Snow mechanical properties variation at slope scale, implication for snowpack stability assessment and snow cover models

Francis Meloche[1,2,3], Francis Gauthier[1,3] and Alexandre Langlois[2,3]

[1]Laboratoire de géomorphologie et de gestion des risques en montagnes (LGGRM), University of Québec in Rimouski, Department of Biology, chemistry and geography, Canada

[2]Groupe de recherche interdisciplinaire en milieux polaire (GRIMP), Sherbrooke University, Department of applied geomatics, Canada

[3]Center for Nordic studies, Université Laval, Canada

Fonds de recherche Nature et technologies Québec

CENTRE D'ÉTUDES NORDIQUES
CEN Centre for Northern Studies

LGGRM
LABORATOIRE DE GÉOMORPHOLOGIE ET DE GESTION DES RISQUES EN MONTAGNE

GRIMP
Groupe de Recherche Interdisciplinaire sur les Milieux Polaires

Introduction

Risk assessment of snow avalanches is difficult due to sparse nature of available observations on snowpack properties.

Snow spatial variability at multiple scales add complexity to this difficult task.

- Snow spatial variability remains significant at the slope scale (Kronholm & Schweizer, 2003; Reuter *et al.*, 2016; Schweizer *et al.*, 2008).
- Affect the overall slope stability (Gaume *et al.*, 2014; Fyffe & Zaise 2004).

<u>We explore the link between the microtopography and snow mechanical properties to explain and predict the snow spatial variability across an avalanche prone slope.</u>

Methodology - Study sites

<u>Rogers Pass, British-Columbia, Canada:</u>

Jim Bay corner: Open trees , low roughness terrain

JBC22_SH : 19/01/2022 Surface Hoar layer (1 mm)

JBC22_PP : 24/01/2022 Precipitation particles (0.5-1mm)

Round Hill : Low angle alpine area, low roughness terrain

RH22_PP : 27/01/2022 Precipitation particles (0.5-1 mm)

<u>Mt Albert, Québec, Canada:</u>

Arête de Roc : Alpine terrain with small trees, High roughness terrain

AR22_PP : 25/02/2022 Precipitation particles (0.5-1 mm)

Structured and random sampling grid ≈ 50 m x 80 m slope

GNSS receiver centimeter precision for each snow measurement

Snowdepth and DTM/DSM (summer) map using *sfm*-photogrammetry with UAV imagery

Methodology - Snowpack properties

High resolution penetrometer - ***SnowmicroPen***

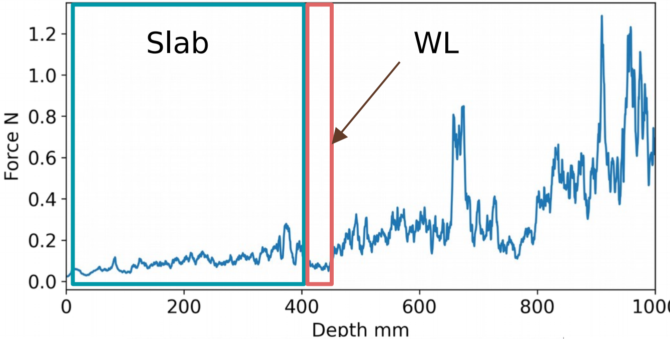
Layers visually interpreted on the SMP signal

Poisson shot noise model 2.5 mm moving window F and L parameters (Löwe & van Herwijnen, 2012)

Density (Proksch *et al.*, 2015) parameters for SMP **v4** (Calonne et al, 2020)

Elastic modulus of the slab (Johnson & Schneebeli, 1999; **Reuter *et al.*, 2019**)

Strength of the weak layer ≈ Micro-structural strength (Johnson & Schneebeli, 1999)



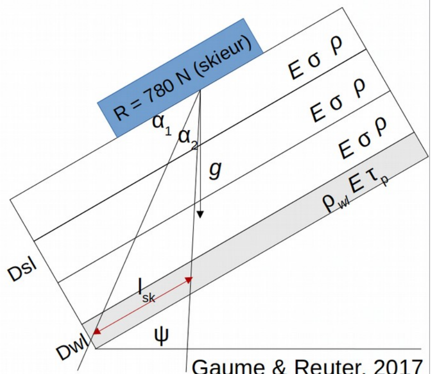
Skier stability metrics Gaume & Reuter, 2017:

