Climate report

Climate change in the Mont-Blanc Massif and its impacts on human activity

November 2019

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Summary

Observed change

Since the end of the 1980s, average annual temperatures in the Espace Mont-Blanc (EMB) have risen between 0.2 and 0.5°C per decade. The rise in temperatures has primarily taken place in spring and summer. No significant trend has been observed in total annual precipitation. Extremely hot days became significantly more frequent.

Expected change

The rise in annual **temperatures** is expected to continue with an **expected warming of 1-2°C above the average established between 1980 and 2010 by 2035**. Warming will be about 1°C in winter (December through February) and 1.5-2°C in summer. By 2050, we expect a temperature increase between 2 and 3 °C, again with the most significant rise occurring in summer months. In summer, the 0° isotherm or freezing level will rise 300 meters in elevation, from 3,800 m today to 4,100 m in 2050. By the end of the 21st century, a temperature increase of 3-6 °C is anticipated, depending on the greenhouse gasses emissions scenario.

In the near future (2035), in the mid (1,000-2,000 m) and high (> 2,400 m) elevations, we expect a **decrease** of 15-20% in the **number of ice days***. By 2050, the number of ice days is expected to decrease by 30 days, and as much as two months by the end of the century, according to the pessimistic emissions scenario. By 2035, at the valley floor, we expect the number of extremely hot days to rise from 2 to 6-10 days per year, and increase to as much as an average of **15-20 extremely hot days* per year** by 2050.

There is less certainty when it comes to annual **precipitation** predictions. The total amount of precipitation is not expected to change from the 1980-2010 average, but will be distributed differently across seasons. **Winter precipitation will increase** (5-15%), whereas **summer precipitation will decrease** 5-10% by 2035 and 10-20% by 2050 and the end of the century. During the summer season, the combination of higher temperatures and reduced precipitation will cause increased drought risk: a 15-40% reduction in the summer water balance is expected by 2035 at all elevations. The frequency of intense precipitation events will also increase: **the total amount of precipitation that falls during extreme weather events** will rise 10-20% over the course of the year, especially during spring (March-May) and winter (December to February).

Impacts on natural environments

Climate change's impacts on temperature, precipitation and extreme weather events will cause major changes in the EMB's natural environments, and many of these changes are already underway. The duration of snow cover on valley floors and south-facing slopes up to 2,000 m is likely to be reduced by 4 to 5 weeks compared to the current levels, and reduced by 2 to 3 weeks at 2,500 m. Glacier retreat will continue to accelerate in the coming decades. Ongoing warming will continue to impact permafrost in the Mont-Blanc Massif, resulting in increased instability on high mountain rock faces.

In terms of biotic factors, **flora and fauna will move to higher elevations** in order to find favorable climatic conditions. These changes, combined with glacier retreat and snowfield melt, will cause **mountain landscapes to undergo profound transformations**, with vegetated and rocky environments

being found at higher and higher elevations. Some emblematic species (both common and rare) will see the extent of their habitat decrease or even disappear, causing further changes to the landscape.

Water

Stream and river flow will be higher in late winter and early spring because precipitation falling more frequently as rain rather than snow. However, reductions in precipitation, snow cover and glacial area will lead to **lower streamflow in late summer and fall.** The extent of the changes will be dependent on the specific conditions of each watershed.

We expect a **significant reduction (15-40%) in the summer water balance (the amount of water available in the ground) by 2035, at all elevations**. This decrease will continue in 2050 and become more and more accentuated by the end of the century.

Agriculture

Agriculture is one of the economic sectors that will be most directly impacted by climate change: rising temperatures and changes in precipitation will have varied effects on plant and animal productivity. Warmer temperatures could result in new opportunities when it comes to (*i*) primary (vegetation) productivity, which may rise by 5 to 15%; (*ii*) longer growing seasons, which could lead to supplemental harvests; or (*iii*) changes in the geographic distribution of crops. For example, **wine growers may be able to plant a wider range of grape varieties on increasingly higher slopes**. The overall trend also leans toward **a decrease in the risk of late frost events***, one of the climatic hazards that can have an important impact on mountain agriculture. For the three crops considered in this report (apples, cherries and pastures), the risk reduction will be most significant around 700 m.
However, some of the benefits will be offset by increased risk for other agricultural practices. For three species of pests found in the valleys, we predict an **increase in the annual number of generations possible by 2035.** Animals such as cows will also experience a **higher number of 'stress days' due to high temperatures, leading to decreases in milk production.**

Forests and biodiversity

Some tree species that are unable to migrate to higher elevations or adapt could disappear locally and be replaced by new species, such as deciduous trees that have migrated upslope from lower zones. Both **biomass production and the total surface occupied by forests is expected to increase as a result of warming**. However, droughts will play a key role in the composition of forests by weakening populations and making them more vulnerable to summer droughts, parasites, disease and extreme weather events.
Plant and animal species will migrate to higher elevations, both at, and above, their current upper limits. The upward migration of high-elevation species will be limited by a decrease in the available surface area and could result in the disappearance of some species adapted to cold environments. As the snow-free season lengthens, climate-related limitations on plant growth will be less significant and so-called "specialist" species (both plants and animals) that are specifically adapted to long periods of snow cover will be progressively replaced by more competitive, generalist species.

Tourism

In the short term (2035 to 2050) ski resorts located below 2,000 m will see their operation viability significantly reduced. For ski areas above 2,000 m, risks will vary depending on the topographic and climatic configuration (south-facing versus north-facing) as well as other conditions necessary for managing snow (water availability, technological advancements, socio-economic sustainability, etc.). Taking only temperature into consideration, **adaptation strategies based on snowmaking should remain viable for ski resorts located above 2,000 m in the short term.** However, this solution is expected to become less and less reliable in the longer term (by the end of the century).

Four-season tourism offerings also stand to benefit from a prolonged summer season. This is particularly true of spring and autumn, which are currently considered to be the “off-season”. We predict **roughly one additional week of pleasant or excellent* weather days at all elevations during June and October in the near future (2035-2050).**

Summer activities (like winter ones) will be impacted by warming temperatures, glacier retreat, permafrost degradation, decrease in snow cover and rising tree-line. **These changes will impact mountain trails, and in particular, trails allowing access to high-mountain huts and mountaineering routes.**

Natural Hazards

The EMB is a territory that is particularly sensitive to natural hazards related to the intensification of the water cycle and cryospheric modifications (snow, glaciers and permafrost). **Permafrost degradation** can reduce slope stability and threaten high-mountain infrastructure (ski lifts, cable cars, roads, buildings, etc.). **Slope instability can also be caused by glacier melt**, which leads to a destabilization of lateral moraines and rock faces. Warming temperatures will also increase the risk of serac fall from the terminus of suspended glaciers, which are often found on very steep slopes. Increased glacier melt in coming years may also be associated with **flash flooding (glacial outburst floods) when water trapped in intraglacial cavities or glacial lakes bursts. Avalanche risk is expected to be reduced at low elevations, while changes in the characteristics of high elevation avalanches are anticipated.** The **risk of rising water levels and floods**, either due to changes in the cryosphere or to the increase in frequency of intense precipitation events, is expected to increase in coming years in the EMB. It is also crucial to consider natural hazards in the context of high mountain environments because they can act in synergistic and additive ways, leading to domino effects. All risk adaptation strategies in the EMB should take into account the possibility of this type of interaction between hazards.

1. Observed and future climate change

1.1 Context and objectives

General climate change context

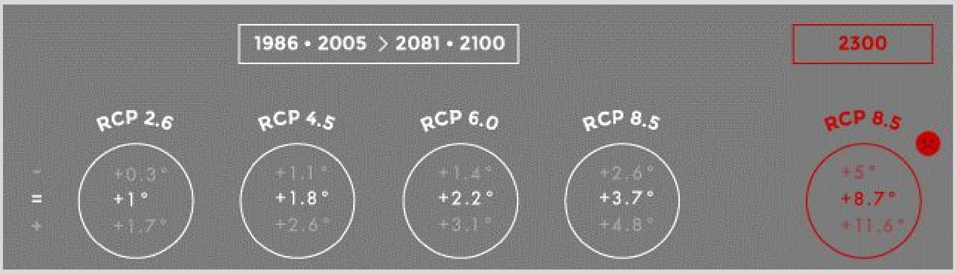
Recent climatic change is a phenomenon that surpasses political borders, both in its origins and its consequences.

Scientists agree and consider it extremely probable (more than 95% certainty) that climate change is both happening on a global scale since the 19th century and is caused by humans. Ongoing climate change is caused by a sharp increase in greenhouse gas emissions*. Natural cycles add a marginal effect to this process. Uncertainty in climate models regarding the rise in future global temperatures is largely **due to the uncertainty about the rate of future greenhouse gasses gas emissions** by human society.

BOX 1: from IPCC scenarios to local scenarios

In 2013, IPCC experts established four different global climate scenarios based on different hypotheses about levels of greenhouse gas (GHG) emission from human activity (Figure 1). The analyses presented in this report rely on three of those scenarios. The most optimistic scenario "RCP 2.6" would require strong reductions in GHG emissions. In light of the emissions since 2013, this scenario is extremely improbable. The intermediate scenario is "RCP 4.5". The most pessimistic scenario, "RCP 8.5", is now the most likely because it corresponds with a continuation of present-day emission levels. For more information about the emissions scenarios, please see Annex 1.

From these global scenarios, climatologists construct local-scale models. The more "zoomed in" the model, the less reliable it is because these models are dependent on complex phenomena and local parameters. Mountain regions are especially complicated to model because of the effects of micro-topography, exposition, seasons, snow cover, etc.



Climate change context in the Espace Mont-Blanc (EMB)

Climate change is not a scenario for the distant future for mountainous regions. It is already readily observable and will increase by 2050. Chapter 1.2 gives an overview of the current situation.

In addition, the impacts of climate change are exacerbated by geographic and economic contexts such as those found in the EMB, which are characterized by their dynamic, inhabited valleys and exceptional topographic relief. Because the mountains are so steep, communities in the EMB are not just economically and socially linked to the high mountains, they are also geographically proximate. The result is that **changes in the natural environments of the high mountains directly impact the human activity at the base.**

From the valley floor to the summits, the EMB is home to an elevation gradient (4,300 meters of vertical gain), and thus a temperature gradient, unique in all of Europe. As a result, the EMB contains a wide variety of different climatic conditions: from the Mediterranean-like climate found in Swiss and Italian valleys to a semi-polar climate at high elevation. **The truly remarkable climatic diversity existing in the massif means that the potential impacts of climate change are varied and extremely localized.**

While it is clear that the region needs to better understand how it will be impacted by climate change, the unique characteristics of the EMB also make it an exceptional setting for this kind of prospective exercise, with its usefulness going beyond the territory's geographic boundaries.

Anthropogenic (human-caused) changes in global climate lead to modifications in a series of specific and essential climatic parameters at the local scale. These parameters have a direct impact on physical and biotic aspects of the mountain environment, which in turn determine what human activities are possible. As a result, climate change has an impact on the cultural, social and economic wellbeing of the people who live in the EMB both directly and indirectly:

- Directly, as a result of **climatic parameters (temperature, precipitation, extreme weather events)**
- Indirectly, but at a deeper level, as a result of the impacts of climatic changes on **biotic and physical** parameters (decrease in snow cover, degradation of permafrost*, glacier retreat, modification of water regimes, advance of seasons, upslope migration of species, and the proliferation and disappearance of species having profound impacts of the landscape)

Figure 1.1 illustrates these relationships as they can be found in the EMB:

