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21st century climate change in the European Alps—A review☆

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HIGHLIGHTS

- Warming is expected to accelerate throughout the 21st century in the Alpine region.
- Seasonal shifts in precipitation, global radiation, and relative humidity are expected.
- Precipitation and temperature extremes are expected to intensify.
- Snow cover is expected to drastically decrease below 1500–2000 m elevation.
- Further changes related to droughts and natural hazards are expected.

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ABSTRACT

Reliable estimates of future climate change in the Alps are relevant for large parts of the European society. At the same time, the complex Alpine region poses considerable challenges to climate models, which translate to uncertainties in the climate projections. Against this background, the present study reviews the state-of-knowledge about 21st century climate change in the Alps based on existing literature and additional analyses. In particular, it explicitly considers the reliability and uncertainty of climate projections.

Results show that besides Alpine temperatures, also precipitation, global radiation, relative humidity, and closely related impacts like floods, droughts, snow cover, and natural hazards will be affected by global warming.

Under the A1B emission scenario, about 0.25 °C warming per decade until the mid of the 21st century and accelerated 0.36 °C warming per decade in the second half of the century is expected. Warming will probably be associated with changes in the seasonality of precipitation, global radiation, and relative humidity, and more intense precipitation extremes and flooding potential in the colder part of the year. The conditions of currently record breaking warm or hot winter or summer seasons, respectively, may become normal at the end of the 21st century, and there is indication for droughts to become more severe in the future. Snow cover is expected to drastically decrease below 1500–2000 m and natural hazards related to glacier and permafrost retreat are expected to become more frequent.

Such changes in climatic parameters and related quantities will have considerable impact on ecosystems and society and will challenge their adaptive capabilities.

1. Introduction

Centrally located in the European continent and densely populated for most of its parts, the European Alps (Fig. 1) constitute a dominant feature of the European landscape. Characterized by extensive lowlands, deeply incised valleys and peaking at an elevation of more than 4800 m, the Alps are subject to a strong topographic variability. The Alpine climate, its spatio-temporal variability and long-term changes as well as its influence on various natural and socio-economic sectors have been of high scientific interest for a long time (e.g., Auer et al., 2007; Beniston and Jungo, 2002; Brunetti et al., 2009; Haeberli and Beniston, 1998; OECD, 2007; Raible et al., 2006; Scherrer et al., 2004; Stefanicki et al., 1998). This resulted in some of the world's longest observational time series of climatic parameters and a comparatively high observational network density (e.g., Barry, 1994).

A comprehensive overview on the Alpine climate, including its major drivers and feedbacks to larger-scale flow conditions, has been provided by Schär et al. (1998). Prominent features include distinct

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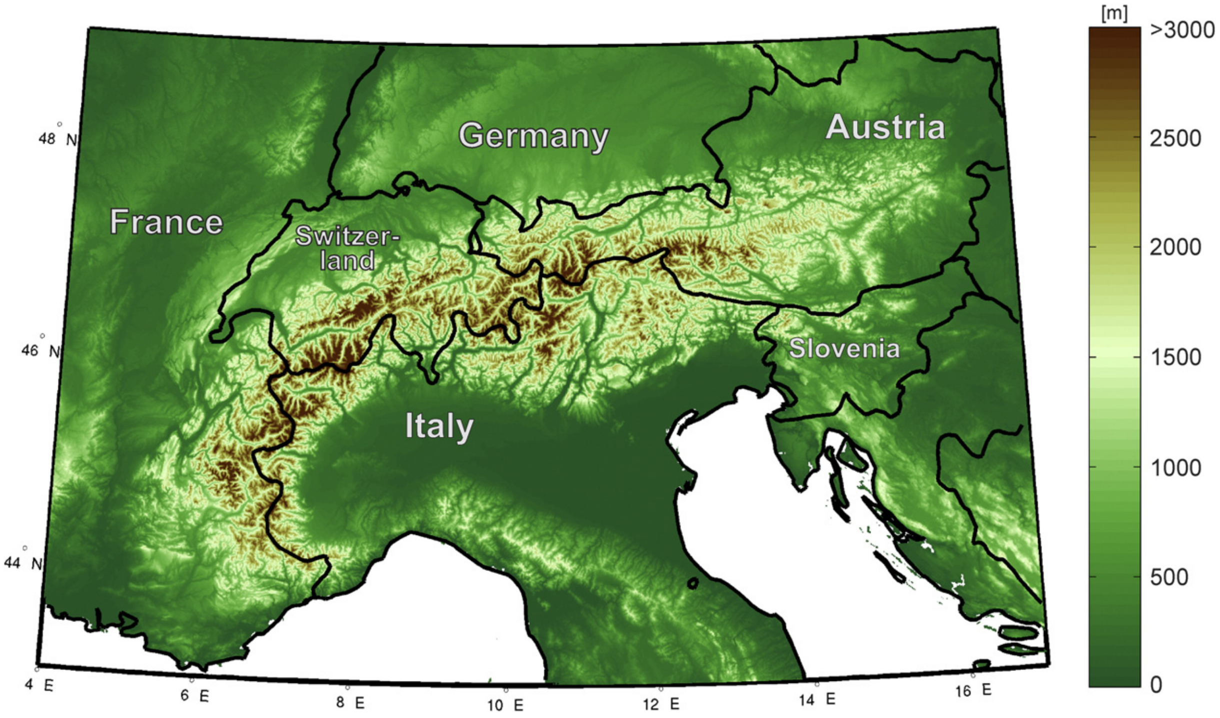

Fig. 1. Topography and location of the European Alps (based on the GTOPO30 digital elevation model, United States Geological Survey).

climatic gradients in all three dimensions of space, the frequent occurrence of extreme precipitation events with associated hazards, the importance of perennial snow and ice cover in the upper reaches as well as the existence of various orographically triggered flow phenomena.

Due to various factors including the high population density, the pronounced susceptibility to climate-related hazards, the importance of Alpine water resources for energy production, the perception of the Alps as "Water towers for Europe" (EEA, 2009), and the high economic importance of both winter and summer tourism, robust and reliable estimates of future climate change in the Alps are ultimately relevant for large parts of the European society. Accordingly, numerous studies have been concerned with the consequences of future climate change on different sectors of the Alpine environment and its economy (e.g., Beniston, 2007a; Beniston et al., 2011b; Elsasser and Bürki, 2002; Haeberli and Beniston, 1998; OcCC, 2007; Steiger, 2010; Wolf et al., 2012). Regional climate service initiatives including the Swiss CH2011 scenarios in the Western Alps (CH2011, 2011) or the Styrian STMK12 scenarios in the Eastern Alps (Gobiet et al., 2012) try to provide the corresponding climate scenario products in an end-user friendly and readily accessible manner.

At the same time and due to a large number of small-scale atmospheric phenomena, the Alpine region poses particular challenges to climate models, which are routinely used to translate an expected future increase in atmospheric greenhouse gas (GHG) and aerosol concentrations into climatic changes at regional to local scales. Previous studies have for instance shown that today's state-of-the-art regional climate models (RCMs) are able to represent the broad characteristics of the Alpine climate, but that important model biases remain for specific aspects (e.g. Frei et al., 2003; Haslinger et al., 2013; Kotlarski et al., 2010; Prömmel et al., 2010; Rajczak et al., 2013; Suklitsch et al., 2008, 2011). These biases partly translate into uncertainties of future climate change projections, thereby adding to other uncertainty sources like assumptions on future anthropogenic GHG emissions or internal climate variability.

The aim of the present study, which was initiated in the framework of the EU FP7 project ACQWA (http://www.acqwa.ch/; Beniston et al., 2011a), is to review the current state-of-knowledge concerning 21st century climate change in the Alps based on existing literature and additional analyses of RCM simulations. In particular, it considers the reliability and uncertainty of climate projections and not only changes of the meteorological variables themselves, but also their impacts on closely related natural systems. The paper is organized in the following way: Section 2 briefly introduces and discusses the climate projections used in this review. Section 3 summarizes the broad characteristics of expected 21st century Alpine climate change and its temporal and spatial variability. Projected changes of extreme precipitation and temperature are presented in Section 4 and further aspects including floods, droughts, snow, and natural hazards are addressed in Section 5. Finally, a summary and discussion is given in Section 6.

2. Climate simulations and their uncertainty in the Alpine region

Future projections of regional climate are subject to different sources of uncertainty stemming from the natural variability of the climate system, unknown future GHG emissions, and errors and simplifications in global climate models (GCMs) and RCMs or statistical downscaling methods. The resulting uncertainties are often assessed by analyzing ensembles of climate simulations, which sample the various sources of uncertainty. In most parts of this review, future climate change in the Alpine region and its reliability are assessed using the currently most comprehensive ensemble of RCM projections for Europe from the EU FP6 Integrated Project ENSEMBLES (van der Linden and Mitchell, 2009), which is based on the A1B emission scenario (Nakicenovic et al., 2000) and covers the entire 21st century. Further sources of information include the PRUDENCE RCM projections (Christensen and Christensen, 2007), which refer to the period 2071–2100 and are based on the A2 and B2 emission scenarios (Nakicenovic et al., 2000), and statistically downscaled regional scenarios from the global CMIP3 multi-model dataset (Meehl et al., 2007).