Skier crack length (Gaume & Reuter, 2017) Multi-layers slab depth (Monti *et al.*, 2016)

Critical crack length : Fwl parameterization based on normalised optical grain size (Gs_{wl}/Gs_0) (Richter *et al.*, 2019)

- L_{wl} parameters instead of the optical grain size with L_0 = 1.09 mm (Pielmeier & Marshall, 2009)

Skier stability index (Gaume & Reuter, 2017)



Gaume & Reuter, 2017

Methodology - Spatial modelling

General additive models - *GAM* (Nussbaum *et al.*, 2017) :

- Spline (non-linear)
- Spline is fitted through the x and y coordinates for residual spatial autocorrelation

Response variables

- **Snow properties :** Slab depth, slab density, weak layer strength
- **Stability :** Skier crack length, critical crack length and skier stability index

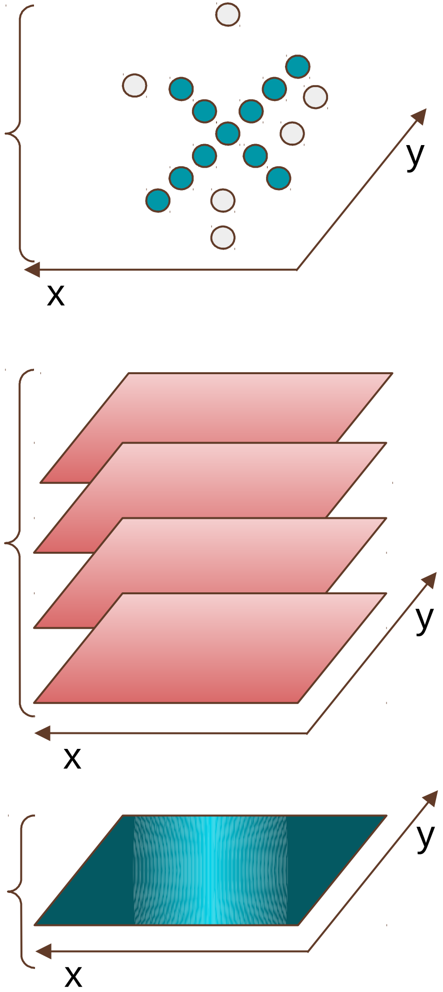
Microtopographic indicators as covariates:

- **Terrain shape :** Slope, Topographic position index (TPI), Terrain roughness index (TRI), convexity
- **Vegetation :** canopy height, distance to canopy (radial proximity)
- **Microclimate :** incoming potential radiation, snowdepth, Winstral index (wind exposed/sheltered).

