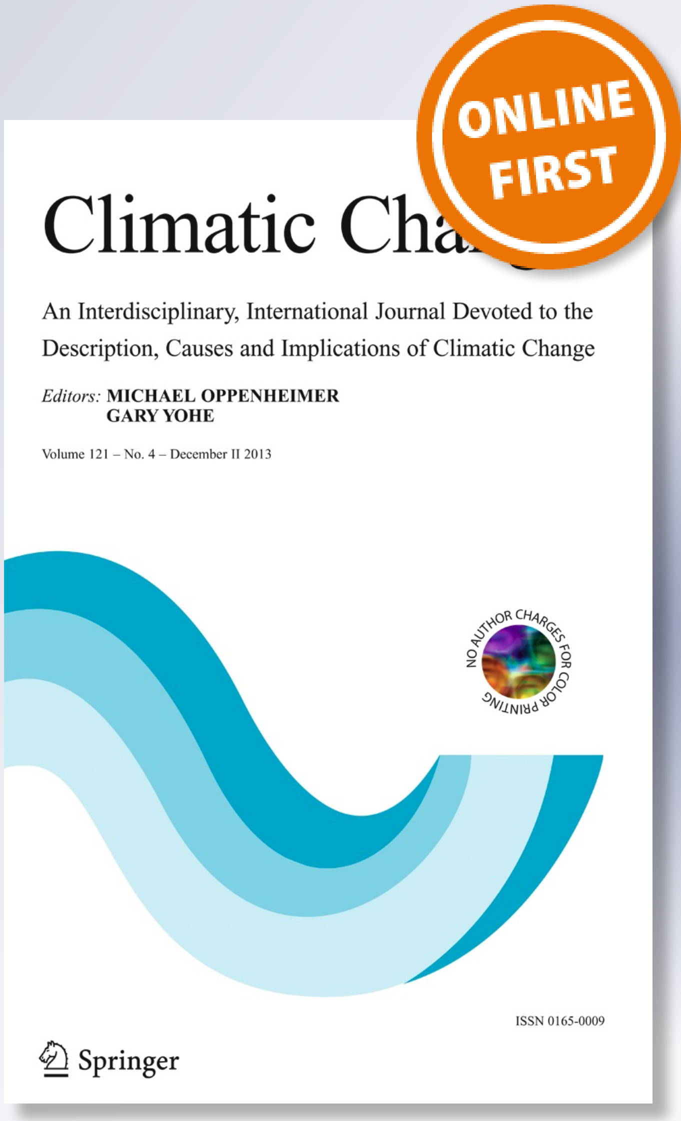
Projected 21st century snowfall changes over the French Alps and related uncertainties

Marie Piazza, Julien Boé, Laurent Terray, Christian Pagé, Emilia Sanchez-Gomez & Michel Déqué

Climatic Change
An Interdisciplinary, International Journal Devoted to the Description, Causes and Implications of Climatic Change

ISSN 0165-0009

Climatic Change
DOI 10.1007/s10584-013-1017-8



Springer

Climatic Change
DOI 10.1007/s10584-013-1017-8

Projected 21st century snowfall changes over the French Alps and related uncertainties

Marie Piazza · Julien Boé · Laurent Terray · Christian Pagé · Emilia Sanchez-Gomez · Michel Déqué

Received: 15 February 2012 / Accepted: 19 November 2013

Abstract Snowfall changes in mountain areas in response to anthropogenic forcing could have widespread hydrological, ecological and economic impacts. In this paper, the robustness of snowfall changes over the French Alps projected during the 21st century and the associated uncertainties are studied. In particular, the role of temperature changes on snowfall changes is investigated. Those issues are tackled through the analysis of the results of a very large ensemble of high-resolution regional climate projections, obtained either through dynamical or statistical downscaling. We find that, at the beginning and at the end of the cold season extending from November to March (included), temperature change is an important source of spread in snowfall changes. However, no link is found between temperature and snowfall changes in January and February. At the beginning and at the end of the cold season, the rate of change in snowfall per Kelvin does not depend much on the bias correction step, the period or the greenhouse gas scenario but mostly on the downscaling method and the climate models, the latter uncertainty source being dominant.

1 Introduction

Mountains areas are among the regions where particularly severe climate changes are expected to occur within the 21st century. As a matter of fact, they already have experienced larger temperature changes than the global average one during the 20th century (Beniston 2003, 2012). Most areas of the Alps have experienced warming up to 2 °C since the beginning of the 20th century (Schöner et al. 2000; Durand et al. 2009) with often no clear differences relatively to altitude. For instance, the Swiss Alps temperature trends over 1931–2010 are remarkably coherent despite differences in altitude and geographic location of the various observation sites (Beniston 2012). Based on observations and reanalyses, many studies have already documented the related decrease in snow cover and its acceleration since the 1980s in several low-to-mid altitude alpine regions (Laternser and Schneebeli 2003; Martin and Etchevers 2005; Durand et al. 2009; Hantel et al. 2000; Schöner et al. 2000; see also Beniston 2012 for a recent review

M. Piazza (✉) · J. Boé · L. Terray · C. Pagé · E. Sanchez-Gomez
Sciences de l'Univers au CERFACS, CERFACS/CNRS, URA1875, Toulouse, France
e-mail: piazza@cerfacs.fr

M. Déqué
Météo-France/CNRS, CNRM-GAME, UMR3589, Toulouse, France

Published online: 08 December 2013

and more references as well as Rousselot et al. 2012 for a study on snowpack changes relying on some of the climate model projections we analyze in this paper). They have also investigated the main drivers for the 20th century evolution and identify temperature change as a dominant factor for the low to mid altitude areas while precipitation changes are important for the high elevation regions.

