CLIMATE CHANGE IN THE ALPS AND ITS CONSEQUENCES FOR SNOW

Andreas Gobiet[1*], Sven Kotlarski[2], Prisco Frei[2,3], Jan Rajczak[2,3], Deborah Verfaillie[4,5], Samuel Morin[4]

[1] *Zentralanstalt für Meteorologie und Geodynamik ZAMG, Vienna, Austria*
[2] *Federal Office of Meteorology and Climatology MeteoSwiss, Zurich, Switzerland*
[3] *ETH Zurich, Switzerland*
[4] *Univ. Grenoble Alpes, Université de Toulouse, Météo-France, CNRS, CNRM, Centre d'Etudes de la Neige, Grenoble, France*
[5] *Barcelona Supercomputing Center, Barcelona, Spain*

ABSTRACT: The European Alps are strongly affected by climate change. Since 1880 the average temperatures rose by 2°C, which is about twice the global mean warming. This has important consequences on the regional climate and on society and ecosystems in the Alpine area. In particular snow is an important resource for, e.g., tourism, hydropower generation, and water management. It is also pivotal for mountainous hazards (avalanches, snow melt floods, glacier evolution). This study reviews the current state of knowledge about climate change in the Alps, with particular focus on future perspectives, based on the latest generation of high resolution climate simulations for the Alpine region. Apart from changes in temperature and precipitation (including extremes), the consequences of climate change for natural snow in various regions, elevation-zones, and seasons is analyzed. The results show that, in addition to already observed warming, the Alps are facing further warming of about 0.3°C per decade on average in all seasons and altitude levels in the coming decades. Total precipitation is expected to increase in winter, but uncertainty in these precipitation projections is high. Heavy precipitation is expected to become more severe in all seasons. Depending on elevation and time of the year, snow cover and snowfall will partly be importantly reduced. However, at higher elevations in the mid-winter season, we can partly expect even more snowfall in future, as a consequence of increased winter precipitation.

KEYWORDS: Climate Change, European Alps, Snow.

1. INTRODUCTION

Climate Change has been recognized as one of the major challenges mankind is currently facing. However, considerable regional differences exist in the magnitude of physical changes as well as in the severity of the impacts on society. The European Alps are particularly subject to rapid changes, not only because regional warming in the Alps is about twice the global warming (+2°C since 1880; Auer et al., 2007), but also due to the high susceptibility of the cryosphere (Beniston et al., 2018) and ecosystems in the Alps. In addition, water management, hydropower generation, agriculture and tourism in the greater alpine area are very sensitive to climate change. Last but not least, natural hazards due to gravitational mass movements in the Alps are affected by temperature and precipitation change.

At the same time mountain climate is difficult to analyze, since it features high spatial variability and steep vertical gradients. The resulting patterns of climate and climate change are often highly complex and very demanding in terms of monitoring, modeling, and analysis. Only very recently regional climate models (RCMs) started to resolve scales that roughly account for these patterns. Therefore each new generation of climate scenarios with higher resolution than the generation before carries new information and potentially new insights into the mechanisms of climate change in the mountains. This paper gives a review of the current state-of-knowledge about future climate change in the Alps, based on the latest generation of climate models. It is an update of a previous review (Gobiet et al., 2014), extends the brief analysis of Smiatek et al., (2016) and additionally focuses on changes in extreme precipitation and the seasonal snow cover.

2. DATA AND METHODS

For the analysis of future climate change in the alpine area (Fig. 1) a total of 81 regional climate simulations carried out in the frame of the EURO-CORDEX initiative (Jacob et al., 2014) and spanning the period from 1981 to 2099 were employed. These simulations were carried out at horizontal resolutions of 12 (EUR11) or 50 km (EUR44) and cover three different IPCC emission scenarios: Representative concentration pathways RCP2.6 (13 simulations), RCP4.5 (30 simulations) and RCP8.5 (38 simulations) (van Vuuren et al., 2011). A reduced set of 14 simulations covering only RCPs 4.5 and 8.5 and the higher 12 km resolution is used for the alpine-wide snow cover analysis.