Building models with point data with covariates values

Spatial prediction using covariates raster data

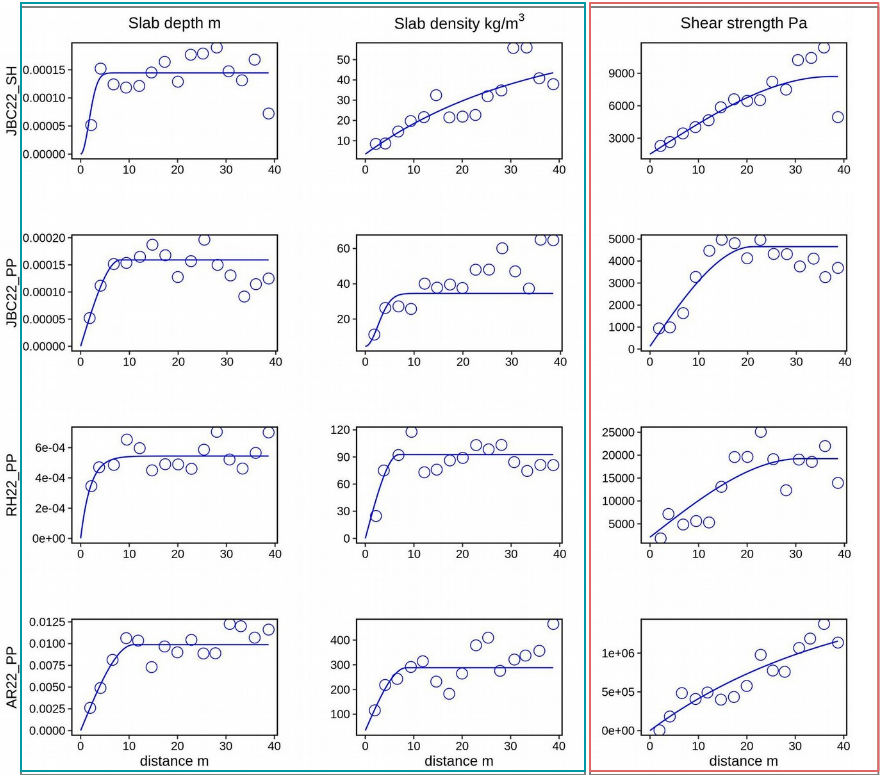
Model prediction

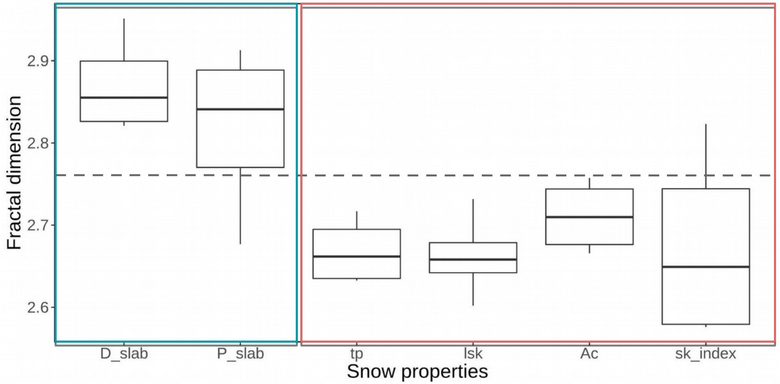


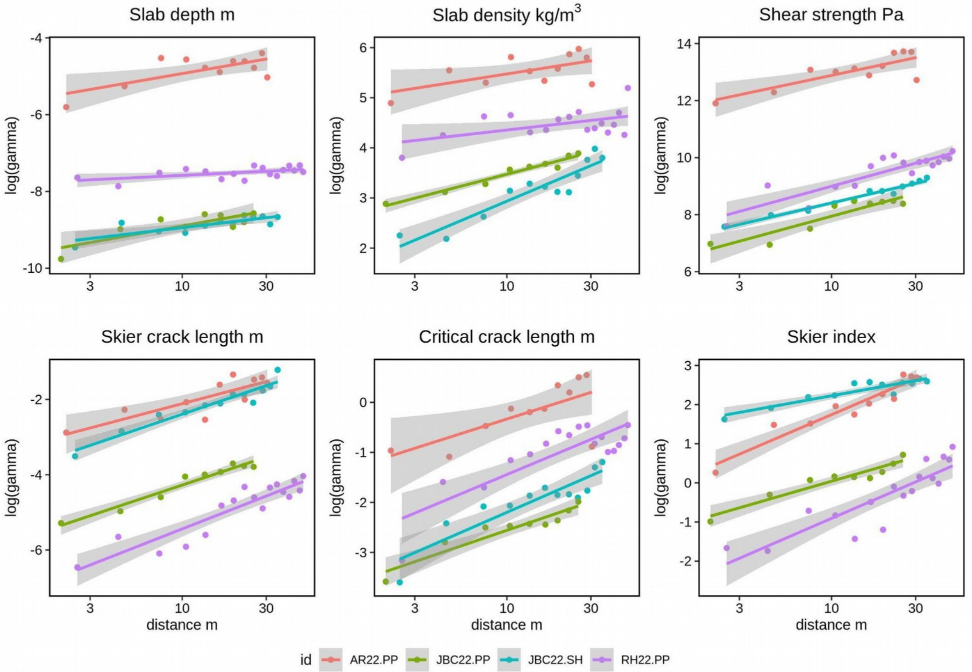
Results - Scaling properties

Fractal dimensions (roughness of a surface)

