Modelling the impact of future Climate Change on operating conditions of ski resorts in the French Alps

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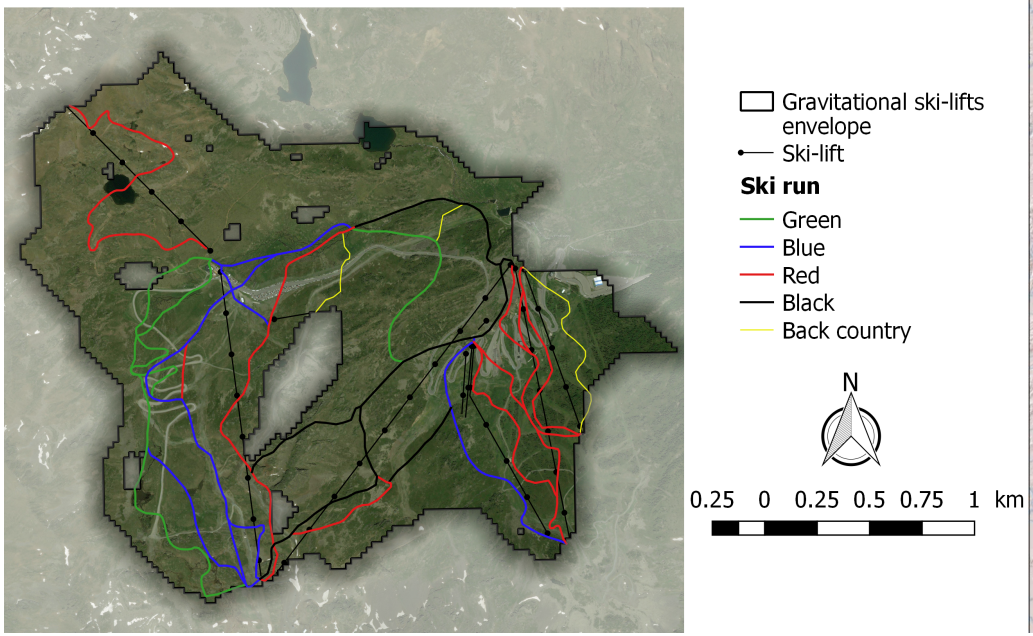
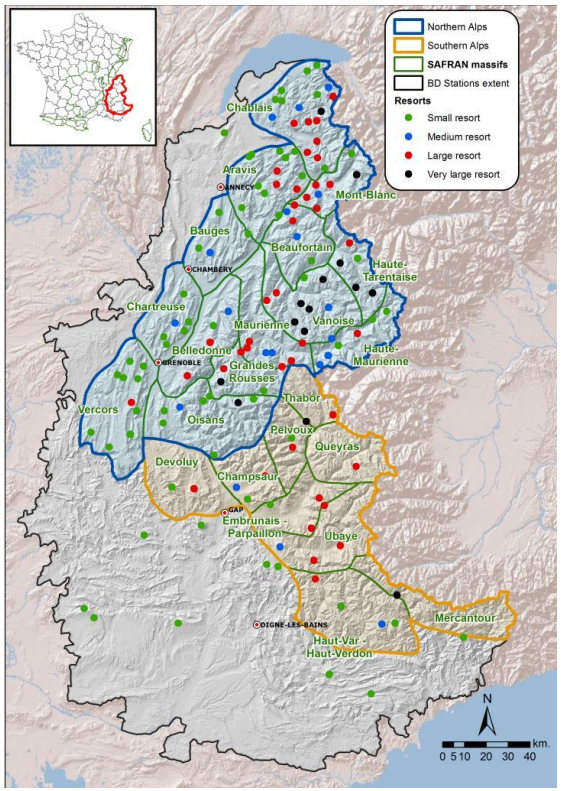


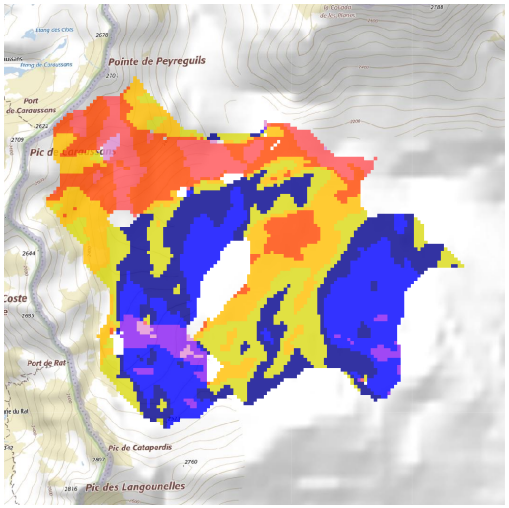


[1] François et al. (2014), "Crossing numerical simulations of snow conditions with a spatially-resolved socio-economic database of ski resorts: A proof of concept in the French Alps" in *Cold Regions Science and Technology*