Snow is a defining component of mountains areas, shaping many of their natural and human uniqueness, but making them particularly sensitive to climate change. Hence the effects of climate change on snow cover, and in the first place snowfall, could therefore have widespread impacts. The continental hydrological cycle in those regions could also be profoundly affected by changes in snowfall (Barnett et al. 2005) along with several economic (for example on ski domains and winter tourism (Uhlmann et al. 2009; OCDE 2007) and on hydropower generation) and natural (for example on freshwater ecosystems) consequences. Winter snow cover indeed acts as a reserve of water, helping to sustain spring and/or summer river discharge through snowmelt (Adam et al. 2009). A modification as simple as the ratio between solid and liquid precipitation during winter could therefore have almost year-long impacts on river discharges, through a remodeling of the seasonal cycle, with an increase in run-off during winter and a decrease during spring and summer (e.g. Barnett et al. 2005; Boé et al. 2009). Finally, snow does not simply respond passively to climate change. It is an active actor of those changes, for example through the snow-albedo feedback (Hall and Qu 2006; Salathé et al. 2008).

In contrast with temperature, detecting observed long term precipitation changes has been more difficult due to the very large amplitude of interannual to decadal variability and sensitivity to the considered spatial scales. This leads to contrasted precipitation trend estimates that depend on season (Frei and Schär 1998) and regions (Beniston 2012; see also Durand et al. 2009 for the French Alps where no significant trends are observed). Interannual to decadal precipitation changes are related to low-frequency changes in climate regimes (such as the North Atlantic Oscillation), due to competing influences between ocean forcing (in particular from the North Atlantic and the Mediterranean) and internal atmospheric variability.

Unfortunately projecting climate change in mountainous areas, and in particular precipitation changes, is especially challenging. Orography, a key factor in shaping landscape-scale climate variability and change, is currently poorly represented in current global climate models. As the phase of precipitation is highly dependent on temperature, a poor representation of orography can have disproportionate effect on snowfall, both in the present and future climates. Orography, through forced lifting of air masses, is also very important for precipitation generation. Consequently, several downscaling methodologies have been developed to better take into account the effect of sharp physiographic features of mountain areas in climate projections. Even if it is now possible to have a more realistic view of mountain climate future changes, important uncertainties remain, some of them being specifically associated with downscaling methodologies themselves as well as model uncertainty (Frei et al. 2003; Beniston 2012; Dutra et al. 2011).

Here we wish to address the difficult question of future precipitation (with a focus on snowfall) changes over the Alps along the 21st century. Soncini and Bocchiola (2011) have suggested that great caution is needed when one wants to use raw results from coarse resolution global coupled general circulation models (GCM) to produce snowfall projections at regional scales. Indeed, it is well known that a bias correction step is absolutely required if one wants to perform regional scale impact studies using climate projections performed by global GCMs. It is worth noting that the bias correction step usually requires the existence of a good quality multiyear observational dataset. It is also well known that the multimodel approach is mandatory as different models can have different biases and responses to the anthropogenic forcing (different climate and hydrological sensitivities). The original aspect of this work is that we use a very large number of high spatial resolution climate projections over the French Alps based on different downscaling approaches (statistical or dynamical downscaling, with or without bias correction for the latter). For instance, in addition to the large set of regional climate models used in the ENSEMBLES project (see http://www.ensembles-eu.org/), we also use results from three very-high resolution (12 km) French regional climate models that have been bias corrected using observations (see http://www.cnrm.meteo.fr/scampei). We also use statistical downscaling techniques to downscale a range of CMIP3 general circulation models. Our main objective is to investigate the robustness of the projected snowfall changes in the French Alps to various sources of uncertainty. We also focus on the associated mechanisms, in particular on the role of temperature changes. The model datasets and downscaling techniques are described in section Data and Model. Then results are discussed in the third section and our main conclusions are drawn in the fourth section.

2 Data and model

An ensemble of 43 regional climate projections is analyzed in this study (Table 1). Both dynamical, through the use of regional climate models (RCM) with or without bias correction, and statistical downscaling approaches are used. Three GHG emission storylines from the Intergovernmental Panel on Climate Change (IPCC) 4th assessment report are considered: A1B, A2 and B1 (note that there are relatively close to the new radiative concentration pathway (RCP) storylines adopted for the 5th assessment report RCP6.0, RCP8.5 and RCP4.5, respectively). The aim of such an ensemble, often called ensemble of opportunity, is to evaluate and eventually sort the different sources of uncertainties in regional climate projections, which are associated to: 1) the emission scenario, 2) the GCM, 3) the downscaling method and eventually, 4) to the bias correction methods. For each time period considered and for each CMIP3 model ensemble simulations, only one member of the ensemble is retained. The period of reference for the current climate is 1961–1990. Note that time periods in the different projections, named subsequently middle and end of 21st century (MC and EC, respectively), do not perfectly match each other because of daily data availability constraints, although they have been optimized to overlap as much as possible among available datasets.

