CLIMATE CHANGE IMPACTS ON THE SNOW RELIABILITY OF FRENCH ALPS SKI RESORTS

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ABSTRACT: The recent evolutions of snowmaking as a mitigation method to address the interannual variability and decrease of natural snow conditions in past decades hampers any relevant investigation of the impacts of climate change on ski resorts activity without accounting for this technology. We introduce here an original approach based on a physically based snowpack model forced by adjusted EURO-CORDEX data over the French Alps, crossed with spatial representations of ski areas, to provide detailed snow conditions at the scale of a single ski resort. Based on 129 French Alps ski resorts (totaling more than 90% capacity), snow reliability indicators were computed with this approach and proved significantly correlated with annual skier days and water requirements for snowmaking. Snowmaking appears as an efficient mitigation method for the near future (2030 – 2050), by means of a significant increase of water requirements due to both the projected increase of surface area equipped with snowmaking facilities and the increasing need for snowmaking due to decreasing natural snow conditions. At the end of the 21st century, the evolution of snow conditions highly depends on the climate scenario and despite increasing water requirements, snowmaking might not be efficient in mitigating the impacts of climate change on the snow reliability of French Alps ski resorts.

KEYWORDS: Ski resorts, Snow Reliability, Snowmaking, Climate Change.

1. INTRODUCTION

Snowmaking as part of the snow management process in worldwide ski resorts is now a central method for the mitigation of the natural variability and on-going decrease of natural snow conditions due to climate changes (Steiger *et al.*, 2017, Beniston *et al.*, 2018). The present work introduces an innovative approach for the investigation of the evolution of the snow reliability in French Alps ski resorts under both the constraints due to climate change impacts (decreasing natural snow conditions and suitable periods for snowmaking due to increasing temperatures) and the effort by ski resorts stakeholders to mitigate these impacts through increasing facilities and snow production. This approach uses a physically based snowpack model forced by adjusted EURO-CORDEX data over the French Alps crossed with spatial representations of ski areas to provide detailed snow conditions at the scale of a ski resort and applied in the present work to a sample of 129 French Alps ski resorts.

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2. MATERIAL AND METHODS

2.1 Snowpack modelling

The multilayer snowpack model SURFEX/ISBA – Crocus (Vionnet *et al.*, 2012) explicitly solves the equations governing the energy and mass balance of the snowpack. The "Crocus Resort" version of the model allows taking into account the effect of grooming and snowmaking on the snow properties (density, microstructure) to provide simulations of a ski slope snow conditions (Spandre *et al.*, 2016b). The impacts of grooming are simulated and machine made snow can be added to the snowpack specifying the precipitation rate ($1.2.10^{-3}$ kg m^{-2} s^{-1}), conditions for triggering the production (wet-bulb temperature threshold T_w < - 2°C, wind speed < 4.2 m s^{-1}), and target quantity of snow: a minimum 150 kg m^{-2} of snow is produced from November 1 to December 15 and further snow is produced until February 28 if snow depth is lower than 60 cm.

2.2 EUROCORDEX Climate Projections

This study uses the EURO-CORDEX dataset (Jacob *et al.*, 2014, Kotlarski *et al.*, 2014) consisting of six regional climate models (RCMs) forced by five different global climate models (GCMs) from the CMIP5 ensemble (Taylor *et al.*, 2012) over Europe, for the historical, RCP 2.6, RCP 4.5 and RCP 8.5 scenarios (Moss *et al.*, 2010). All EURO-CORDEX data were adjusted using the ADAMONT method (Verfaillie *et al.*, 2017). Historical runs generally cover the period 1950 – 2005 and RCPs cover the period 2006 – 2100 (Table 1). The SAFRAN meteorological observational dataset at hourly time resolution was used as a reference over the historical period 1958 – 2016 (Durand *et al.*, 1993).

2.3 Spatial representation of ski resorts

The geographical location of ski lifts was used to infer an estimate of ski slopes at the scale of a single ski resort (François *et al.*, 2014). We refer here to the representation of ski slopes named “gravitational envelopes” (25 m spatial resolution pixels) derived from the ski lifts locations and defined as the ensemble of points that can be reached from the top of a ski lift and from where the bottom of a ski lift can be reached. Since 1985 snowmaking facilities have been increasingly used in French Alps ski resorts with approximately 15% of ski slopes surface area equipped with this technology in 2005, 30% in 2015 and 45% projected in 2025 (Spandre *et al.*, 2015). Similarly to the “gravitational envelope”, we designed for every ski resort a “snowmaking envelope” i.e. the area for the set up of snowmaking facilities based on priority rules (Spandre *et al.*, 2016a) and a target ratio of equipped ski slope surface area (15, 30 or 45%).