-Slope of a log-log variogram



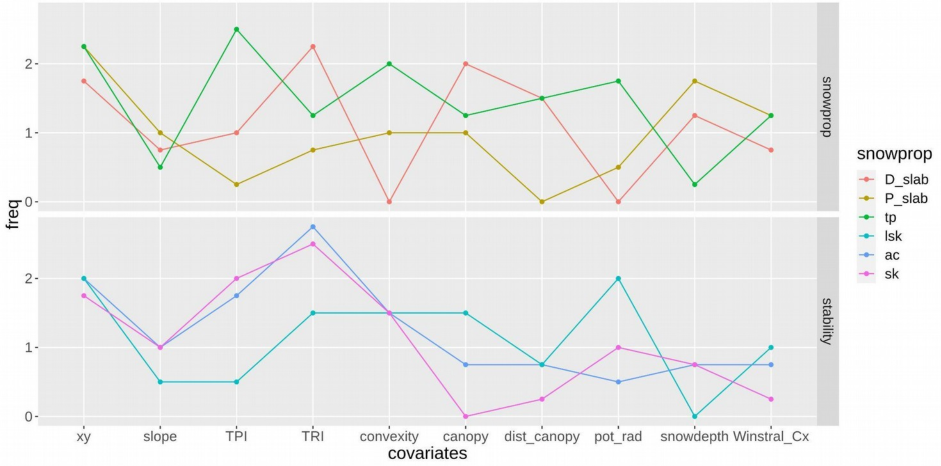




Results - Covariates

R^2 from 0.2 to 0.8 with mean of 0.4

Most used covariates: TPI and TRI

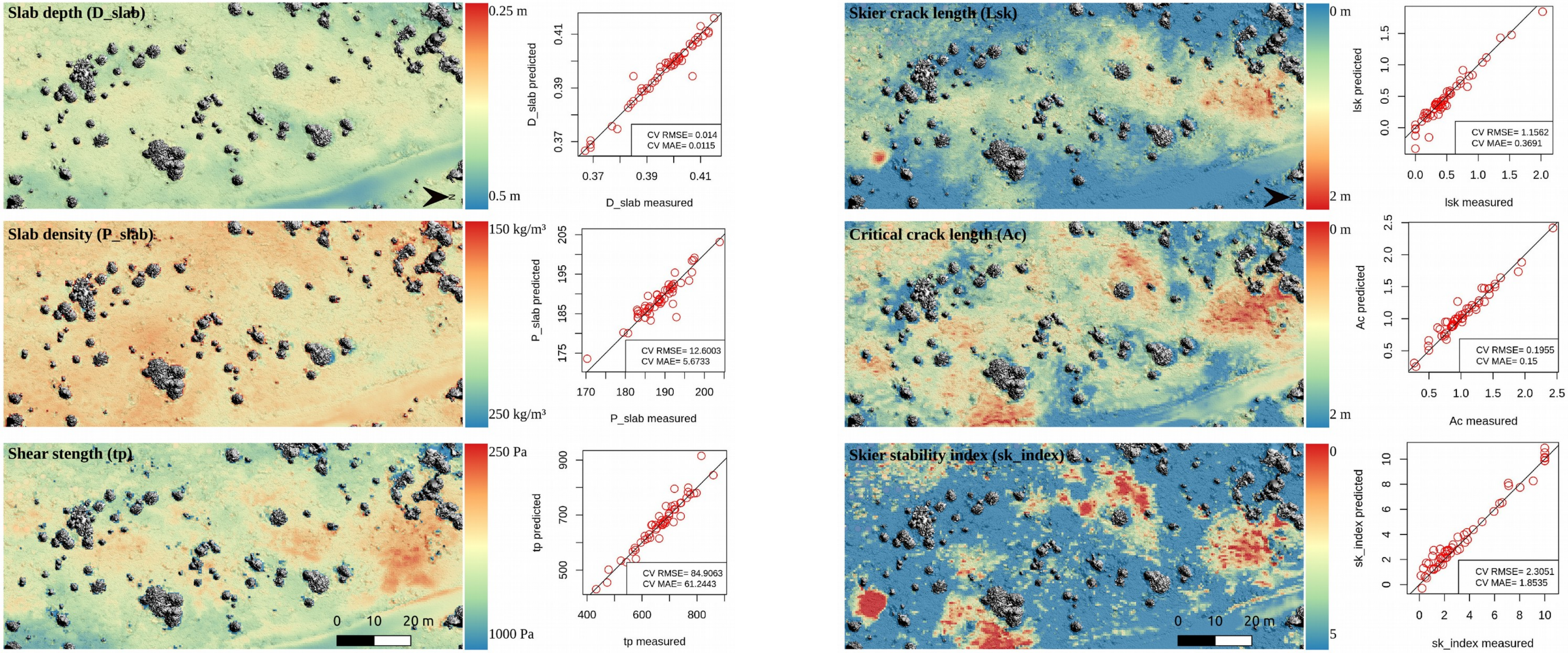


Site	Snow properties	Covariates	R2	% dev.	scale	CV RMSE	CV MAE
JBC22_SH	D_slab	(x+y)*** + TPI. + TRI*** + snowdepth* + dist_canopy*	0.36	43.3	9.45e-5	0.014	0.015
	P_slab	(x+y)** + slope** + TPI. + snowdepth** + pot_rad. + canopy*	0.40	49.3	17.197	12.60	5.67
	Shear_strength	(x+y)** + TPI*** + TRI** + pot_rad. + convexity* + canopy**	0.56	61.7	3276.4	84.90	61.24
JBC_PP	D_slab	TRI* + canopy**	0.2	25.8	0.0001	0.014	0.011
	P_slab	(x+y). + slope. + TRI** + snowdepth* + Winstral_Cx*	0.33	39.7	27.55	6.17	4.94
	Shear_strength	(x+y)*** + TPI* + dist_canopy** + Winstral_Cx*	0.5	55	1860	58.79	43.45
RH22_PP	D_slab	Slope** + TPI** + TRI** + snowdepth. + canopy*** + dist_canopy*** + Winstral_Cx*	0.49	54.6	0.0003	0.025	0.018
	P_slab	(x+y)* + canopy* + Winstral_Cx**	0.22	26.6	73.958	11.29	8.55
	Shear_strength	Slope. + TRI* + pot_rad** + convexity* + canopy* + Winstral_Cx**	0.32	38.7	12385	142.10	105.06
AR22_PP	D_slab	(x+y)** + snowdepth* + canopy.	0.28	35.7	0.006	0.12	0.09
	P_slab	(x+y)** + snowdepth. + pot_rad. + convexity***	0.47	53.5	210.42	20.73	15.29
	Shear_strength	(x+y)* + slope. + TPI*** + snowdepth. + pot_rad** + convexity*** + dist_canopy**	0.64	69.8	2.78e5	759.28	584.87

Site	Snow properties	Covariates	R2	% dev.	scale	CV RMSE	CV MAE
JBC22_SH	lsk	(x+y)*** + slope* + TRI*** + pot_rad** + canopy*	0.53	58.4	0.07	1.15	0.36
