# LINKING VARIATIONS OF METEOROLOGICAL AND SNOW CONDITIONS IN THE FRENCH MOUNTAIN REGIONS TO GLOBAL TEMPERATURE LEVELS

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ABSTRACT: Long term records of Alpine meteorological and snow conditions are prominent indicators of ongoing climate change. However, there have been limited assessments of the impact of global air temperature levels on their local variations. Such approaches are particularly required at present time, because international scientific assessments, forming the basis of climate negotiations, have partially shifted into an era of global warming levels rather than scenario based approaches. Addressing local impacts of global temperature variations may better inform policy makers than scenario-based visualizations, because of the direct relationship, regardless of the lead time, between local climate impacts (required for local climate adaptation planning) and the global temperature targets (largely discussed and showcased in national and international public debates and negotiations). This contribution describes the application of a method addressing the links between variations of global temperature and local indicators of meteorological variables (temperature, precipitation, snow/rain partitioning) and snow on the ground (mean snow depth, peak snow water equivalent, onset/melt-out date of the snowpack, number of days above selected snow depth threshold values) in mountainous areas. Past and future variations of these indicators were computed based on the SAFRAN reanalysis from 1958 to 2016, and using CMIP5/EURO-CORDEX GCM/RCM pairs spanning historical (1950-2005) and RCP2.6 (4), RCP4.5 and RCP8.5 (13 each) future scenarios (2006-2100). The adjusted climate model runs were used to drive the detailed snowpack model Crocus. While such an approach makes it possible to generate continuous scenarios of meteorological and snow conditions for the time period from 1950 to 2100, we specifically process the obtained results in order to highlight the local impacts of 1.5°C, 2°C, 3°C etc. global temperature increases since pre-industrial levels, based on 30 years average values of the indicators selected. The method is illustrated for a representative location of the Northern French Alps, the Chartreuse massif (near Grenoble) at an altitude of 1500 m. In this case, regardless of the time period into the future, variations of local meteorological and snow conditions generally show a significant correlation with global temperature variations, except total winter precipitation which does not show any significant relationship to global temperature. Global temperature levels on the order of 1.5°C above pre-industrial levels correspond to a 25 % reduction of winter mean snow depth (reference 1986-2005). Even larger reduction is expected for global temperature levels exceeding 2°C. Beyond this illustrative example, this contribution also provides an analysis of the results obtained in the French Alps and in the Pyrenees and introduces how the method can address other sectoral indicators, in the field of hydropower, mountain tourism or natural hazards.

KEYWORDS: climate change, snow, French Alps, Pyrenees, global warming level.

## 1. INTRODUCTION

Long term records and climate projections of meteorological and snow conditions in European mountains are prominent indicators of ongoing climate change (e.g. Beniston et al., 2018, and references therein). However, there have been limited assessments of the impact of global air temperature levels on local changes. Such approaches are particularly required at present time, because international scientific assessments, forming the basis of climate negotiations, have partially shifted into an era of global temperature targets rather than the traditional scenario based

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approach (e.g., IPCC Special Report Global Warming of 1.5 °C, http://www.ipcc.ch/report/sr15/). Identifying local impacts of global temperature variations may better inform some policy makers than scenario-based visualizations, because of the direct relationship, regardless of the lead time, between local climate impacts (required for local climate adaptation planning) and the global temperature warming level (largely discussed and showcased in national and international public debates and negotiations).

Here we describe the application of a method addressing the links between changes of global temperature and local indicators of meteorological variables (temperature, precipitation, snow/rain partitioning) and snow on the ground (mean snow depth, peak annual snow water equivalent, onset/melt-out date of the snowpack, number of days above selected snow depth threshold values) in mountainous areas. The method compares the rate of change of 30-years averages of local indicators with the corresponding global mean temperature change, based on global climate model output (James et al., 2017). Such a method is increasingly used to relate local impacts of climate change to global warming levels (see IPCC Special Report Global Warming of 1.5 °C, or Kraaijenbrink et al., 2017, for a recent example). It has recently been implemented in the context of snow conditions in French mountain regions by Verfaillie et al. (2018). Here the method is illustrated for a representative location of the Northern French Alps, the Chartreuse massif (near Grenoble, France) at an altitude of 1500 m. Beyond this illustrative example, this contribution provides an analysis of the results obtained in the French Alps and in the Pyrenees and introduces how the method can address other sectoral indicators, in the field of hydropower, mountain tourism or natural hazards.