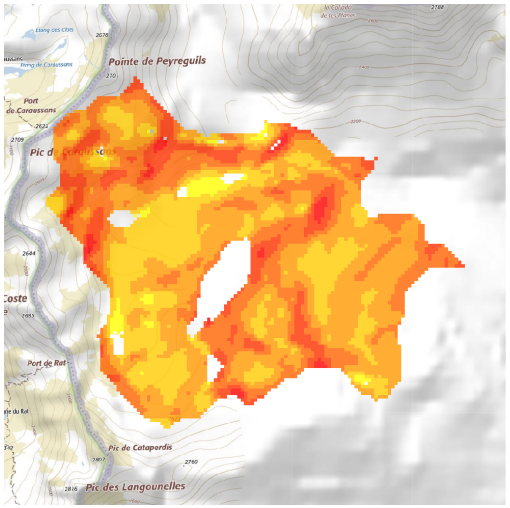
CrossCut method

Spatial representation of ski resorts

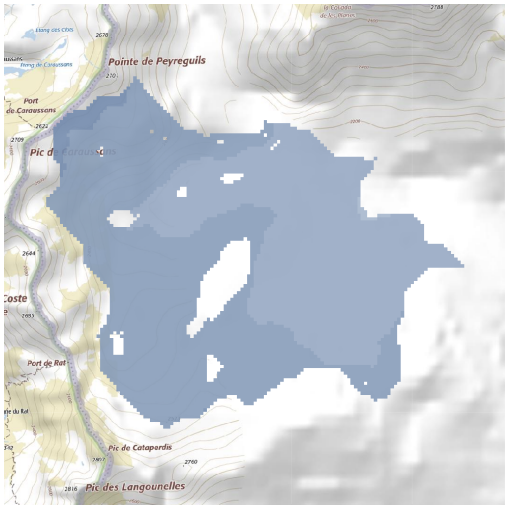
Slope Aspect



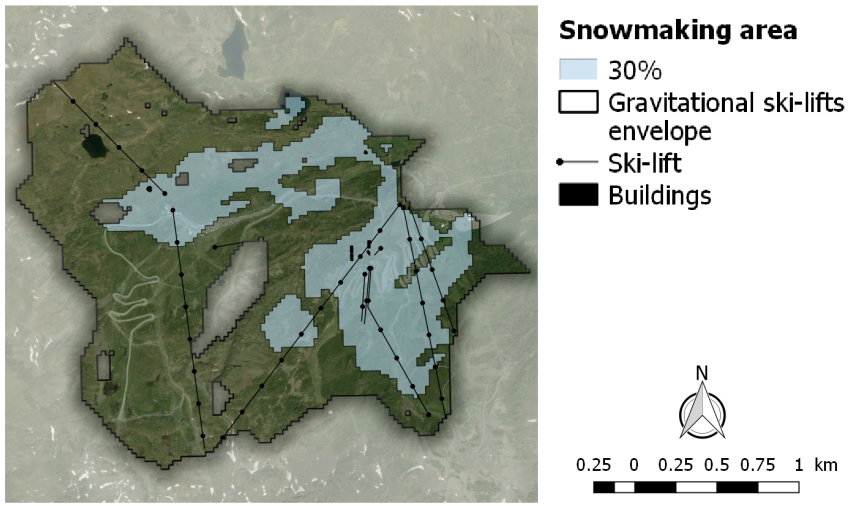
Slope Angle



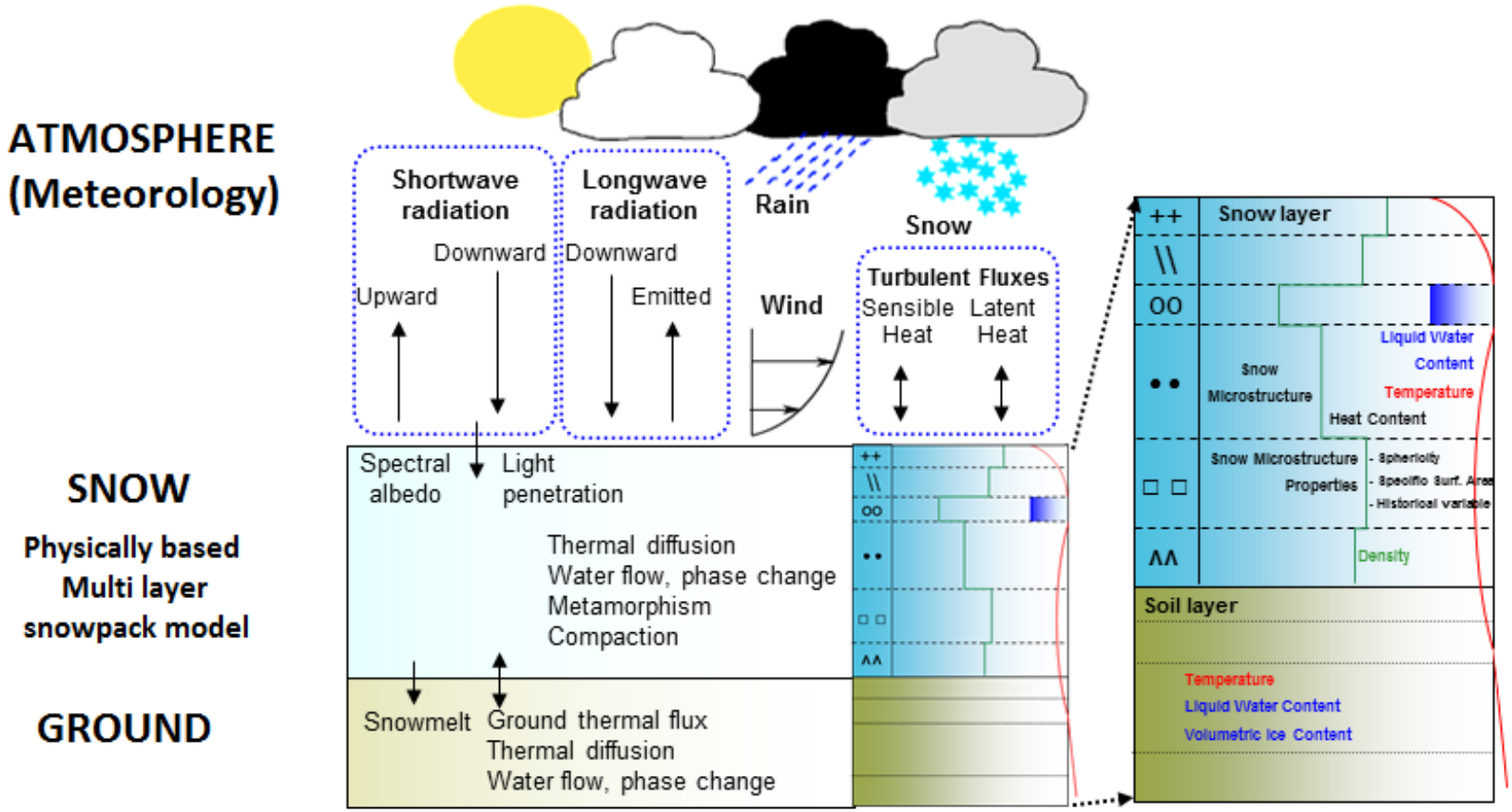
Elevations



Snowmaking equipment



Crocus - Natural Snow[2]