Table 1 List and characteristics of the different ensemble of climate projections used in this study

	Downscaling method		Data treatment		Period		Emission scenario		
	Dynamical	Statistical	Raw	Debiased	Middle	End	A1B	A2	B1
CMIP3 (14)		X	–	–	2046–2065	2081–2100	X		
ARP SCEN (3)		X	–	–	2036–2055	2081–2100	X	X	X
ARP INT (4)		X	–	–	2036–2055	2081–2100	X		
ENSEMBLES (16)	X		–	–	2036–2055	–	X		
ALADIN (3)	X		X	X	2031–2050	2071–2100	X	X	X
LMDZ (2)	X		X	X	2031–2050	2071–2100	X		
MAR (1)	X		X	X	2031–2050	2071–2100	X		

Details about the ensembles are given in the text. The names of the ensembles are given in the left column with the number of associated models (in the case of CMIP3 or ENSEMBLES) or simulations (all other cases) in brackets

2.1 Statistical downscaling

In this study, statistical downscaling has been performed with the software DSClim (Pagé et al. 2009) and is based on previous weather typing and conditional resampling of the days of a reference dataset. The configuration used here is the same as in Boé et al. 2009, both with respect to the number of weather types, the large-scale region and fields, the learning period (1981–2005) and the reference observational dataset, which is the re-analysis SAFRAN (Quintana-Seguí et al. 2008; Vidal et al. 2010). The reader is referred to Boé et al. 2009 for the complete description and evaluation of the method. The basic concept of this statistical downscaling method relies on two steps:

1) the development of a transfer function between large-scale predictors (pressure at sea level and temperature at 2 m over a domain covering Europe and Eastern Atlantic) from the NCEP re-analysis and observed precipitation from SAFRAN at 8 km over France. The transfer function is thus generated in the observed space.
2) the application of this transfer function to the large-scale predictors from the GCMs climate projections to generate downscaled projections at 8 km horizontal resolution over France. Note that this transfer function applied to the model present climate is implicitly correcting most of mean model precipitation biases.

Fourteen GCMs projections for the middle and end of 21st century (2046–2065 and 2081–2100, respectively) from the Coupled Model Intercomparison Project 3 (CMIP3, Meehl et al. 2007b) have been downscaled (see Table 1). Two additional ensembles of time-slice projections with the GCM ARPEGE-Climat in a variable resolution configuration (with a 50-km resolution over Europe, Gibelin and Déqué 2003) have also been statistically downscaled. The first one (ARP-SCEN thereafter) includes three simulations with different greenhouse gases emission scenarios. The second (ARP-INT) has four simulations using the same scenario (A1B) but with slightly different initial conditions.

2.2 Dynamical downscaling

Sixteen regional climate projections from the ENSEMBLES European project (Christensen et al. 2010; Déqué et al. 2012) have been analyzed. Those projections have been obtained through a combination of several GCMs/RCMs originated from several climate modeling centers in Europe (see the project website http://www.ensembles-eu.org/for details). All the RCMs used have a resolution of 25 km over Europe and are forced by the SRES A1B emission scenario. We also study high-resolution climate projections done within the framework of the French project SCAMPEI (Climate Scenarios for Mountain Areas: Extreme Events, Snow Cover and Uncertainties, www.cnrm.meteo.fr/scampei/). Three RCMs have been used at a horizontal resolution of 12 km: ALADIN (Radu et al. 2008; Farda et al. 2010) with three emissions scenarios, LMDZ (Chen et al. 2011) with two sets of boundary forcing and MAR (Gallée et al. 2005).

As we are going to focus on solid precipitation, we now describe in very general terms how this is usually dealt with in GCM/RCMs The fraction of large-scale stratiform solid precipitation (snow) within an atmospheric layer includes a part linked to freezing/melting cloud microphysics processes and a part related to the fall of precipitation within that layer. For the precipitation part, the estimation often differs according to the layer temperature value relative to the triple point. It then depends on the snow fraction and precipitation flux of the upper layer as well as on the precipitation flux at the base of the considered layer For the cloud part, models use different parameterizations of processes acting on cloud water: melting of snow and precipitation freezing. In ALADIN for instance, a scheme based on Smith (1990) and Kessler (1969) is used. The formulation then only depends on the difference between the layer temperature and the triple point temperature, precipitation fluxes at the bottom and above the layer and pressure.

In general, it is necessary to correct the climatological bias of RCM results before using model outputs in order to interpret future climate projections or to force impact models. However, one should be aware that the bias correction step leads to an additional source of uncertainty. Here we use a quantile-quantile correction method to correct model results. This method relies on using distribution function adjustment factors computed for the current climate to correct the RCM future distribution for a given variable and a given season (Déqué 2007). The adjustment factors are derived from a comparison of the model and SAFRAN distribution functions. The reference period to determine the correction function is 1961–1990. In this paper, both raw and bias-corrected results are studied to evaluate the associated uncertainty.