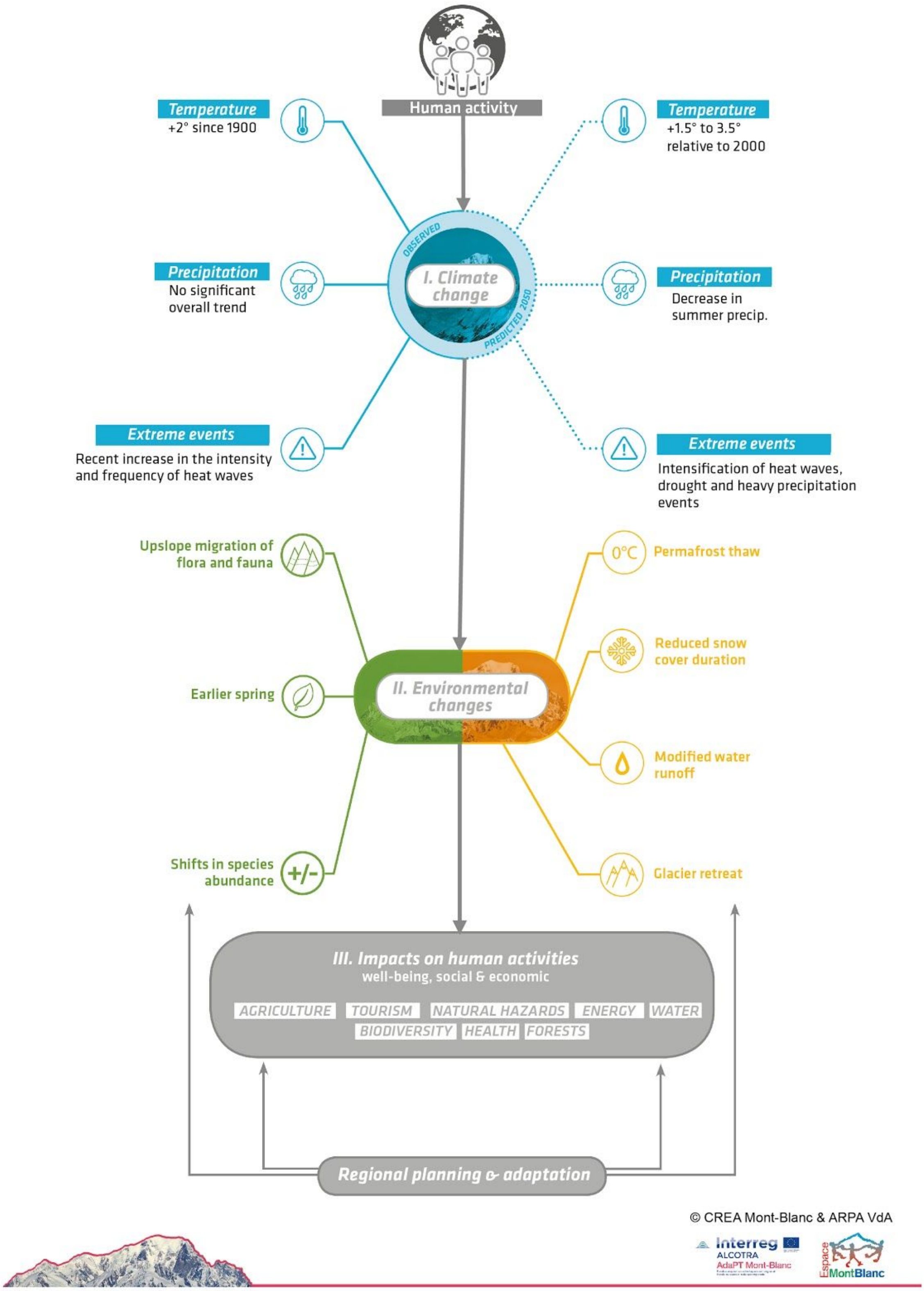


Figure 1.1. Diagram summarizing the sequence of consequences, from climatic parameters to human activities. This sequence will be referred to throughout this report.

Objectives of this report: Climate scenarios and socio-economic sectors

Given that the objectives of this report are i) the analysis of climate change scenarios, ii) the evaluation of impacts on natural environments, and iii) on human activities, we began the process by pooling information from local and regional stakeholders and decision-makers at the EMB scale.

With this in mind, we collaborated with partners in France, Italy and Switzerland in order to:

- Synthesize and present the available scientific data from Mont-Blanc's three border nations in the clearest and most homogenous way possible
- Use an active participative process (Adapt Mont-Blanc project WP2) to determine high-priority sectors of socio-economic activity to focus on in our impact analyses

The **objective of the report** is to provide the EMB's elected officials and decision-makers with an overview of recent and expected impacts of climate change on natural environments and priority sectors of socio-economic activity. By natural environments, we are referring to the ensemble of physical (glaciers, snow cover and permafrost) and biotic (biodiversity, forests, grasslands, etc.) components that make up the EMB's landscape that impact many sectors of human activity. Local stakeholders were called upon to identify, among the many sectors of human activity that are impacted by climate change both at the local and global scale, the sectors they wished to have prioritized in this report. As such, this report will take into account natural resources (water, agriculture, forests, biodiversity), tourism and natural hazards, but will not include other important sectors including health, energy, and transport.

BOX 2: Weather or climate?

In order to study and understand the impacts of climate change, it is essential to distinguish between weather, which refers to short-term climatic events, and climate, which refers to long-term trends, studied over periods of at least 30 years in order to be considered statistically significant.

Accordingly, climate refers to averages of observed or predicted weather values. Like any average, it includes values above and below the average. This explains how, even with an overall average reduction of snow cover of 25 days per year since the 1960s (climate index), we can still experience exceptional snow years like 2018 (weather index). Likewise, a predicted 2°C increase in summer temperatures is an average which implies that some summers will be much hotter.

This report is structured in the same way as Figure 1.1. In the first part, we present an overview of changes in temperature and precipitation in the EMB region since 1900. Next, we present climate scenarios for the coming decades and expected changes in selected climate indices that have significant impacts on human activity (section 1). We finish with a synthesis of the main impacts of climate change on natural environments (section 2) and on priority socio-economic sectors (section 3).

Annex 1 includes details on the methodology used as well as sources for the data used. A bibliography of scientific articles and reports cited in this report is found in Annex 2. A list of all acronyms used in this report can be found in Annex 3.

1.2 Recent climate change observed in the Mont-Blanc massif since 1900

At a global scale, the rise in temperatures observed since the middle of the 19th century is extremely fast and without precedent (IPCC 2018, SR1.5). Studies of ice cores have revealed that current concentrations of greenhouse gas emissions, including CO_2 (> 400 ppm*) are the highest they have been in the last 800,000 years. More recently, on a global scale, sixteen of the last seventeen years have been the warmest ever recorded (IPCC 2019-4).

At the scale of the European Alps, since 1864, average annual temperatures have risen about 2°C, which is more than double the increase of 0.9°C recorded on a global scale (CH2018*).

BOX 3: Before 1900

The climate in Europe and in the Alps has had some significant variations over the last few thousand years, including, notably, the Würm glaciation which ended about 11,000 years ago (Davis *et al.* 2003). More recently, Europe experienced a relatively warm, wet period (the *Medieval Warm Period*) between 900 and 1350, followed by a cold, wet period between 1300 and 1850 (the *Little Ice Age*) (Kress et al., 2014). This era was marked by a spectacular expansion of glaciers in the Alps, with the Mer de Glace extending all the way to Chamonix.

It is important to note that we have only had reliable and continuous weather records since the beginning of the 20th century. Earlier climatic variations are determined using indirect indicators such as ice cores and tree rings.

A recent study (Neukom et al., 2019) showed that the warming recorded on a planetary scale in recent decades has been more intense and homogenous than any of the climate variations of the last 2,000 years.

Temperatures

Rises in temperatures have been particularly significant since the end of the 1980s, with an **observed warming of 0.2 to 0.5°C per decade** (Gobiet et al., 2014, Météo-France, Météo-Suisse, Centro Funzionale Valle d'Aosta ; Figure 1.2). This temperature rise is roughly equivalent to the difference in temperature typically observed between two elevations that are 100 vertical meters apart. At this rate, in order to maintain the same temperature conditions, species would have to move upslope 100 m every ten years. In terms of seasonality, observed warming in the Alps has been **especially marked in the spring and summer**. For example, in the Aosta Valley, while annual temperatures have risen by 0.58°C per decade, spring and summer temperatures have risen by 0.81°C and 0.72°C respectively (Centro Funzionale Regione Autonoma Valle d'Aosta et ARPA VdA).

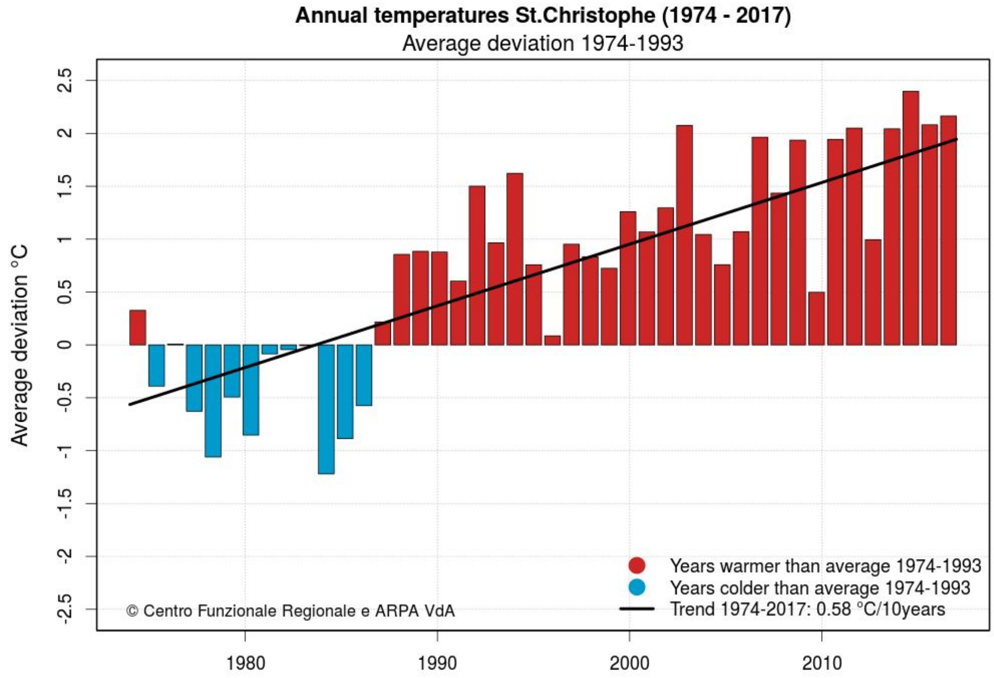


Figure 1.2. Increase in average annual temperatures since 1974. This graph illustrates the deviation of average annual temperatures from the average established between 1974 and 1993 in Saint Christophe in the Aosta Valley. We note the acceleration of the rise in temperatures beginning at the end of the 1980s, as well as the variability of annual averages (see the « weather index » in BOX 2).

Precipitation

While average precipitation regimes have seen strong **contrasts between regions and seasons,** over the course of the 20th century, at the scale of the Alps, precipitation regimes have not shown overall trends of change. None of the regions of the EMB have experienced a significant change in total annual precipitation since 1864 (Météo-France, Météo-Suisse, Centro Funzionale Valle d'Aosta - Figure 1.3). Nonetheless, much greater interannual variability in terms of precipitation quantity has been recorded.

BOX 4: The seasons in climatology

In climatology, seasons are not the same as calendar seasons and are represented as follows: winter: December/January/February (**DJF**), spring: March/April/May (**MAM**), summer: June/July/August (**JJA**), Fall: September/October/November (**SON**).

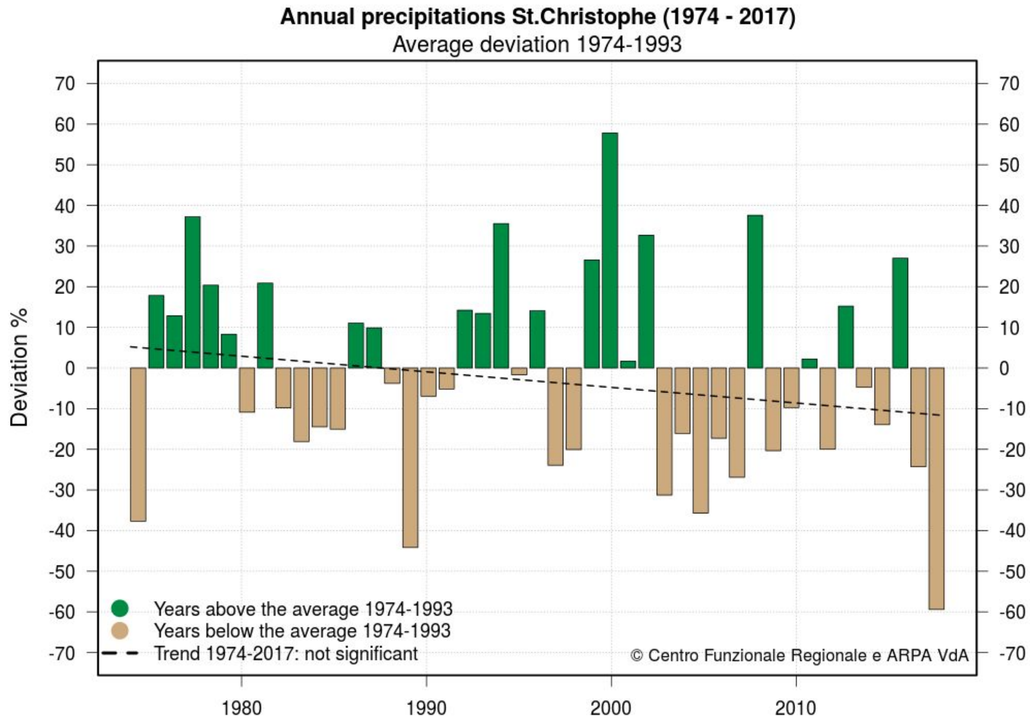


Figure 1.3. Observed change in annual precipitation since 1974. This graph illustrates the deviation of average annual precipitation from the averages established between 1974 and 1993 in Saint Christophe in the Aosta Valley. We can note that while there is no significant trend apparent (despite a slight decrease observed in recent years), there is a great variability from year to year.

Extreme weather events

The IPCC emphasizes that climate change does not result in a single and uniform rise in temperatures but rather in a multitude of climatic changes. Among these changes, we can note a redistribution of precipitation on a global scale and an increase in **extreme weather events**, which is to say, **larger and larger deviations from the meteorological average.** The rise in extreme weather events in the EMB has been characterized by an increase in the number and the length of summer heatwaves and late frost events* at high elevation (particularly since the 1970s). Warming in the EMB has also been characterized by a decrease in the number of frost days* (days per year with minimum temperatures below 0°C) of about 6.5 days per decade since the 1970s at an elevation of 600 m (Figure 1.4). On the other hand, in the spring, the rise in temperatures has been accompanied by increased vulnerability to spring frost events: **between 1975 and 2016, the risk of late frost events increased by 20-40% above 800 m** (Vitasse et al., 2018). This phenomenon is the result of early vegetation growth (both cultivated and natural) due to warmer spring temperatures. This strategy is risky for plants because it exposes them to a higher risk of cold events, which are frequent early in the season (February-April).