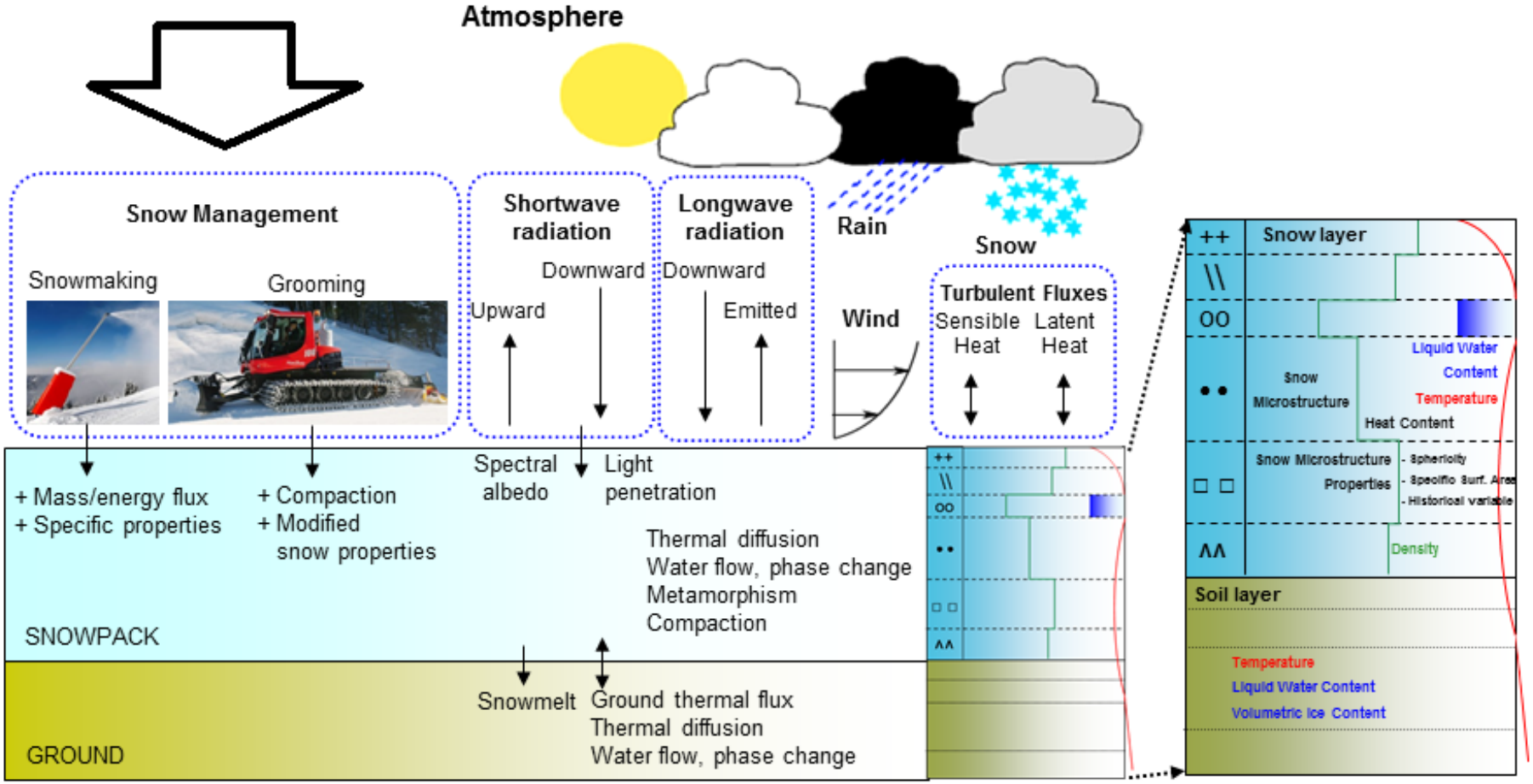


[2] Vionnet et al. (2012), "The detailed snowpack scheme Crocus and its implementation in SURFEX v7.2" in *Geosci. Model. Dev.*

CrossCut method

Numerical simulations of snowpack conditions
using a detailed approach of snow management

Crocus-Resort - Introduction of grooming and snowmaking[3]



[3] Spandre et al. (2016), "Integration of snow management in a detailed snowpack model" in *Cold Regions Science and Technology*

Crocus-Resort - Snowmaking approach[4]

- Evolution of snowmaking facilities
  From 0% (1985) to 30% (2015) and projected 45% (2025)[5]
- "Base layer" production (Nov. 1 to Dec. 15) and "Improvement" snowmaking (Dec. 16 to Feb. 28)
- 40% water volume lost for production[6]

[4] Spandre et al. (2016), "Panel based assessment of snow management operations in French ski resorts" in *Journal of Outdoor Recreation and Tourism*

[5] Spandre et al. (2015), "Snowmaking in the French Alps. Climatic context, existing facilities and outlook" in *Revue de Geographie Alpine-Journal of Alpine Research*