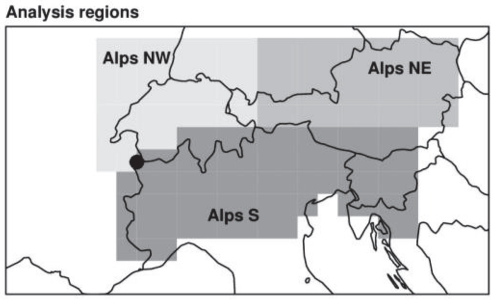

Fig 1: Analysis regions in the European Alps. Results for the entire alpine region, region Alps NE and the case study Mont-Blanc (black dot) are presented.

For the case study Mont-Blanc in the French Alps (section 3.4), a rather similar, but not identical set of simulations from EURO-CORDEX was used: 13 GCM/RCM pairs for the scenarios RCP 4.5 and RCP 8.5, respectively and 4 pairs for RCP 2.6, adjusted against the SAFRAN reanalysis using the ADAMONT adjustment method, followed by the detailed snow model Crocus to compute the evolution of snow on the ground. Full details about the method and data are given in Verfaillie et al. (2017) and Verfaillie et al. (2018).

3. RESULTS

3.1 *Temperature in Alps NE*

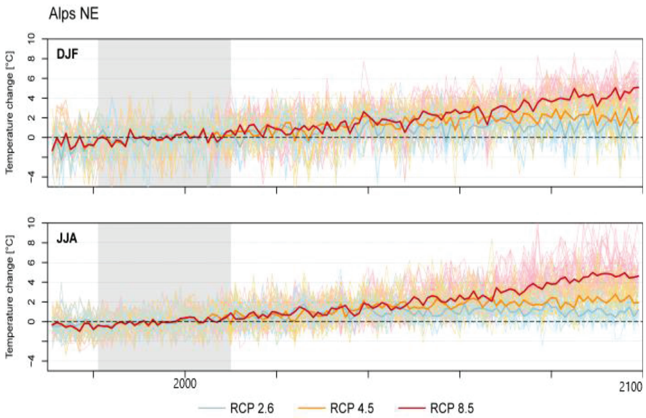

Fig 2: Temperature change time series for Alps NE. The bold lines show the multi-model mean, the thin lines individual model results. Blue lines correspond to RCP2.6, orange lines to RCP4.5 and red lines to RCP8.5.

Fig. 2 shows the (projected) temperature evolution from 1970 until 2100 in the region Alps NE. The other regions in the Alps (not shown) feature very similar results. Until 2050, all emission scenarios show quite similar warming of about 0.3 °C per decade. However, towards the end of the century (Fig. 3), the level of future greenhouse-gas emissions play a crucial role and expected additional warming ranges from slightly over +1°C (RCP2.6) to +4°C (RCP8.5) (Reference period: 1981-2010; future period: 2070-2099). These results are qualitatively valid for all seasons and altitude levels and are exemplified for summer and winter in Fig. 3.

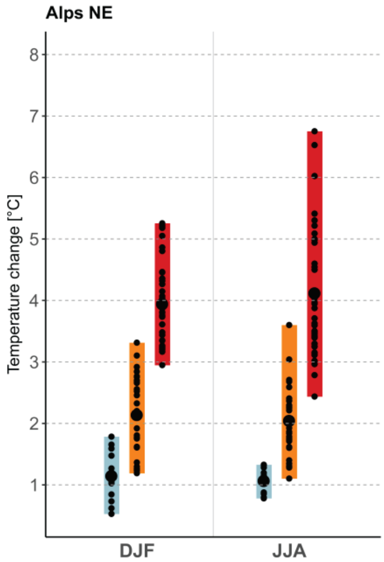

Fig 3: Temperature change signals in winter (DJF) and summer (JJA) until the end of the 21st century for Alps NE (Reference period: 1981-2010; future period: 2070-2099). The blue bars correspond to the range of results of RCP2.6 simulations, orange bars to RCP4.5 and red bars to RCP8.5. Small dots correspond to single model results, the large dot is the multi-model mean.

3.2 *Precipitation and Precipitation extremes in Alps NE*

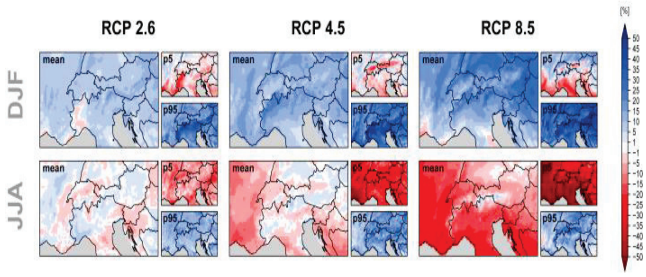

Fig 4: Precipitation change in the greater alpine region until 2100 compared to 2000 (Reference period: 1981-2010; future period: 2070-2099) in winter (DJF) and summer (JJA). For each of the emission scenarios RCP2.6, RCP4.5 and RCP8.5 the multi-model mean (mean), and the 5 (p5) and 95 (p95) percentiles are shown.