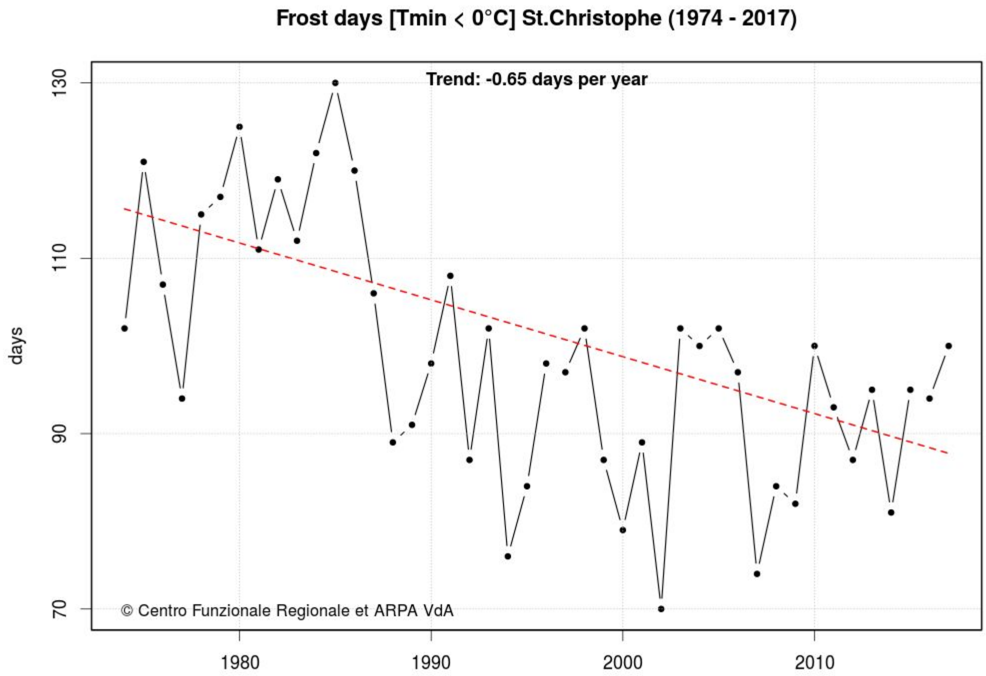


Figure 1.4. Observed change in the number of frost days* (daily minimum temperature below 0°C) per year in Saint Christophe in the Aosta Valley between 1974 and 2017. We see a large decrease (6.5 days per decade) in the number of frost days.

An **increase in heatwaves has been observed.** For example, in the Aosta Valley, the number of "tropical" days* (days with a maximum temperature above 30°C), has increased at a rate of 7.3 days per decade (figure 1.5). This intensification is particularly marked since the start of the early 2000s, and heatwave summers have become warmer and more frequent. For example, 2003, 2016 and 2017 all greatly exceeded the number of tropical days observed during the 1980s and 1990s.

A drought event is a prolonged period with either insufficient or no precipitation, leading to a water deficit. At the scale of Switzerland, since the end of the 19th century, no significant rise in the length and intensity of droughts has been observed (Meteo Suisse). To date in the EMB, we have not observed a clear trend in the occurrence of droughts in recent decades. Nonetheless, in more recent years, we have seen a sharp increase in the variability and frequency of precipitation (Figure 1.6).

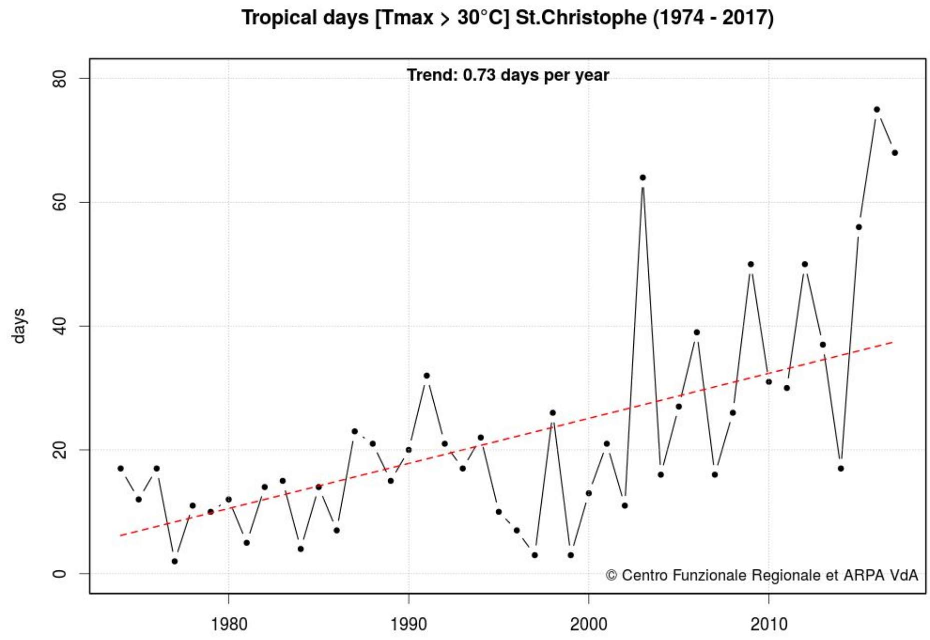


Figure 1.5. Observed change in the number of tropical days (maximum daily temperature above 30°C) per year in Saint Christophe in the Aosta Valley between 1974 and 2017. There is strong variability between years, with for example the extreme heatwaves of 2003, 2016 et 2017, and a clear trend toward an increase in the number of tropical days* (7.3 days per decade).

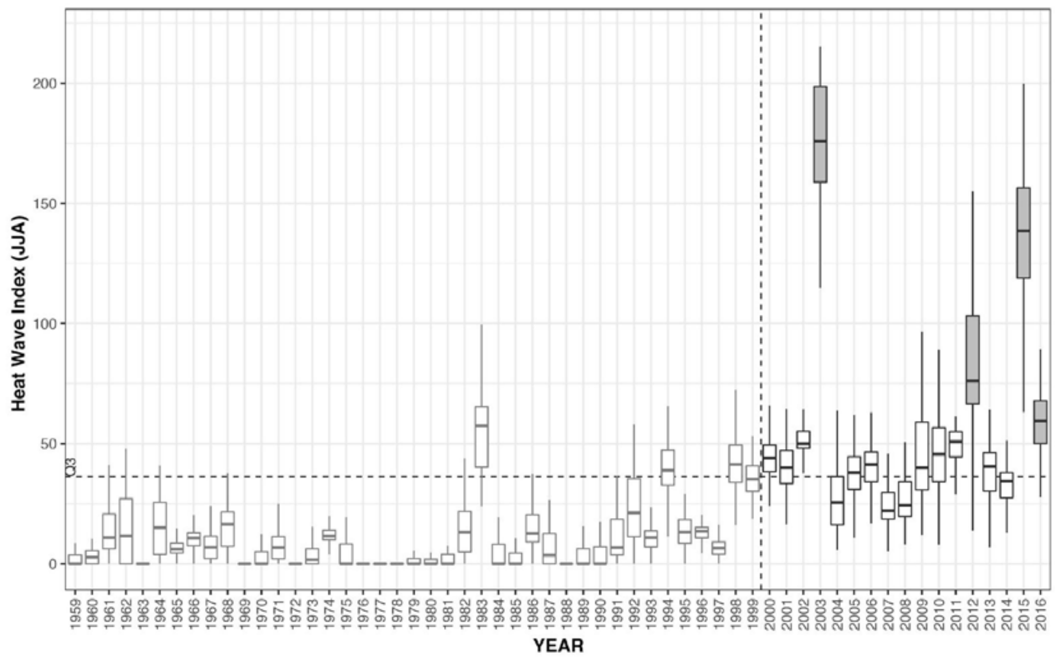


Figure 1.6. Observed change of the heatwave index in pastures in the French Alps (Corona-Lozada et al., 2019). ***Source:*** **LECA***

1.3 Climate projections in the Mont-Blanc massif for the coming decades

Climate scenarios indicate an **intensification of the observed trends in the coming decades.** In particular, we expect temperatures to continue to rise in all seasons, accompanied by a seasonal redistribution of precipitation. To create these projections, we used the following three types of data:

- the results of existing analyses at the scale of the Alps, taken from scientific articles (see bibliography)
- the climate scenarios produced by Météo Suisse (CH2018)
- a projection of CHELSA* climate data (Karger et al., 2017) available at a global scale, "zoomed in" and applied to the EMB for 2050

The use of three data sources means that the models used are not identical; however, they yielded comparable results. As a reminder, for each climate model, three greenhouse gas emission scenarios (see BOX 1) are considered: an optimistic scenario (RCP 2.6) that relies on significant reductions in emissions by the end of the century, an intermediate scenario (RCP 4.5) and a pessimistic scenario (RCP 8.5), based on a continuation of current emission rates. At the time of this report, global greenhouse gas emissions rose 2% in 2016 and 2017 and are projected to continue to rise in 2018 (Global Carbon Budget 2018, Le Quéré et al., 2018). This rise in emissions levels places us on a trajectory of a global temperature increase greater than 2°C, which is the target stipulated in the Paris Agreement. Annex 1 details the choice and use of these datasets to obtain cross-border indicators and maps, common to the entire EMB.

BOX 5: Reading the figures – average and range of uncertainty

The future changes in climate indexes are expressed by a number that represents an average value (in a graph, this is generally a point or a curve), within a margin of uncertainty (in a graph, this is generally a bar or vertical line) within which a value may lie.

Temperatures

Average annual temperatures will rise **between +1°C and +3°C by 2035, according to the emissions scenarios used**, when compared to 1980-2010. The temperature rise projected by each of the scenarios varies more and more in the coming decades, with the pessimistic scenario predicting even greater increases. This divergence can be explained by climate inertia in relation to the concentration of greenhouse gases: today's emissions have a delayed impact. In the RCP 4.5 emissions scenario (where short-term emissions are greatly reduced), the climate inertia remains strong in the short term (because of previous emissions), but decreases over time (after 2050) when compared to RCP 8.5, where emissions continue to rise in the years to come.

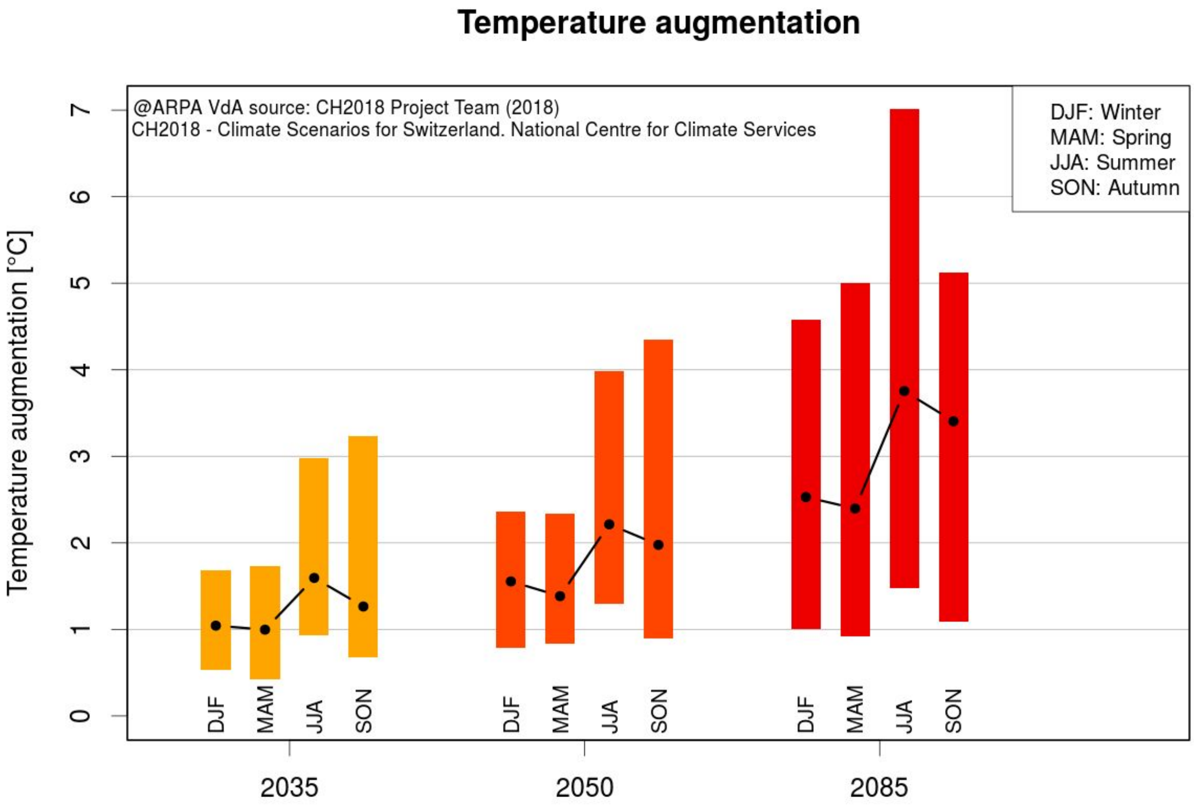


Figure 1.7. Expected change in average seasonal temperatures for the EMB for three future time periods (2035, 2050 and 2085). These projections represent a synthesis of the three different emissions scenarios (RCP2.6, 4.5 and 8.5) and climate models. The vertical bars represent the margin of uncertainty, which increases over the decades (principally because of the divergence among the different GEG scenarios). The impacts are different and increasingly divergent depending on the season.

