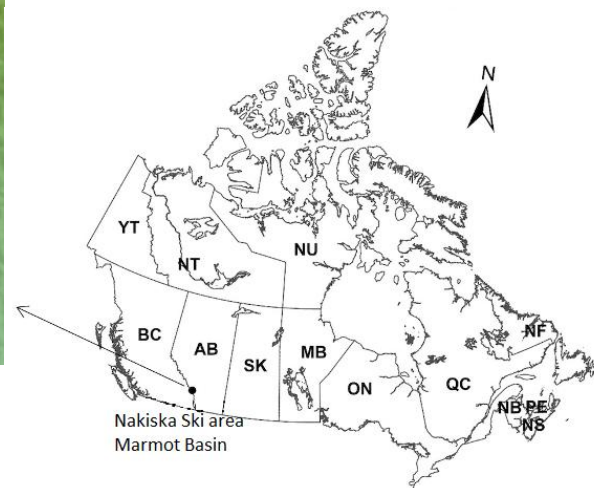
3. NEW CHRM SNOW MANAGEMENT IN NAKISKA SKI AREA



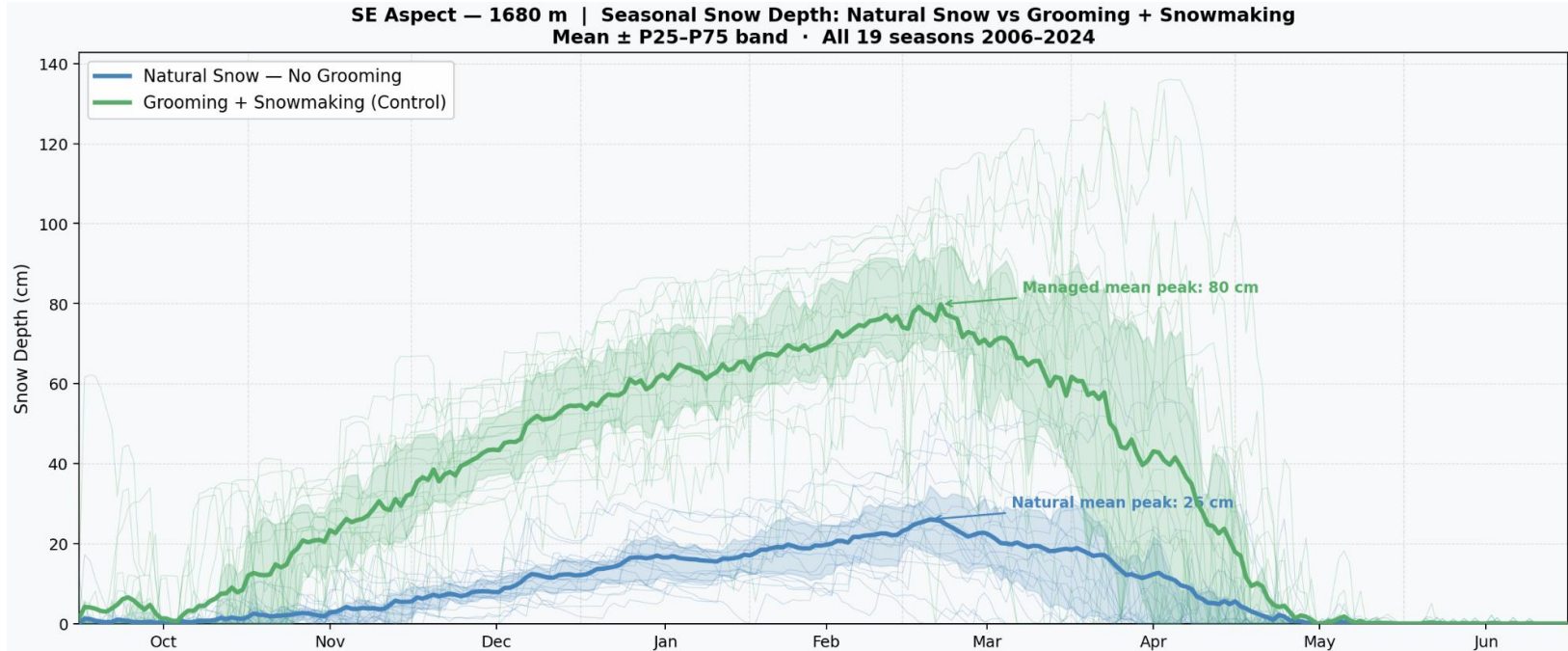
SE 1680m
Gap between forest

**Next to Marmot Creek
Research Basin**

NE 2190m
Open Terrain

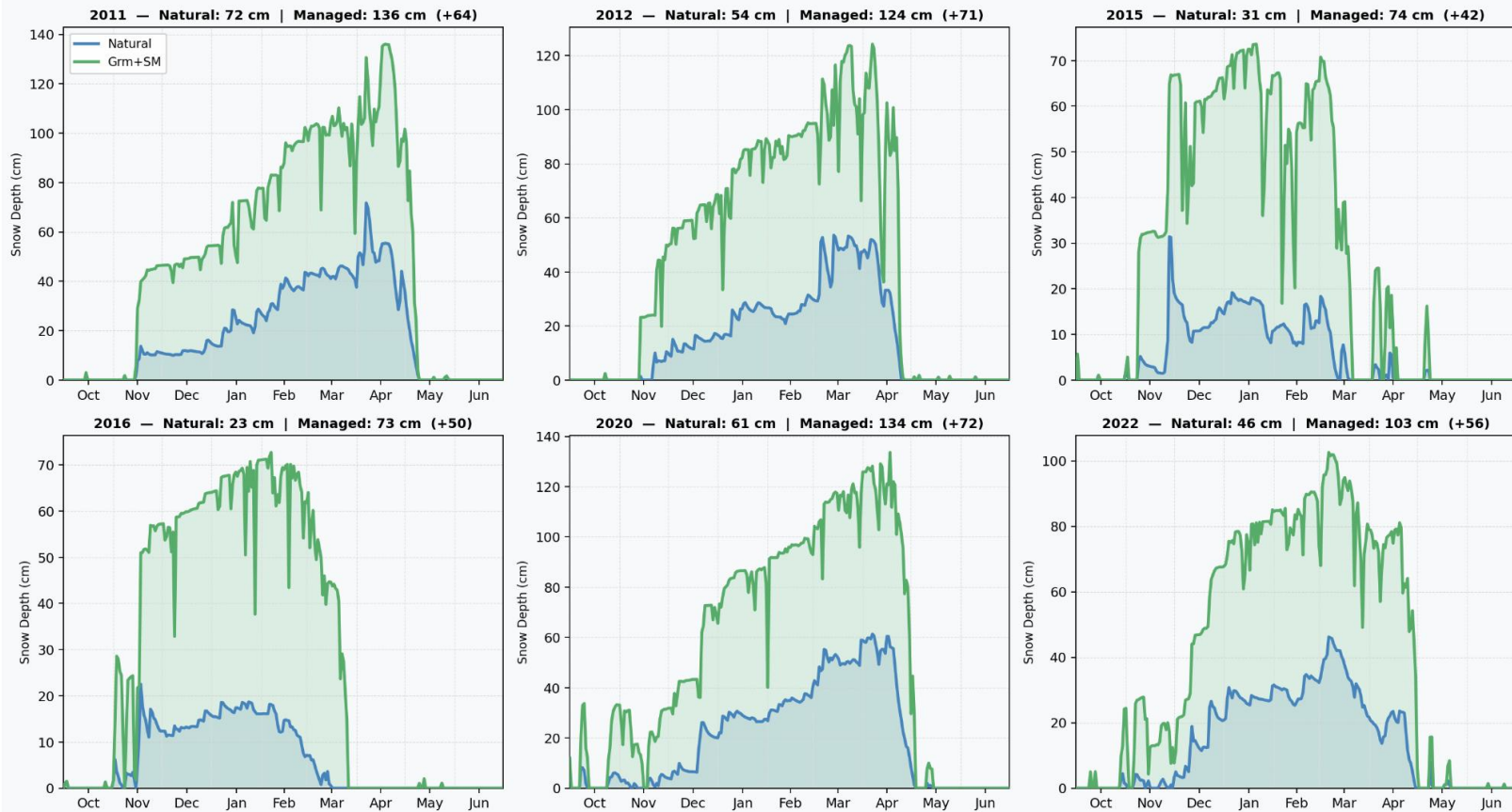


CRHM – Natural Snow vs Managed Snow



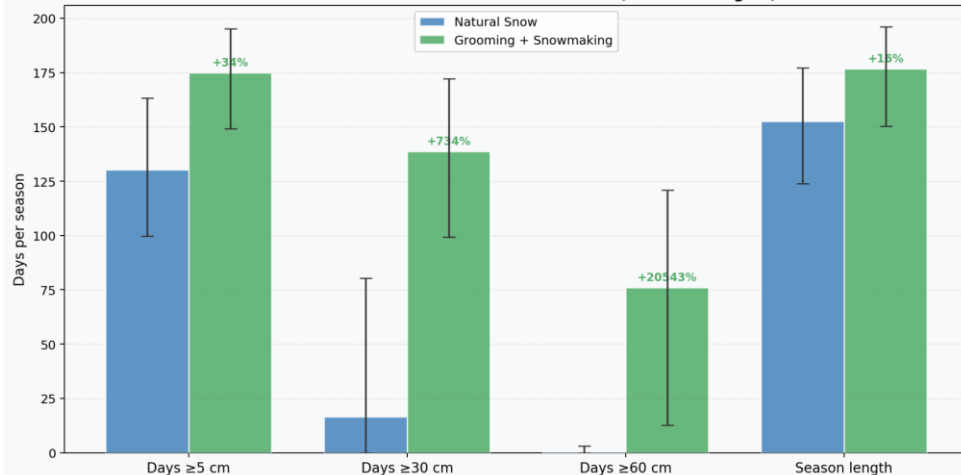