[6] Spandre et al. (2016), "Seasonal evolution of a ski slope under natural and artificial snow: detailed observations and modelisation" in *The Cryosphere*

CrossCut method

Past and future climate forcing data

- Reference meteorological data **(1958 - 2016)**
  - SAFRAN system[7]
  - Combines observations and modelling
  - Available over all French mountain ranges
- Climate data **(1950 - 2100)**
  - EUROCORDEX dataset (13 pairs RCM/GCM)
  - Scenarios RCP 2.6, RCP 4.5 and RCP 8.5
  - Adjusted using the ADAMONT method[8]

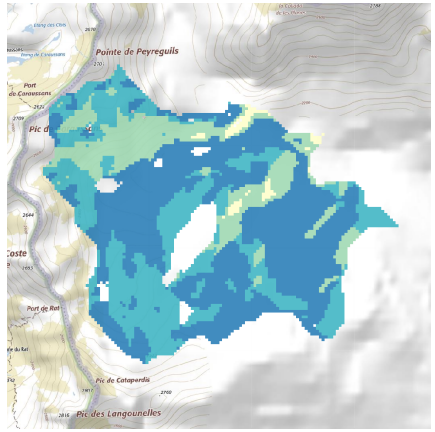
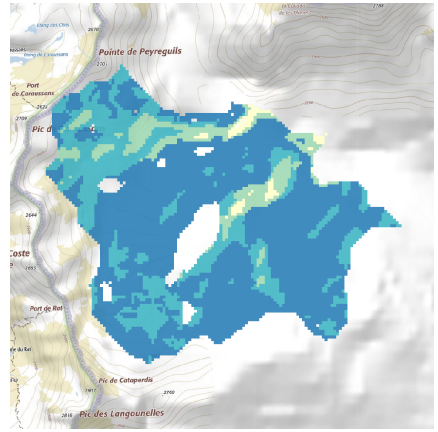
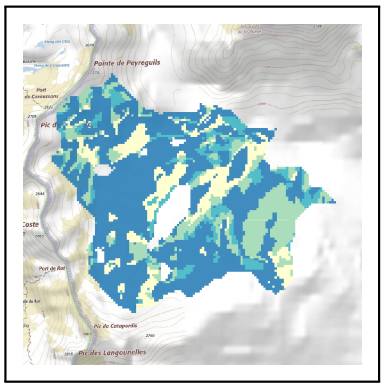
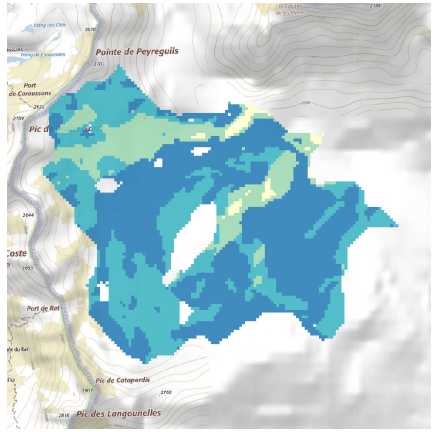
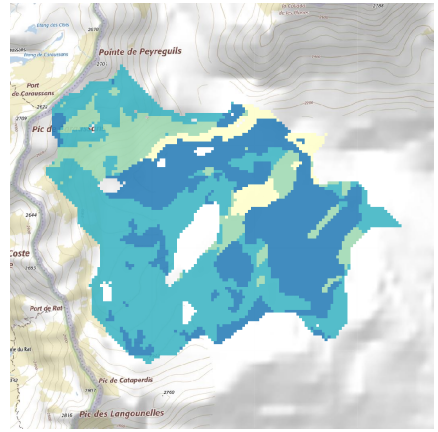
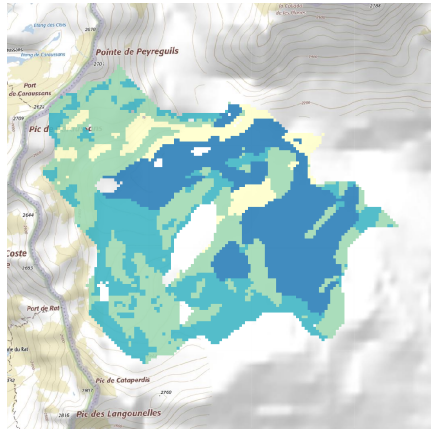
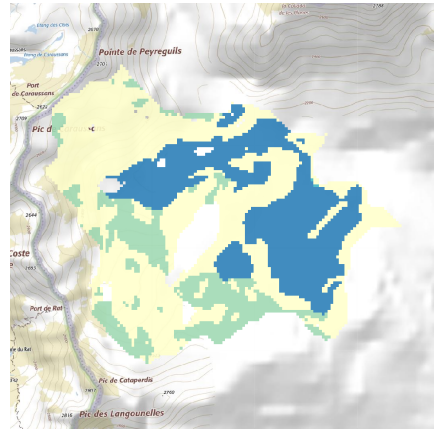
[7] Durand et al. (1993), "A meteorological estimation of relevant parameters for snow models" in *Ann. Glaciol.*

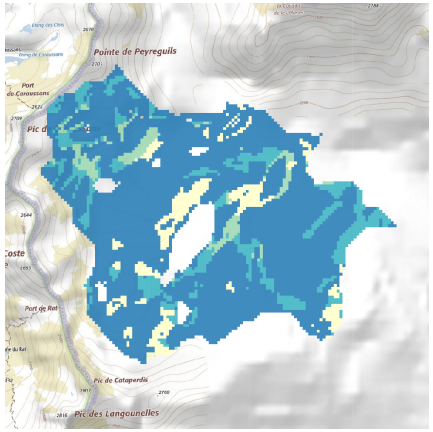
[8] Verfaillie et al. (2017), "The method ADAMONT v1.0 for statistical adjustment of climate projections applicable to energy balance land surface models" in *Geosci. Model Dev.*