Temperatures will continue to rise in all seasons, with the greatest increase occurring in summer and fall (Figure 1.7), across all time periods. In the intermediate scenario (RCP 4.5), after 2050, the rise in temperatures in the EMB will be significantly higher than the target defined by the 2015 Paris Agreement. In winter, temperature is expected to increase somewhat homogenously across the elevation gradient. In contrast, summer temperatures are expected to rise the most at mid and high mountain elevations (Figure 1.8).

BOX 6: Valley floor / mid mountain / high mountain

Analyses of scenarios and impacts are presented for three different elevation ranges in the EMB: the valley floor (400-1,000 m), mid mountains (1,000-2,000 m) and high mountain elevations (> 2,400 m).

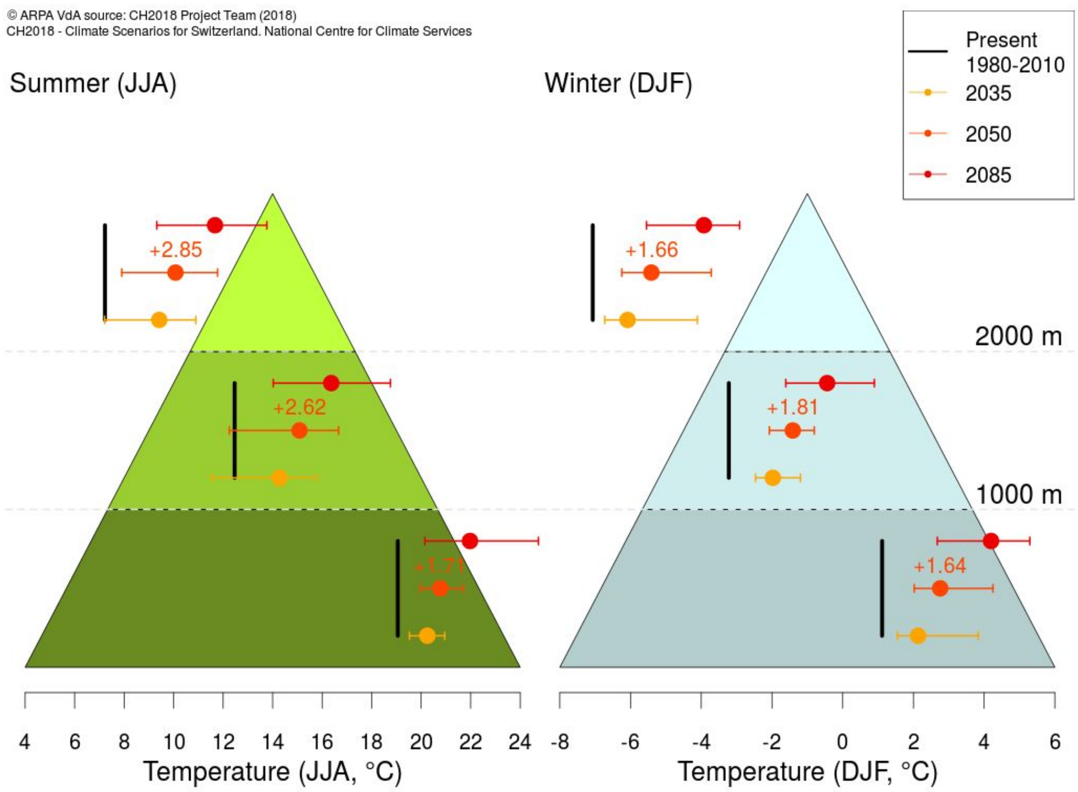


Figure 1.8. Expected change in summer and winter temperatures in the EMB for three future time periods (2035, 2050 and 2085) and for three elevation ranges (valley floor, mid mountain and high mountain). The points represent the average of the three different emissions scenarios. The horizontal bars represent the margin of uncertainty, for all scenarios and models combined. The vertical black lines represent the average established between 1980-2010.

In summer, the **0°C isotherm*** will rise 300 m in elevation, from 3,800 m today during the summer season to 4,100 m in 2050 (Figure 1.9). This rise in the 0°C isotherm corresponds with an increase in summer temperatures of 2°C in the EMB. In the pessimistic scenario (RCP 8.5), the 0°C isotherm level is expected to rise 400 m, corresponding to a nearly 3°C rise. **In two scenarios, (RCP 4.5 and RCP 8.5), the 0°C isotherm will be above 4,100 m of elevation**, leaving only a few of the EMB's high points below freezing. In the spring, the 0°C isotherm will rise from about 2,200 m today to 2,400 to 2,500 m in 2050, depending on the aspect and climate scenario.

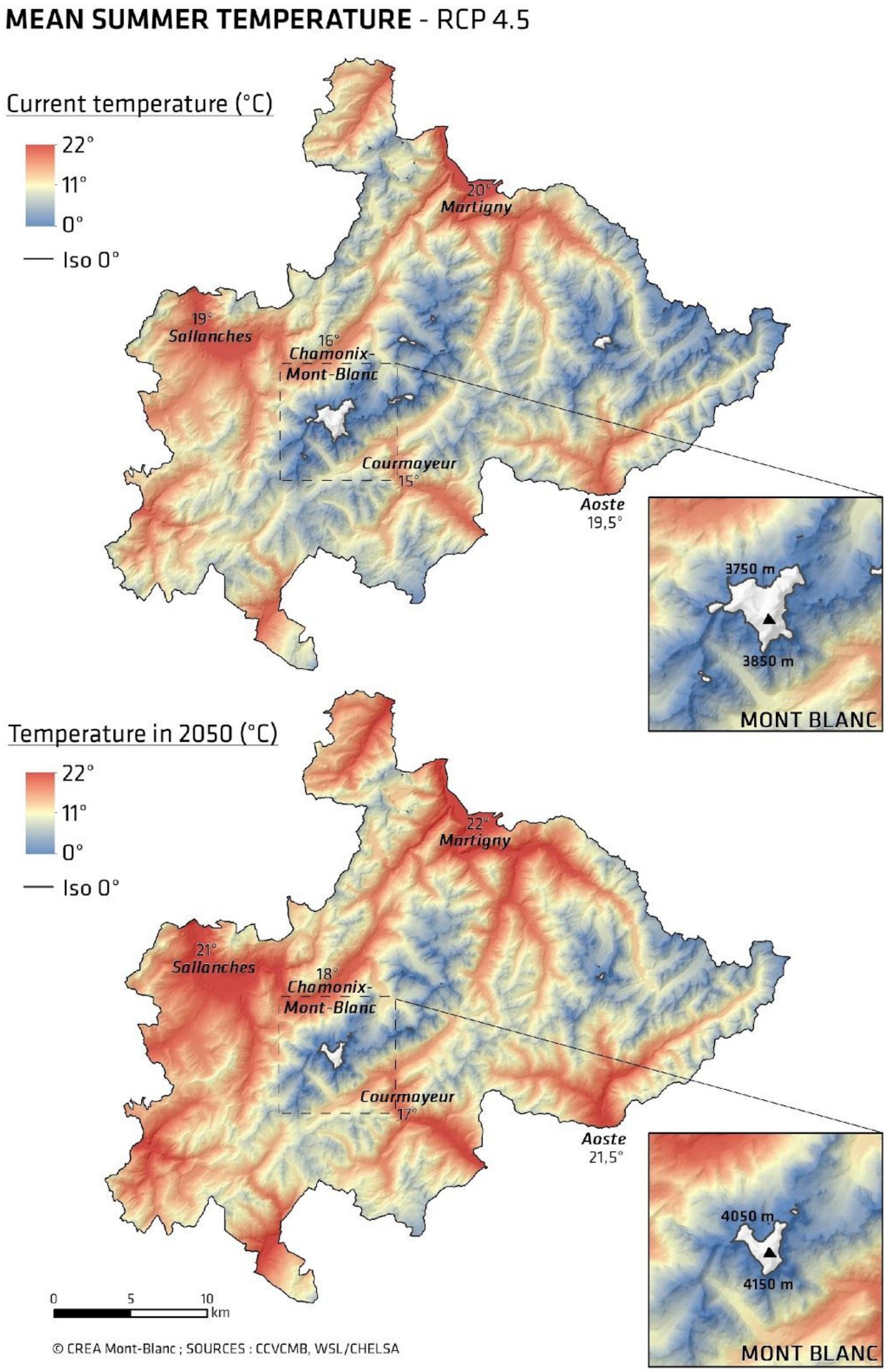


Figure 1.9. Average summer temperatures today and in 2050 in the Espace Mont-Blanc, according to the intermediate climate scenario (RCP 4.5). We note that only the summit of Mont-Blanc and a few high peaks (Grandes Jorasses, Grand Combin) remain below freezing.

Precipitation

When it comes to annual precipitation, **there is still much uncertainty** (-10% to +10%) and the scenarios predict **no change in cumulative annual precipitation**. However, we expect a **rise in winter precipitation** (+15-20%), with precipitation falling more and more frequently as rain rather than snow below 2,300-2,500 m. We also predict **a 10-20% decrease in summer precipitation by 2035**. There is still a lot of uncertainty for the other periods of the year (Figure 1.10).

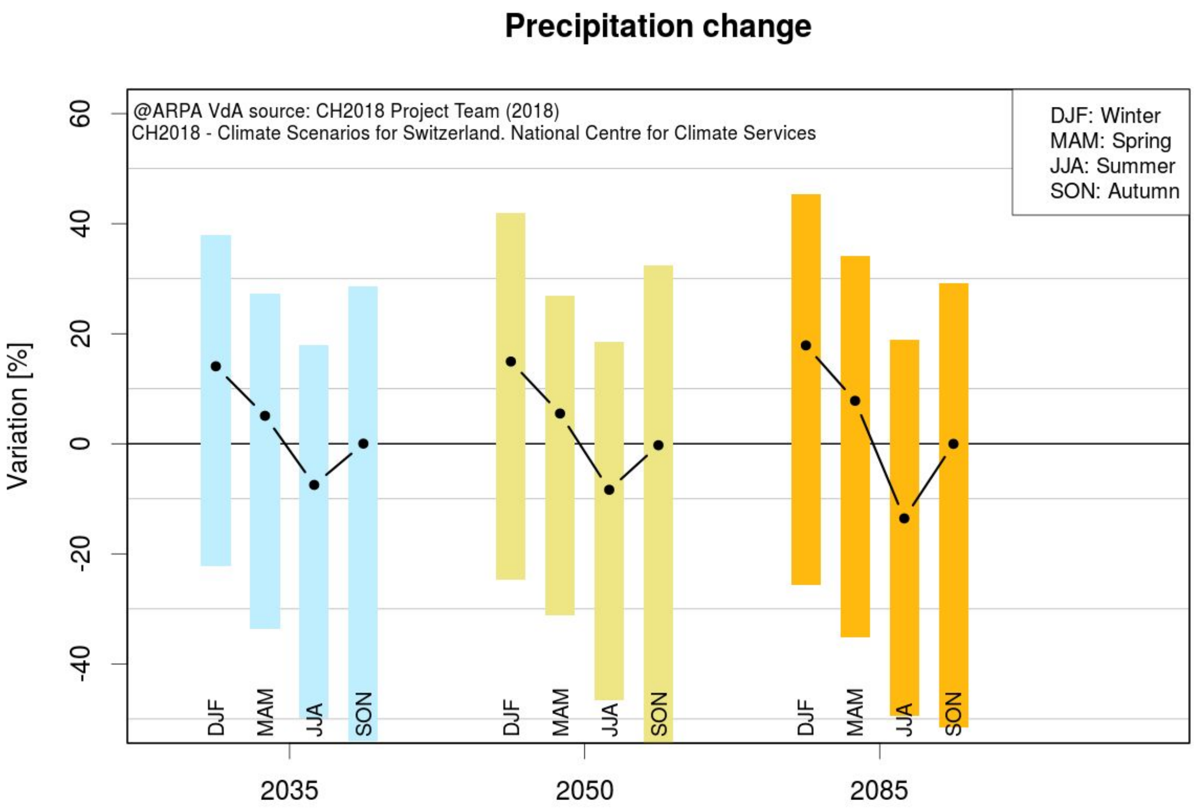


Figure 1.10. Percentage of expected change in seasonal precipitation in the EMB for three future time periods (2035, 2050 and 2085). The vertical bars represent the margin of uncertainty, for all scenarios and models combined.

When summer precipitation changes are combined with significant increases in summer temperatures, the result is a greater risk of heatwaves and droughts in the coming decades. It is important to note that there will be a greater decrease in precipitation in the western part of the EMB (Figure 1.11), in absolute values but not in percentage, because this region currently receives more precipitation. While changes in summer precipitation are not expected to vary with elevation (Figure 1.12), the models predict a larger increase in winter precipitations in the high mountains.