Due to its dominant role in this review, some aspects of the ENSEMBLES multi-model dataset are discussed in the following. ENSEMBLES consists of 22 high resolution RCM simulations until mid of the 21st century (2050), 15 of them ranging until the end of the century (2100). The simulations are available on a 25 km grid.

The ensemble has been constructed by applying 17 different RCMs driven by lateral boundary conditions from 8 different GCMs, and therefore mainly addresses model uncertainty. Uncertainty due to natural variability is implicitly considered by using different GCMs. Concerning future GHG emissions, only the A1B emission scenario is used. Hence, three of the four major uncertainty components are at least roughly covered. Although only a small fraction of the possible GCM–RCM combinations could be realized and by far not all available GCM simulations could be included due to computational constraints, Heinrich et al. (2013a) could demonstrate that the ENSEMBLES multi-model dataset does not underestimate GCM uncertainty, compared to the much larger CMIP3 multi-model ensemble. A rough estimate to which extent the overall uncertainty is underestimated by using only one emission scenario can be obtained from Prein et al. (2011), who showed that over Europe emission scenario uncertainty is small in the first half of the 21st century (<10% of the total uncertainty), but becomes considerable towards the end of the century (30–40% of the total uncertainty of temperature). This can be exemplified by the temperature evolution over Europe, which only differs slightly between the A1B and the other two major scenarios from the IPCC AR4 report (Solomon et al., 2007), B1 and A2 before 2050. For the late 21st century, however, the temperature induced by the A1B scenario differs remarkably from the other emission scenarios, being about 1 °C warmer than B1 and about 1 °C cooler than A2 (Fig. 2). This can be expected to be valid also for the Alpine region and to affect also other meteorological elements than temperature. For the interpretation of the results of this review, it has to be kept in mind that in many parts only the A1B scenario has been analyzed.

Based on ensembles of climate simulations, the best estimate of various aspects of expected climate change in this review is mostly expressed by the multi-model mean or median. In addition, the uncertainty or reliability is expressed by either comparing the results of several single simulations or by displaying percentiles of the multi-model ensemble spread. In some cases also more qualitative measures of uncertainty are used.

3. The major patterns of climate change in the Alpine region

During the past decades the Alpine climate has been subject to pronounced decadal-scale variability, but also to distinctive long-term trends consistent with the global climate response to increasing GHG concentrations. From the late 19th century until the end of the 20th century Alpine temperatures have risen at a rate about twice as large as the northern-hemispheric average, amounting to a total annual mean temperature increase of about 2 °C (Auer et al., 2007). This observed warming was comparatively homogeneous over the Alpine region and was particularly pronounced from 1980 onwards with annual mean warming rates of about 0.5 °C per decade (EEA, 2009), mainly caused by water vapor-enhanced greenhouse warming (Philipona, 2013). Past changes of total precipitation, in contrast, considerably depend on the region, period, and season considered. For Switzerland, Schmidli and Frei (2005) and Widmann and Schär (1997) show that mean precipitation has particularly increased in the 20th century in fall and winter. However, the analysis of more recent data (1961–2012) confirms this trend only in northern Switzerland in autumn (www.meteoswiss.ch). In terms of spatial patterns of annual mean precipitation, Brunetti et al. (2006) show that the north-western parts experienced slight precipitation increases during the 20th century (mainly due to positive trends in winter and spring), while the south-eastern Alps have been subject to a significant drying (mainly caused by pronounced negative trends in autumn). A more comprehensive overview of observed climate change in different meteorological variables is given by Brunetti et al. (2009). In the following Sections 3.1 and 3.2 the major patterns of expected monthly and seasonal mean climate change in the Alpine region for various meteorological variables are described, mainly based on the ENSEMBLES multi model dataset (Section 2) and the analysis of Heinrich et al. (2013b).

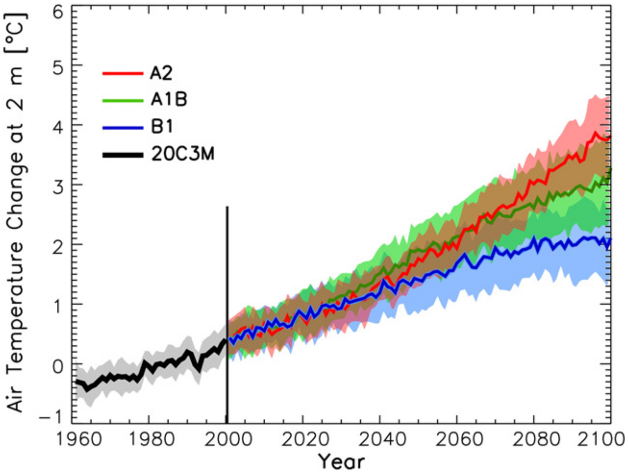

Fig. 2. Temperature evolution over Europe based on the CMIP3 simulations driven by the emission scenarios A2 (red), A1B (green) und B1 (blue). The bold colored lines depict the multi-model mean for each scenario; the shadings indicated the standard deviation. Adopted from Prein et al. (2011).

3.1. Spatial patterns of change

Fig. 3 depicts the spatial patterns of seasonal mean temperature (T), precipitation (P), global radiation (G), relative humidity (RH), and wind speed (WS) change in the Alpine region until the mid (2021–2050) and the end of the 21st century (2069–2098) relative to the reference period 1961–1990 in summer and winter, expressed as multi model mean change.

The projected changes of 2 m air temperature are positive for the entire Alpine region in both time horizons and all seasons (spring and autumn not shown). In summer, stronger warming in the southern Alpine region and along the Western Alpine ridge is indicated. In winter, regions south of the Alps show more moderate warming than the rest. The spatially averaged warming is seasonally varying between +1.2 °C in spring and +1.6 °C in summer and winter until the mid of the 21st century and +2.7 °C in spring and +3.8 °C in summer until the end of the 21st century. As annual average, 1.5 °C warming (0.25 °C per decade) is expected in the first half of the 21st century. Until the end of the century, warming is expected to accelerate and to amount 3.3 °C (0.36 °C per decade if only the second half of the 21st century is considered). The warming signal is very robust, which is indicated by the fact that all models agree on the sign of change (Heinrich et al., 2013b), but the amount of warming varies by about 3 °C between the lower and the higher estimates at the end of the century.

Precipitation change patterns indicate less precipitation in summer, particularly south of the Alps, and more precipitation in winter at the end of the 21st century. A distinct impact of the Alpine ridge on the spatial pattern is present in spring and autumn, although the area average change is low due to a compensation of increases in the north and decreases in the south (not shown, Heinrich et al., 2013b). In numbers, the spatial average change is seasonally varying between −4.1% in summer and +3.6% in winter until the mid of the 21st century and −20.4% in summer and +10.4% in winter until the end of the 21st century. However, the sign of change is highly diverse among the models. The largest accordance is obtained for the decrease in summer precipitation at the end of the 21st century, where 89% of the models agree in sign. In a larger European context, the described pattern of change in the Alpine region is part of a roughly dipolar north–south pattern with reduced precipitation in Southern Europe in summer and increased precipitation