2.4 Snow reliability indicators

Every day the simulated snow conditions are associated to every pixel within the gravitational envelope of a ski resort based on its main geographical features: elevation, slope angle, slope aspect and whether the pixel is within the “snowmaking envelope”. A daily snow reliability index (%) was defined as the ratio of the surface area of the gravitational envelope with a minimum quantity of snow for skiing (100 kg m^{-2}). The annual snow reliability index of a ski resort is further derived from daily indexes of Christmas and February holidays (Spandre *et al.*, *Under Review*) and can be aggregated, weighted by the ski lift power of every resort, to provide a snow reliability index over all French Alps ski resorts (François *et al.*, 2014).

A snow scarcity threshold was defined as the quantile 20% (Q20) of the annual snow reliability index based on groomed snow conditions (no snowmaking) over the SAFRAN past period (1958 – 2016). This threshold corresponds to 20% of snow seasons which have been highly challenging for the ski tourism economy in the past years, thereby providing context for upcoming decades. Computing the value of this threshold was derived from a bootstrap method (n = 10 000 resampling of snow reliability index values) and defined as the quantile 10% of computed quantile Q20 from the resampling.

The annual water volume for snowmaking can also be computed for every ski resort based on the simulated amount of Machine Made (MM) snow for every pixel within the “snowmaking envelope”. The annual French Alps water volume for snowmaking is the sum of all ski resorts water volume, usually expressed in millions of cubic meters (Mm^3).

RCM (institute) / GCM	Period	CNRM-CM5	EC-EARTH	HadGEM2-ES	MPI-ESM-LR	IPSL-CM5A-MR
CCLM 4.8.17 (CLMcom)	HIST	1950 - 2005	1950 - 2005	1981 - 2005	1950 - 2005	
	RCPs	2006 - 2100	2006 - 2100	2006 - 2099	2006 - 2100	
ALADIN 53 (CNRM)	HIST	1950 - 2005				
	RCPs	2006 - 2100				
WRF 3.3.1F (IPSL-INERIS)	HIST					1951 - 2005
	RCPs					2006 - 2100
RACMO 2.2E (KNMI)	HIST			1981 - 2005		
	RCPs			**2006 - 2099**		
REMO 2009 (MPI-CSC)	HIST				1950 - 2005	
	RCPs				**2006 - 2100**	
RCA 4 (SMHI)	HIST	1970 - 2005	1970 - 2005	1981 - 2005	1970 - 2005	
	RCPs	2006 - 2100	**2006 - 2100**	2006 - 2099	2006 - 2100	

Table 1. EURO-CORDEX GCM–RCM combinations used in this study (rows: RCMs; columns: GCMs), with the time period available for the HIST and RCP 4.5 and 8.5 scenarios (RCPs). Model combinations additionally using RCP 2.6 are displayed in bold. Contributing institutes are indicated inside parentheses – CLMcom: Climate Limited-area Modelling community with contributions by BTU, DWD, ETHZ, UCD,WEGC; CNRM: Météo France; IPSL-INERIS: Institut Pierre Simon Laplace, CNRS, France – Laboratoire des Sciences du Climat et de l’Environnement, IPSL, CEA/CNRS/UVSQ – Institut National de l’Environnement Industriel et des Risques, Verneuil en Halatte, France; KNMI: Kingdom of Netherlands Meteorological Institute, Ministry of Infrastructure and the Environment; MPI-CSC: Max Planck Institute for Meteorology, Climate Service Center, Hamburg, Germany; SMHI: Swedish Meteorological and Hydrological Institute, Rossby Centre, Norrköping Sweden

3. RESULTS

3.1 Definition of a snow scarce season

The snow scarcity threshold (Q20 = 74.6%) was defined based on past groomed snow conditions aggregated over all French Alps ski resorts. During the reference period (1986 – 2005) four seasons showed snow reliability values below this threshold: 1988-1989, 1989-1990, 1992-1993 and 2001-2002. The three first ones are often referred to as the "early 1990's snow scarce seasons" and highlighted for the first time the dependency of winter tourism to natural snow conditions and climate variability. Their impact on the economic activity of ski resorts played a large role in the on-going development of snowmaking in the French Alps (Spandre *et al.*, 2015). Since 2006, two additional snow seasons showed reliability index lower than the Q20 threshold: 2006-2007 and 2016-2017.