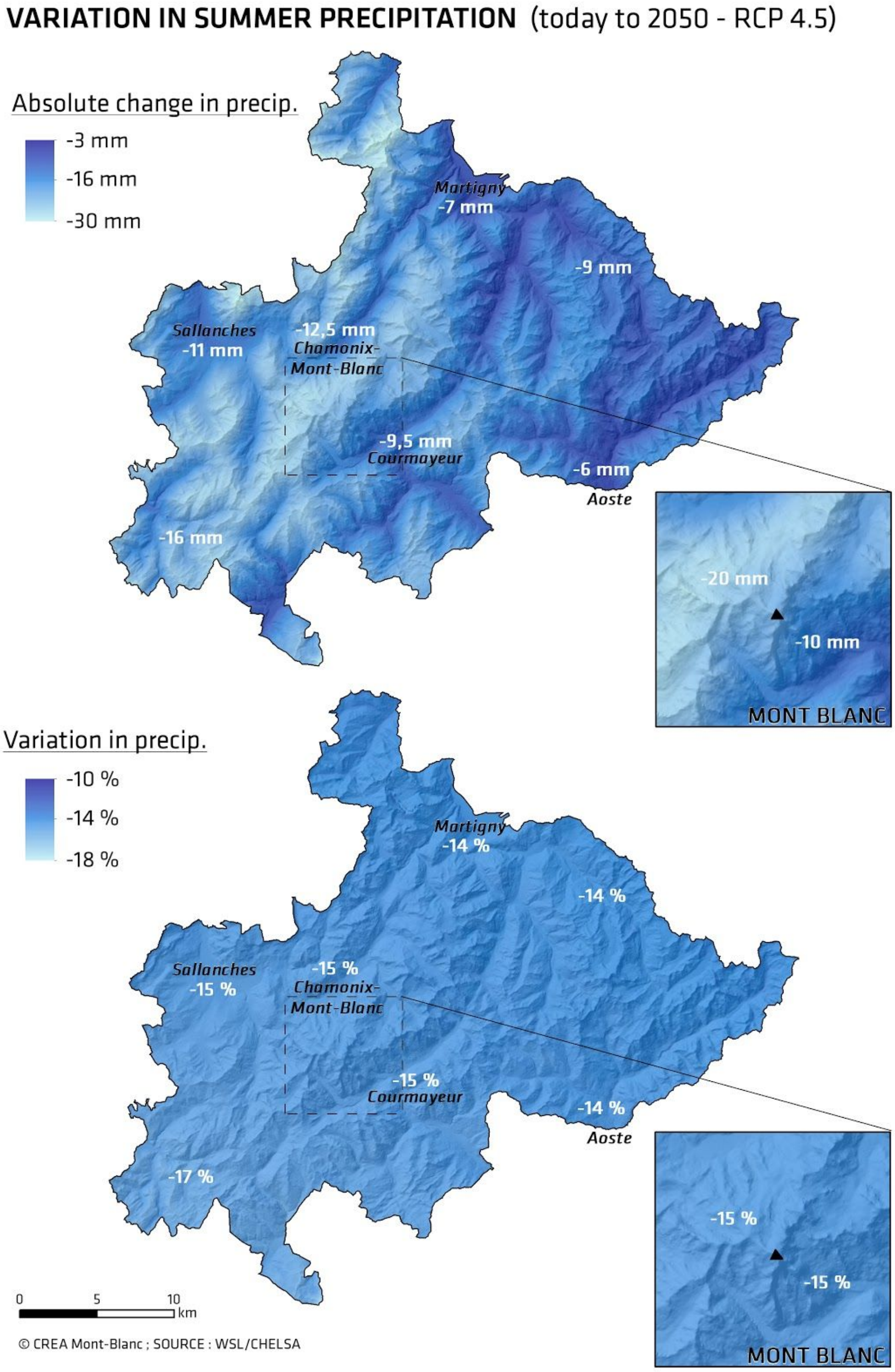


Figure 1.11. Expected change in summer precipitation, today and in 2050, according to the intermediate climate scenario (RCP 4.5). We expect a 15% reduction in precipitation across the whole territory, though that number increases to 18% when RCP 8.5 is applied.

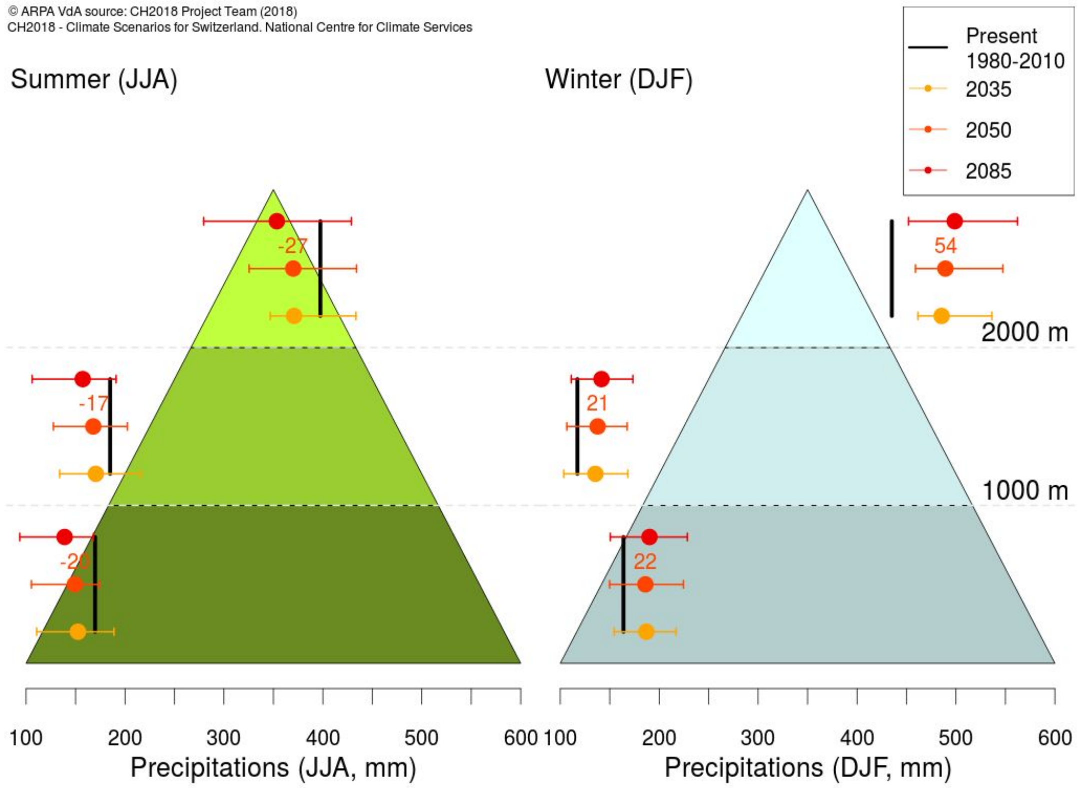


Figure 1.12. Expected change in average summer and winter precipitation in the EMB for three future time periods (2035, 2050 and 2085) and for three elevation gradients (valley floor, mid-mountain and high mountain). Points represent the average for the three emissions scenarios. The horizontal bars indicate the margin of uncertainty for all emissions scenarios and climate models combined. Vertical black lines represent the average values established from 1980 to 2010.

Frost days and ice days

In addition to increasing temperatures and a seasonal redistribution of the frequency and intensity of precipitation, all emissions scenarios predict an increase in the occurrence of extreme weather events. In the EMB, we expect a significant decrease (-20 to -80 days) in the number of frost days per year (days with a minimum temperature below 0°C) by 2085 (Figure 1.13). The impact is expected to differ depending on elevation, with the largest decrease occurring at the base of the valley in all scenarios and time periods. At the valley floor, there will be a 15% reduction by 2035 (about 15 days) and up to 30% by the end of the century. At other elevations, we expect a 10% decrease in the number of frost days by 2035, and 16-18% by the end of the century. The level of uncertainty linked to the different scenarios becomes greater for all altitudes towards the end of the century: by 2085, the most pessimistic scenario predicts a decrease of 30 to 40% in the number of frost days in mid and high mountains.

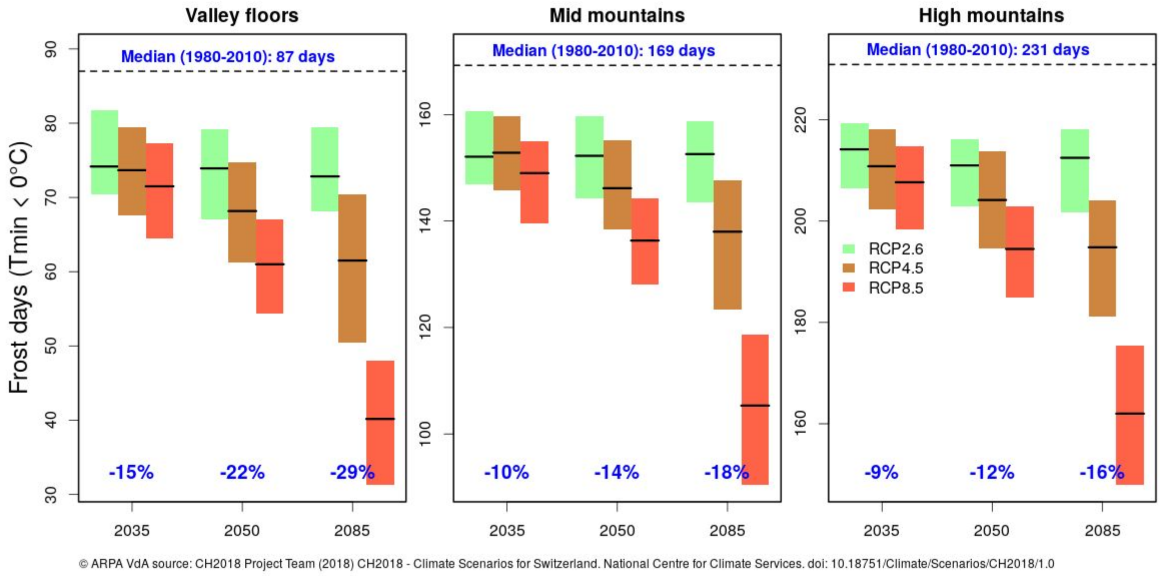


Figure 1.13. Expected change in the annual number of frost days for three elevations. The color of the vertical bars represents the different emissions scenarios. The height of the bars represents the range of uncertainty (10th and 90th percentile), taking into account the different climate models considered in the study.

The number of **ice days** (days when the maximum temperature does not exceed 0°C) is an extremely important parameter for high mountain environments, particularly for the conservation of permafrost, glaciers and snow. During the period from 1980 to 2010, between 2300 and 2700 m, there were more than four months of ice days per year, and nearly two months per year in the mid mountains. **According to the pessimistic emissions scenario the number of ice days per year in the high mountains may decrease by more than a month by 2050 and up to two months by the end of the century.** This is the equivalent of a 50% reduction in ice days when compared to today (Figure 1.14). **In the near future (2035), we expect a 15-20% reduction in ice days in both mid and high mountains.** This reduction of ice days could have significant impacts on the stability of rock faces and on the dynamics of natural hazards, as well as on alpinism more generally (see section 3.6, Natural Hazards).

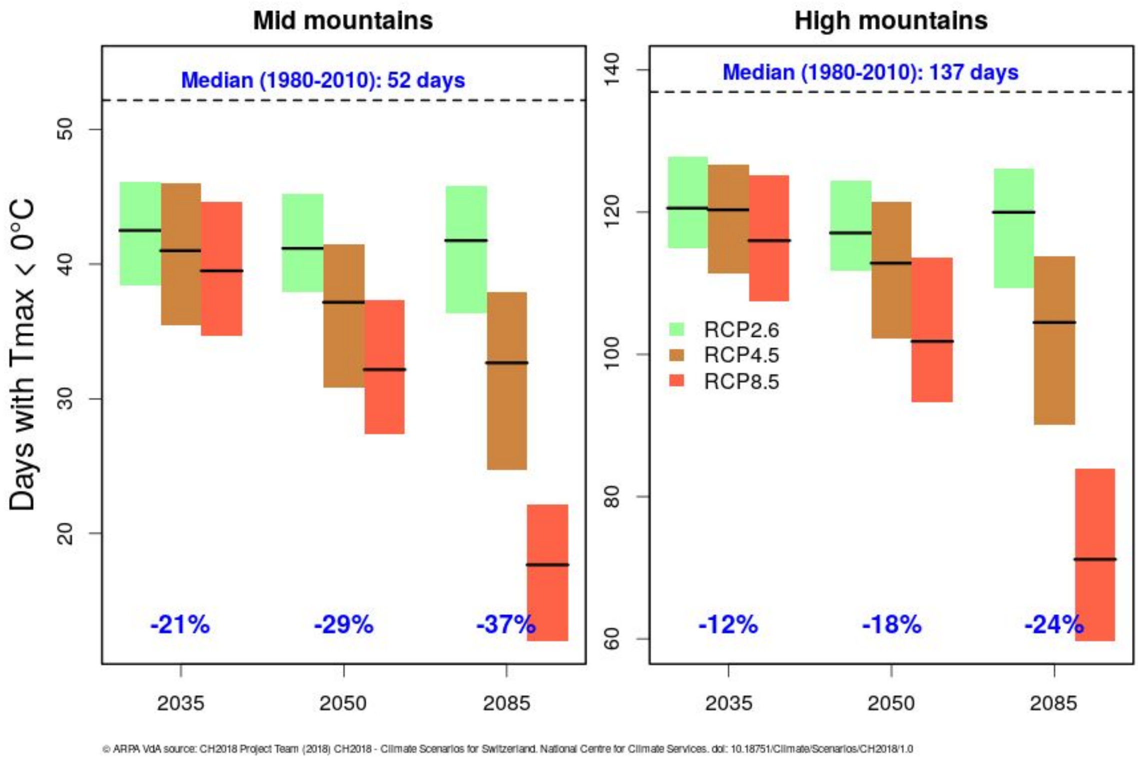


Figure 1.14. Expected change in the number of ice days per year in the mid and high mountains. The color of the vertical bars represents the different emissions scenarios. The height of the bars represents the margin of uncertainty (10th and 90th percentile), taking into account the different climate models considered in the study.