CRHM – Natural Snow vs Managed Snow

SE Aspect – 1680 m | Selected Seasons: Natural Snow vs Grooming + Snowmaking

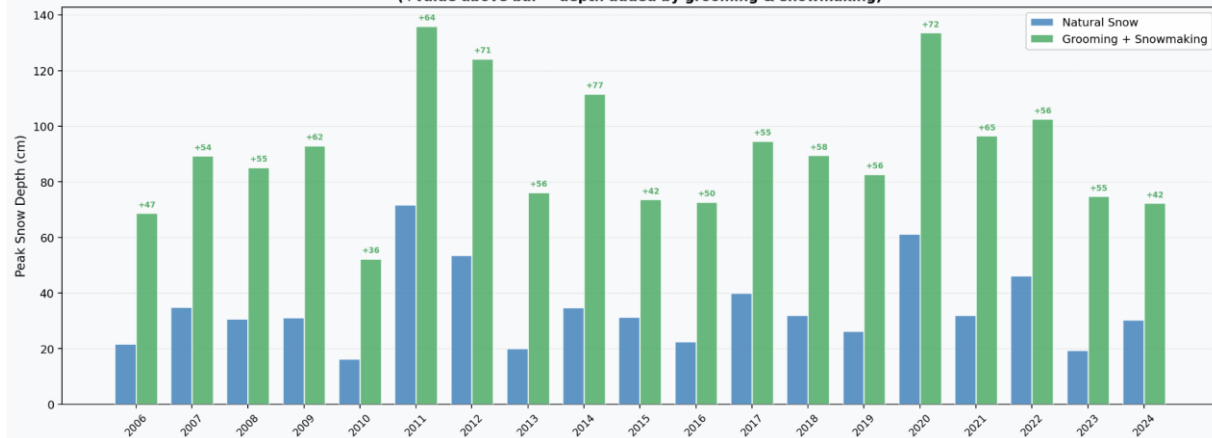


CRHM – Natural Snow vs Managed Snow

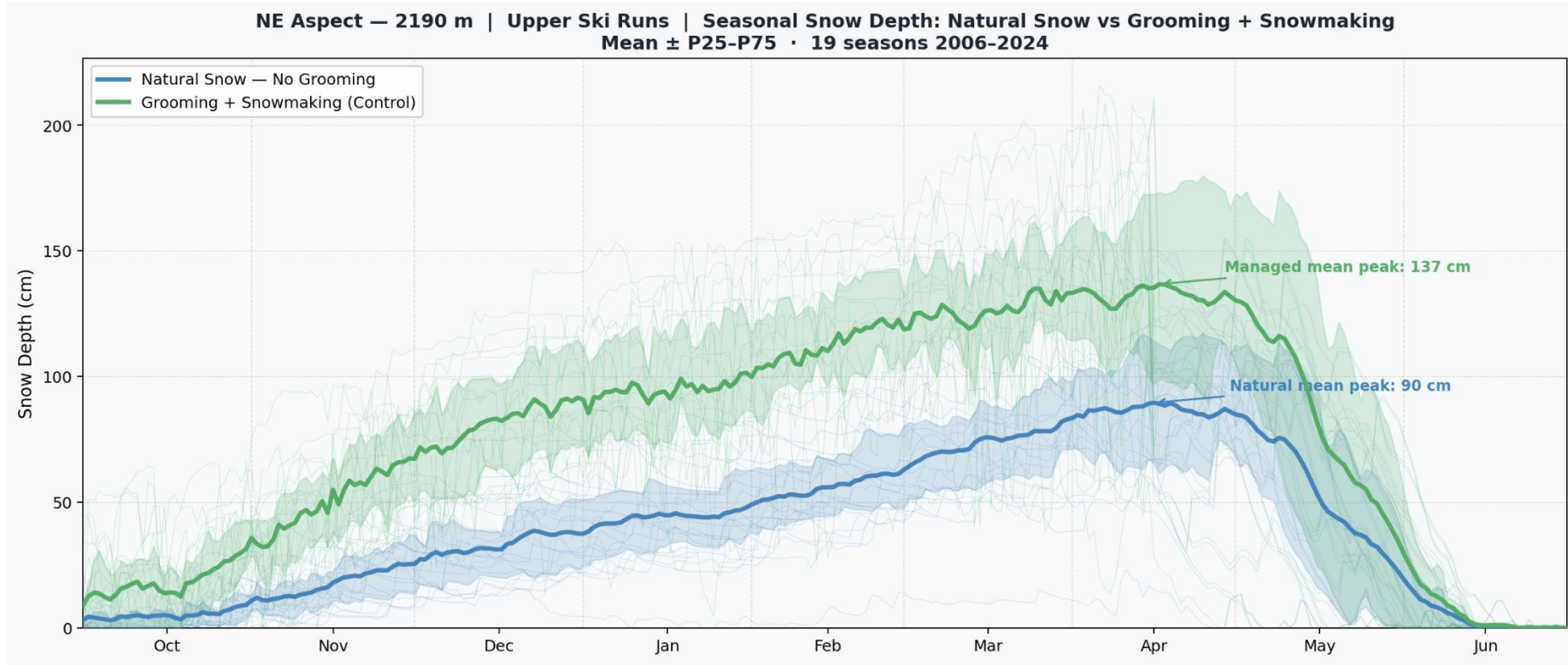
SE Aspect – 1680 m | Season Metrics: Natural Snow vs Grooming + Snowmaking
Mean $\pm$ P5-P95 error bars · 19 seasons · (% = relative gain)