Results

Impact of future Climate Change on operating conditions of ski resorts in the French Alps

Including Grooming and Snowmaking

1961 - 1990		2050 (15-yr r. Mean)	2090 (15-yr r. Mean)
Natural snow	RCP 2.6		
	RCP 4.5		
	RCP 8.5		



Number of days

- Below 50
- Below 80
- Below 100
- Below 150
- Over 150

Results

Impact of future Climate Change on operating conditions of ski resorts in the French Alps

Computation[9] of the following indicators[10]

- **Snow Reliability Index** of snow conditions[11]
- **Frequency** of challenging snow seasons below Q20[12]
- **Water volumes** for snowmaking

[9] Mean μ and deviation σ' of 15 years running averages of climate models. σ' is defined as 1.64 the standard deviation, mimicking 5 and 95% quantiles

[10] Spandre et al. (Under Review), "Investigations on economic indicators of French Alps ski industry from an explicit spatial modelling of managed snow on ski slopes" in *Journal of Tourism Management*

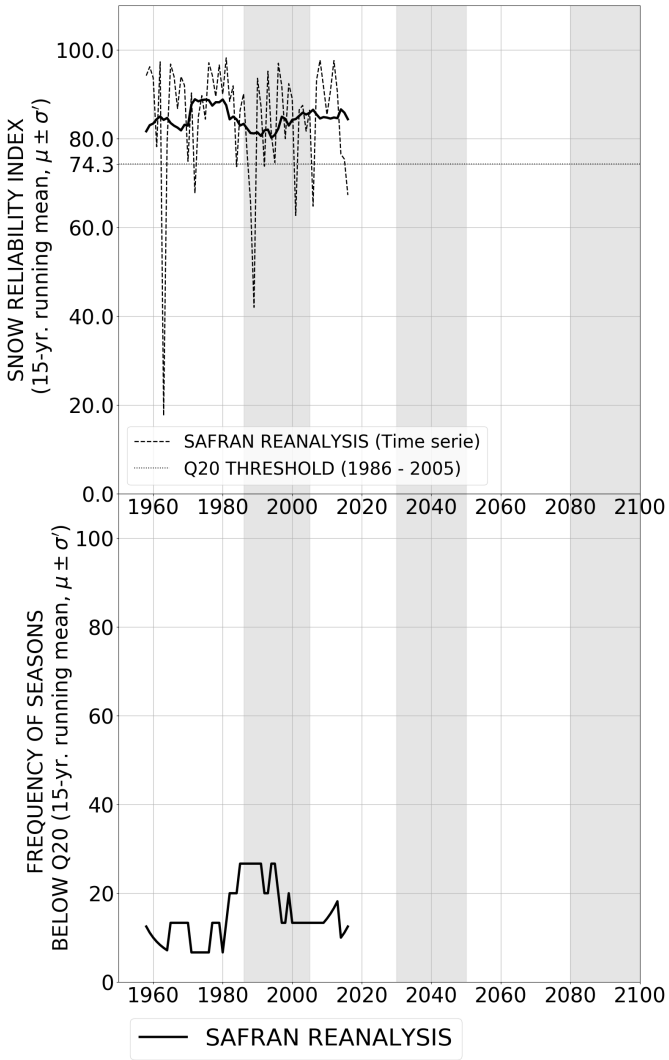
[11] Defined as the ratio of a given ski resort surface area with a minimum 100 kg m^{-2} of snow on the ground, on average for the Christmas and New Year holidays (17%) and February school holidays (83%). Proved significantly correlated to ski lifts tickets sales over 2001 - 2016.

[12] Defined as the the sixth worst reliability index over the 30 years period 1986 - 2016 in groomed snow conditions only (no snowmaking)

Results

Impact of future Climate Change on operating conditions of ski resorts in the French Alps

Groomed snow conditions



Results

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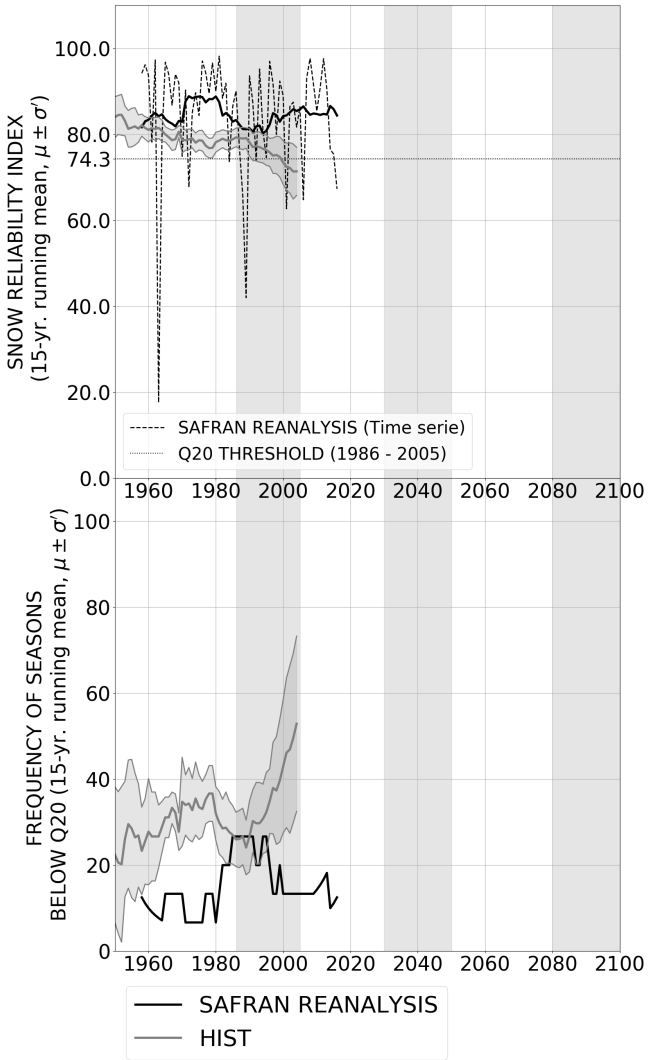
Groomed snow conditions