Extreme weather events and heatwaves

At the valley floor and in the mid mountains, we anticipate that the number of summer days per year (days where the maximum temperature is above 25°C, see Figure 1.15) **will increase by about 20 days by 2035.** In the mid mountains in particular, where there are currently only about 5 summer days per year, we will see an increase to about 15-20 summer days per year by 2035. The number of summer days may increase to about three months in the valley floors and a full month in mid mountains by 2050. Projections for the end of the century remain rather uncertain with values varying between 80 and 140 summer days for the valley floor and 20 and 80 days for the mid-mountains.

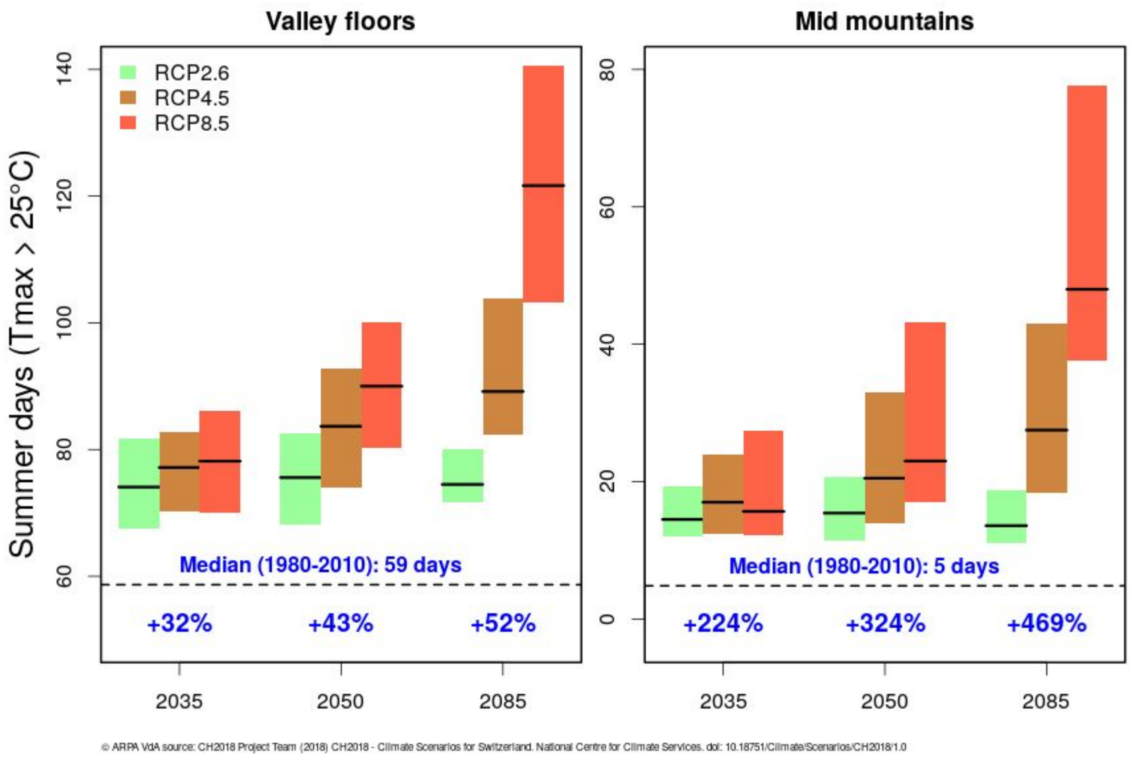


Figure 1.15. Expected change in the number of summer days in the valley floors and mid mountains. The color of the vertical bars represents the different emissions scenarios. The height of the bars represents the margin of uncertainty (10th and 90th percentile), taking into account the different climate models considered in the study.

The increase in summer days will also result in a significant increase in the number of **extremely hot days*** (days with a maximum temperature above 32°C). On the valley floor (Figure 1.16), **the number of extremely hot days will increase from 2 (currently) to 6-10 days in 2035 and 15-20 days in 2050**. For the end of the century, the uncertainty of the scenarios is very high and the predictions vary between 10 and 50 days.

If temperatures remain too high at night (i.e. **tropical nights**, where the minimum temperature remains above 20°C), it is difficult for the human body to cool down, particularly for the sick and the elderly. An increase in the number of tropical nights (Figure 1.17) can therefore have negative impacts on health and wellbeing. By 2035, the expected increase remains small (fewer than 5 tropical nights); however, we expect between 4 and 10 tropical nights per year by 2050. By the end of the century, uncertainty remains high for the scenarios, but both 4.5 and RCP 8.5 project between 8 and 35 tropical nights per year.

These indices point to an increase in the frequency (number of days per year) of days in which different temperature thresholds will be exceeded. A **heatwave duration index** (at least 6 consecutive extremely hot days) is also used to assess the duration of these extreme events. By 2035, the number of extremely hot days will increase (Figure 1.16), but in general, the days will not be consecutive, so the heatwave duration index will remain at an average of zero (Figure 1.18). By 2050, we expect an increase of 5-10 days in the duration of heatwaves, and climate scenarios project heatwaves lasting 5-20 days by the end of the century. **In summary, in the EMB,** like in the rest of Europe, **heatwaves will become more frequent, more intense and longer.**

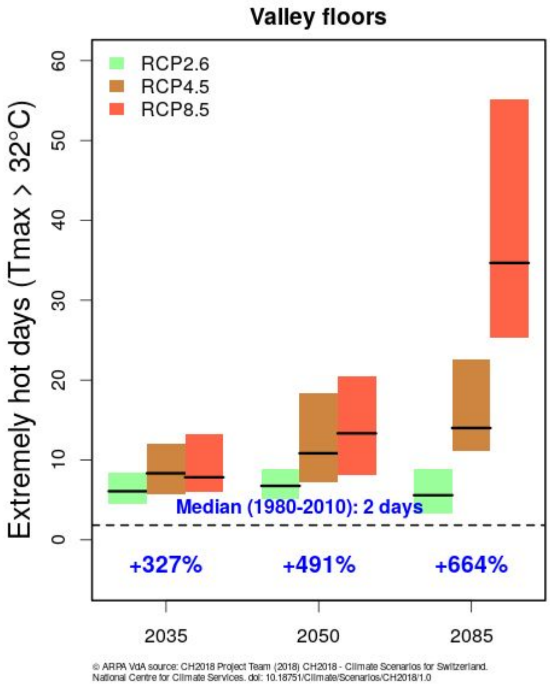


Figure 1.16. Expected change in the number of extremely hot days* per year in the valley floor. The threshold used to define extremely hot days (32°C) represents the 95th percentile of the maximum temperature distribution observed at the scale of the EMB during the historic period from 1980 to 2010. The color of the vertical bars represents the different emissions scenarios. The height of the bars represents the margin of uncertainty (10th and 90th percentile), taking into account the different climate models considered in the study.

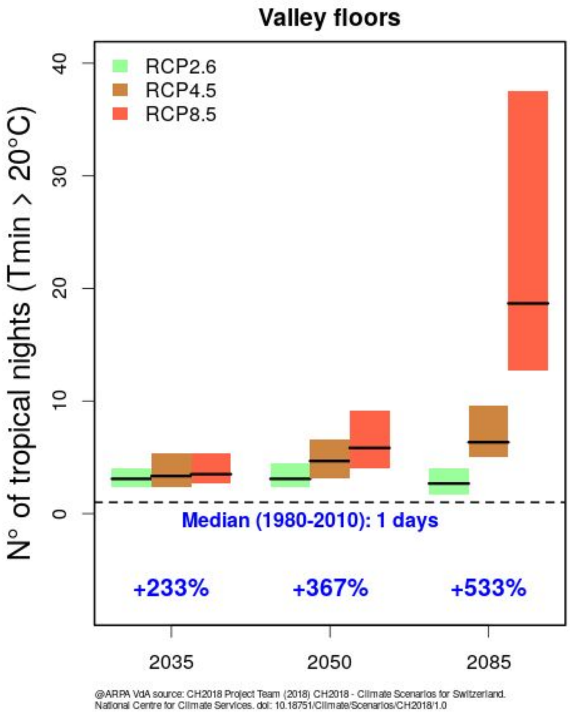


Figure 1.17. Expected change in the number of tropical nights per year in the valley floor. The color of the vertical bars represents the different emissions scenarios. The height of the bars represents the margin of uncertainty (10th and 90th percentile), taking into account the different climate models considered in the study.

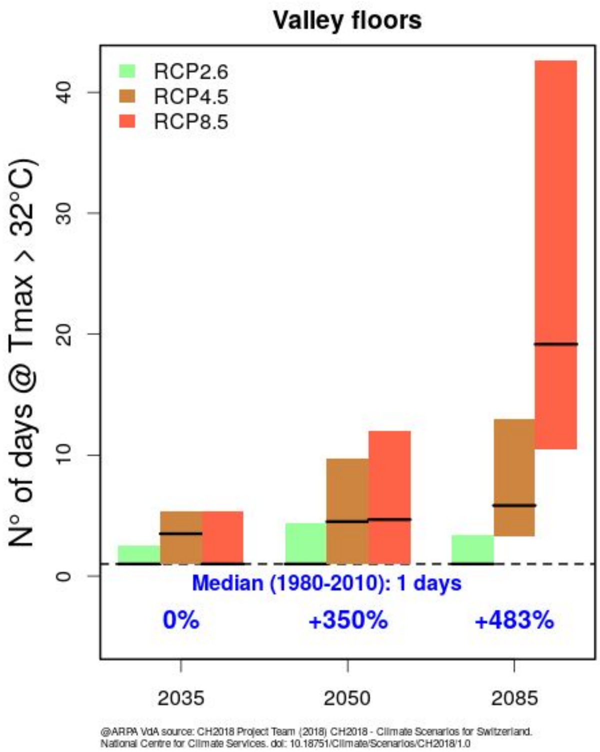


Figure 1.18. Expected change in heatwave duration in the valley floor. The color of the vertical bars represents the different emissions scenarios. The height of the bars represents the margin of uncertainty (10th and 90th percentile), taking into account the different climate models considered in the study.

Extreme weather events and droughts

Given the expected changes in precipitation and temperature, we can also expect more frequent and severe drought events in the coming decades, particularly in summer and fall. The indices used to describe drought scenarios are:

- Drought length: the number of consecutive days without rain (or the maximum number of consecutive days with less than 1mm of precipitation)
- Summer water availability more generally, calculated by subtracting potential evapotranspiration (ETP) from precipitation (P): P-ETP: a negative value indicates a potential lack of water, while a positive value indicates a water surplus.

These indices are more uncertain than frost and heatwave indices because precipitation scenarios themselves are more uncertain than temperature scenarios.

We expect a negligible increase in the length of droughts by 2035, remaining low (2-10%) in 2050 at all elevation levels. For the end of the century, changes largely depend on emissions scenarios (Figure 1.19).

However, while we have observed a negative water availability (P-ETP) in valley floors and mid mountains, and a positive water availability in the high mountains (Figure 1.20) during the period from 1980-2010, **by 2035, we expect a significant reduction (between -14 and -38%) in the water availability (P-ETP) at all elevations.** Water availability will be further reduced by 2050 (-17 to -40%) and even more by the end of the century (-22 to -60%). **The greatest impact will be felt in the mid mountains**, and the pessimistic climate scenario predicts a negative water balance even in the high mountains by the end of the century.