3 Results

The spatial domain of interest in this study is land areas highest than 500 m in the French Alps region and included in the box defined by the following latitude-longitude coordinates: 5°E–7°6′E and 42°9′N–45°8′N. Two sub-regions are considered according to altitude ranges 500 m–1,700 m and higher than 1,700 m, named respectively low and high altitudes in the following (Fig. 1). The seasonal cycle of temperature and snowfall for the 1961-1991 period and averaged over the whole region are shown for both statistically and dynamically downscaled results (Fig. 2). Note that statistically downscaled results (Fig. 2c, e) are very close to the observations as the downscaling method can be simply viewed as a resampling of daily observations. This implies that RCMs biases can be assessed by comparing results from

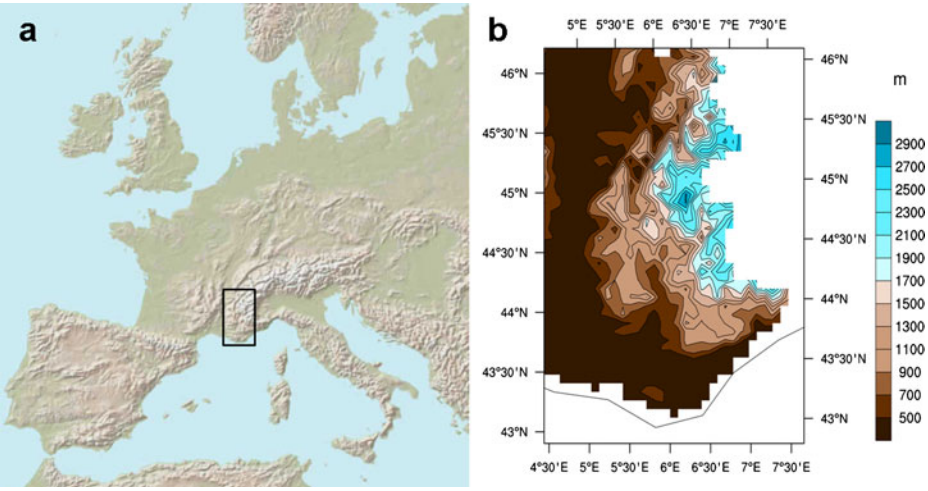
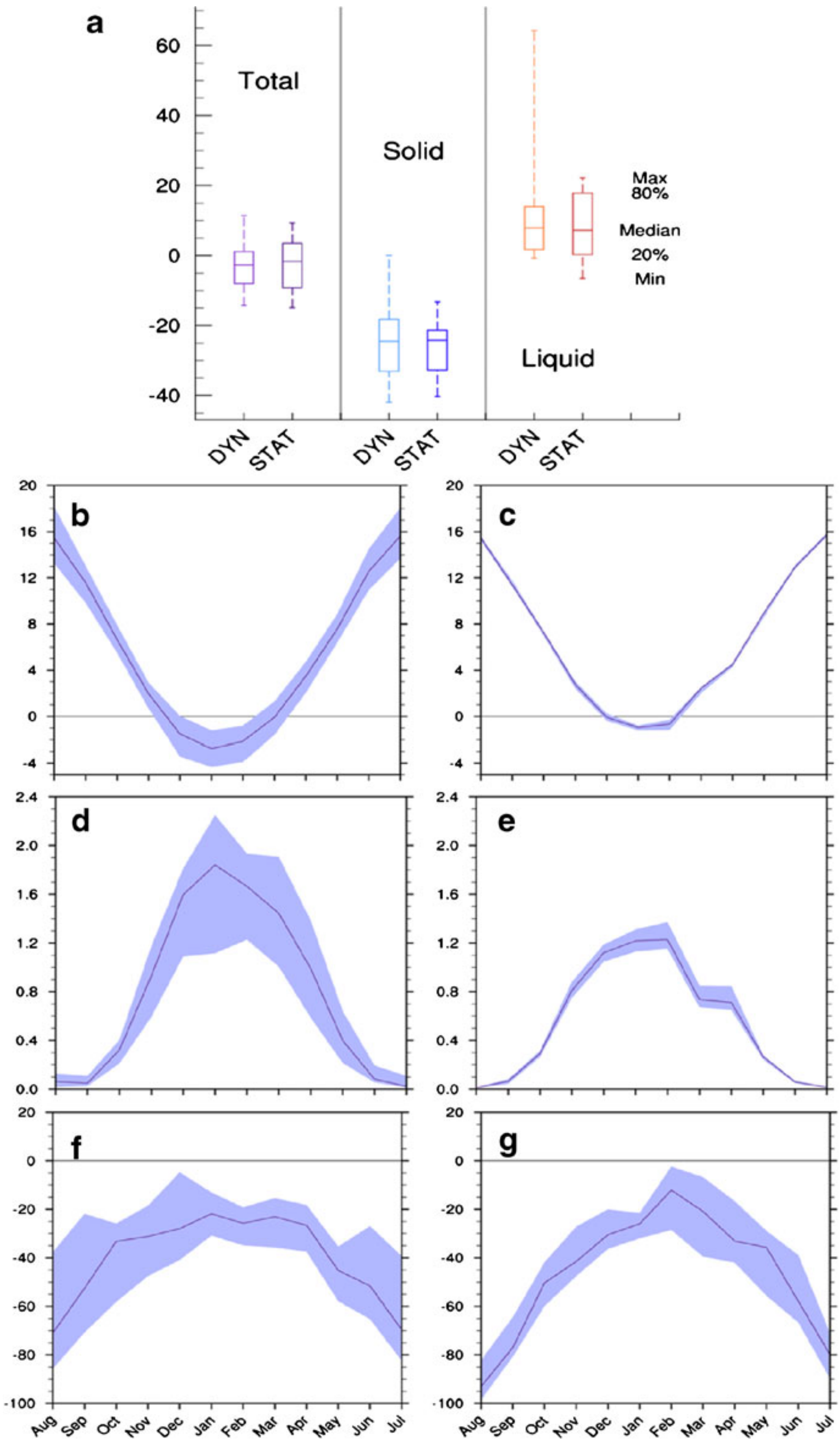