3.2 Impact of snowmaking during the Reference period (1986 – 2005)

During the reference 1986 – 2005 period, the snow reliability of the scarcest snow seasons (Q5) is simulated to have improved from 50% without snowmaking to 55% including snowmaking while the most abundant snow seasons remained steady (Q95), by means of annual water consumptions for snowmaking ranging between 1 Mm^3 (Q5) and 14 Mm^3 (Q95), with a median of 6 Mm^3 (Table 2). These computations of the snow reliability index and simulated water volumes (Table 2) proved significantly correlated with, respectively, skier days over the 2001 – 2016 period (Spandre *et al.*, *under review*) and with observations of water volumes used for snowmaking over the 1995 – 2006 period (Badré *et al.*, 2009). Such conclusions can be reached at all elevations with distinct magnitude. As an example, the snow reliability of scarcest snow seasons (Q5) at lowest elevations (ski resorts with median elevation below 1350 m.a.s.l) are simulated to have improved from 16% without snowmaking to 23% including snowmaking (+7%) while the snow reliability of the most abundant snow seasons has remained steady (Q95), by means of a maximum annual water consumption (Q95) of 0.5 Mm^3.

3.3 Impact of climate change in near future (2030 - 2050)

For the near future (2030 - 2050), groomed snow reliability may decrease by 17% (Q5 and Q17) to 4% (Q95) while the projected increase of equipped ski slopes with snowmaking facilities may improve the snow reliability of scarcest snow seasons by 9% (Q5) to 6% (Q17) and mitigate the decrease of the snow reliability of the most abundant snow seasons (Q50, Q83, Q95, Table 2). Considering the decreasing natural snow conditions and increasing surface area equipped with snowmaking facilities, the water volume requirements for snowmaking would therefore increase. Assuming a 45% surface area equipped with snowmaking facilities for the near future, the simulated water volume would range between 27 Mm^3 (Q5) and 54 Mm^3 (Q95) with a median 42 Mm^3. The decreasing natural snow conditions would be responsible for a 10 to 20% increase of snowmaking requirements if considering a constant equipment rate between the reference period and the near future. The significant increase of water requirements for snowmaking (about a factor 7 for the median requirements compared to the reference period) would remain highly dependent on the evolution of the surface area equipped with snowmaking facilities. Such conclusions could also be reached at all elevations. As an example, the groomed snow reliability at lowest elevations (ski resorts with median elevation below 1350 m.a.s.l) may decrease by 14% (Q5), 22% (Q17) to 7% (Q95) while the projected increase of snowmaking facilities may improve the snow reliability by 18% (Q5), 8% (Q17) to 2% (Q95), by means of an annual water consumption ranging between 1.0 Mm^3 (Q5) and 2.0 Mm^3 (Q95) with a median 1.5 Mm^3. It is interesting to note in the case of a constant 45% equipment in snowmaking facilities that the snow reliability decreases in the near future compared to the reference period. This may be related to the decrease of natural snow conditions at all elevations combined to the higher occurrence of snow scarce seasons with low production at lower elevations related to the lack of suitable meteorological conditions for snowmaking. For the near future, these conclusions do not depend on the RCP scenario with similar evolutions of snow conditions and temperatures between scenarios due to the inertia of the climate system and the past emissions of greenhouse gases.