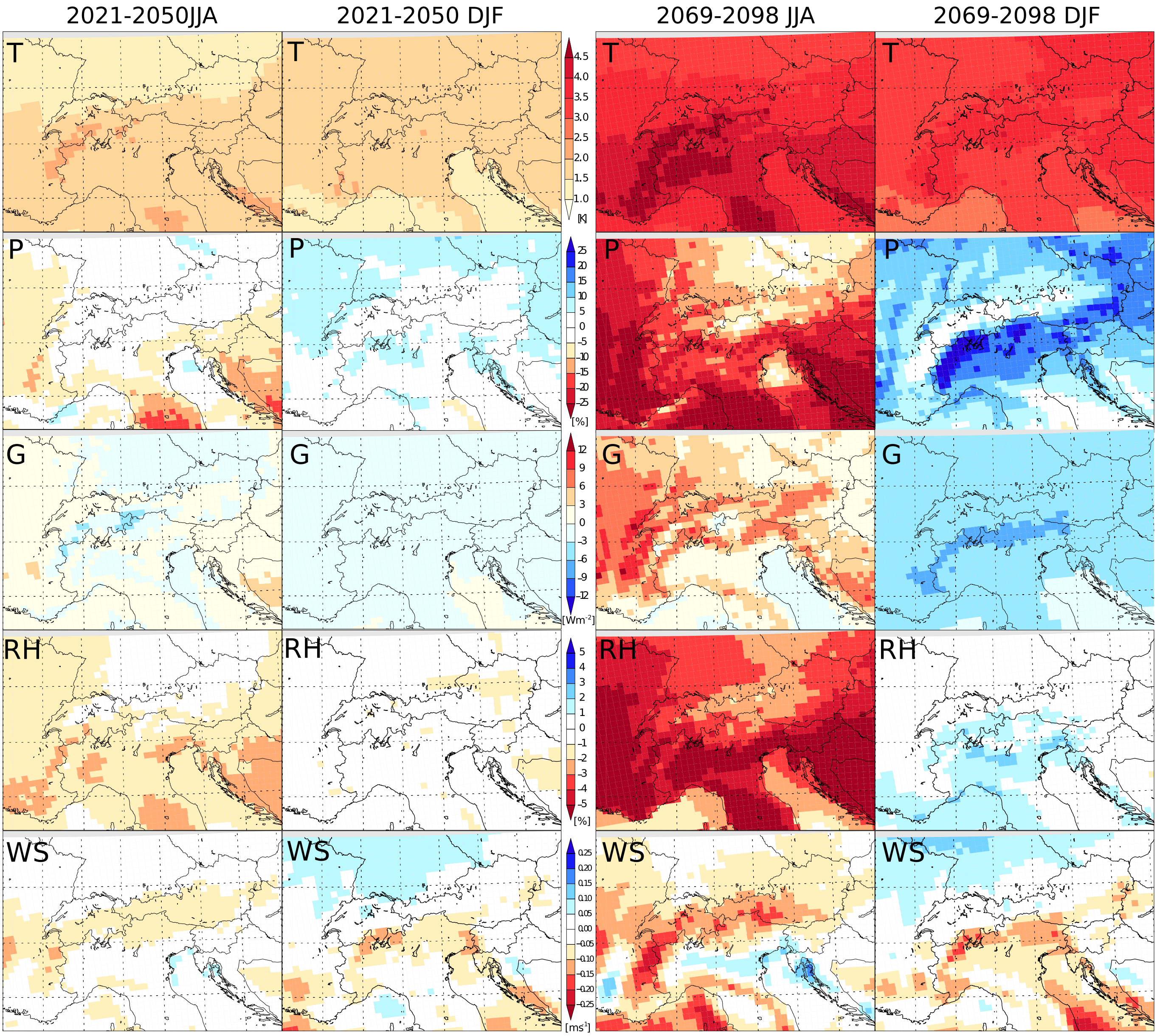

Fig. 3. Spatial pattern of expected seasonal mean change in the Alpine region for temperature (T), precipitation (P), global radiation (G), relative humidity (RH), and wind speed (WS) relative to the reference period 1961–1990 in summer and winter. Left columns: 2021–2050, right columns: 2069–2098.

in Northern Europe in winter and a transition zone which is shifting northwards in summer and southwards in winter. This pattern is referred to as the European Climate change Oscillation (ECO; Giorgi and Coppola, 2007) and the Alpine region is located at the transition zone between increasing and decreasing precipitation, which is characterized by large uncertainties of the projected precipitation changes (Heinrich et al., 2013b).

Areas with increased and decreased global radiation largely correspond to the opposite areas of precipitation change. This is plausible as the precipitation producing lower clouds reflect the incoming solar radiation. The spatial average change of global radiation is seasonally varying between +0.4 W/m^2 in summer and −1.2 W/m^2 in winter until the mid of the 21st century and +3.4 W/m^2 in summer and −4.0 W/m^2 in winter until the end of the 21st century. The spatial pattern also reveals a pronounced decrease until the end of the 21st century along the Alpine ridge in spring. Although uncertainty is high in most regions and seasons, most RCMs agree on the decrease of global radiation along the Alpine ridge, particularly in winter, and on increasing global radiation in summer at the end of the century (Heinrich et al., 2013b).

The change patterns of relative humidity are also related to precipitation change, with increased humidity in regions with precipitation increases and vice versa. This is again plausible, since it can be related to the soil moisture–atmosphere feedback. More precipitation leads to wetter soils, which in turn increases moisture flux due to evapotranspiration into the atmosphere. This results in increased humidity and potentially to cloud formation and precipitation, creating a positive feedback loop. In contrast, dry soils increase the sensible heat flux, resulting in a warmer, drier, and deeper boundary layer which potentially inhibits convection and cloud formation (e.g., Alexander, 2011). In numbers, the spatial mean change in relative humidity is seasonally varying between −0.5% in winter and −1.4% in summer until the mid of the 21st century and 0.5% in winter and −3.9% in summer until the end of the 21st century.

The projected changes of mean wind speed are close to zero in the area average. Some decreases are found along the Alpine ridge and for the northern parts of the Mediterranean and the Adriatic Sea, particularly in summer and autumn at the end of the 21st century. High accordance between the RCM projections is only found in autumn with decreasing wind speed in the southern parts until the end of the 21st century (not shown, Heinrich et al., 2013b).

3.2. Annual cycle of change

Fig. 4 depicts the annual cycle of the spatially averaged monthly mean change of T, P, G, RH, and WS in the Alpine region until the mid (2021–2050) and the end of the 21st century (2069–2098) relative to

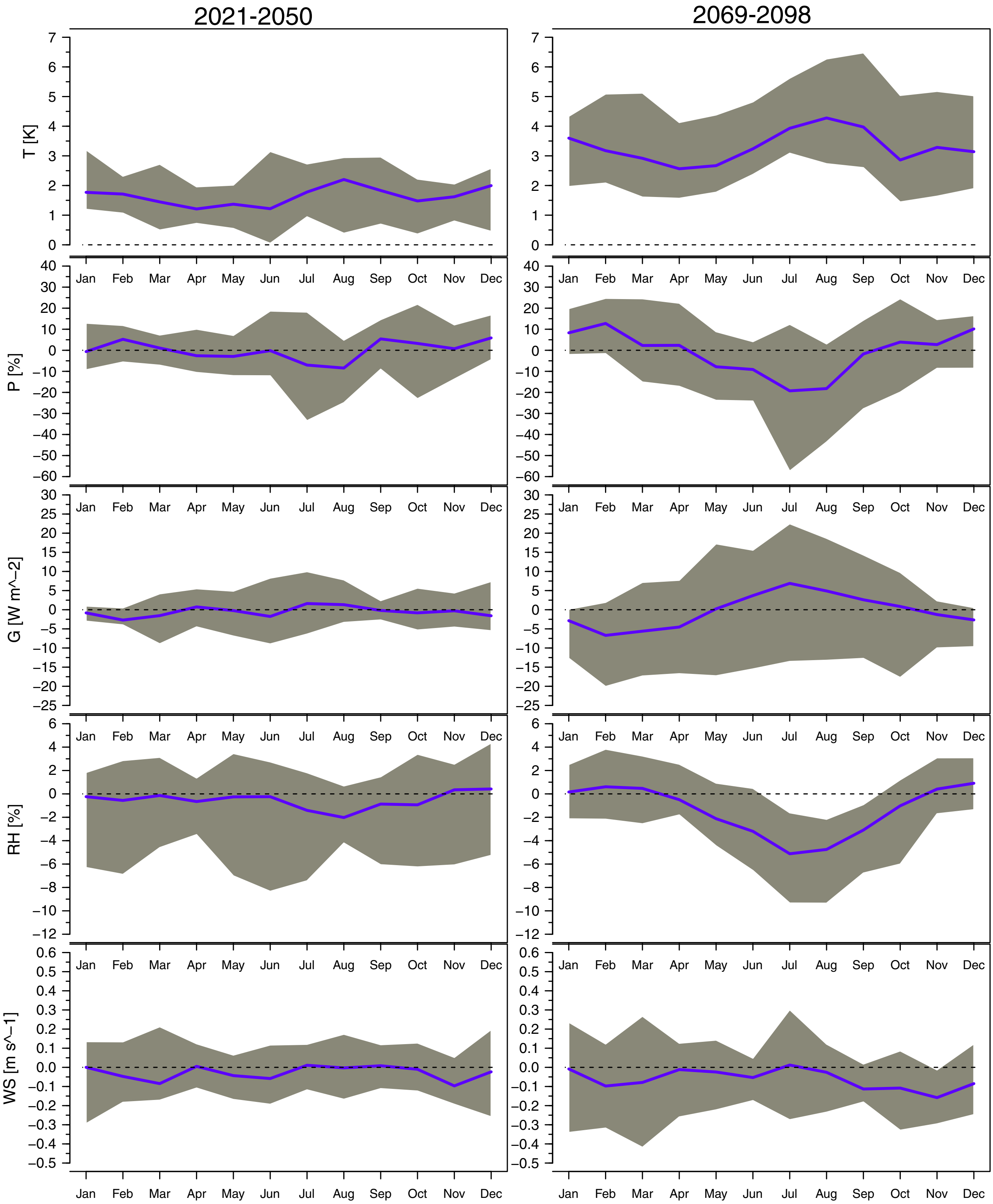

Fig. 4. Annual cycle of expected monthly mean change in the Alpine region of temperature (T), precipitation (P), global radiation (G), relative humidity (RH), and wind speed (WS) relative to the reference period 1961–1990. Left column: 2021–2050, right column: 2069–2098. The blue line indicates the median, the grey area the 10–90 percentile range.

the reference period 1961–1990 in summer and winter, expressed as multi model median (bold line) and the 10 to 90 percentile-range (grey areas). In these results, the missing RCM projections in the ENSEMBLES GCM–RCM simulation matrix have been statistically reconstructed as described by Heinrich et al. (2013b).