Projected precipitation (seasonal precipitation sum) changes are much more uncertain than temperature changes. While each single model projects warming, the results are more diverse with regard to precipitation. In any season some models with increasing and some with decreasing precipitation exist (Fig. 4). However, there is a rather clear tendency of increasing precipitation in winter. In summer, less precipitation or no change is expected.

Contrary to the seasonal precipitation sum, expected changes in extreme precipitation (exemplified here as maximum 1 day precipitation sum per season; Fig. 5) are more robust and range from +5% to +20% depending on emission scenario and season.

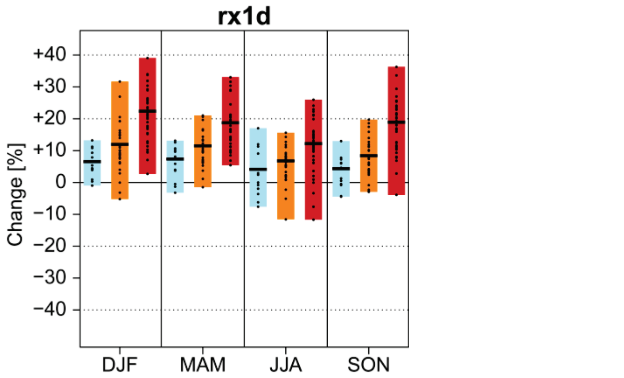

Fig 5: Change in extreme precipitation (maximum 1 day precipitation sum per season) in the greater alpine region until the end of the 21st century for Alps NE (Reference period: 1981-2010; future period: 2070-2099). The blue bars correspond to the range of results of RCP2.6 simulations, orange bars to RCP4.5 and red bars to RCP8.5. Small dots correspond to single model results, the black line is the multi-model mean.

3.3 Snow: Greater alpine area

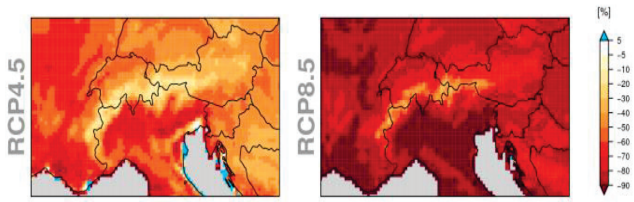

Fig 6: Change of snow cover (SWE) in the greater alpine region until 2100 compared to 2000 (Reference period: 1981-2010; future period: 2070-2099). Only EUR11 simulations are considered.

Fig. 6 shows the change of the snow cover (expressed in snow water equivalent; SWE) in the greater alpine region. Particularly for the RCP8.5 scenario, drastic decreases up to -80% are projected until the end of the 21st century. However, it is also shown, that higher altitudes are less affected and that the mitigation oriented scenario RCP4.5 is expected to lead to more moderate decrease of the snow cover.

Analysis of snowfall changes (not shown) reveals, that regions above 2000m altitude are considerably less affected than lower altitudes and that even an increase of snowfall is possible in mid-winter (Jan. and Feb.). However, in early and late winter, snowfall is decreasing in all altitudes.

3.4 Snow: Case study Mont-Blanc

A detailed analysis of changes in snow cover (expressed in snow depth) has been conducted for the Mont Blanc mountain range (Northern French Alps). Fig. 7 shows the evolution of mean snow depth from December to April, at 1200 m, 2100 m and 3000 m in the Mont-Blanc mountain range since 1960 until 2100. For this, multi-model average and standard deviation of the multi-annual average for periods of 15 years were computed. This method highlights the long-term changes by removing a large fraction of the interannual variability.