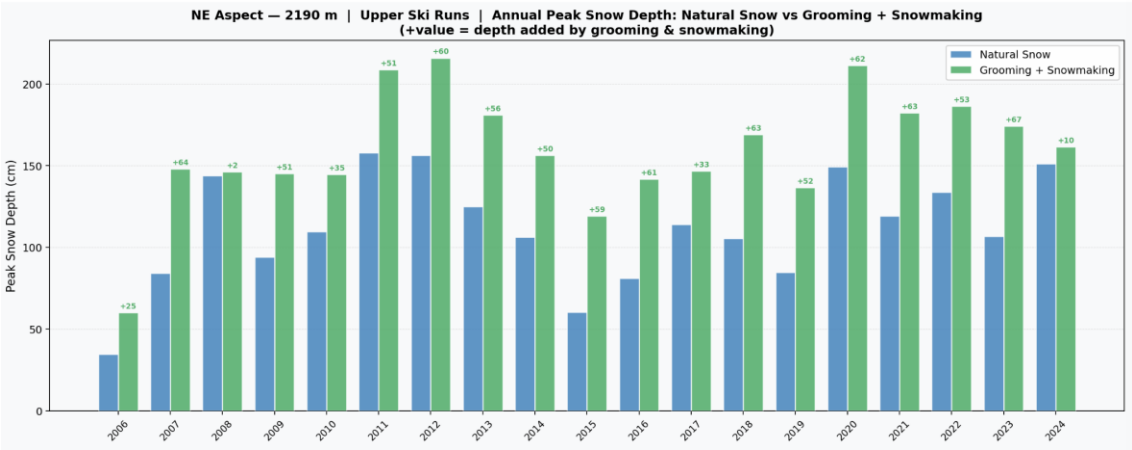
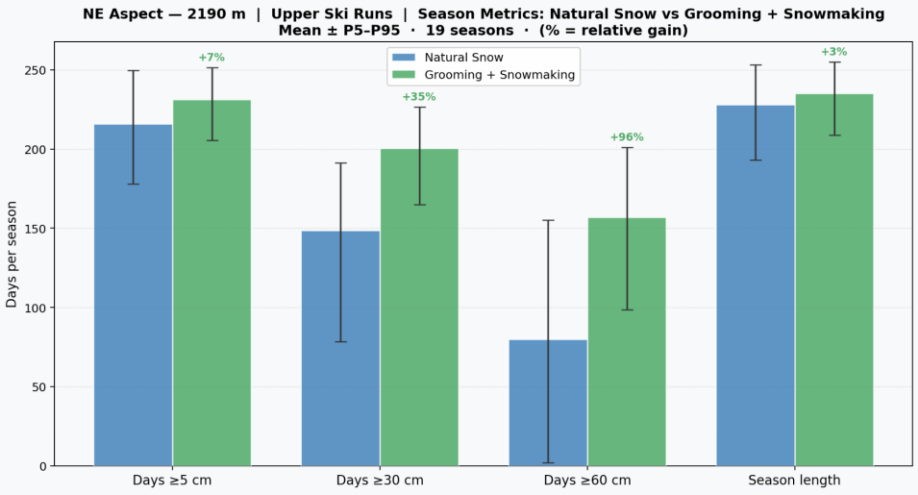
SE Aspect – 1680 m | Annual Peak Snow Depth: Natural Snow vs Grooming + Snowmaking
(+value above bar = depth added by grooming & snowmaking)



CRHM – Natural Snow vs Managed Snow



CRHM – Natural Snow vs Managed Snow



4. Perturbed climate scenarios

4. PERTURBED CLIMATE SCENARIOS

Data set:

Observational Data: Marmot Creek Research Basin meteorological stations (2005-2023)

Canadian Downscaled Climate Scenarios, Univariate, CMIP6 (CanDCS-U6), EEECBCCAQv2 (Bias Correction / Constructed Analogues with Quantile mapping).

MSC Open Data Datamart (dd.weather.gc.ca); method described in Sobie & Murdock et al. (2024)

Resolution & coverage : ~10 km grid (0.086° lat $\times$ 0.086° lon), monthly mean air temperature ($^{\circ}\text{C}$) and total precipitation (mm/month), spanning 1950–2014 historical and 2015–2100 future scenarios; values used here are the Pct50 ensemble median across all available GCMs.

Site match: Nearest grid cell to Nakiska (50.944°N , 115.147°W) is 50.958°N , 115.125°W

GCM Ensemble

The CanDCS-U6 Pct50 product aggregates statistically downscaled output from 26 CMIP6 general circulation models (GCMs).

Including:

ACCESS-ESM1-5, CanESM5, CNRM-CM6-1, EC-Earth3, GFDL-ESM4, IPSL-CM6A-LR, MIROC6, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL,

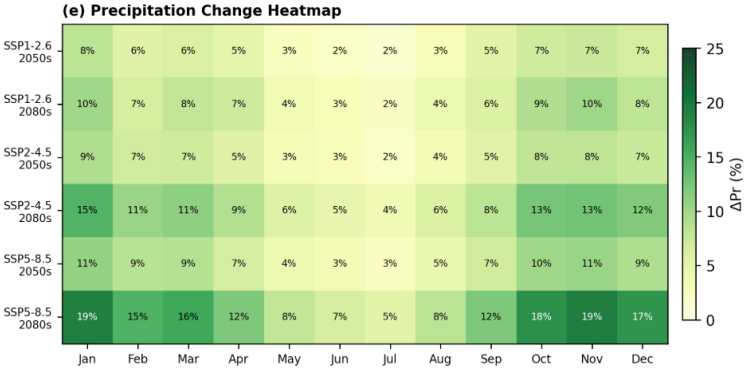
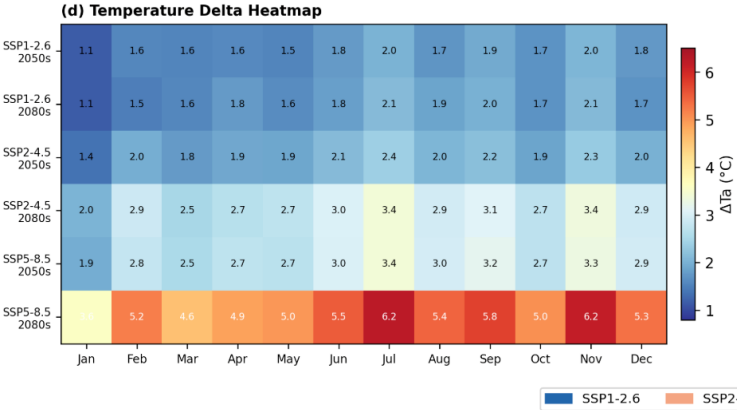
Emission Scenarios

Scenario	Forcing (W/m ²)	Description	Role in study
SSP1-2.6	2.6	Ambitious mitigation; warming limited to ~1.5–2°C globally by 2100	Lower bound / optimistic
SSP2-4.5	4.5	Intermediate; current policy trajectory; ~2.7°C global warming by 2100	Central / reference scenario
SSP5-8.5	8.5	High fossil fuel dependency; ~4.4°C global warming by 2100	Upper bound / stress test

Temporal Horizons

Period	Years	Climate normal span	Purpose
Baseline	1991–2020	Current WMO standard normal (30-yr)	Reference for delta computation
Mid-century	2041–2070	30-yr future average ("2050s")	Near-term planning horizon
End-century	2071–2100	30-yr future average ("2080s")	Long-term stress test