Fig. 4 indicates stronger warming in late summer and winter than in the rest of the year, which is more pronounced at the end of the 21st century. The median warming of about 1.5 °C until the mid-century and 3.3 °C until the end-century is associated with a bandwidth of about 2 °C and 3 °C between the 10 and 90 percentiles, respectively. With regard to precipitation changes, the annual cycles indicate increases in winter and decreases in summer. This is hardly detectable until the mid-21st century, but becomes a quite clear signal at the end of the century. However, uncertainty is much larger than for temperature and only at the end of the century in a few months 85%–90% of the models agree in the sign of change (January and February with increases, June and August with decreases). The annual cycles of global radiation and relative humidity change follow the precipitation change as already discussed in Section 3.1. One remarkable feature of the projected decrease of relative humidity in summer is its larger robustness compared to precipitation change, indicated by the entire 10–90 percentile range being clearly negative. With regard to wind speed, only a minor median decrease between 0.0 ms^{-1} and 0.2 ms^{-1} is indicated, particularly in winter in the late 21st century.

3.3. Altitude gradients of change

Climatic changes can generally be expected to vary in all three dimensions of space, i.e. vertical dependencies may arise in addition to horizontal patterns of change. In this respect, one has to distinguish between gradients in the free troposphere and the dependency of near-surface climate change on the elevation of a specific site or model grid cell. Assessing and understanding the latter type is of particular importance for impact assessments in Alpine terrain as estimates of near-surface changes of meteorological variables are often used to drive impact models of different kinds. Given the considerable temporal storage of water in form of snow and ice in the higher regions of the Alps, changes in high-elevation climate are of particular interest for research on climate-related hydrological impacts in Alpine catchments.

Observational evidence suggests that in particular near-surface temperature trends can considerably depend on elevation (e.g., Beniston et al., 1997; Beniston and Rebetez, 1996; Diaz and Bradley, 1997; Seidel and Free, 2003), with higher rates of warming often found at high elevations. This rule of thumb, however, is not always true and depends on the region and the period under consideration (see Rangwala and Miller (2012) for a comprehensive review or, e.g., Böhm et al. (2001)). The picture is even less coherent for precipitation changes. The reasons for elevation-dependent temperature trends are manifold and include changes in large scale atmospheric circulation (e.g., Ceppi et al., 2012) as well as elevation-dependent changes in the surface energy balance induced by, e.g., snow cover changes (Kotlarski et al., 2012; Scherrer et al., 2012) or changes in downward radiation fluxes following changes in atmospheric transmissivity (Marty et al., 2002; Philipona, 2013). High-elevation sites can be assumed to be partly decoupled from boundary layer processes, i.e. more strongly affected by conditions in the free troposphere and less by local factors such as air pollution or near-surface temperature inversions. For the Swiss Alps and the period 1959–2008, Ceppi et al. (2012) identified in their recent study anomalously-strong warming at low elevations in autumn and early winter and above-average spring temperature trends at elevations close to the snow line. The latter can partly be attributed to declining snow cover and an amplification of the general warming by the snow albedo feedback (Scherrer et al., 2012). Several previous studies applying global and regional climate models have also confirmed the importance of the snow albedo feedback for future temperature changes in the Alps and other mountain regions (Fyfe and Flato, 1999; Giorgi et al., 1997; Im et al., 2010). Recently, Kotlarski et al. (2012) investigated the elevation dependency of 21st century near-surface climate change over Europe based on a high-resolution climate change scenario carried out with the RCM COSMO-CLM (Rockel et al., 2008). For the Alps, they found strong evidence of an amplification of projected 21st century warming at high elevations, again presumably connected to the snow albedo feedback. Also summer precipitation changes were found to considerably depend on elevation, with strongest relative drying signals in the lowlands.

We here present an extension of the study of Kotlarski et al. (2012), taking into account ten regional climate simulations. They were carried out by eight different RCMs which, in turn, were driven by six different GCMs at their lateral boundaries. All experiments are provided by the ENSEMBLES database at a horizontal resolution of about 25 km and are based on the SRES A1B emission scenario (see Section 2). Fig. 5 shows the vertical profile of changes in 2 m temperature (a), precipitation (b) and number of snow days (c) in the Alps until the end of the 21st century. Note that only elevations below about 2700 m are covered by the model topographies and no information can be deduced for higher elevations. This analysis confirms the results of Kotlarski et al. (2012) and shows for most parts of the year an anomalous warming at higher elevations, but also an amplified low-elevation warming in summer (left row). In spring and partly also in summer and autumn, the former effect can be related to a reduction of snow cover (right row) and the snow-albedo effect. For precipitation (middle row) no clear systematic altitude dependence of the climate change signal can be found, except for a tendency towards a reduced summer drying and a reduced winter moistening (in relative terms) at high altitudes compared to low-lying regions. The 10-model ensemble reveals an astonishing inter-model agreement on the shape of the vertical profiles, despite considerable differences in the overall rate of change. For temperature and precipitation, the latter is obviously controlled by the driving GCM and also depends on the season.

4. Changes in precipitation and temperature extremes

4.1. Precipitation extremes

Heavy precipitation events possess the potential to cause natural disasters and serious damage to infrastructure facilities. Subsequently such events can imply vast societal, economic and environmental impact. In this respect and with anticipated climate change, there is particular interest in the future behavior of precipitation extremes.

The European Alps are a region of major concern by reason of frequent affliction by heavy precipitation events (e.g. the events in August 2005 in Switzerland; MeteoSchweiz, 2006). This is primarily due to orographic mechanisms that extract ambient atmospheric moisture. Also, the Alps are influenced by both Atlantic and Mediterranean climatic regimes including events of stratiform and short-lived convective nature (Frei and Schär, 1998). For this reason they feature a large spatial variability of climatic regimes.

Assessing changes in heavy precipitation events and the hydrological cycle in general contains the interplay of several complex processes (Allen and Ingram, 2002; Emori and Brown, 2005; Held and Soden, 2006; O'Gorman and Schneider, 2009). These include thermodynamic processes that can lead to an intensification of precipitation. The most important is an increased moisture uptake capacity of air under warmer conditions, but also possible changes in atmospheric stratification (Christensen and Christensen, 2003; Frei et al., 1998; Pall et al., 2007). Moreover, dynamic effects like changes in atmospheric circulation can importantly contribute to an altered frequency of heavy precipitation events.

Several observational studies have investigated changes in heavy precipitation at global to regional scale (Solomon et al., 2007). For the