Fig. 1 **a** Topographic map of Western Europe showing the area of study (*black rectangle*). **b** Zoom on the area of study: the French part of Alps topography as represented on the SAFRAN reanalysis grid at 8 km. In this study, two sub-regions are distinguished: low (500 m–1700 m, in *light brown*) and high (>1700 m, in *blue*) altitude sub-regions. Grid points out of France and over the Mediterranean Sea are masked



a
Total
Solid
Liquid
Max
80%
Median
20%
Min
DYN
STAT
b
c
d
e
f
g
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul

◀ **Fig. 2** **a** Boxplots (min/20th quantile/median/80th quantile/max) indicate relative changes (%) in total/solid/liquid/precipitation at the middle of the century for extended wintertime (Nov-Apr), using the A1B scenario, for the ensemble of projections obtained through dynamical (DYN) and statistical (STAT) downscaling methods. Climatological seasonal cycle of (**b**, **c**) temperature at 2 m (°C) and (**d**, **e**) solid precipitation (mm.day^{-1}), for dynamical (**b** and **d**) and statistical (**c** and **e**) downscaling, for the period of reference 1961–1990. (**f**, **g**) Relative changes in the seasonal cycle for solid precipitation (%) for the (**f**) dynamical and (**g**) statistical downscaling ensembles in the middle of 21st century. The *dark line* shows the ensemble median, and the *blue shaded area* depicts the 20 %–80 % inter-quintile range. Note that only the uncorrected RCMs are accounted for in dynamical downscaling in **b**, **d** and **f**

Fig. 2b, d and c, e. The three RCMs thus have a cold bias in the winter months leading to an excess of snowfall.

Solid and liquid precipitation changes for the cold season (November to March) in downscaled climate projections and averaged over the domain of interest are shown in Fig. 2a. The median of total precipitation change over the French Alps is slightly negative, but the sign of the change is very uncertain. Despite small changes in total precipitation, consequent changes in solid and liquid precipitations are projected. In the ensemble mean, the hydrological cycle changes over the Alps during the cold season are largely related to a change of the ratio between solid and liquid precipitation and therefore to temperature.

Snowfall strongly decreases over the French Alps under the A1B storyline, with an ensemble median of -25 % in the middle of the 21st century. All models simulate a decrease in snowfall, but the range of possible changes is large with a 20–80 % inter-quintile range of −20 % to −35 %. Note also that a few models have barely noticeable changes while others simulate decreases as large as −45 %. In parallel, liquid precipitation increases in most models, with an ensemble median change of 10 %. The general consistency between statistically and dynamically downscale results gives confidence in the overall robustness of those results with respect to the downscaling methodology.

The seasonal cycle of snowfall relative changes and the associated uncertainties are depicted in Fig. 2f and g. Both dynamical and statistical downscaling methods give the same general behavior. A seasonal aspect can be identified with largest (relative) decrease in August and July and smaller changes in January and February. The sensitivity of snowfall relative change to temperature is higher in summer than in winter simply because the average temperature is closer to the freezing point during the warmer months.

In agreement with previous studies, these results suggest that changes in temperature, via modifications of the precipitation solid-to-liquid ratio, are very important from an ensemble perspective to evaluate hydrological changes over the French Alps. In the following, we investigate the model uncertainty associated to the snowfall changes. We precisely ask to what extent the spread in temperature changes impact the inter-model spread in snowfall changes.

The inter-model correlation between temperature and snowfall changes is shown for each month of the cold season in Fig. 3a. When the correlation is significant at the 0.05 level, the corresponding regression coefficient is plotted in Fig. 3b. Results are shown separately for high and low altitudes, as well as for statistical and dynamical downscaling methods. Generally, a large inter-model correlation is found between snowfall and temperature changes at the beginning (October, November) and at the end (March, April) of the cold season, with a regression coefficient that varies between −10 and −40 %/K. During those transition months, snowfall is generally limited by too high temperature and therefore an increase in temperature could have large impacts on snowfall. On the opposite, in January and February, temperature changes present a weak relationship with snowfall changes, as shown by non-significant correlations in Fig. 3b. Temperature then is often sufficiently below the freezing point so that an increase of few degrees is not sufficient to change the phase of precipitation. Increase in