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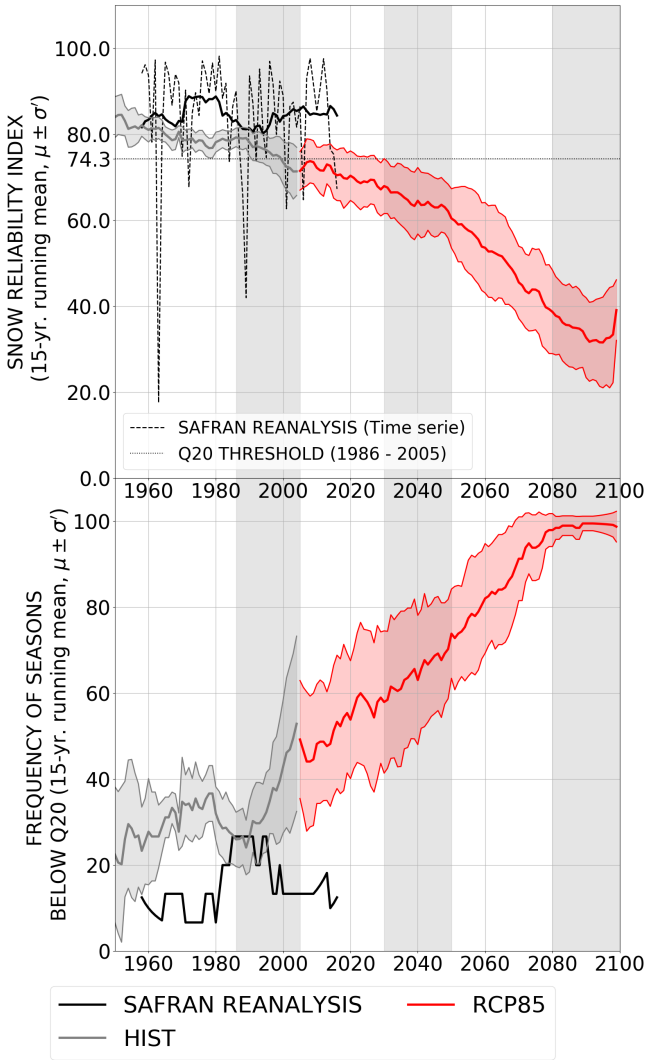
Groomed snow conditions



Results

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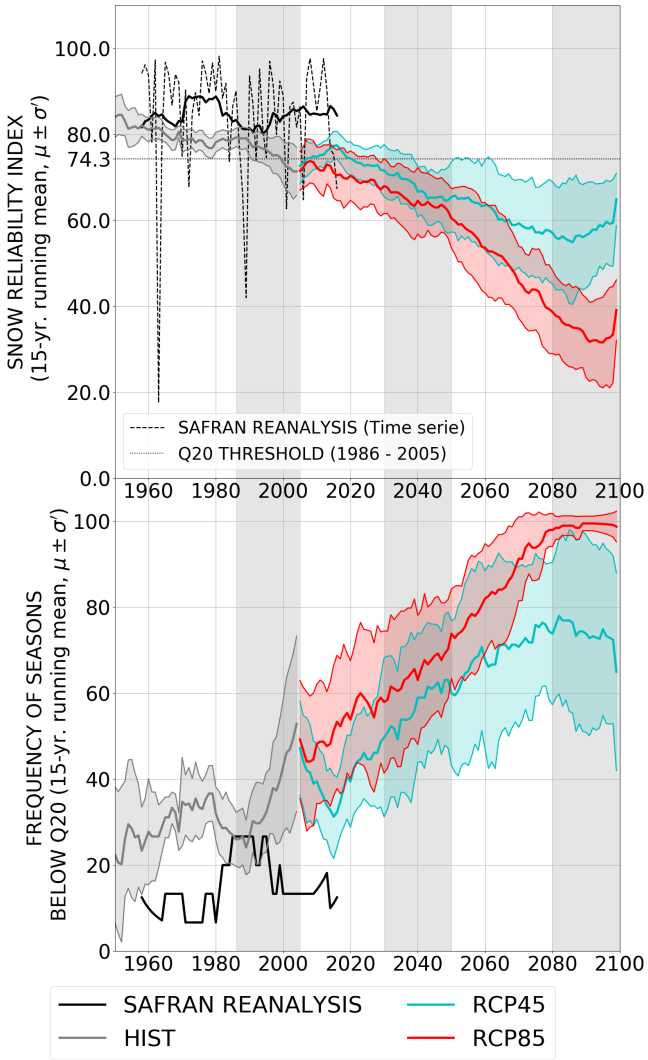
Groomed snow conditions