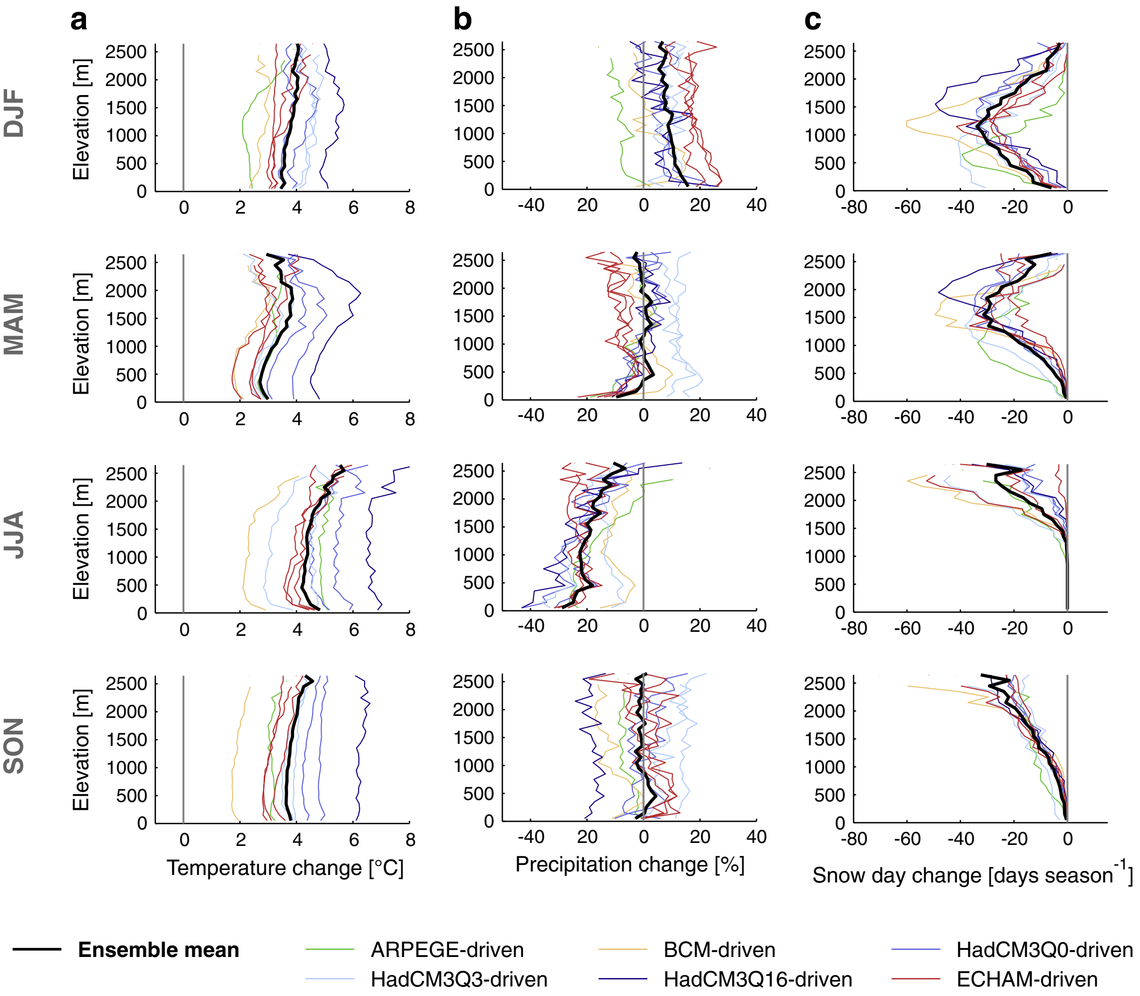

Fig. 5. Elevation dependency of mean seasonal changes in (a) 2 m temperature (b) precipitation and (c) number of snow days in the Alps (based on 100 m elevation bins). For the latter, a snow day threshold of 3 mm we has been applied. Results are based on ten GCM–RCM chains of the ENSEMBLES project, all of them assuming the SRES A1B emission scenario. Changes refer to the period 2070–2099 with respect to the reference period 1961–1990. The color indicates the driving GCM. The Alpine domain is defined according the Steger et al. (2013).

Alpine region, Schmidli and Frei (2005), show that precipitation in Switzerland has intensified in the 20th century. Furthermore, Schmidli and Frei (2005) and Widmann and Schär (1997) show that mean precipitation has particularly increased in fall and winter. However, long-term reconstructions of precipitation (Pauling et al., 2006; Pauling and Paeth, 2007; Casty et al., 2005) and flood-records (Schmocker-Fackel and Naef, 2010a,b) for the European Alpine region show large decadal variations in the frequency of heavy events and floods. Therefore, recent changes might be explained by natural climate variability. In addition, the small scales of heavy precipitation events tend to suffer from greater uncertainty than is the case for regional atmospheric patterns, especially when projecting their future behavior.

In a recent study Rajczak et al. (2013) have assessed projected changes in Alpine precipitation and its extremes in large detail. The study used a set of 10 regional climate simulations from the ENSEMBLES multi model dataset at a resolution of 25 km (see Section 2). Based on this study, Fig. 6 presents and overview on projected 21st century changes (2070–99 compared to 1970–99) for impact-relevant precipitation indices at the seasonal scale for the Alpine region. The Figure illustrates, that the frequency of wet days (left column) is projected to substantially decrease in summer across the entire Alpine region, whereas in fall and spring substantial reductions are only projected for southern Alpine regions. In winter, no clear changes in precipitation frequency are obvious. However, for some southern Alpine areas projections suggest an increased number of wet days, which could be due to changes in atmospheric circulation. Projections of mean precipitation (middle column) show overall increases in winter and decreasing signals in summer, as already presented in Section 3.1. Model agreement on changes is more obvious in Alpine foreland regions than in central Alpine areas. Especially in winter and also for extreme diagnostics (right column), signals are smaller and afflicted with model uncertainty for inner-alpine regions. In spring and fall, the Alpine ridge presents a part of a distinct transition zone separating increasing signals in the north from decreasing signals in the south of Europe.

Considering extreme precipitation events, Fig. 6 (right column) presents projected changes in the 5-year return value of daily precipitation events as estimated by generalized extreme value theory. The Alpine region is expected to experience an increase in the intensity of extreme precipitation events in all seasons and for most regions. This is equivalent to a reduction (increase) of return periods (values) under future climatic conditions with respect to present-day conditions. Exceptional from this general behavior are only summer-time events in the southern Alpine region, where return periods associated with small return periods tend to decrease. The most substantial and widespread intensifications are projected to occur in fall and in the northern Alpine region, where changes in intensity amount up to +30%, representing more than a halving of return periods (not shown, Rajczak et al., 2013).

It is obvious that changes in mean (frequency) and heavy precipitation do not scale proportionate. Depending on season and location, projected changes are even oppositional, highlighting not only

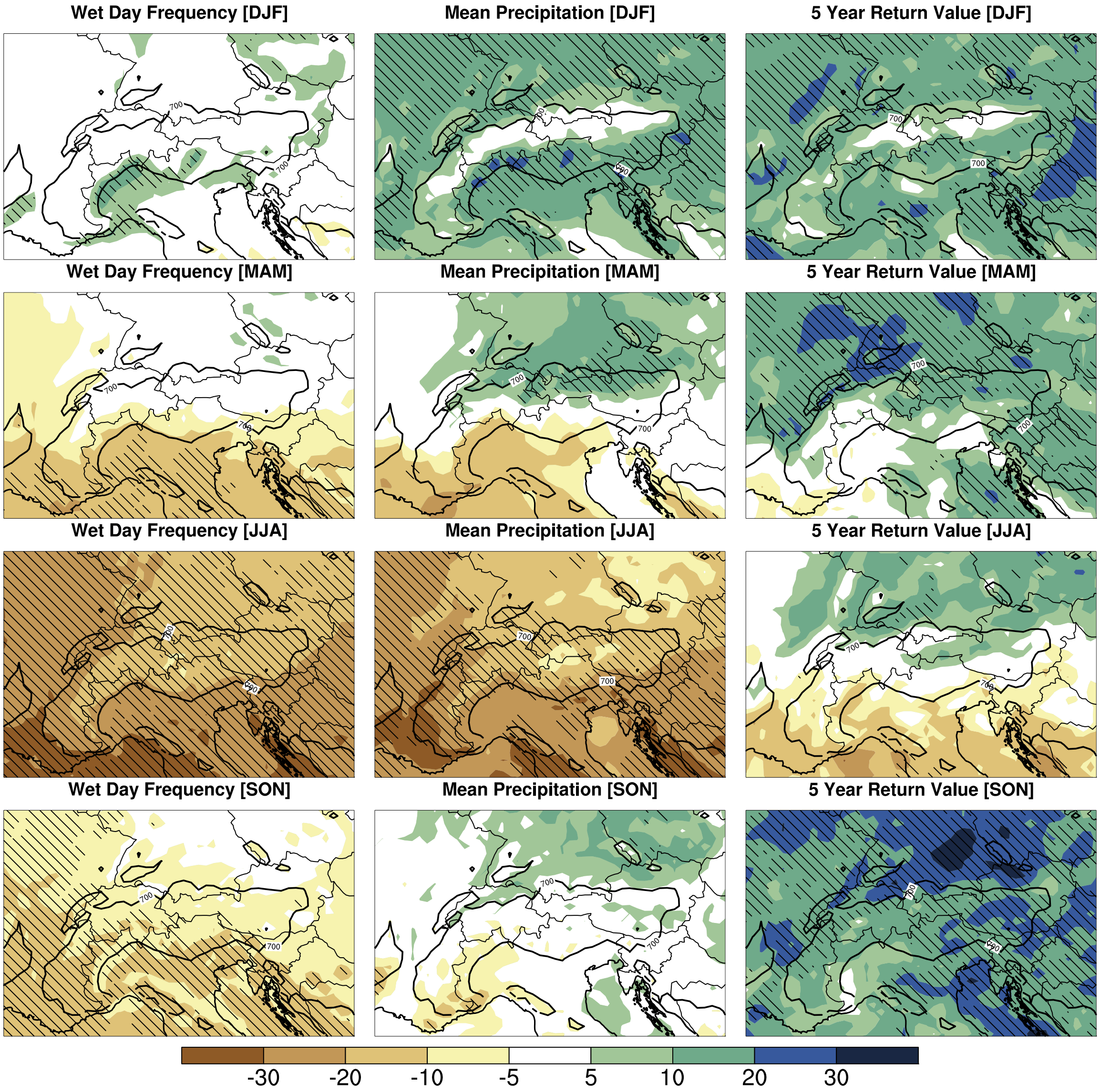

Fig. 6. Projected changes in wet day frequency [days > 1 mm], mean precipitation, and the 5-year return value of 1-day precipitation events (left to right) for the four climatological seasons (top to bottom) for the European Alpine region. Colored contours show the median change signals from a 10-member multi-model ensemble and are expressed as the percentage change for period 2070–2099 with respect to period 1970–1999. Hatching denotes agreement in the sign of change in 90% of the considered models. The results are based on a set of 10 ENSEMBLES RCMs at a resolution of 25 km. Bold lines indicate the 700 m-isoline as presented by the E-OBS topography (Haylock et al., 2008). Figure and results are adapted from Rajczak et al. (2013).

the complexity of the hydrological response to climatic change, but also the increasing probability of both more intense precipitation and drought conditions.

4.2. Temperature extremes

Anomalously warm months or seasons in the last 1–2 decades of the observational record have prompted many publications to explore and explain these events (e.g., Beniston, 2004, 2005; Schär et al., 2004; Luterbacher et al., 2007). For example, the links between soil–moisture deficits and heat waves have recently attracted much interest as an explanatory causal mechanism (e.g., Seneviratne et al., 2006). Vautard et al. (2007) have shown that the northward spread of droughts that originate in the Mediterranean during winter yield preconditions capable of triggering intense and persistent heat waves in Europe. Such conditions are likely to be amplified in the future, since higher mean temperatures facilitate the exceedance of thresholds considered to be extreme (e.g., taking the 90% quantile as the threshold of extreme temperature).