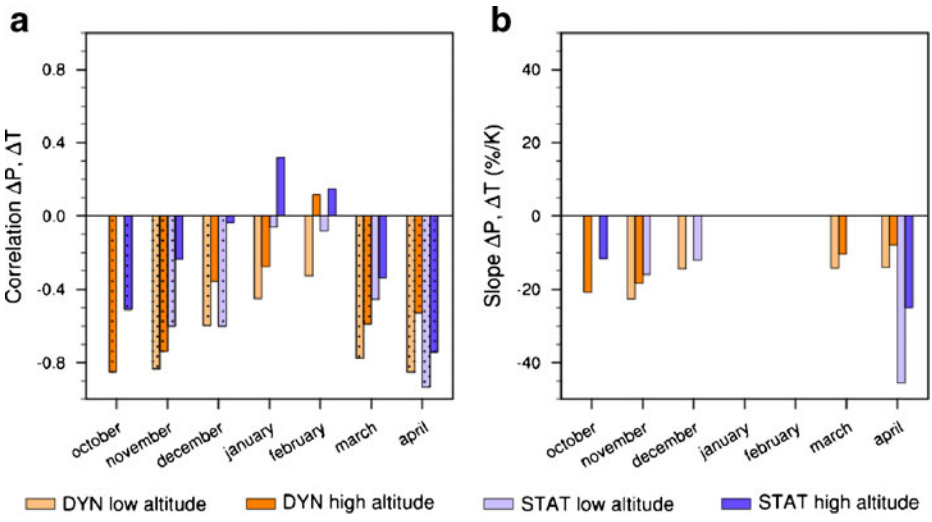


Fig. 3 Monthly inter-model **a** linear correlation and **b** regression coefficients between solid precipitation relative change (ΔP) and temperature change (ΔT), from October to April, for the middle of the century and considering the A1B scenario. *Dots* in Fig. 3a indicate where the correlation is significant at the 0.05 level. Regression coefficients in Fig. 3b are plotted only when the correlation is significant. Results are shown separately for dynamical and statistical downscaling methods, and for low and high altitude areas

temperature could even have an opposite effect on precipitation during the coldest months. As a consequence of the Clausius-Clapeyron relation, which implies a positive relationship between temperature and specific humidity at saturation, atmospheric moisture could be an important limiting factor on precipitation in a very cold and therefore dry atmosphere (Trenberth and Shea 2005). In this case, an increase in temperature and consequently an increase in moisture could result in an increase in precipitation, especially at high altitudes (Christensen et al. 2007). Therefore, there may be a trade off between the direct effect of temperature on precipitation phase and the effect of the increase in moisture associated with temperature rise. It could explain why no significant inter-model relationship, or sometimes even a non-significant positive link, is seen between temperature change and snowfall change during the coldest months.

Temporal variations of the relation between temperature and snowfall changes may mirror the effects of lapse rate with altitude. In particular, a significant relationship between temperature and snowfall change can only be identified at low altitudes in December. During this month, climatological temperatures are already too cold at high altitudes for temperature changes to play any significant role on snowfall, but this is not the case at low altitudes. The same general temporal pattern is seen for statistical and dynamical downscaling methods, likely indicating the robustness of our findings. Nevertheless, a closer inspection reveals some differences. In particular, in March, no significant correlation between temperature and snowfall changes is found with statistical downscaling while a relationship can be identified with dynamical downscaling (Fig. 3a). Conversely, snowfall sensitivity to temperature change is much stronger for statistical downscaling in April (Fig. 3b).

Finally, in Fig. 4 we assess the robustness of simulated snowfall sensitivity to temperature changes. We show the impact of the downscaling method (dynamical versus statistical), the bias-correction step (quantile-quantile correction versus no correction), the period studied, and the greenhouse gas scenario. In the following we characterize this hydrological sensitivity by using the ratio of relative precipitation change to the absolute temperature change. Note that

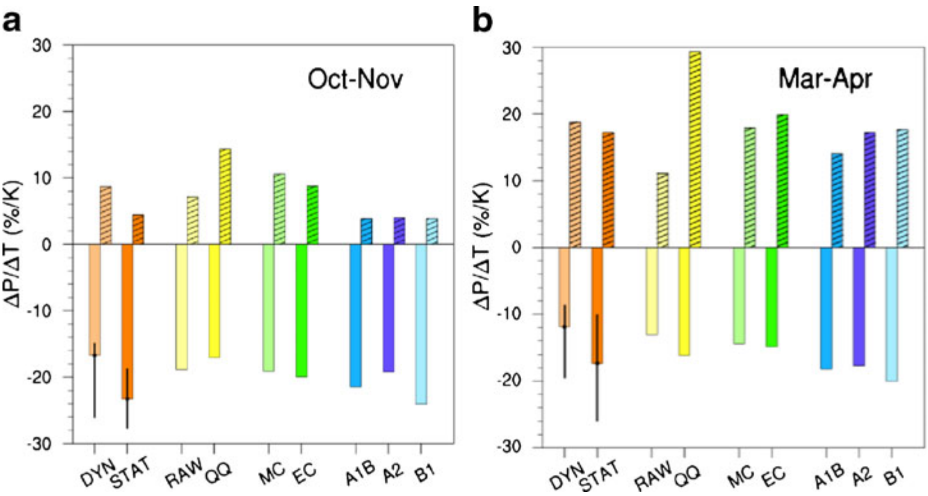


Fig. 4 Ratio between relative snowfall change and temperature change for multiple sets of projections (hatching for liquid precipitation, solid precipitation elsewhere). **a** Average for October-November and **b** March–April. Different comparisons are shown: (1) between statistical (STAT) and dynamical (DYN) downscaling, (2) between raw (RAW) and bias corrected (QQ) results of dynamical downscaling, (3) between the middle (MC) and the end (EC) of the century and (4) between different emission scenarios (A1B, A2, B1). For dynamical downscaling and statistical downscaling, *blacks bars* give the inter-model spread (as measured by the 20–80 inter-quintile range)

the same climate models are used in the comparison, i.e. when comparing the ratio for different periods, the same models are used in the two cases and only the periods differ. Note also that uncertainty bars are only shown for the comparison between statistical and dynamical downscaling (other sample sizes are too small to be useful).