	Ac	(x+y). + slope*** + TPI** + TRI*** + snowdepth** + convexity*	0.50	56	0.08	0.19	0.15
	sk_index	Slope** + TRI** + snowdepth.	0.31	36.9	7.06	2.3	1.85
JBC_PP	lsk	(x+y)*** + TPI** + pot_rad. + dist_canopy. + Winstral_Cx*	0.48	53.5	0.008	0.11	0.08
	Ac	(x+y)* + TPI*** + TRI*** + pot_rad* + Winstral_Cx.	0.74	77.5	0.02	0.13	0.10
	sk_index	(x+y)*** + TPI*** + TRI*** + pot_rad* + Winstral_Cx*	0.82	84.5	0.24	0.43	0.35
RH22_PP	lsk	TRI* + pot_rad** + convexity** + canopy* + Winstral_Cx*	0.34	40.3	0.006	0.11	0.07
	Ac	(x+y)** + TRI**	0.25	28.4	0.39	0.66	0.52
	sk_index	(x+y)** + slope. + TRI** + pot_rad. + convexity**	0.335	39.9	0.71	1.15	0.78
AR22_PP	lsk	Convexity** + canopy* + dist_canopy*	0.39	44.6	0.12	0.51	0.40
	Ac	(x+y)* + convexity*** + canopy** + dist_canopy** + Winstral_Cx*	0.60	65.8	0.58	1.42	1.17
	sk_index	TPI*** + snowdepth* + pot_rad. + convexity** + dist_canopy.	0.54	59.1	6.65	4.02	2.96

Results - Spatial prediction

Jim Bay corner (Rogers Pass) : Weak layer surface hoar (0.5-1mm)



Discussion/Conclusion

- Difference in spatial pattern between slab properties and weak layer/stability.
  - Slab properties is smaller and rough
  - Weak layer/stability is longer and smoother
- **Practical use** : Variation of slab properties can be visually identify rather than weak layer properties for route finding.

What's next?

- How the spatial variability affect the probability of skier triggering and possible size?
- Can we simulate sub-grid variability in snow cover models using microtopographic indicators and conditional gaussian simulation?

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