## 2. METHODS

### *2.1 Climate data*

This study builds on the methodological developments introduced in Verfaillie et al. (2017) and Verfaillie et al. (2018) for generating climate projections of meteorological and snow conditions in the French mountain regions, based on EURO-CORDEX Regional Climate Model (RCM) projections for the 21$^{st}$ century, driven by CMIP5 Global Climate Models (GCM) (Taylor et al., 2012, Jacob et al., 2014). In short, we used 13 GCM/RCM pairs from EUROCORDEX RCP 4.5 and RCP 8.5, and 4 pairs for RCP 2.6, and adjusted them against the SAFRAN reanalysis using the ADAMONT adjustment method, followed by Crocus model runs to compute the evolution of snow on the ground. SAFRAN provides hourly meteorological data for French mountain regions, within zones of approximately 1000 km$^2$ referred to as “massifs”, within which meteorological conditions are assumed to depend primarily on altitude, by steps of 300 m altitude. The SAFRAN reanalysis results from the combination of large scale synoptic weather forecast or reanalysis and remotely sensed and in-situ meteorological observations, available from 1958 until present (Durand et al., 2009). There are 23 massifs in the Alps and the Pyrenees (including Spanish Pyrenees and Andorra), the method was applied to the entire dataset. ADAMONT is a quantile mapping adjustment method operating on daily RCM data, using different quantile distributions for 4 weather patterns and 4 seasons (Verfaillie et al., 2017). The method provides adjusted data at daily time resolution, which are disaggregated to the hourly time resolution using analogue dates from the SAFRAN reanalysis to reconstruct the shape of the diurnal variations of the meteorological variables. This provides adjusted time series making it possible to drive energy balance models, in particular the multi layer detailed snowpack model Crocus (Vionnet et al., 2012, Lafaysse et al., 2013). « Note that for each RCM within the EUROCORDEX data set, the same grid point is used for all altitude levels in a given SAFRAN massif. Therefore, the result of the adjustment does not account for the altitude dependency of the climate response from the RCM itself. The altitude dependency of the meteorological variables results entirely from the altitude dependency of the SAFRAN reanalysis itself, which is implicitly embedded into the application of the quantile mapping method, based on relationships calculated using data from the adjustment period. Here we used SAFRAN data from 1980 to 2011, and RCM data from 1974 to 2005 (i.e., the last 30 years of the historical period simulated by CMIP5 GCMs), to establish the quantile distributions. For most GCM/RCM pairs, historical model runs span the period from 1950 to 2005 and climate projections span the period from 2006 to 2100. See Verfaillie et al. (2018) for details.

### *2.2 Snow and meteorological indicators*

Based on meteorological and snow-related variables at daily time resolution, we computed and analyzed different indicators. Defining “winter” as the period from December to April inclusive (5 months long), the following snow condition indicators were computed: mean winter snow depth (SD), exceedance duration over a snow depth threshold for thresholds values of 5 cm, 50 cm and 1m (STED5, STED50, STED100, expressed in days). In terms of meteorological indicators, we considered mean winter temperature (T), cumulated winter total (rain and snow) precipitation (P) and mean winter ratio between snow and total precipitation (R). We also computed the maximum annual snow water equivalent (SWE) as well as the snowpack onset and melt-out dates (SOD and SMOD), which correspond to the earliest/latest time bounds of the longest period of time with snow depth values exceeding 5 cm, which can be interpreted as the longest period of time with continuous snow cover.

Altogether, the implementation of the method leads to approximately 3000 model years of data (combining multiple RCP and multiple GCM/RCM pairs for the period from 1950 to 2100).

### 2.3 *Relationship between global warming level and local indicators*

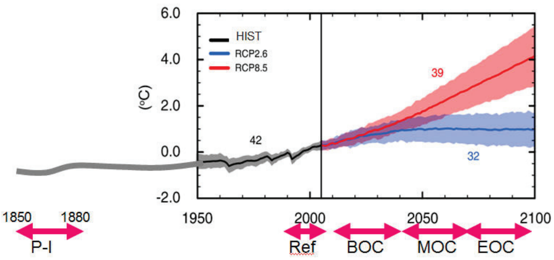


Figure 1: Outline of the method applied to relate local changes of indicators to global warming levels (modified, from IPCC, 2013).