While it is difficult to use RCM results to directly quantify changes in extremes, their statistics can nonetheless help identifying the possible change in frequency of anomalously hot seasons in the future. For example, Beniston (2007b) showed that RCM outputs from the EU FP5 project PRUDENCE (see Section 2) can be used to define the "envelope" of quantiles around the mean monthly temperatures of a future climate.

An example is provided in Fig. 7, where the mean monthly course of daily maximum temperature in a scenario climate is plotted for Basel (north–west Switzerland) in a high-emissions scenario (A2). The RCM ensemble statistics also serve to define the quantile boundaries around the multi-model mean. For the hottest months of July and August, the mean Tmax is close to 31 °C (i.e., about 6 °C more than today), while the 90% quantile is around 39 °C. In order to compare the future climate statistics with those that have been observed in a recent past, the 2003 monthly statistics and summer Tmax have been added. The observed statistics show that Tmax in June and August was not only well beyond

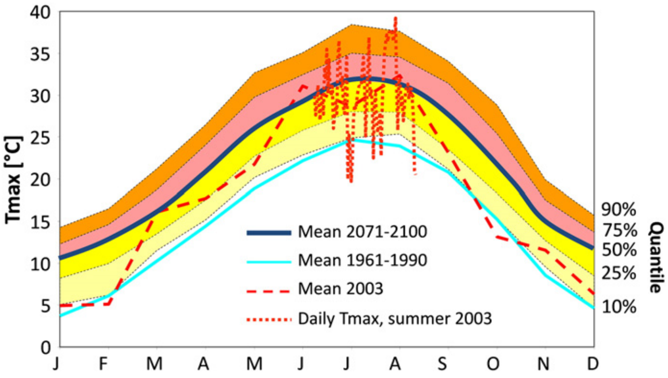

Fig. 7. Future (2071–2100) monthly-mean daily maximum temperatures (Tmax) for Basel, Switzerland (mean and quantiles of the RCM ensemble). The monthly and summer daily Tmax for 2003 are also included (red lines) (Adapted from Beniston, 2007b).

the norm of the reference period 1961–1990, but that it was slightly higher than the average Tmax of the future climate at the end of the 21st century. Similarly for the daily course of Tmax during the 2003 summer, the observed statistics show that some days of the heat-wave were close to or even in excess of the 90% quantile of the future climate.

By analyzing these statistics more closely, it is possible to define what would be the frequency of occurrence of observed record-breaking seasons in the future. Schär et al. (2004) suggested that one summer in two by 2100 would be at least as hot as the 2003 summer. The statistics examined by Beniston (2007b) not only confirm this finding, but also show that 6 winters out of 10 would be as hot as the record-breaking winter 2006–2007, 7 springs in 10 as hot as the record spring of 2007, and 6 autumns in 10 as hot as the 2006 autumn.

5. Further aspects

5.1. Floods

Major floods have been rather scarce in the Alps over much of the 20th century before several catastrophic floods occurred during the last three decades, with associated substantial increases in flood-related losses (Bezzola and Ruf, 2009). In the case of Switzerland, 16 major floods have been recorded since the early 19th century, with nine of these during the last 30 years. Over the course of the past 500 years, catchments in northern Switzerland were affected by marked fluctuations in flood frequencies, with periods of frequent flooding AD 1560–1590, 1740–1790, 1820–1940, and since the 1970s (Schmocker-Fackel and Naef, 2010a). During several of these periods, debris flows have been more frequent in the Valais Alps as well (Stoffel and Beniston, 2006; Bollschweiler and Stoffel, 2010; see Section 5.4). Although there is reason to believe that climate change will likely lead to more and more severe floods in the Alps, the current increase in flood frequency remains, for the time being, comparable to past periods of increased flood frequency mentioned above (Schmocker-Fackel and Naef, 2010a). Allamano et al. (2009) detected an increase in flood peaks in Swiss rivers over the course of the last century, possibly influenced by the large events over the past forty years, and have ascribed this increase to increasing temperature and precipitation (Allamano et al., 2009). In other regions of the Alps, however, trend detection is not feasible due to short observational records and because extreme events are rare per definition (IPCC, 2012). At the same time, apparent changes in flood frequency and magnitude have also been aggravated by the concreting of river reaches and the waterproofing of settled areas. At almost 2.5 billion Euros, the August 2005 flood (MeteoSchweiz, 2006) represents the most extensive financial loss for Switzerland ever caused by a single natural disaster, despite the fact that several floods of the 19th century actually matched or even exceeded the extent of damage of the 2005 event (FOEN, 2007).

The occurrence of heavy or extended precipitation events will likely increase in a future greenhouse climate (see Section 4.1) and possibly cause more frequent severe flooding events in Europe (e.g., Christensen and Christensen, 2003), despite the general drying of future summers (Section 3.1). It thus seems possible that the size and frequency of winter and spring floods will increase, in particular north of the Alps and at altitudes up to 1500 m above sea level (KOHS, 2007). According to Allamano et al. (2009), and assuming a 2 °C increase and a 10% increase in precipitation intensity, the return period of a current-day 100-year winter flood could be reduced to a 20-year event. Summer floods are by contrast expected to occur less frequently in the future (KOHS, 2007). South of the Alps, floods are predicted to become more severe in all seasons except for summer (OcCC, 2007).

5.2. Droughts

Drought can be regarded as a natural recurrent phenomenon which occurs on a variety of different temporal and spatial scales and significantly affects natural and socio-economic systems. The vulnerability of the Alpine region to drought was clearly revealed in 2003 with, e.g., large scale losses in agriculture and forestry, lowering of the ground water level, shortages in the generation of hydropower electricity, and pronounced snow and glacier-melt leading to increased rock and ice falls in the mountains (see Section 5.4; Gruber et al., 2004; Jolly et al., 2005; Fischer et al., 2007; Garcia-Herrera et al., 2010).

During the 20th century, evidence for increasing drought risk was found especially in central, eastern, and southern Europe (e.g., Szinell et al., 1998; Lloyd-Hughes and Saunders, 2002; Bonaccorso et al., 2003; Dai et al., 2004; Trnka et al., 2009; Briffa et al., 2009). For the Alpine region, van der Schrier et al. (2007) investigated monthly moisture variability for the period of 1800–2003 based on a simple drought index and found that the late 1850s into the 1870s and the 1940s to the early 1950s stand out as persistent and exceptionally dry periods. The driest summers on record, in terms of the amplitude of the index averaged over the Alpine region, are 1865 and 2003. For Switzerland, Rebetez (1999) investigated the change in frequency of drought episodes based on precipitation and detected increased drought frequency and persistence during the 20th century in the southern parts.

Future changes in drought conditions are primarily driven by altered precipitation regimes along with increased evapotranspiration related to higher temperatures and increased water demand (Briffa et al., 2009; Sheffield and Wood, 2008). Based on the analysis of GCMs, Giorgi (2006) detected the Mediterranean and north-eastern parts of Europe as most responsive regions to climate change by the end of the 21st century worldwide and the high vulnerability of southern European regions to future drought regimes was underpinned by various other studies (e.g., Lehner et al., 2006; Burke and Brown, 2008; Sheffield and Wood, 2008; Warren et al., 2009). For Switzerland, changes in hydrological drought characteristics until the mid and the end of the 21st century are available from the EU FP7 project DROUGHT R&SPI (Alderlieste and van Lanen, 2013). In this project, a set of three statistically downscaled and bias corrected GCM projections forced by the SRES A2 and B1 emission scenarios are used to drive a set of different Global Hydrological Models (GHMs) and Land Surface Models (LHMs). As expected, the changes are generally larger for the A2 emission scenario. However, the change in number of drought events doesn't show a clear pattern among the emission scenarios and future time periods. Until the end of the 21st century (2071–2100), the expected multi-model mean changes for the B1 (A2) scenario are: +4.7% (+4.7%) for the number of drought events, +89.9% (+143.1%) for the average duration, +375.2%

(+467.4%) for the average deficit volume, and +70.6% (+67.1%) for the average intensity.

Calanca (2007) investigated the occurrence and severity of droughts for the Alpine region until the end of the 21st century based on results from a RCM. In this study, a simple soil water balance model was driven by a single RCM simulation from the PRUDENCE project forced by the SRES A2 emission scenario. The conclusions are that there are clear indications that in the future the Alpine region will increasingly suffer from droughts. The RCM projects a decrease in the frequency of wet days of about 20% with respect to the growing season of summer crops (April to September) which consequently results in an increase of drought frequency from about 15% to more than 50%. Furthermore, the results indicate an overall shift of the distribution towards higher severity of drought events.