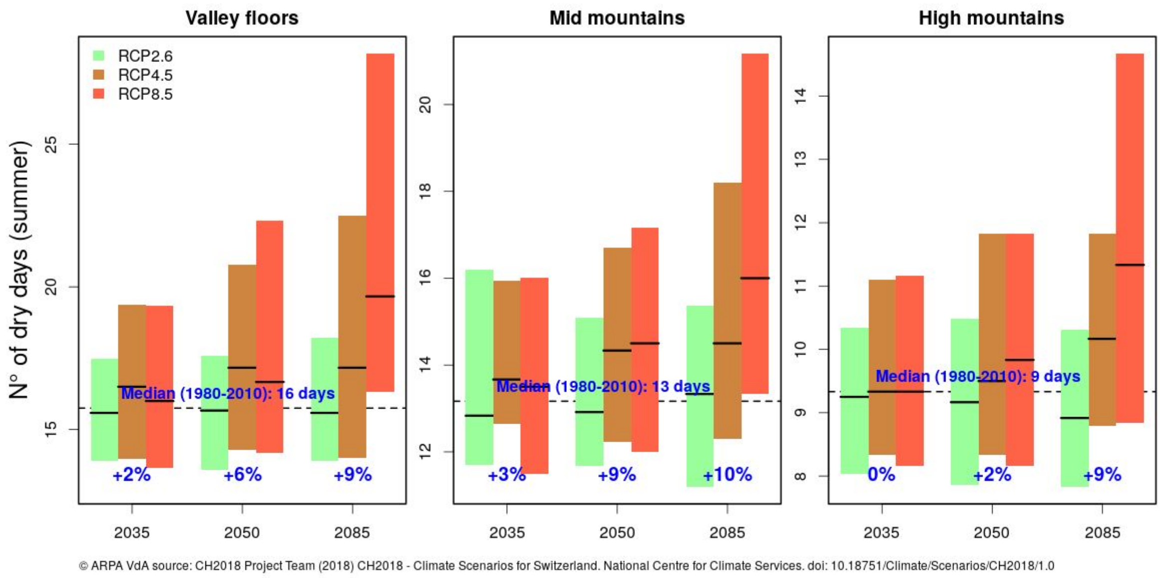


Figure 1.19. Expected change in the number of consecutive days without rain. The color of the vertical bars represents the different emissions scenarios. The height of the bars represents the margin of uncertainty (10th and 90th percentile), taking into account the different climate models considered in the study.

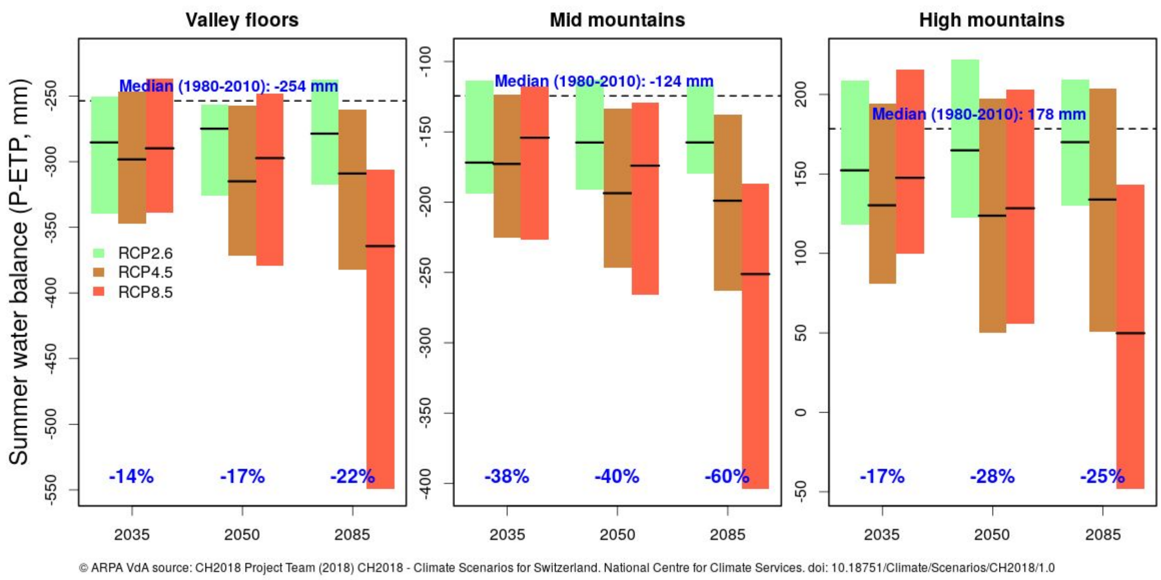


Figure 1.20. Expected change in the balance between precipitation (P) and potential evapotranspiration (ETP) in summer (P-ETP). The color of the vertical bars represents the different emissions scenarios. The height of the bars represents the margin of uncertainty (10th and 90th percentile), taking into account the different climate models considered in the study.

Extreme weather events and intense precipitation

Given the general climatic context of warmer, more humid air, we also expect an increase in the frequency and intensity of precipitation both in the Alps and in Europe more generally (Gobiet et al., 2014, CH2018). At the scale of the EMB, all climate scenarios predict an increase in:

- the **intensity of precipitation** (cumulative precipitation in mm on days with precipitation greater than 1 mm divided by the number of days with precipitation > 1 mm)
- the **annual cumulative precipitation that falls in extreme precipitation days** (annual cumulative precipitation in mm on days of precipitation greater than 20 mm, defined as extreme precipitation days).

Even given the non-negligible uncertainty of the models, all scenarios predict a small increase (2-6%) in the intensity of precipitation (Figure 1.21) at all elevations.

The **quantity of precipitation that will fall during extreme events will rise between 10 and 20%** (Figure 1.22) annually, but especially in winter and spring. **In the spring, valley floors will see the largest increase**: +17% by 2035 and +33% by the end of the century. **In winter, the models have greater levels of uncertainty; however, we expect a significant rise by 2035**: between +13 and +35% at all elevations.

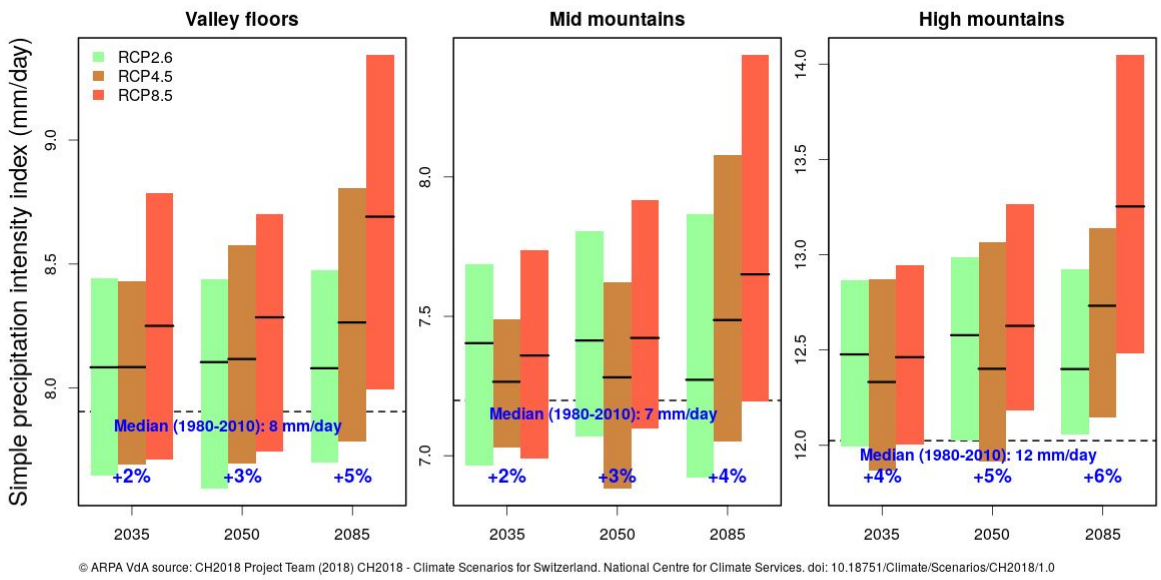


Figure 1.21. Expected change in precipitation intensity. The color of the vertical bars represents the different emissions scenarios. The height of the bars represents the margin of uncertainty (10th and 90th percentile), taking into account the different climate models considered in the study.

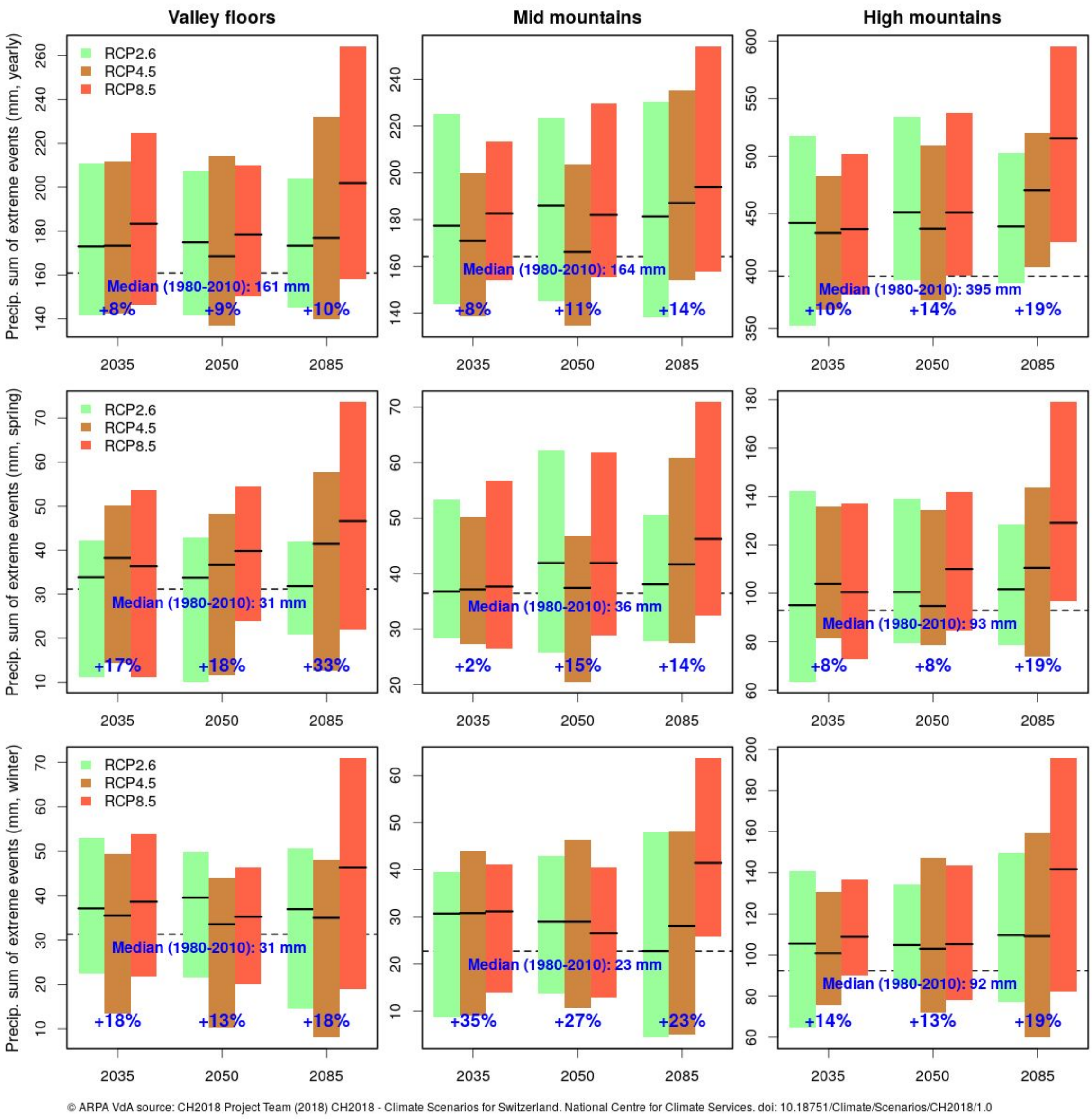


Figure 1.22. Expected change in the annual cumulative precipitation that falls in extreme precipitation days. The threshold used to define extreme precipitation days (20 mm) represents the 95th percentile of the distribution of observed precipitation in the EMB during the historic period from 1980 to 2010. The color of the vertical bars represents the different emissions scenarios. The height of the bars represents the margin of uncertainty (10th and 90th percentile), taking into account the different climate models considered in the study.

2. Evolution of natural environments and ecosystems

The evolution of different climatic parameters including temperature, precipitation and extreme weather events has already had, and will have in the future, a direct impact on the natural environments of the EMB. The evolution of these parameters will profoundly modify landscapes and seasons in the EMB, leading to substantial impacts on various sectors of human activity (Figure 1.1). The expected impacts on natural and physical environments will be considered in the following paragraphs.

2.1 Reductions in snow cover

The presence of snow on the ground for a longer or shorter period of time, depending on the topographic context (elevation, exposition, slope, etc.), is one of the defining characteristics of mountains. Snow cover shapes mountain environments thanks to the insulation it provides for living organisms and because it provides a large reserve of water in the spring. A rise in temperatures in winter, but especially in spring, leads to a reduction in the length of snow cover* through two principal processes: i) a rise in the elevation at which precipitation falls as snow instead of as rain and ii) accelerated snowpack melt in spring and summer in the high mountains. **In the northern Alps, the duration of snow cover at elevations between 1,100 m and 2,500 m has been reduced by 5 weeks since the 1970s** (Klein *et al.* 2016). In addition, at the scale of the EMB, the Cignana ski resort (2,150 m), in Aosta Valley (Italy), which has one of the longest series of snow measurements (1927-2018), has observed a 50% decrease of the maximum snowpack compared with the 1961-1990 period (-12% per decade; Figure 2.1).