Figure 1 introduces the basic principles used to relate local change in meteorological and snow indicators to global warming levels. For the reference period 1986–2005 (Ref) and for three 30-year periods during the 21st century (beginning of century (BOC), 2011–2040, middle of century (MOD) 2041–2070 and end of century (EOC), 2071–2100), we computed interannual mean values corresponding to a given GCM/RCM pair for the meteorological and snow indicators introduced above, for all RCPs available for a given GCM–RCM pair. We also computed the mean surface air temperature for each GCM–RCM run under each available RCP configuration, for the same time periods. Based on these datasets, we also computed linear regression curves (intercept forced to 0) between interannual means of the local meteorological and snow indicators during BOC, MOC and EOC, and the corresponding global annual temperature difference between the corresponding time period and the reference period. Linear regressions were also computed using all future time periods together (ALL). In addition, the future values of the local meteorological and snow indicators of all future time periods were binned according to the corresponding global temperature by steps of 0.5°C, and the mean and standard deviation of all values within a given bin were computed. This method corresponds to one of the approaches reviewed by James et al. (2017).

## 3. RESULTS FOR CHARTREUSE, 1500 M

Figure 2 shows the relationships between computed changes in the snow and meteorological indicators between 1986–2005 (reference period for this study) and three future time periods (BOC, MOC and EOC, see section 2.3) and the corresponding global temperature changes simulated by the driving GCM. With the notable exception of the cumulated winter precipitation P, all indicators show a consistent relationship with global warming rate. The slope of the regression curve is very similar for all three future time periods as well as when all future time periods are pooled together. The maximum correlation is found for the snow precipitation ratio with a coefficient of determination of 0.90, followed by local air temperature with a coefficient of determination of 0.86. The worst correlation is found for STED100 ($R^2$=0.48 for all time periods). All other snow-related indicators $R^2$ values range between 0.76 and 0.83. The slope of the regression curve, in terms of % change per global temperature difference with the Ref value, is larger for snow depth (about -25%°C$^{-1}$), than for SWE (-20%°C$^{-1}$). The SOD and SMOD changes are not symmetrical, i.e., the date of snowpack onset exhibits a lower relative reduction (12 days °C$^{-1}$) than the date of snowpack melt out (17 days °C$^{-1}$). Taking the sum of absolute values of SOD and SMOD as a measure of the changes in total snow season length, it is found that the total snow season length is decreased by 29 days, i.e., about one month, per global °C difference with the Ref value. The slope of the local temperature regression curve is 1.1°C°C-1, which indicates that the local rate of winter warming only slightly exceeds the global warming rate during the 21st century, using this method. For more details on this particular case, see Verfaillie et al., (2018).