In order to account for the uncertainties in RCM projections, Heinrich and Gobiet (2012) used a set of eight downscaled and error-corrected RCM projections from ENSEMBLES forced by the SRES A1B emission scenario and calculated a set of commonly used drought indices for nine European subregions until the mid of the 21st century (2021–2050). The study revealed that there is large structural uncertainty among the different drought indices and climate scenarios for the Alpine region. Statistical significant changes in drought characteristics are only obtained for indices which account for the effect of increasing air temperature. The self-calibrated Palmer Drought Severity Index (scPDSI), which is based on simplified soil water balance model, shows an increase of +7.1% for the average length, +24.7% for the average magnitude, and +4.1% for the average area of dry events with respect to the baseline period of 1961–1990.

In summary, a rather systematic picture of increasing drought characteristics is projected for the near- as well as long-term future for the Alpine region. The exact numbers of the changes are subject to considerable uncertainties which can be related to the different climate scenarios applied in the various studies and structural uncertainty of the models which are used for the quantification and definition of drought. Although the projected changes in the Alpine region are more dissonant and less reliable than for, e.g., Southern Europe, they still indicate increasing drought stress and call for flexible and adaptable water management strategies.

5.3. Snow

Snow in a populated and economically-diverse region such as the Alps plays an important role in both natural environmental systems, (e.g., hydrology and vegetation), and a range of socio-economic sectors (e.g., tourism or hydropower). Shifts in snow amount and duration as a result of a changing climate are likely to impact upon these systems in various ways (Beniston, 2012). The behavior of the snowpack is obviously related to geographic characteristics, in particular altitude, orientation, exposure to dominant atmospheric flows, and location at the bottom of a valley floor (possibly subject to temperature inversions), slopes or mountain tops.

The 20th century has already seen significant changes in snow amount and duration, which generally exhibit a large degree of interannual and inter-decadal variability. The observational record shows periods of snow-abundant winters (e.g., in the 1960s) and snow-sparse seasons as experienced from the latter part of the 1980s to the mid-1990s for example. In some instances, particularly snow-sparse winters seem to be related to the positive (or warm) phase of the North Atlantic Oscillation (NAO; e.g., Beniston, 1997), but the NAO is by no means the only explanatory factor that explains the variability of snow in the Alps. For example, Scherrer and Appenzeller (2006) suggest that half the variability of Alpine snow cover is related to the establishment of blocking patterns over Europe, not always related to influence of the NAO. For the Swiss Alps, Marty (2008) has identified what appears to be a regime shift in snow, i.e., a stepwise decline in snow amount and duration in the 1980s, with no definite trend occurring since then.

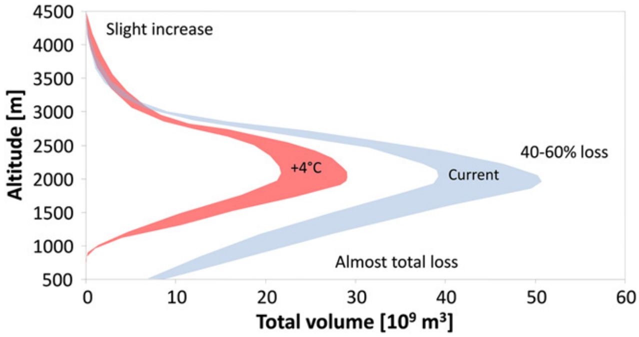

Fig. 8. Snow volume under current climate and a possible future climate with winters 4 °C warmer than today (slightly warmer than median estimate for the end of the 21st century, see Section 3.2). The spread within the two curves indicates the variability of winters ("snow-sparse" to "snow-abundant"). Total snow volume is computed as the average snow depth multiplied by the surface area on which it lies, for elevation levels between ranging from 200 m to 4500 m in Switzerland.

As a "rule of thumb", the average level of the snowline rises by roughly 150 m per degree Celsius. With regional climate model projections suggesting wintertime increases of temperature of 2 °C–4 °C in the latter part of the 21st century (e.g., CH2011, 2011), this implies an upward snowline shift by 300–600 m. However, it has to be noted that this simple concept might overestimate the rise of the snow line, as it doesn't regard the effect of temperature inversions and cooling by melting precipitation (Unterstrasser and Zaengl, 2006). While changes in precipitation patterns are also likely to influence the abundance and geographic distribution of snow, a number of studies have emphasized the fact that in a warmer climate, temperature is likely to be the dominant control on snow cover, and the wintertime precipitation increases that most models project for the Alps (Section 3.2) will not compensate the large losses in snow volume that more elevated temperatures will induce.

Because of their relatively coarse grids, regional climate models have in the past not proven sufficient to provide detailed information on snow precipitation and snow amount, although Steger et al. (2013) have shown that current generations of RCMs now capture the spatial and seasonal snow variability, but with over- or under-estimations of quantities according to altitude. Assessing the behavior of snow in complex topography can also involve interfacing techniques that enables to estimate of snow depth and duration at a very local scale. Statistical downscaling techniques can be applied, but also physically-based snow models that use RCM-generated outputs as initial and boundary conditions for snow and surface energy-balance models at the very local scales (e.g., Martin et al., 1996; Uhlmann et al., 2009) have proven to be fairly powerful tools to assess snow in the Alps.

Studies by Beniston et al. (2003) Uhlmann et al. (2009), or Steger et al. (2013), among others, all agree on the likelihood of seeing large decreases in Alpine snow amount and duration below about 1500 m elevation, and even above 2000 m the declines in snow amount are a feature common to the different methodologies applied to future climatic conditions (Fig. 8). In addition, Steger et al. (2013) show that the reduction of snow cover is greatest in the spring; the snow cover thus exhibits an asymmetric reduction within the winter season.

Beniston et al. (2011b) have attempted to see whether snow-abundant winters may still occur on occasion by the end of the 21st century, based on a typology of winters using joint quantiles of temperature and precipitation. It was shown that when a combination of warm and dry winter days is less frequent, more snow can fall and remain on the ground. Transposing this particular temperature-precipitation mode to the future, the authors have shown that the number of snow-abundant winters by the end of the century would represent a 1-in-30 year's event, compared to 8 in the reference climate (1961–1990).

5.4. Natural hazards in the Alps

Changes in temperature and precipitation are considered to likely have a range of secondary effects, including on the occurrence of natural hazards in mountain environments. However, while there is theoretical understanding for increased mass-movement activity as a result of predicted climate change, changes can hardly be detected in observational records (Stoffel and Huggel, 2012).

5.4.1. Glacier retreat and related hazards

One of the most obvious consequences of climate change at high-elevation sites is the widespread retreat and disintegration of glaciers (Zemp et al., 2007; Diolaiuti et al., 2011). The consequences for natural hazards following increasingly rapid changes in glacier geometry are multiple and include the formation of ice-marginal lakes, ice avalanches, and mass movements originating from the recent debuttressing of previously glacierized walls and hill slopes.

Rapid lake formation and growth that has been accelerated in recent years is a global phenomenon but has been observed in much of the Swiss Alps (Künzler et al., 2010; Werder et al., 2010). Several lakes have formed within the past decade at the terminus of glaciers where subglacial topography has been overdeepened by the glacier. Positive feedback processes, mainly related to the thermal energy of water, accelerated glacier melt and has been observed to result in the formation and extensive growth of proglacial lakes over periods of only a few years (Kääb and Haeberli, 2001). Some of the lakes have become major tourist attractions, but considerable concern exists about hazards in case of a lake outburst that could be triggered by ice avalanches or rockfalls following debuttressing of the steep lateral slopes (Dalban Canassy et al., 2011).

By way of example, downwasting of the Lower Grindelwald glacier in its terminal part resulted in a loss of between 60 and more than 80 m of ice thickness between 1985 and 2000 (Paul and Haeberli, 2008). In recent years a glacial lake started to form in the terminus area of the glacier (Fig. 9). In 2004 and 2005, the lake had a limited volume but has subsequently grown continuously in the spring and early summer seasons, resulting in lake volumes of 250,000 m^3 in 2006, 1.3 million m^3 in 2008 and 2.5 million m^3 in May 2009 (Werder et al., 2010) and the occurrence of a glacier-lake outburst flood in 2008 (Worni et al., in press). The rock slope failures above the terminus of the Lower Grindelwald glacier (Fig. 9b) are yet further textbook examples of glacier retreat, downwasting and associated debuttressing effects on rock slope stability, and could in fact serve as a model case for increasingly destabilized future high-mountain environments (Stoffel and Huggel, 2012). Similar examples can be found in the Mount Blanc massif, where the Brenva and Triolet rock avalanches (18th and 20th centuries; Deline, 2009) have been considered characteristic examples of rock slope instability related to glacial oversteepening or debuttressing.

The current rapid glacier downwasting is likely to promote many rock slope failures at rather short future time scales, probably on the order of decades. For the future, Glacier downwasting is expected to result in the formation of further ice-marginal lakes and subsequent problems of glacier-lake outburst floods (Frey et al., 2010; Worni et al., 2012).