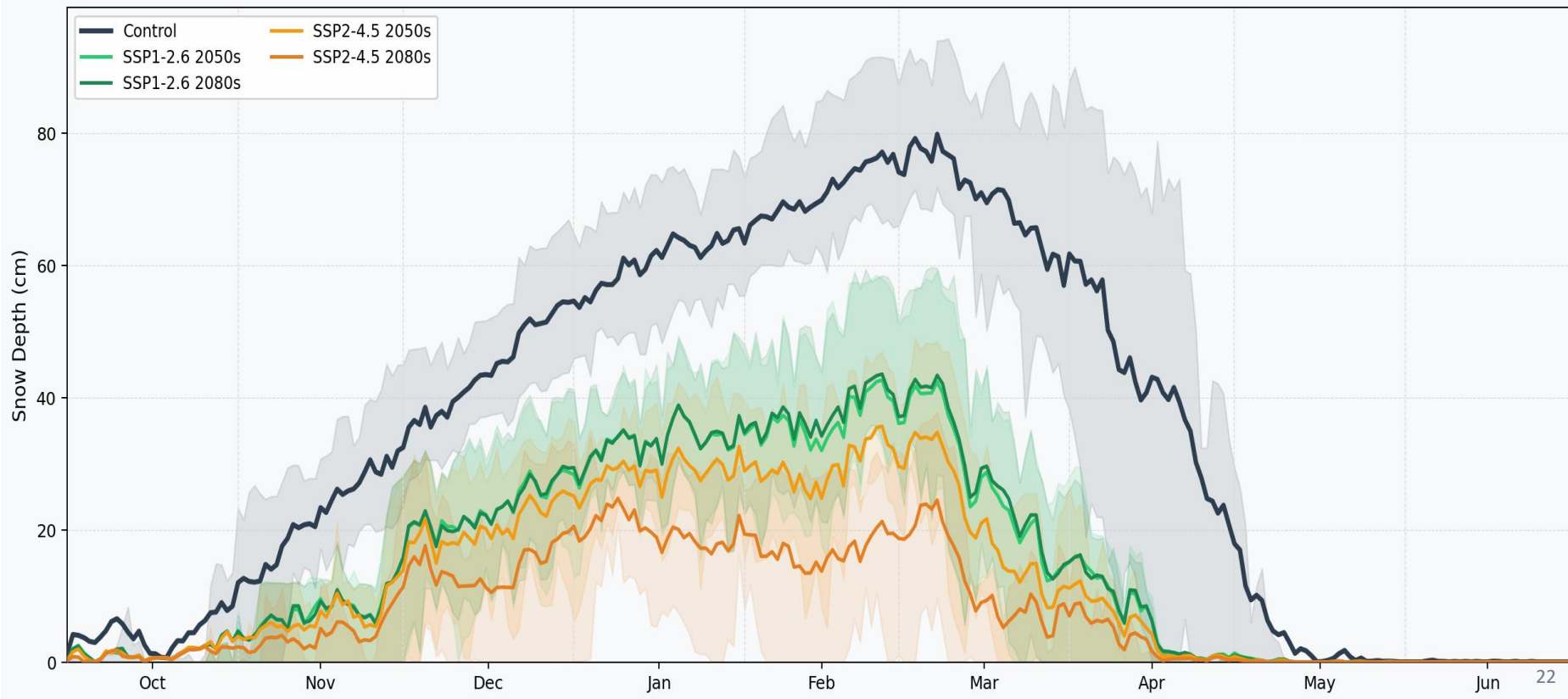
Delta Changes of Climate Perturbation



Delta Changes of Climate Perturbation

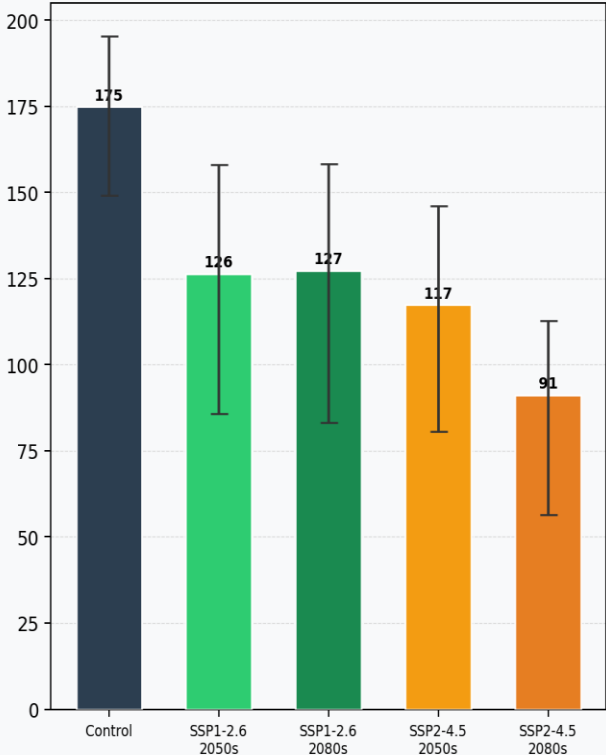
Scenario	Period	ΔT_a annual ($^{\circ}\text{C}$)	ΔT_a DJF ($^{\circ}\text{C}$)	ΔPr annual (%)	ΔPr DJF (%)
SSP1-2.6	2050s	+1.75	+1.62	~4%	~9%
SSP1-2.6	2080s	+1.81	+1.41	~5%	~11%
SSP2-4.5	2050s	+2.04	+1.67	~4%	~9%
SSP2-4.5	2080s	+2.90	+2.45	~7%	~14%
SSP5-8.5	2050s	+2.90	+2.37	~6%	~11%
SSP5-8.5	2080s	+5.12	+4.40	~10%	~19%

SE Aspect 1680 m | SSP1-2.6 & SSP2-4.5 only | Mean Seasonal Snow Depth — Climate Scenarios
P25-P75 band · 19 seasons 2006-2024

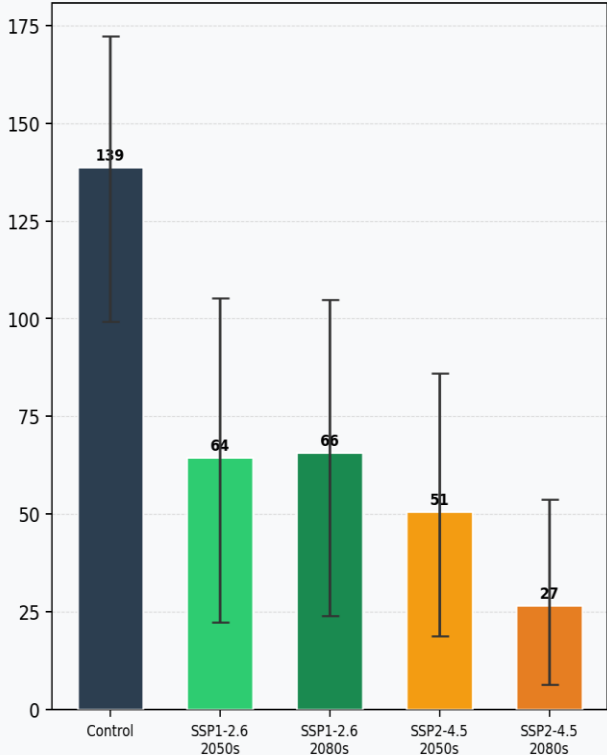


SE Aspect 1680 m | SSP1-2.6 & SSP2-4.5 only | Days Above Thresholds (P5-P95 error bars)