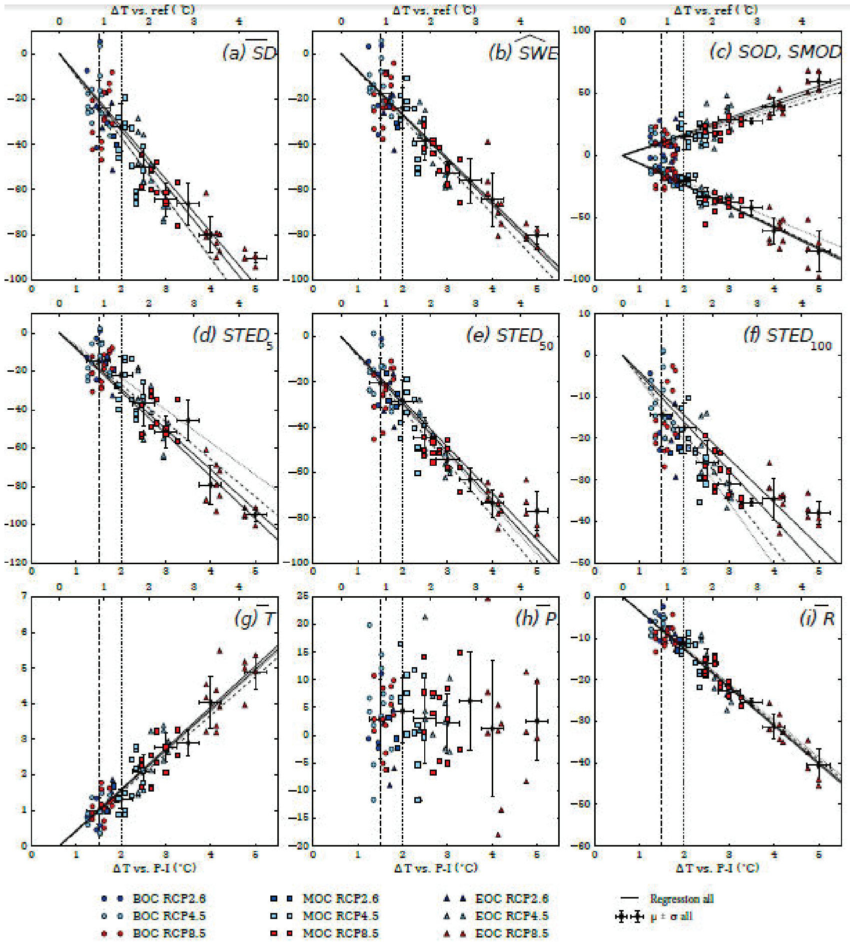


Figure 2: Response of local meteorological and snow indicators to global warming level. Indicator response is computed as the difference of multi-annual means between end of century (EOC, 2071-2100), middle of century (MOC, 2041-2070), or beginning of century (BOC, 2011-2040) and the reference period (Ref, 1986–2005). Global warming level is computed as the difference in global mean surface air temperature between EOC, MOC or BOC and either the reference period (top axes) or the preindustrial period (P-I, 1851–1880) (lower axes). Each point corresponds to a snow or meteorological indicator computed using a given RCP and one GCM–RCM pair, for which the global surface air temperature change is inferred from the corresponding GCM run: (a) Snow depth (%), (b) Peak SWE (%), (c) SOD and SMOD (days), (d) STED5 (days), (e) STED50 (days), (f) STED100 (days), (g) T (°C), (h) P (%), and (i) R (%). Warming levels of 1.5 and 2°C compared to preindustrial are shown with the vertical dashed lines. Regression lines are shown for the response at EOC, MOC, BOC or all three periods (ALL) (except for P). Mean values and standard deviations among ALL changes in each indicator for 0.5°C global warming intervals are shown as error bars.

## 4. RESULTS IN THE FRENCH ALPS AND PYRENEES

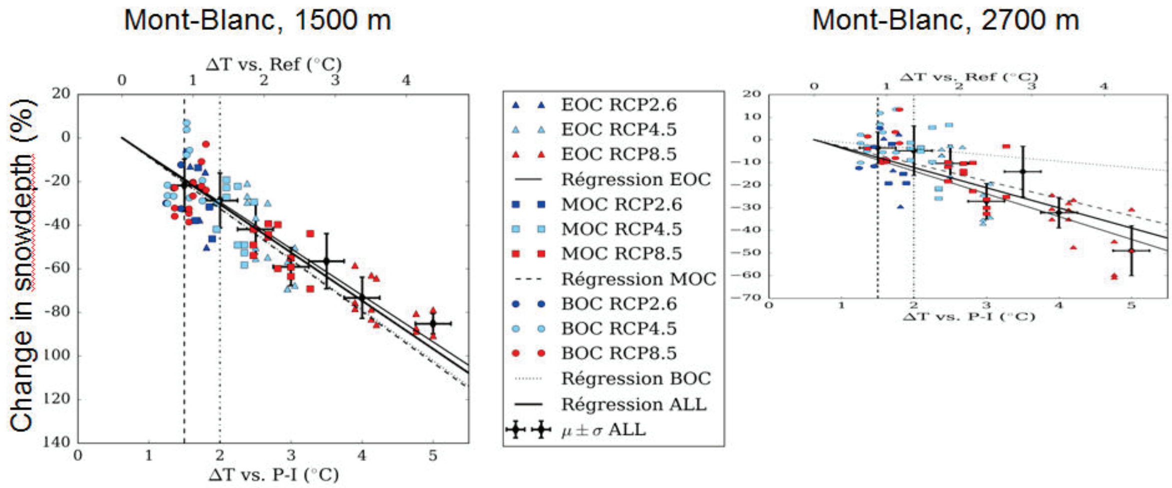


Figure 3: Response of snow depth in the Mont-Blanc are to global warming level, at 1500 m altitude (left) and 2700 m altitude (right). See Figure 2 caption for a description of the symbols and colors used.