Snowfall sensitivity to temperature change is found to be roughly between −17 % and −24 % per K in October-November (Fig. 4a) and between −12 and −18 % per K in March–April (Fig. 4b), depending on the downscaling technique. Associated changes in liquid precipitation are between 4 %/K and 8 %/K in October–November (Fig. 4a) and between 16 %/K and 18 %/K in March–April (Fig. 4b). While the sensitivity of liquid precipitation change to temperature change is different for corrected and non-corrected results from regional models (respectively 12 %/K and 7 %/K in October–November, and 29 %/K and 11 %/K in March–April) (hatched yellow bars on Fig. 3a and b), the sensitivity of snowfall change is robust to the correction (respectively −19 %/K and −17 %/K in October–November, and −14 %/K and −12 %/K in March–April), showing the potential importance of this step on liquid precipitation.

It is also noted that the link between temperature and snowfall changes does not evolve with time. The sensitivity of snowfall changes to temperature is basically the same for both the mid and end of the century periods. No evidence of any non-linearity is seen here as well as between changes for the different greenhouse gases emission scenarios.

4 Conclusions

Based on a very large ensemble of both statistically and dynamically downscaled high-resolution climate projections, we suggest that large changes in solid precipitation over the French Alps are to be expected in the future climate, with a winter decrease of roughly 25 % in the middle of the 21st century with a 20–80 % quantile range of −20 %–−35 % under the median A1B greenhouse gas scenario.

We find that the projected snowfall relative changes (per degree of warming) are relatively robust among the different downscaling techniques.

Interestingly, temperature changes only play a minor role in snowfall changes uncertainties during winter coldest months. However, in late fall and early spring, the spread in temperature changes is explaining an important part of snowfall change uncertainty. During those months, snowfall sensitivity to temperature changes is not affected by the bias correction step applied to dynamical downscaling results, the chosen projection period or the emission scenario. A limited sensitivity to the type of downscaling approach is found and the dominant source of spread is the climate model (global for statistical downscaling, regional for dynamical downscaling).

The close relationship between temperature change and snowfall change has important consequences. First, it could be argued that changes due to temperature can be better projected than changes due to other processes, like large scale atmospheric circulation (they have a higher signal to noise ratio). Qualitatively, the fact that snowfall changes are closely linked to temperature changes gives therefore higher confidence to the model estimation of those changes. Second, in the middle of the 21st century, temperature changes associated with different emission scenarios are relatively similar (e.g. Fig. 10.4 in Meehl et al. 2007a) while emission scenario at the end of century clearly becomes the dominant source of uncertainties (Hawkins and Sutton 2009). Given the nature of uncertainties associated with the emission scenario and the high dependency of snowfall changes during transition months to temperature, it would be difficult to significantly reduce this part of the uncertainties in late 21st century snowfall projections. However, as model uncertainty is also important all along the 21st century, reducing model bias has the potential to enable improvements in the accuracy of snowfall projections.

Several other research projects are currently interested in the regional impacts of climate change, based on different GCMs and RCMs and using other downscaling methods and scenarios than those presented in this study. This is the case of the French project DRIAS (http://www.drias-climat.fr/) and the international project CORDEX (Coordinated Regional climate Downscaling Experiment) with the European branch EURO-CORDEX (http://euro-cordex.net/) performing a set of fine-scale climate projections over Europe in order to serve impact and adaptation studies to climate change in the context of the Fifth Assessment report of the IPCC.

Acknowledgments This work has been partially supported by the French National Agency (ANR) in the framework of its Scientific Research Vulnérabilité Milieux et Climat (VMC) program (SCAMPEI, project N° ANR-08-VULN-0009-01). The ENSEMBLES data used in this work was funded by the EU FP6 Integrated Project ENSEMBLES (Contract number 505539) whose support is gratefully acknowledged. We acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the World Climate Research Programme's Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, U.S. Department of Energy.

References

Adam JC, Hamlet AF, Lettenmaier DP (2009) Implications of global climate change for snowmelt hydrology in the 21st century. Hydrol Process 23(7):962–972

Barnett TP, Adam JC, Lettenmaier DP (2005) Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438:303–309

Beniston M (2003) Climatic change in mountain regions: a review of possible impacts. Clim Chang 59:5–31

Beniston M (2012) Is snow in the Alps receding or disappearing ? WIREs Clim Chang. doi:10.1002/wcc.179

Boé J, Terray L, Martin E, Habets F (2009) Projected changes in components of the hydrological cycle in French river basins during the 21st century. Water Resour Res 45, W08426

Chen W, Jiang Z, Li L, Yiou P (2011) Simulation of regional climate change under the IPCC A2 scenario in southeast China. Clim Dyn 36:491–507

Christensen JH et al (2007) Regional Climate Projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Christensen JH, KjellstÖm E, Giorgi F, Lenderink G, Rummukainen M (2010) Weight assignment in regional climate projections. Clim Res 44:179–194. doi:10.3354/cr00916

Déqué M (2007) Frequency of precipitation and temperature extremes over France in an anthropogenic scenario: model results and statistical correction according to observed values. Glob Planet Chang 57:16–26

Déqué M, Somot S, Sanchez-Gomez E, Goodess CM, Jacob D, Lenderink G, Christensen OB (2012) The spread amongst ENSEMBLES regional scenarios: regional climate models, driving general circulation models and interannual variability. Clim Dyn 38(5–6):951–964. doi:10.1007/s00382-011-1053-x