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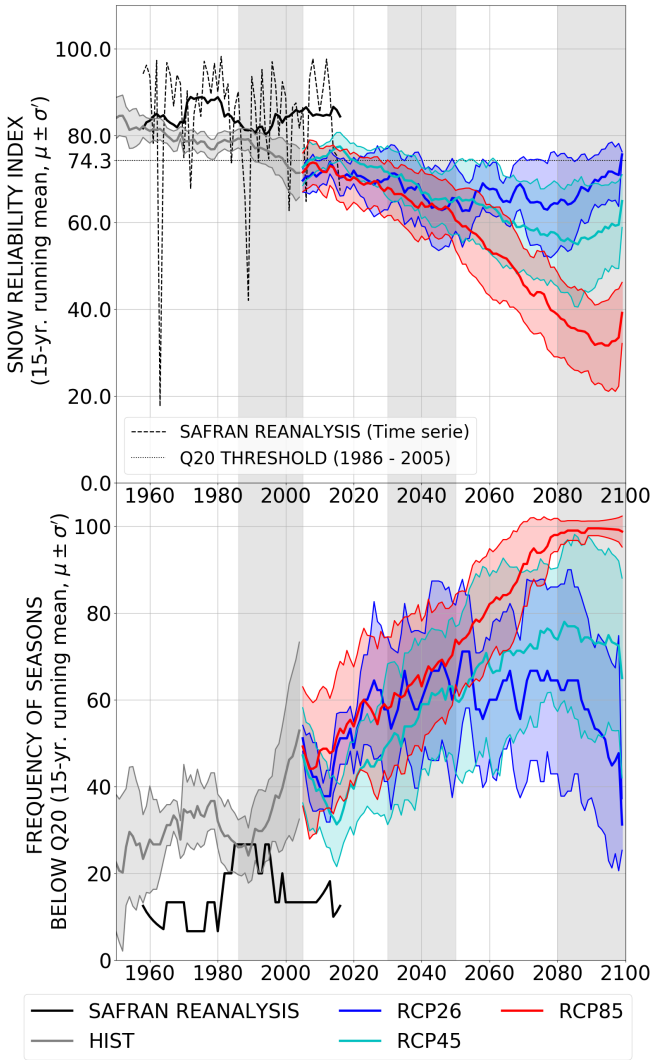
Groomed snow conditions



Time Slot		French Alps ski resorts: Snow Reliability Index (SRI) $\mu \pm \sigma'$	French Alps ski resorts: Frequency (SRI $<$ Q20) $\mu \pm \sigma'$
1986 - 2005	SAFRAN	82	20
1986 - 2005	HIST	76 $\pm$ 3	35 $\pm$ 11
2030 - 2050	RCP 2.6	66 $\pm$ 8	65 $\pm$ 19
	RCP 4.5	68 $\pm$ 6	54 $\pm$ 16
	RCP 8.5	65 $\pm$ 8	63 $\pm$ 16
2080 - 2100	RCP 2.6	68 $\pm$ 7	56 $\pm$ 22
	RCP 4.5	57 $\pm$ 13	74 $\pm$ 22
	RCP 8.5	35 $\pm$ 10	99 $\pm$ 2

Aggregated index over the French Alps ski resorts.

Results

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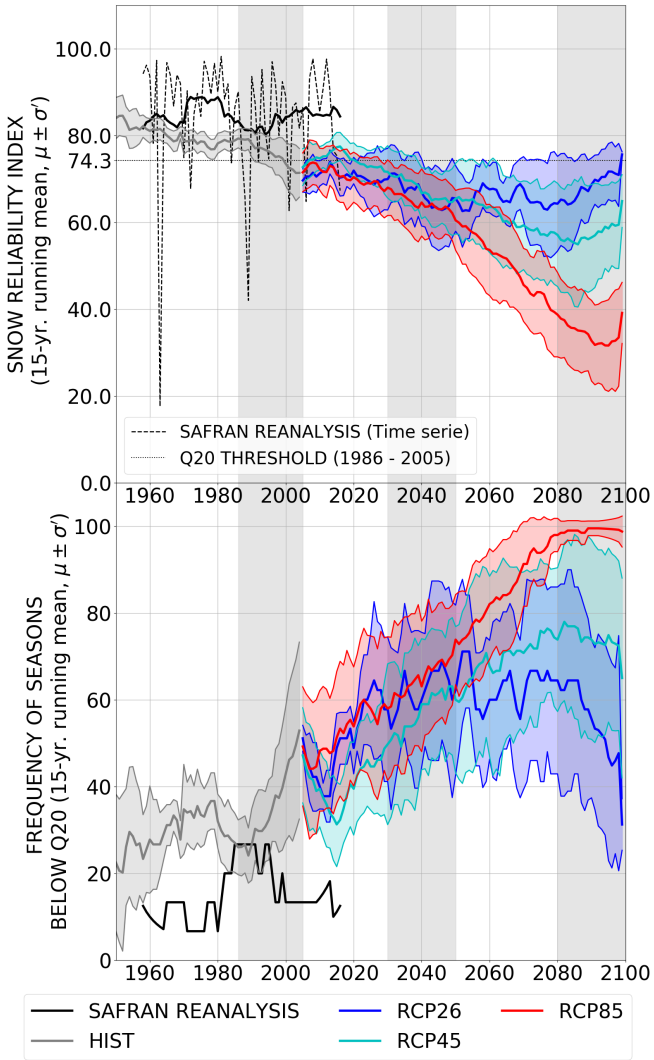
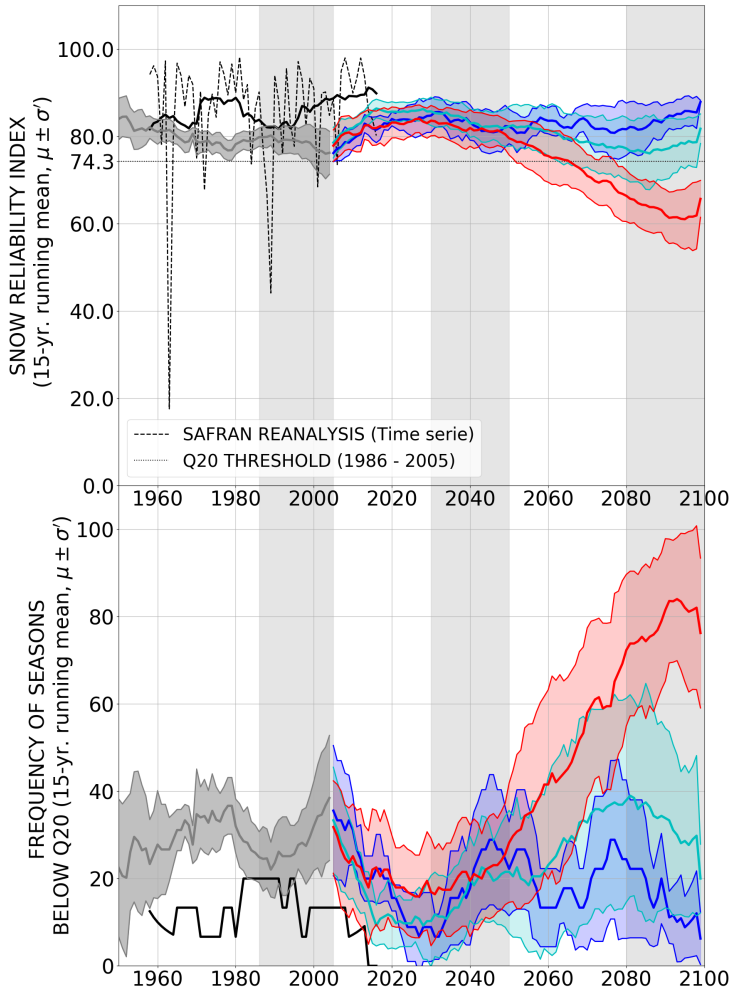
Groomed snow conditions (left) and including Snowmaking (right)