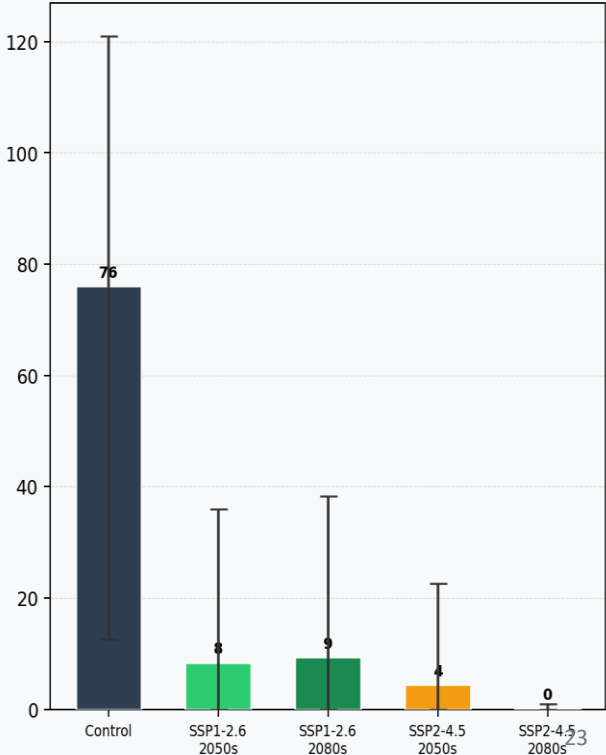
Days ≥ 5 cm



Days ≥ 30 cm



Days ≥ 60 cm

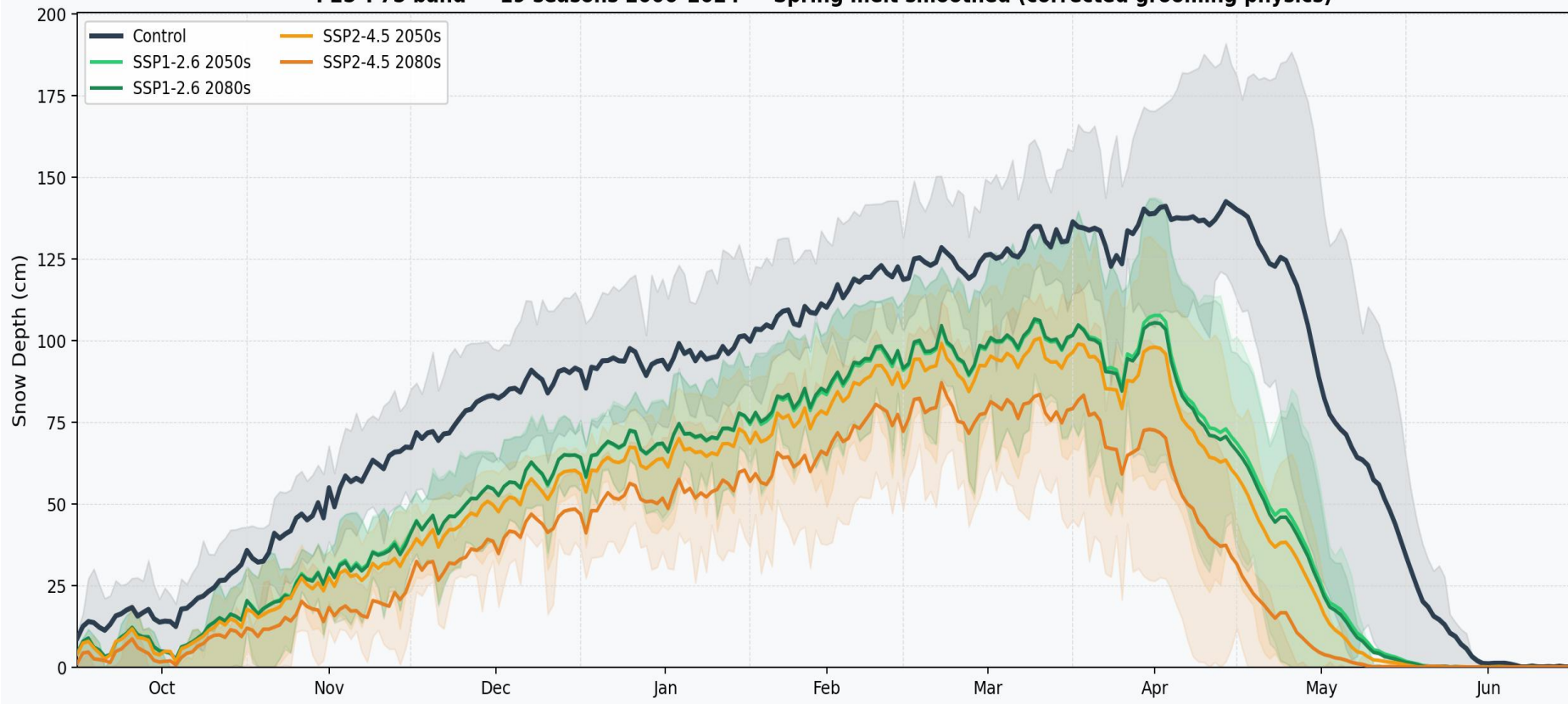


CLIMATE SCENARIOS

NE Aspect — 2190 m | Upper Ski Runs

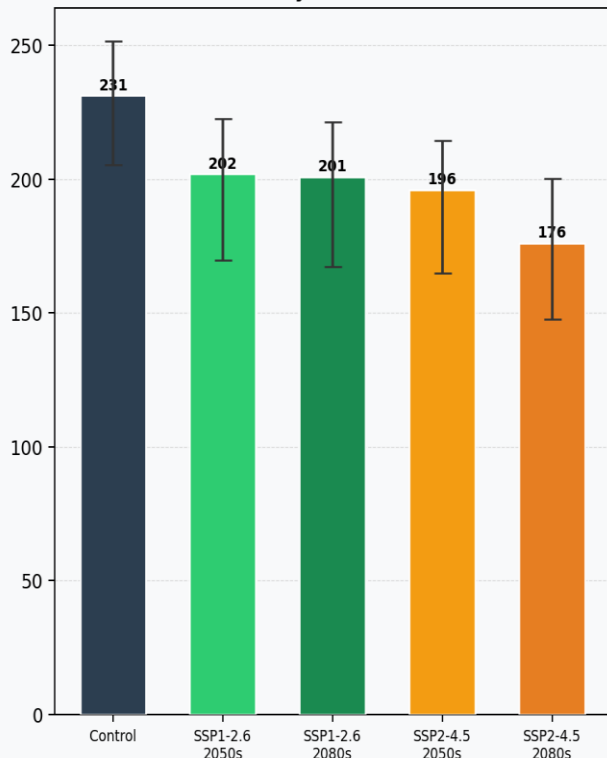
All SSP Scenarios: SSP1-2.6 · SSP2-4.5 · SSP5-8.5 · 2050s & 2080s

NE Aspect 2190 m | SSP1-2.6 & SSP2-4.5 only | Mean Seasonal Snow Depth — Climate Scenarios
P25-P75 band · 19 seasons 2006-2024 · Spring melt smoothed (corrected grooming physics)

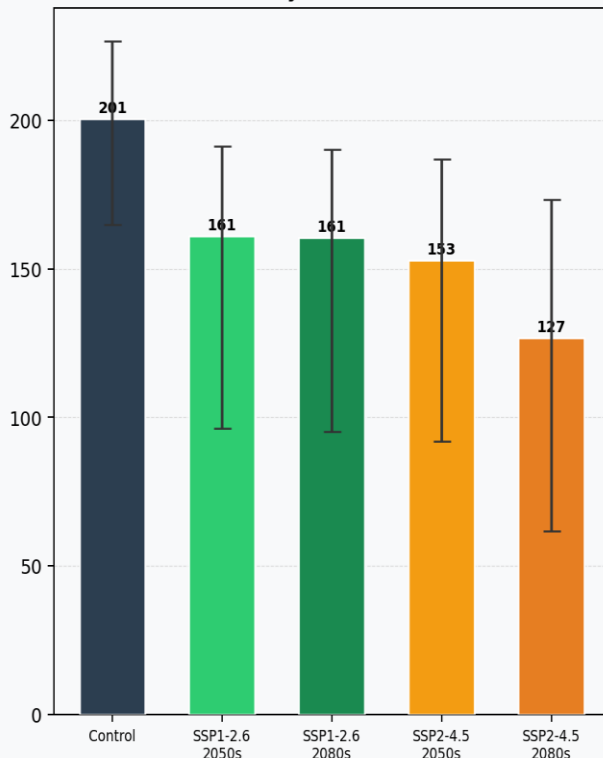


NE Aspect 2190 m | SSP1-2.6 & SSP2-4.5 only | Days Above Thresholds (P5-P95 error bars)