### 4.1 *Altitude relationship,example from Mont-Blanc area*

Figure 3 shows the relationship between snow depth change and global warming level for the Mont-Blanc area (Northern French Alps) at the contrasting altitudes of 1500 m and 2700 m. It shows that at 1500 m, the correlation is similarly strong as in Chartreuse mountain range (Figure 2). However, at 2700 m altitude, the relationship shows lower correlation and a lower slope of the regression. At 1500 m altitude, the slope of the relationship is -22 $\%°C^{-1}$, while it amounts only -9 $\%°C^{-1}$ at 2700 m altitude. A similar exercise carried out in terms of the length of the snow season reveals that the reduction of snow season length amounts 24 $days°C^{-1}$ at 1500 m, and 12 $days°C^{-1}$ at 2700 m altitude. The local response of snow conditions to climate change does not only vary with altitude. Indeed, it also specifically depends on the indicator of interest.

Table 1 shows a synthesis of the amount of reduction in snow depth for three contrasting altitudes 1500 m, 2100 m and 2700 m altitude, as a function of global warming since pre-industrial time, in the Mont-Blanc area.

| | 1.5°C | 2°C | 3°C | 4°C | 5°C |
|---|---|---|---|---|---|
| 2700 m | -4% ± 7 | -5% ± 11 | -27% ± 8 | -32% ± 7 | -49% ± 11 |
| 2100 m | -11% ± 10 | -16% ± 12 | -42% ± 10 | -54% ± 9 | -69% ± 9 |
| 1500 m | -22% ± 12 | -29% ± 13 | -49% ± 9 | -73% ± 9 | -85% ± 5 |

Table 1: 30-years average winter snow depth reduction with respect to the 1986-2005 reference period in the Mont-Blanc area as a function of the level of global warming since the pre-industrial period.

As shown in Table 1, the snow depth reduction rate between the reference period 1986-2005 and future time periods in the 21st century depends on altitude and on the global warming level with respect to the pre-industrial period. For example, a comparably similar reduction rate is found at 1500 m for a 2°C global warming than at 2700 m altitude for a 4°C global warming (around -28%). A similar reduction rate of -50% is expected for 3°C warming level at 1500 m and 5°C warming level at 2700 m. This example highlights that this relationship is non linear, due to the combination of multiple factors and processes driving long term changes in snow conditions in the mountain areas. This implies that the difference, in terms of local impacts, between a 1.5°C or 2°C warmer world depends on the altitude, and this must be taken into account specifically depending on the application of interest. Table 1 also shows that there is a significant uncertainty around the relationship between local indicators and global warming levels. The uncertainty arises from the contribution of multiple RCP and GCM/RCM pairs taken into account, at multiple time periods into the 21st century. It reflects both the impact of the natural variability of climate, and uncertainty associated to global and regional climate models.

### *4.2 Pyrenees*

Figure 4 illustrates the geographical and altitudinal deviation of the number of days with snow depth exceeding 5 cm, in the Pyrenees, as a function of altitude and global warming level since the pre-industrial. Although the plot does not appropriately shows the uncertainty around the mean deviation value, it illustrates key concepts of the relationship between local indicators and global warming levels. First of all, the magnitude of impact generally shows increasing values with increasing global warming levels. The response is regionally variable, but shows an even stronger relationship to the altitude, and, correspondingly, the reference value. Indeed, for low elevations (e.g., 900 m altitude), the number of days exceeding 5 cm of snow depth is already low, on the order of a few tens of days per year on average. Changes, expressed in terms of number of days, show small figures even if the snow on the ground virtually disappears for some warming levels. Conversely, at high altitude (e.g., 2700 m altitude), the number of days with more than 5 cm of snow from December to April reaches the maximum value when on average all days meet this threshold. It is only with a global warming level of 3°C that the reduction becomes visible, because for lower global warming rates the impact on snow conditions does not affect the presence of snow on the ground, but rather the amount (see section 3.2). Changes are visible already with 1.5°C global warming, and show spatial patterns related to altitude and geographical location, related in part to the climatological value calculated for the reference period.