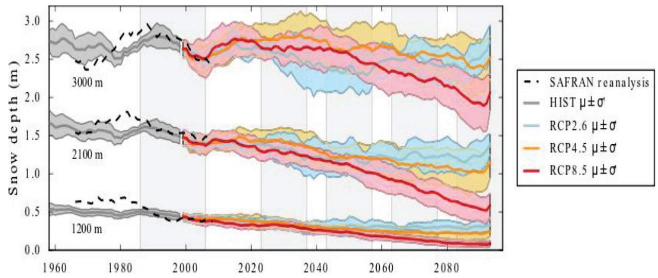

Figure 7: Mean winter snow depth at 1200, 2100 and 3000 m altitude in the Mont-Blanc mountain range. The 15-year running mean (μ) ± 0.95 times the standard deviation (σ') of all GCM–RCM pairs is represented. Blue lines correspond to RCP2.6, orange lines to RCP4.5 and red lines to RCP8.5. The historical simulations are represented in grey, and the SAFRAN reanalysis with dashed black lines.

Changes in terms of the snow cover are most pronounced at 1200 m altitude, where the solid/total precipitation ratio is smallest during the reference period, and the mean winter temperature is close to 0°C. Although warming trends are significant also at 3000 m altitude, the effect on snow cover characteristics is limited. Only for RCP8.5 at the end of the century (“worst case”), the climate projections indicate a reduction of snow depth, despite an increase in precipitation.

Quantitatively, we focus on the comparison of RCP2.6 and RCP8.5, and on the 15-year periods centered around 2050 and 2090, compared to the 1986-2005 reference period (Table 1).

	1200 m	2100 m	3000 m
REF 1995	0,45	1,50	2,68
RCP 2.6 2050	0,32 (-29%)	1,23 (-18%)	2,40 (-10%)
RCP 8.5 2050	0,23 (-49%)	1,08 (-28%)	2,51 (-6%)
RCP 2.6 2090	0,31 (-31%)	1,26 (-16%)	2,57 (-4%)
RCP 8.5 2090	0,07 (-84%)	0,51 (-66%)	1,84 (-31%)

Table 1: Mean snow depth [m] in the Mont-Blanc massif for 1200, 2100 and 3000 m altitude under RCP2.6 and RCP 8.5. Relative changes compared to 1995 are given in brackets.

For the three altitudes considered, the local response of mean snow depth to climate change is a reduction of -29% to -49% at 1200 m, -18% to -28% at 2100 m and -6% to -10% at 3000 m until the middle of the 21st century. At the end of the century the RCP2.6 scenario shows no significant additional decrease, while RCP8.5 results in a -84% loss at 1200m, -66% at 2100m and -31% at 3000m.

4. SUMMARY AND DISCUSSION

This review of the latest climate scenarios for the European Alpine Area demonstrates that in addition to already observed warming (+2°C since 1880), the Alps are facing further warming of about 0.3°C per decade (on average) until mid-century, regardless of the emission scenario considered. This warming trend is qualitatively similar in all seasons and at all altitude levels. However, it is superposed by natural annual and decadal variability, so that tangible forecasts for the coming 10 to 20 years are not possible, particularly for the winter season, where natural variability is high (Gobiet et al., 2017). Until the end of the 21st century, the level of future greenhouse-gas emissions play a crucial role and expected additional warming compared to today ranges from +1°C (RCP2.6, this corresponds to the “+2 degree goal”) and +4°C (RCP8.5; this corresponds to a “business as usual” world, with no additional efforts to mitigate greenhouse gas emissions).

The seasonal precipitation sum is expected to increase in winter, but uncertainty in these precipitation projections is high. Other than in temperature projections, different climate models partly contradict each other in the precipitation projections. A clearer climate change signal is found for heavy precipitation events, indicating that heavy precipitation is expected to become more severe in all seasons. These model-results are also supported by physical considerations.

The effect of climate change on snow cover is a subtle interaction between temperature, precipitation, seasonality, and local conditions (mainly altitude). Particularly for the RCP8.5 scenario, up to 80% less snow cover is projected until the end of the 21st century. However, it is also shown, that higher altitudes are less affected and that the mitigation-oriented scenario RCP4.5 is expected to lead to more moderate decrease of snow cover. Regions above 2000m altitude are considerably less affected than the lower-lying areas and even an increase of snowfall is possible in mid-winter (Jan. and Feb.) above 2000m. However, the natural snow season will become shorter at all altitudes, since less snowfall in autumn and spring and earlier melting in spring has to be expected.

It has to be noted, that these results don’t directly relate to future snow availability for winter tourism, since technical measures to generate and conserve snow are not regarded.

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