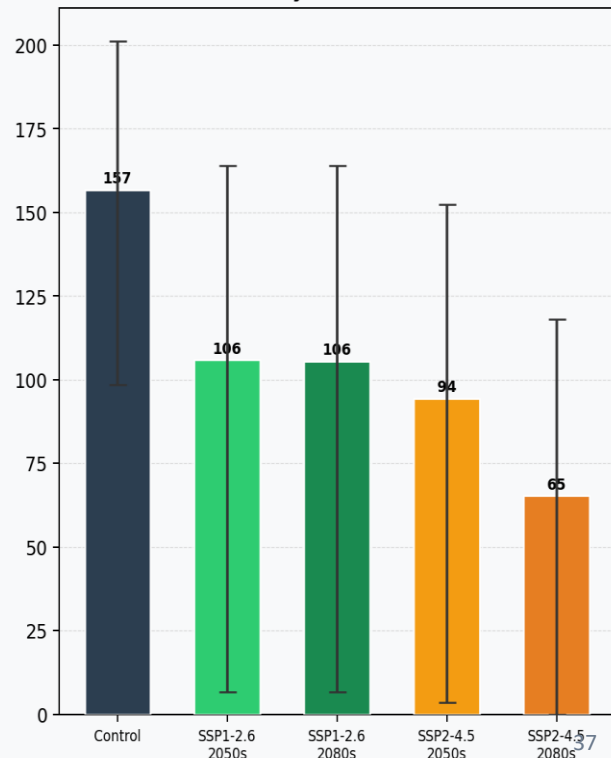
Days ≥ 5 cm



Days ≥ 30 cm



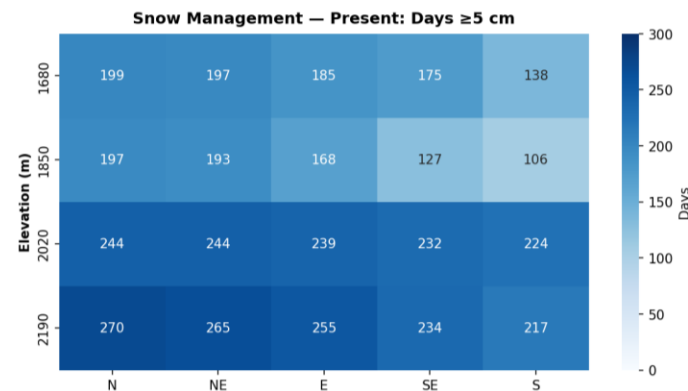
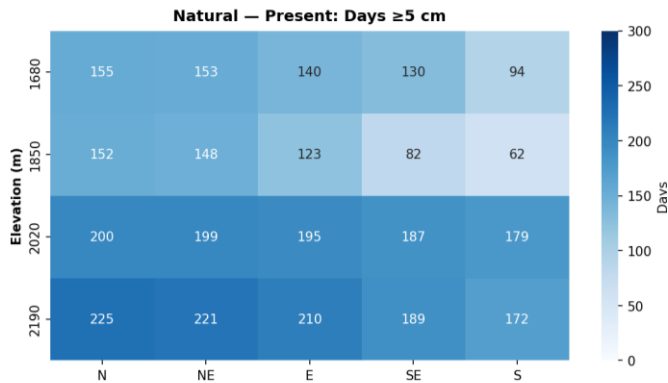
Days ≥ 60 cm



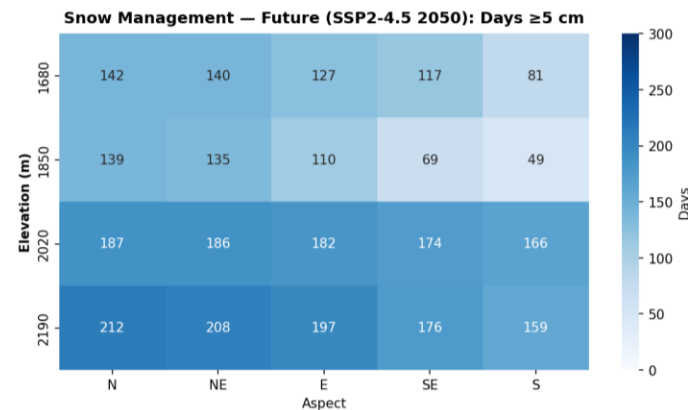
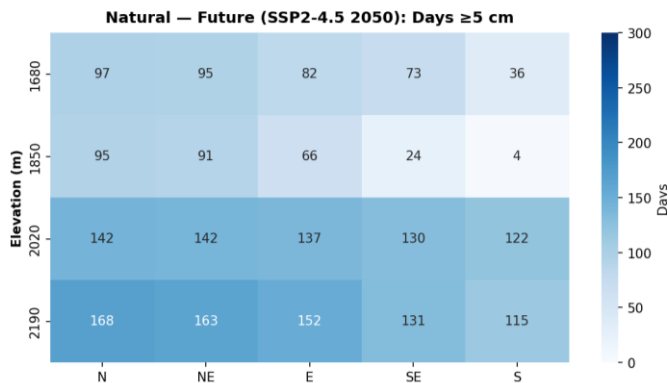
4. SNOW SENSITIVITY TO CLIMATE FOR ASPECT AND ELEVATION

Days with at least 5cm

PRESENT



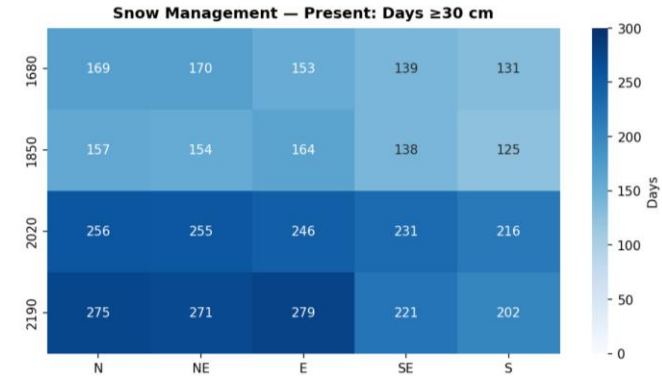
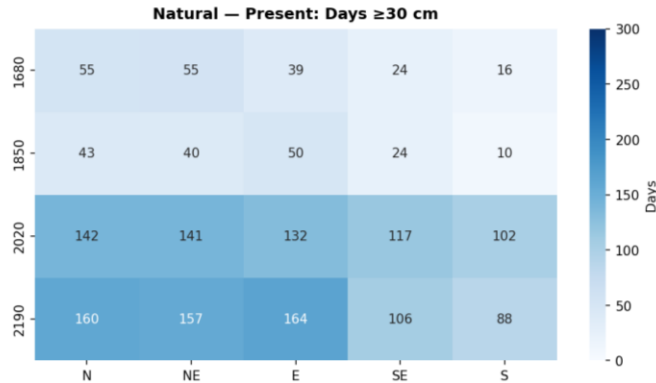
SSP2-4.5
2050