3.4 Impact of climate change by the end of century (2080 – 2100)

By the end of the century, the evolution of snow conditions is highly dependent on the RCP scenario (Table 2). Groomed snow reliability may remain steady (RCP2.6, data not shown), slightly decrease and stabilize (RCP 4.5) or continuously decrease (RCP8.5) compared to the near future, consistently with underneath assumptions of the global greenhouse gases emissions and related increase of the air surface temperature. It is interesting to note for the RCP4.5 a distinct evolution of the groomed snow reliability with a lower decrease of the most abundant snow seasons from 5% (Q83) to 3% (Q95) and a higher, continuous 14% (Q17) to 21% (Q5) decrease of the scarcest snow seasons compared to the near future. The snow reliability including a constant 45% snowmaking (RCP 4.5) between the near future and end of the century may decrease by 2% (Q50, Q83, Q95), 9% (Q17) and 13%

(Q5), by means of annual water consumptions ranging between 28 Mm^3 (Q5) and 53 Mm^3 (Q95) with a median 41 Mm^3. A significant evolution of the groomed snow conditions is expected for the RCP8.5 with the snow reliability of scarcest snow seasons Q5 and Q17 below respectively 5% and 20% and a frequency of seasons showing a snow reliability index lower than the snow scarcity threshold higher than 95%. These conclusions can be reached at all elevations. The groomed snow reliability are projected to decrease by 35% (Q17) to 24% (Q95) compared to the near future. The snow reliability including a constant 45% snowmaking between the near future and end of the century are projected to decrease by 24% (Q17) to 14% (Q95) despite an increasing consumption of water ranging between 42 Mm^3 (Q5) and 66 Mm^3 (Q95) with a median 54 Mm^3 by the end of the century. The increasing occurrence of scarce snow seasons with low production due to the lack of suitable meteorological conditions may be over compensated by the increasing need for snowmaking at higher elevations (data not shown). Hypothetically, if snowmaking equipment keep increasing after the near future until covering 100% of ski slopes surface area by the end of the century, the snow reliability would range between 84% (Q5) and 98% (Q95), by means of annual water consumptions ranging between 88 Mm^3 (Q5) and 143 Mm^3 (Q95) with a median 115 Mm^3 (about a factor 20 with median requirements for the reference period).

			SNOW RELIABILITY INDEX (%)					WATER VOLUMES (Mm^3)				
Time Slot	**Scenario**	**Snowmaking facilities (%)**	Q5	Q17	Q50	Q83	Q95	Q5	Q17	Q50	Q83	Q95
Reference **(1986 – 2005)**	HIST	0% (grooming)	50	64	80	90	95					
		Evol.	55	67	82	91	95	1	2	6	11	14
		45%	74	82	90	95	97	25	29	35	43	47
Near Future **(2030 - 2050)**	RCP 8.5	0% (grooming)	33	47	67	83	91					
		45%	64	73	83	92	96	27	34	42	49	54
End of Century **(2080 – 2100)**	RCP 4.5	0% (grooming)	12	33	62	79	88					
		45%	51	64	81	90	94	29	36	44	53	59
	RCP 8.5	0% (grooming)	2	12	34	56	67					
		45%	43	49	64	77	82	42	46	54	61	66

Table 2. Evolution of the snow reliability index (%) and water volume (Mm^3) for snowmaking of French Alps ski resorts for the reference period 1986 - 2005, near future (2030 – 2050) and end of century (2080 – 2100), depending on the RCP scenario and the surface area of equipped ski slopes with snowmaking facilities (in % of total ski slopes surface area). “Evol.” refers to the situation of a linear increase of snowmaking facilities between 0% (1985) and 15% (2005). Snow reliability values below the snow scarcity threshold (Q20, corresponding to 74.6%, see section 3.1) are highlighted in orange.

4. CONCLUSIONS

The evaluation of the impact of snowmaking on the snow reliability of French Alps ski resorts was investigated in the present work along with the expected evolutions due to the climate change during the 21st century based on a physically based approach of snowpack evolution forced by EUROCORDEX dataset and crossed with detailed geographical information on ski resorts. By near future (2030 – 2050), the conclusions do not depend on the climate scenario with similar computed impacts. The use of snowmaking on increasing surface area may be a technically efficient method to mitigate (Q50, Q83, Q95) or even improve (Q5, Q17) the reliability of snow conditions, by means of a significant increase of water volume requirements and related costs. Beyond the near future, the evolution of snow conditions would highly depend on the scenario and despite increasing water requirements, snowmaking might not be efficient in mitigating the impacts of climate change on the snow reliability of French Alps ski resorts. This might be the consequence of a combined effect of increasing snowmaking requirements at high elevations due to the decreasing reliability of natural snow conditions and the decreasing snow reliability at lower elevations where snowmaking may no longer be efficient in mitigating the snow scarcity. The feasibility of such production would however remain dependent on the availability of the water resource at affordable costs, a major issue which is beyond the scope of the present work.

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