Durand Y, Laternser M, Giraud G, Etchevers P, Lesaffre B, Mérindol L (2009) Reanalysis of 44 years of climate in the French Alps (1958–2002): methodology, model validation, climatology and trends for air temperature and precipitation. J Appl Meteorol Climatol 48:429–449. doi:10.1175/2008JAMC1808.1

Dutra E, Kotlarski S, Viterbo P, Balsamo G, Mirando PMA, Schar C, Bissolli P, Jonas T (2011) Snow cover sensitivity to horizontal resolution, parameterizations, and atmospheric forcing in a land surface model. Geophys Res Lett 116, D21109. doi:10.1029/2011JD016061

Farda A, Déqué M, Somot S, Horányi A, Spiridonov V, Tóth H (2010) Model ALADIN as regional climate model for Central and Eastern Europe. Stud Geophys Geod 54(2):313–332. doi:10.1007/s11200-010-0017-7

Frei C, Schär C (1998) A precipitation climatology of the Alps from high-resolution rain-gauge observations. Int J Climatol 18(8):873–900

Frei C, Christensen JH, Déqué M, Jacob D, Jones RG, Vidale PL (2003) Daily precipitation statistics in regional climate models: evaluation and intercomparison for the European Alps. J Geophys Res 108:4124. doi:10.1029/2002JD002287, D3

Gallée H, Peyaud V, Goodwin I (2005) Temporal and spatial variability of the Antarctic Ice Sheet Surface Mass Balance assessed from a comparison between snow stakes measurements and regional climate modeling. Ann Glaciol 41:17–22

Gibelin AL, Déqué M (2003) Anthropogenic climate change over the Mediterranean region simulated by a global variable resolution model. Clim Dyn 20:327–339

Hall A, Qu X (2006) Using the current seasonal cycle to constrain snow albedo feedback in future climate change. Geophys Res Lett 33, L01702

Hantel M, Ehrendorfer M, Haslinger A (2000) Climate sensitivity of snow cover duration in Austria. Int J Climatol 20:615–640. doi:10.1002/joc489

Hawkins E, Sutton R (2009) The potential to narrow uncertainty in regional climate predictions. Bull Am Meteorol Soc 90:1095

Kessler E (1969) On the distribution and continuity of water substance in atmospheric circulation Meteor. Monogr., No. 32, Am Meteorol Soc

Laternser M, Schneebeli M (2003) Long-term snow climate trends of the Swiss Alps (1931–99). Int J Climatol 23:733–750. doi:10.1002/joc.912

Martin E, Etchevers P (2005) Impact of climatic changes on snow cover and snow hydrology in the French Alps. In: Huber UM, Bugmann HM, Reasoner MA (eds) Global change and mountain regions (a state of knowledge overview). Springer, Dordrecht, pp 235–242

Meehl et al. (2007a) Global climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Meehl GA, Covey C, Delworth T, Latif M, McAvaney B, Mitchell JFB, Stouffer RJ, Taylor KE (2007b) The WCRP CMIP3 multi-model dataset: a new era in climate change research. Bull Am Meteorol Soc 88:1383–1394

OCDE (2007) Climate change in the European Alps: adapting winter tourism and natural hazards management. http://www.oecd.org/document/45/0,3746,en_2649_34361_37819437_1_1_1_1,00.html#Info

Pagé C, Terray L et Boé J (2009): dsclim: a software package to downscale climate scenarios at regional scale using a weather-typing based statistical methodology. Technical Report TR/CMGC/09/21, SUC au CERFACS, URA CERFACS/CNRS No1875, Toulouse, France

Quintana-Seguí P, Le Moigne P, Durand Y, Martin E, Habets F, Baillon M, Canellas C, Franchisteguy L, Morel S (2008) Analysis of near-surface atmospheric variables: validation of the SAFRAN analysis over France. J Appl Meteor Climatol 47:92–107

Radu R, Déqué M, Somot S (2008) Spectral nudging in a spectral regional climate model. Tellus A 60(05):898–910

Rousselot M, Durand Y, Giraud G, Mérindol L, Dombrowski-Etchevers I, Déqué M, Castebrunet M (2012) Statistical adaptation of ALADIN RCM outputs over the French Alps—application to future climate and snow cover. Cryosphere 6:785–805

Salathé EP Jr, Steed R, Mass CF, Zahn PH (2008) A high-resolution climate model for the United States Pacific Northwest: mesoscale feedbacks an local response to climate change. J Clim 21:5708–5726

Schöner W, Auer I, Böhm R (2000) Climate variability and glacier reaction in the Austrian eastern Alps. Ann Glaciol 31:31–38

Smith RNB (1990) A scheme for predicting layer clouds and their water content in a general circulation model Q.J.R. Meterol Soc 116:435–460

Soncini A, Bocchiola D (2011) Assessment of future snowfall regimes within the Italian Alps using general circulation models. Cold Reg Sci Technol 68:113–123. doi:10.1016/j.coldregions.2011.06.011

Trenberth KE, Shea DJ (2005) Relationships between precipitation and surface temperature. Geophys Res Lett 32, L14703

Uhlmann B, Goyette S, Beniston M (2009) Sensitivity analysis of snow patterns in Swiss ski resorts to shifts in temperature precipitation and humidity under condition of climate change. Int J Climatol 29:1048–1055

Vidal JP, Martin E, Franchistéguy L, Baillon M, Soubeyroux JM (2010) A 50-year high-resolution atmospheric reanalysis over France with the Safran system. Int J Climatol 30:1627–1644