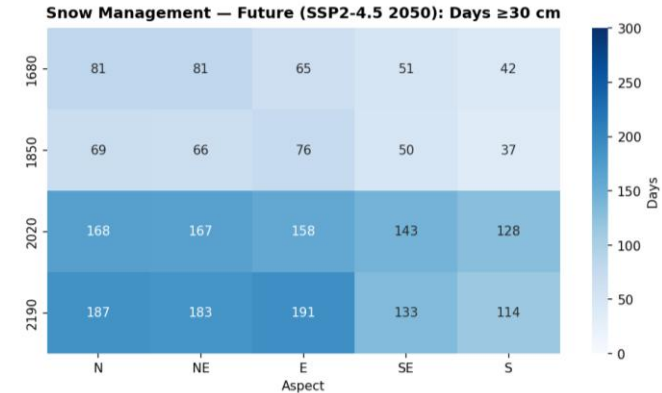
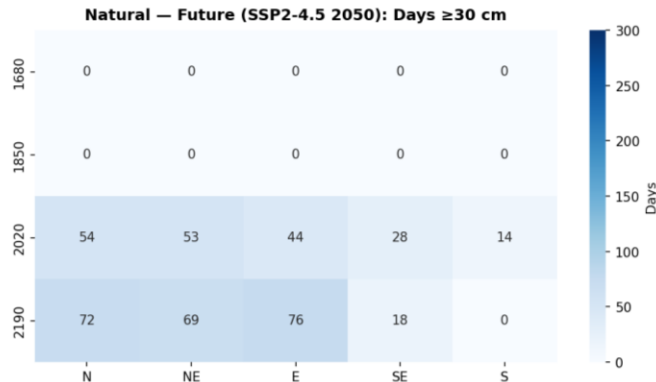
4. SNOW SENSITIVITY TO CLIMATE FOR ASPECT AND ELEVATION

Days with at least 30cm

PRESENT



SSP2-4.5
2050



5. DISCUSSION AND CONCLUSIONS

- Natural snow models are not appropriate to reproduce snowpack dynamics in ski areas

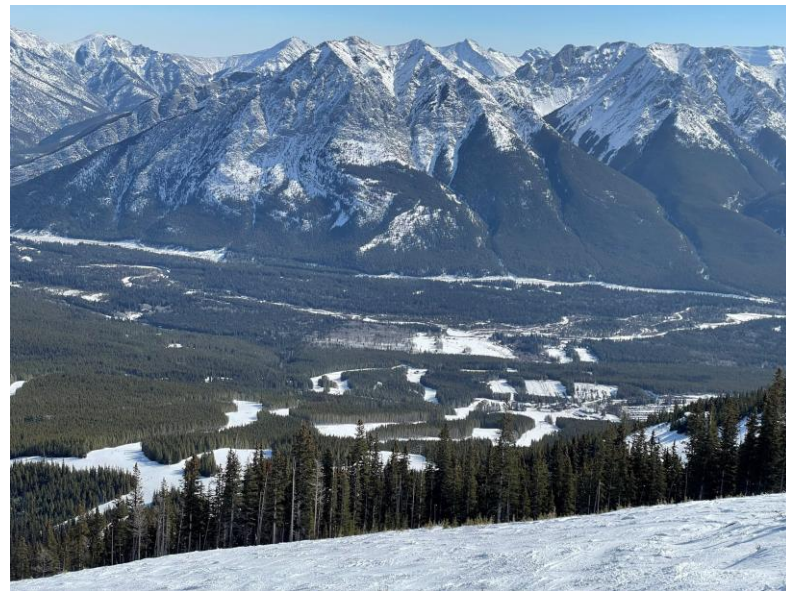
Usually leading to overly pessimistic future climate projections

- Previous approaches oversimplified the snowpack dynamics

Didn't capture local scale reality of snowpack dynamics

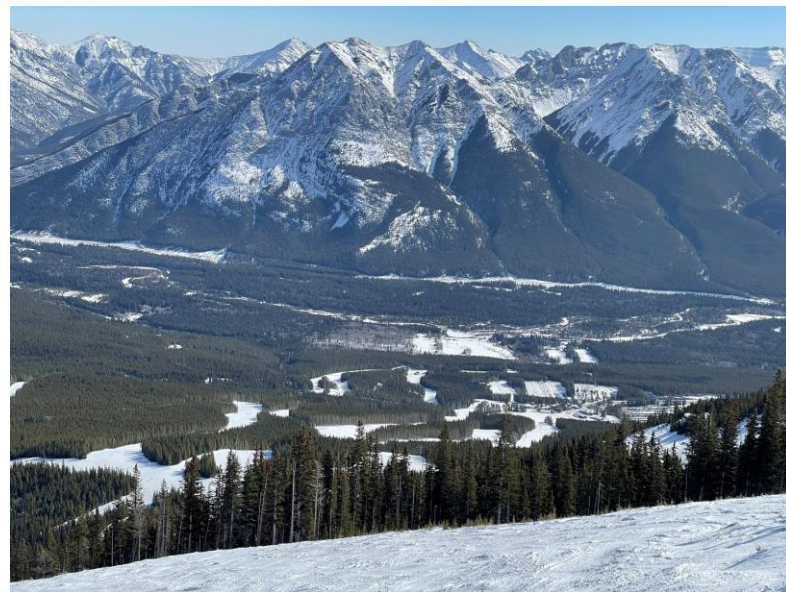
- or were very intensive in data, parameters and computation (NWM-based)

Uncertain application



5. DISCUSSION AND CONCLUSIONS

- **Applying CHRM with a specific module simulating snow management, CRHM-SKI, efficiently simulated real local snowpack dynamics in the ski area with a less intensive data, calibration and computational needs than previous studies**
- Snow management increases the number of days with snow depth ≥ 5 cm by $\sim 34\%$ at the low SE site (130 $\rightarrow$ 175 days) but only $\sim 7\%$ needed at the high NE site
- Snow management builds a deep pack everywhere: # days ≥ 30 cm depth increases from more than 300% at 1680 m SE and +35% at 2190 m NE.



5. DISCUSSION AND CONCLUSIONS

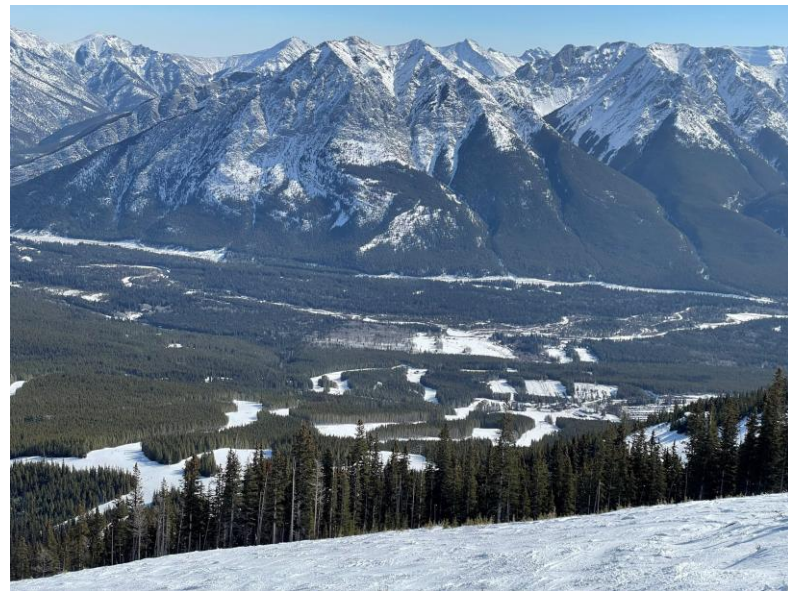
- Under SSP2-4.5, the managed low elevation SE pack loses $\sim\frac{1}{3}$ of its ≥ 5 cm depth days by the 2050s and $\sim\frac{1}{2}$ by the 2080s.

The high NE site is far more resilient, losing only $\sim 15\text{--}24\%$ across the same scenarios.