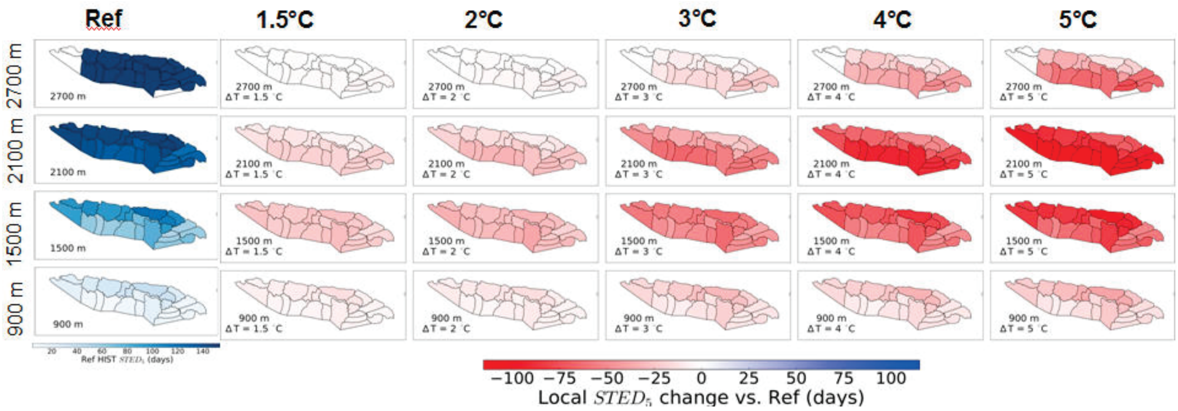


Figure 4: Deviation, with respect to the reference period 1986-2005 (left column), of the number of days exceeding 5 cm of snow on the ground from December to April, as a function of altitude (900 to 2700, y-axis), and global warming level since the pre-industrial (1.5°C, 2°C, 3°C, 4°C and 5°C, x-axis). The graph shows only the average deviation and does not represent the uncertainty around this average value.

## 5. DISCUSSION AND CONCLUSION

This study illustrates a general framework for assessing the relationship between local changes in meteorological and snow indicators in mountainous areas, and global warming levels, either since the pre-industrial period or for a common reference period with the local indicators. The method employs similar ingredients as climate change impact studies presented in the form of climate projections. It takes advantage of all the output of the climate projections, regardless of the RCP, GCM/RCM pair, and time period into the 21st century used. Using all of this data together potentially increases the robustness of the results. While scenario, narrative-based climate projections are certainly useful for multiple stakeholders to apprehend the time dimension of the impact of climate change, we believe that this global warming approach has potential to align local impact studies with the framework of international negotiation and climate agreements. As such, it can be used not only for natural snow conditions, as exemplified in this study, but also for any relevant multi-variable or geographically aggregated indicator for a series of ecosystem or socio-economic sectors, such as natural hazards (e.g., avalanches), water resources, ski tourism etc. All the method requires is an annual-scale indicator, which can be computed based on the post-processed (downscaling, impact modeling, etc.) output of global climate models.

Because it uses the same underlying data as scenario-based approaches, it shares the same disadvantages and limitations. Firstly, the use of a snowpack model in an uncoupled manner can lead to inconsistencies between the meteorological forcing and the state of the snow cover, and the absence of specific feedbacks where the snow cover plays a role. Second, the fact that only one RCM grid point is used for all altitude levels within a given massif makes it impossible to account for potential elevation dependent changes in meteorological conditions simulated by the RCMs, other than those elevation-dependent signatures which can be found during the period of time used to compute the quantile distributions. This shortcoming is partly overcome by the fact that the snowpack model used is sensitive to multiple variables including incoming radiation, and not only temperature and precipitation, as it is generally the case for hydrological models, but it is likely that elevation dependent enhancements in e.g. warming are underestimated using this approach.

## 6. ACKNOWLEDGEMENTS

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