Results

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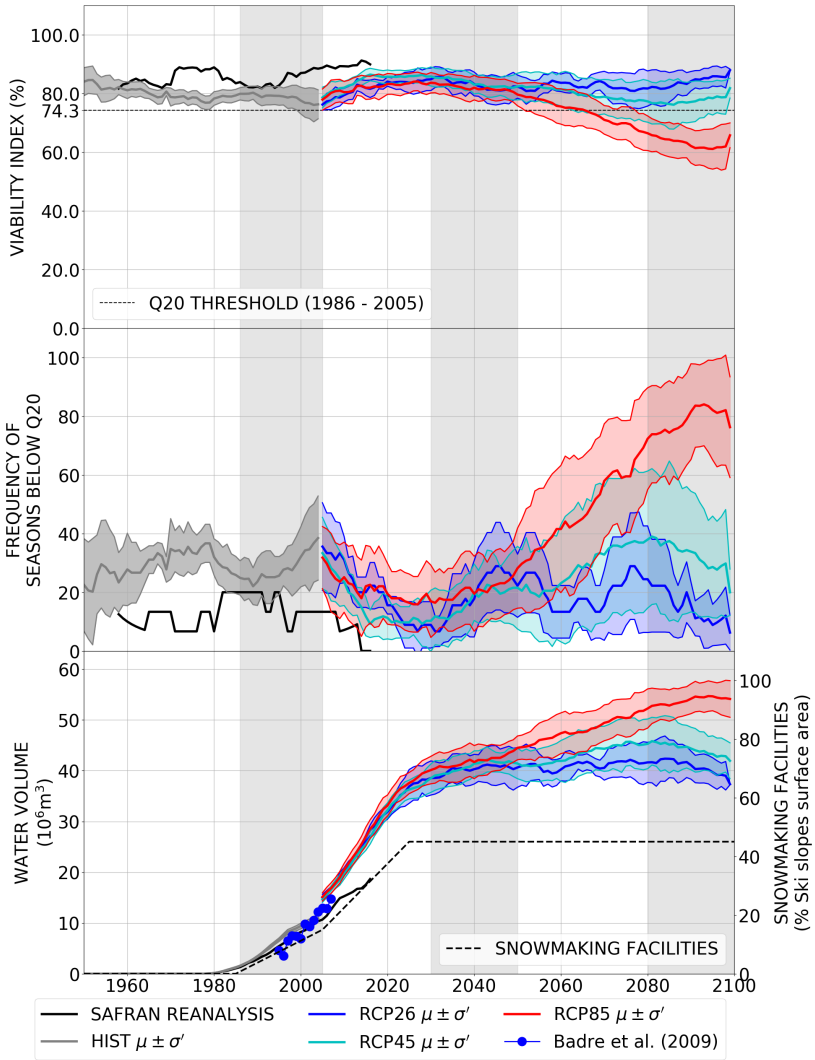
Snow conditions including Snowmaking

Time Slot		French Alps ski resorts: Snow Reliability Index (SRI) $\mu \pm \sigma'$	Frequency (SRI < Q20) $\mu \pm \sigma'$	Water volume (Mm^3) $\mu \pm \sigma'$
1986 - 2005	SAFRAN	83	15	5.2
1986 - 2005	HIST	79 ± 3	28 ± 9	6.5 ± 0.3
2030 - 2050	RCP 2.6	83 ± 4	20 ± 11	40.8 ± 3.7
	RCP 4.5	84 ± 3	17 ± 9	40.5 ± 2.7
	RCP 8.5	82 ± 4	20 ± 12	41.5 ± 3.2
2080 - 2100	RCP 2.6	84 ± 4	15 ± 9	41.0 ± 3.2
	RCP 4.5	78 ± 7	32 ± 23	44.3 ± 4.7
	RCP 8.5	63 ± 7	78 ± 17	53.7 ± 3.2

Evolution of snowmaking facilities from 0% (1985) to 45% (2025)



5th International Conference on Climate, Tourism and Recreation

Work under progress![a]

Thank your for your attention...

and feedback!

[a] Spandre et al. (In prep.), "Climate constraints on ski tourism sustainability in the French Alps in the 21st century" in *xxx*