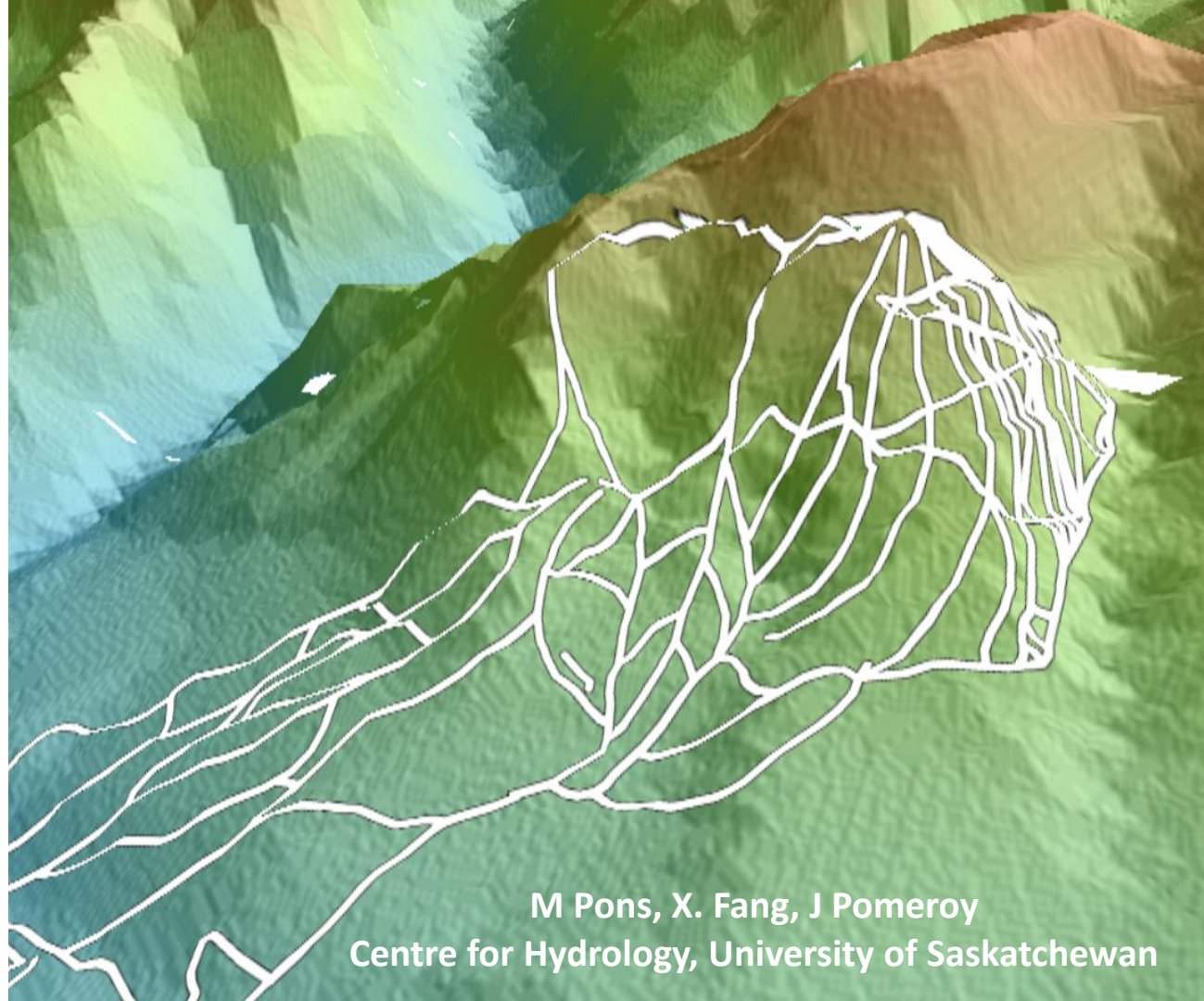
- Ranking of natural and managed snow depths is invariant with elevation/aspect

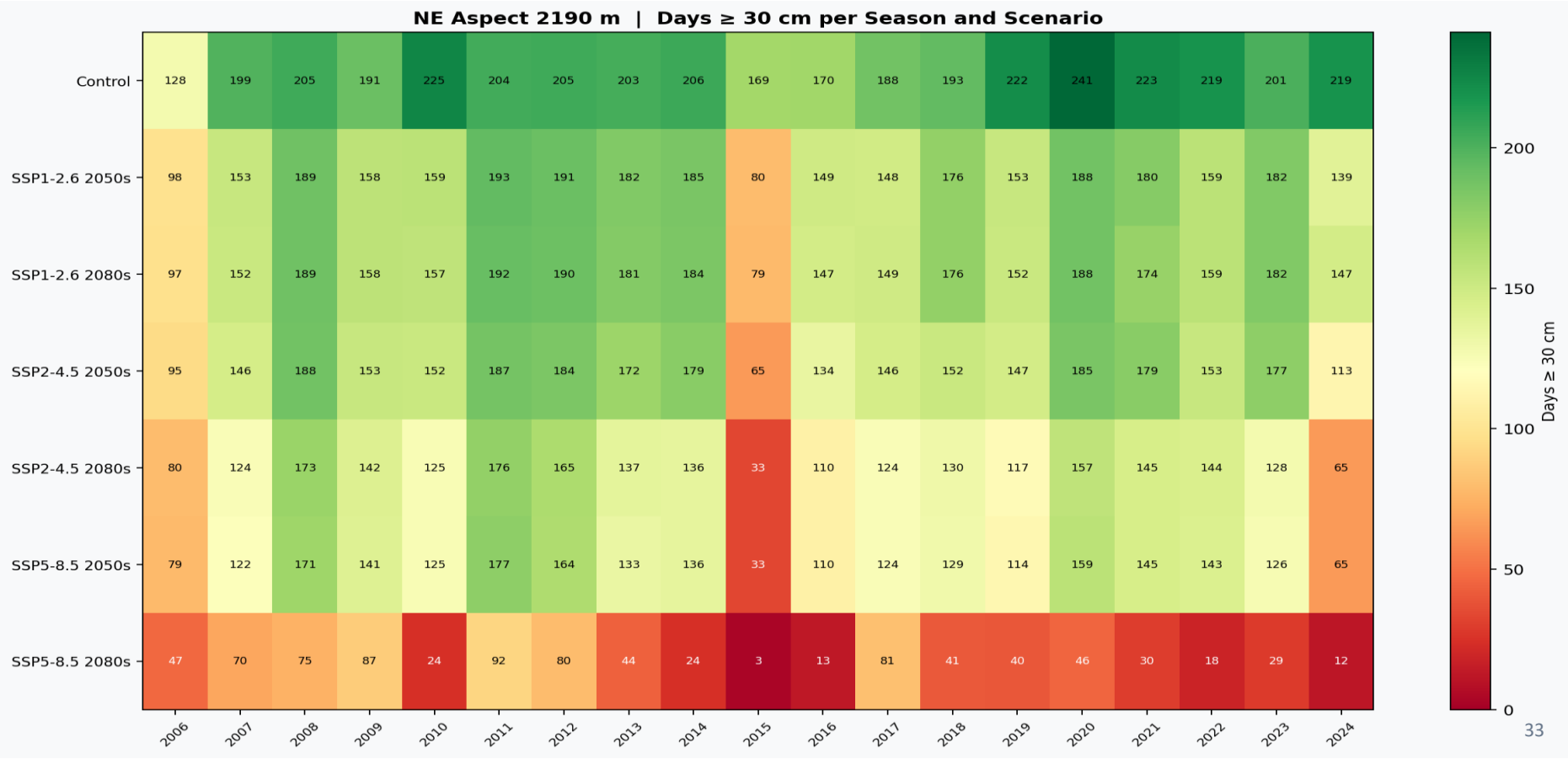
$N \approx NE > E > SE > S$, rising with elevation

- but snow management narrows the spread, making managed snow much less sensitive to aspect, elevation and climate change.



Simulating natural and managed snow and future climate sensitivity at Nakiska Ski Area, Kananaskis Valley





NE Aspect 2190 m | SSP1-2.6 & SSP2-4.5 only | Days ≥ 30 cm per Season and Scenario