5.4.2. Permafrost thawing and mass movements

Important effects of climate change on mountain slope stability are also related to the warming and thawing of permafrost. Permafrost exists in many steep rock slopes in high-mountain environments (Salzmann et al., 2007) and its degradation due to global warming can affect slope stability. Although this link might be intuitively clear, the mechanisms of permafrost degradation and related slope stability remain complex and only poorly understood (Gruber and Haeberli, 2007). A number of recent slope failures have been documented in permafrost areas, and related to increasing temperatures in general or to the heat wave of summer 2003 and the related excessive thawing of the active layer of permafrost bodies in particular (Gruber et al., 2004; Stoffel et al., 2005; Fischer et al., 2011; Ravanel and Deline, 2011).

Changes in sediment supply and land-use are further key determinants for mass-movement frequency and magnitude. Recent observations in the Swiss Alps indicate that sediment supply can in fact change significantly as a result of permafrost degradation of rock and scree slopes or mass movements related to other processes (Huggel et al., 2012). Average flow velocities of rock glaciers have increased drastically in many parts of the Alps (Kääb et al., 2007; Roer et al., 2008), probably as a result of increasing mean annual air temperatures (Kääb et al., 2007). As such, warming has been reported to exert indirect control on debris-flow magnitude and frequency (Stoffel et al., 2011) through the delivery of larger quantities of sediment into the debris-flow channels under current conditions than in the past (Lugon and Stoffel, 2010). As a consequence, the volume of the largest debris flows has risen by one order of magnitude since the 1920s (Stoffel, 2010) and is likely to further increase with ongoing permafrost degradation (Stoffel and Beniston, 2006).

The temporal frequency of debris flows, was, in contrast, not directly affected by these changes, as their release depends primarily on meteorological triggers such as intense rainfall in summer. Triggering

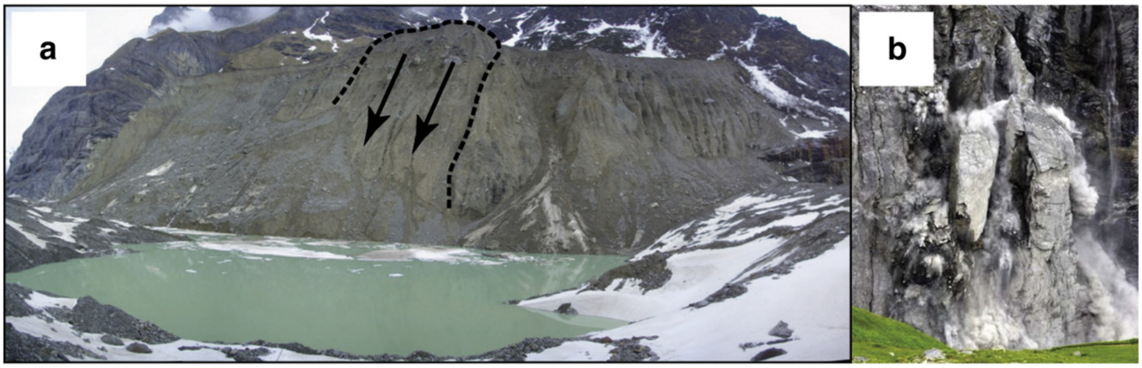

Fig. 9. (a) Glacial lake at Lower Grindelwald glacier with destabilized moraine that partly failed on 22 May 2009. The dashed line indicates the failed mass. The volume of the landslide was about 300,000 m^3, with 100,000 m^3 reaching the lake and generating an impact wave. A glacier lake outburst flood was recorded at the site in 2008. The volume of the lake reached $>2.5 \times 10^6$ m^3 water in 2009 (Source: www.gletschersee.ch). (b) Rockslide from the Eiger resulting from the debuttressing after the retreat of the Lower Grindelwald glacier (adapted from Stoffel and Huggel, 2012).

meteorological conditions have been shown to occur less frequently under current climatic conditions as compared to those of the late 19th and early 20th centuries (Stoffel et al., 2011; Schneuwly-Bollschweiler and Stoffel, 2012), and are not expected to increase in a future greenhouse climate (Stoffel et al., submitted for publication). Recent debris flows from other regions of the Swiss Alps tend to confirm the recent magnitude increase and related changes in erosive power which have proven to be sufficient to remobilize large amounts of sediment on Holocene fans (Stoffel and Huggel, 2012).

Despite uncertainties, recent developments at high-elevation sites have shown clearly that the sensitivity of mountain and hill slope systems to climate change is likely to be acute, and that events beyond historical experience will continue to occur as climate change continues (Goodfellow and Boelhouwers, 2012). The effects of changing mean and extreme temperature and precipitation are likely to be widespread and to influence both the occurrence (in terms of temporal frequency) and the magnitude of future mass movements across the Alps and other mountain environments around the globe. Despite uncertainties, slopes currently underlain by degrading permafrost will probably become less stable at progressively higher altitudes with ongoing climate change (Harris et al., 2009). One can also speculate that the probability of rock instability and the incidence of large ($>10^6$ m^3) rockfalls will increase in a warming climate (Holm et al., 2004; Huggel, 2009). On steep slopes, warming firn and ice temperatures may result in new sites of ice falls and ice avalanches. Provided that sediment supply is not a limiting factor, debris flows have the potential to become larger in the future than they were in the past, but not necessarily more frequent and clearly conditioned by local site conditions (Stoffel et al., 2008; Bollschweiler and Stoffel, 2010). The generation of cascading processes at high elevations might increase and result in chain reactions which are often difficult to predict (Carey et al., 2012; Worni et al., in press).

6. Summary and discussion

Climate in the Alpine region is expected to be considerably affected by 21st century global warming. This refers not only to rising temperatures, but also to changes in the seasonal cycle of precipitation, global radiation, and humidity, to changes in temperature and precipitation extremes, and closely related impacts like floods, droughts, snow cover, and natural hazards.

Under the A1B emission scenario, about 0.25 °C warming per decade until the mid of the 21st century and accelerated 0.36 °C warming per decade in the second half of the century is expected. The positive sign of change can be regarded as a very robust projection, but its magnitude is subject to considerable uncertainties. It has to be noted, that the expected rates of change in the 21st century are clearly below the observed rates in the past few decades (about 0.5 °C per decade). The reason for this could be natural variability, but the amount of the discrepancy and a study showing systematically underestimated trends in historical simulations of the ENSEMBLES multi-model dataset (Lorenz and Jacob, 2010) may indicate other reasons. This can be interpreted as a warning, that the possibility of even stronger warming than presented here cannot be excluded.

The annual cycle of precipitation is expected to change considerably until the end of the 21st century with decreases in summer, particularly in the southern regions, and increases in winter. This reflects that the Alpine region is located at the transition zone of a larger and seasonally shifting pattern of increasing precipitation in the North of Europe and decreasing precipitation in the South. The annual cycles of global radiation and relative humidity are expected to change consistently with the precipitation cycle, with a particularly strong decrease in relative humidity in summer. Other than for temperature, uncertainty in the projected sign of change is rather high in these meteorological variables. With regard to mean wind speed, no considerable changes are expected.

An analysis of the altitude gradients of change shows for most parts of the year an anomalous warming at higher elevations, but also an amplified low-elevation warming in summer. The former effect can be related to a reduction of snow cover and the snow-albedo effect. For precipitation no clear systematic altitude gradient can be found, except for a tendency towards a reduced summer drying and reduced winter moistening at high altitudes compared to low-lying regions.

Climate projections also suggest changes in extremes, such as a reduction of return periods of extreme precipitation events. This indication for more intense precipitation extremes is particularly severe in autumn and in the northern parts of the Alpine region, where changes in intensity may amount up to +30% at the end of the 21st century. However, more intense precipitation extremes are also expected in other regions in the entire colder season of the year. In terms of temperature extremes, it has been shown that conditions as during the record breaking heat wave in summer 2003 or warm winter 2006–2007 could occur about every second year at the end of the 21st century under the assumptions of the A2 emission scenario.

Changes in temperature and precipitation are very likely to have a range of secondary effects on floods, droughts, snowpack, and the occurrence of natural hazards. For instance, the intensification of precipitation is likely to cause more frequent severe flooding in the Alps. Increased temperatures are expected to lead to more severe drought regimes and large decreases in alpine snow amount and duration below about 1500–2000 m elevation. Also natural hazards, which are often related to downwasting of glaciers and melting of permafrost, are expected to respond to climate change by more frequent rockfalls and landslides and more intense debris flows.

The impacts of these projected 21st century climate changes in the Alpine region on society and ecosystems will be manifold. Warm winters and reduced snow cover will have obvious impacts on the timing and amount of surface runoff, with consequent impacts on a range of socio-economic sectors such as tourism, agriculture, or hydropower and, e.g., involve shortfalls in mountain community revenue resulting from a reduction in the number of days where skiing is possible. In addition, warm winters reduce the period of dormancy that many plants require, and often fail to destroy the precursor condition for pest and disease outbreaks later in the year. As seen during the 2003 heat wave, extreme summer temperatures and associated droughts have numerous and negative impacts on human health, agriculture, ecosystems, hydrology and the mountain cryosphere. In addition, more intense precipitation extremes and associated flooding can be expected to cause serious damage to life and infrastructure. Detailed investigations are needed to elaborate effective and flexible adaptation strategies well in advance, in order to alleviate the most negative impacts of climate change in the Alpine region.

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