By 2050, in the EMB, we expect snow cover to continue to diminish, especially in the mid-mountain and on sunny slopes. In the Chamonix Valley, **at 1,000 m, we project a further loss of 25-45 days of snow cover**, when compared with the 1973-2013 period, depending on the climate scenario (Figure 2.2). At higher elevations and on north-facing slopes, for example at the top of les Grands Montets, **around 3,000 m, we expect a loss of 10-15 days of snow cover by 2050**. While we expect a generalized reduction of snow cover up to 3,000 m, **topographic context will play an important role in the degree of snow cover reduction**. These predictions for the EMB are corroborated by simulations carried out in other locations in the Northern Alps. For example, at Col de Porte (1,500 m) in the Chartreuse massif, the duration of snow cover is expected to decrease by 26-48 days by 2050, according to the intermediate climate scenario (Verfaillie et al., 2018).

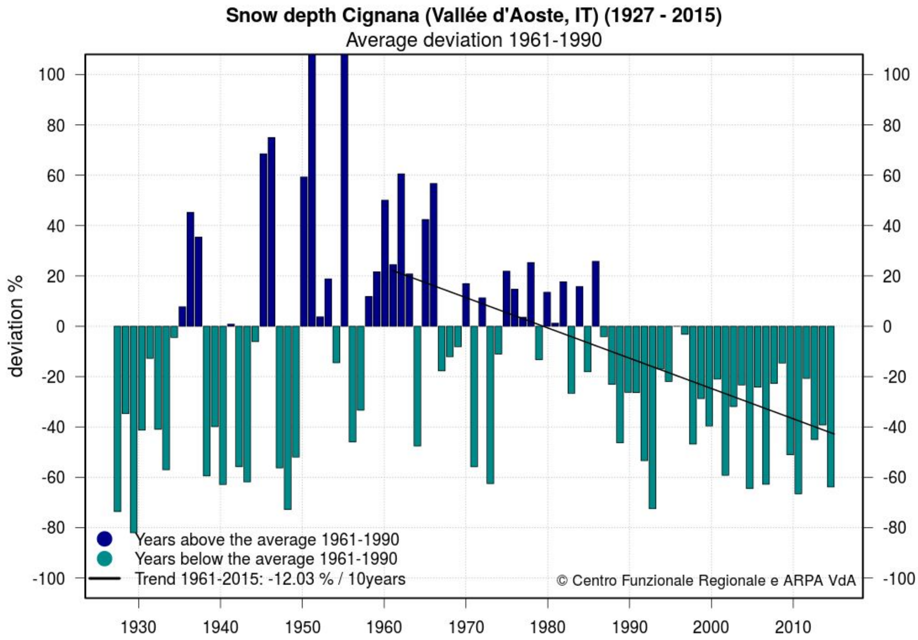


Figure 2.1. Observed reduction in annual snow depth at the Cignaga Lake weather station (2,150 m) in the Aosta Valley (Italy), using the average established from the reference period 1961-1990 as a baseline.

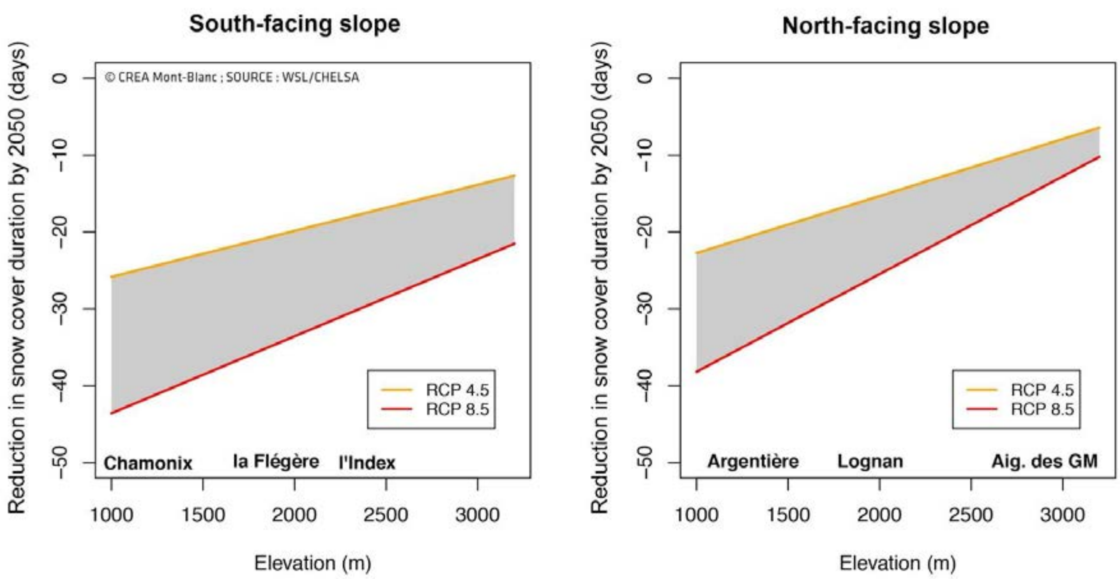


Figure 2.2. Reduction in the duration of snow cover between the current period and 2050 on south-facing and north-facing slopes in the Chamonix Valley (France).

2.2 Glacier retreat

Figure 2.3. Observed change of the Argentière glacier in the Chamonix Valley (France) between 1890 and 2015. *© Amis du Vieux Chamonix (left) and CREA Mont-Blanc (right).*

Between 1850 and the 1980s, the Alps' glaciers lost between 30 and 40% of their surface and half of their volume. Since 1980, they have lost an additional 10-20% of their remaining volume. In the French Alps, glaciers have lost roughly 25% of their surface area since the end of the 1960s (Gardent et al., 2014 and Figure 2.4). This loss is more accentuated in the southern Alps (loss of 32% in the Ecrins, compared to only 10% in the Mont-Blanc Massif). We should note that glacier melt accelerated considerably in recent years with, for example, **more than a 400 m retreat of the Mer de Glace since 2003** (Vincent et al., 2014).

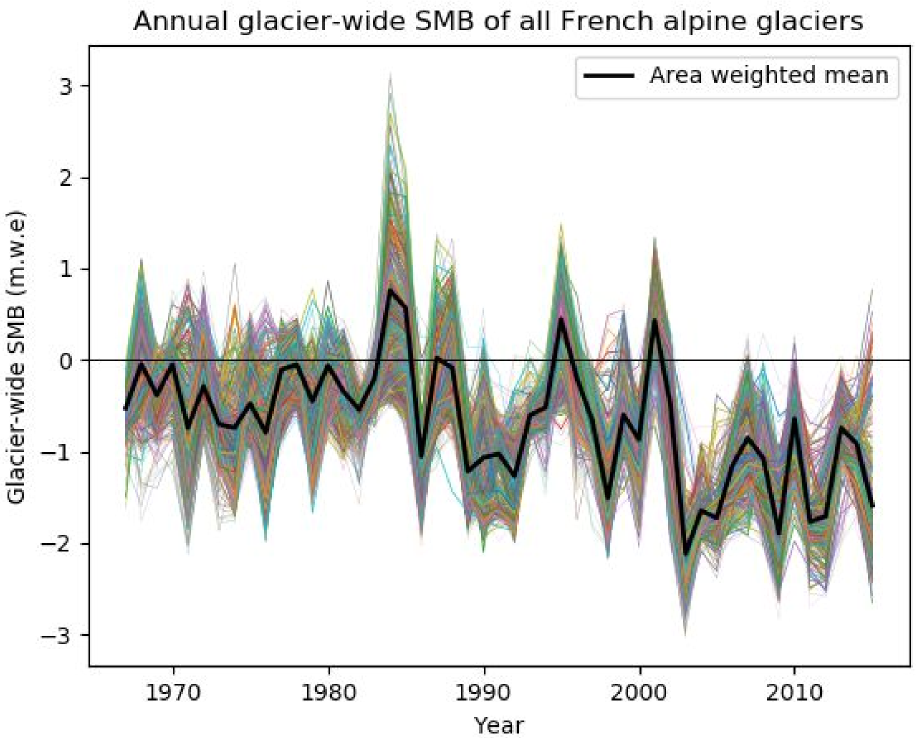


Figure 2.4. Reconstruction of glacier mass balance in the French Alps for the period 1967-2015. ***Source:*** **IGE*/CNRS***

Swiss glaciologists anticipate that 90% of the Swiss glaciers will disappear by 2090 in the intermediate emissions scenario (CH2014-Impacts). By 2050, the Mer de Glace (France) will have shrunk and thinned considerably, and will have receded all the way to the Flamme de Pierre ridge (Vincent et al., 2014 ; Figure 2.5). According to the pessimistic climate scenario (RCP 8.5), the Argentière glacier will disappear by 2080, and the Mer de Glace will melt entirely by the end of the century (Vincent et al. 2019). Generally speaking, in the EMB, both observed and predicted trends clearly indicate an acceleration in glacier retreat.

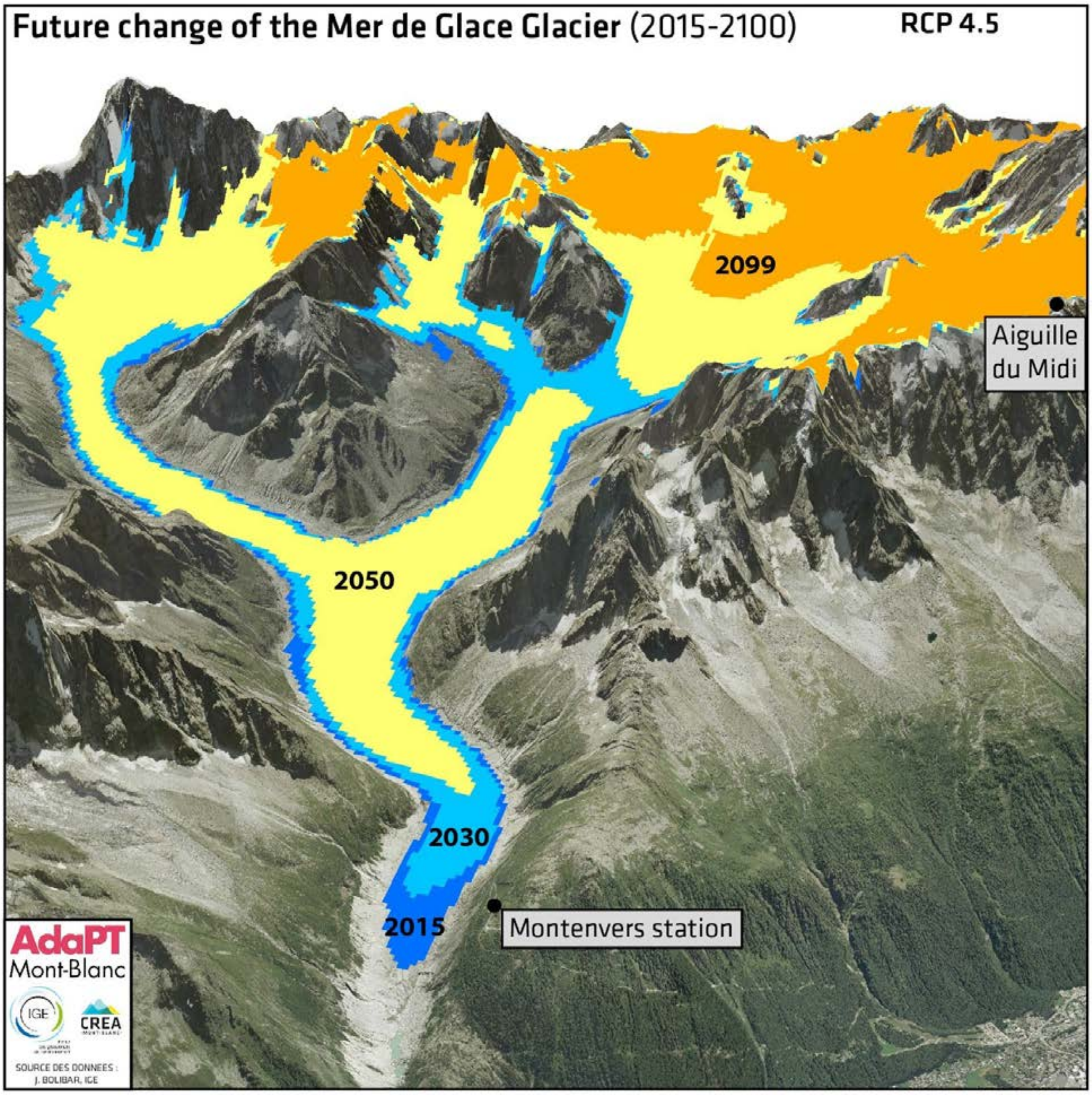


Figure 2.5. Expected change to the Mer de Glace (Chamonix Valley, France) in 2030, 2050 et 2099 according to climate data and the physical parameters of the glacier. The retreat of the toe of the Mer de Glace will be accompanied by a significant reduction in the thickness of the glacier. The background image is from a 2008 IGN aerial photo.

Glacial retreat also implies a reduction in the amount of water stored as ice, which plays an important role for several of the EMB's waterways. Figure 2.6 show the expected change in the amount of water stored in six representative glaciers (in France: Mer de Glace and Argentière glaciers; in Italy's Aosta Valley: Rutor and Pré de Bar glaciers; in Switzerland's Valais: Trient and Corbassière glaciers), according to a recently published Alps-scale study (Zekollari et. al, 2019).

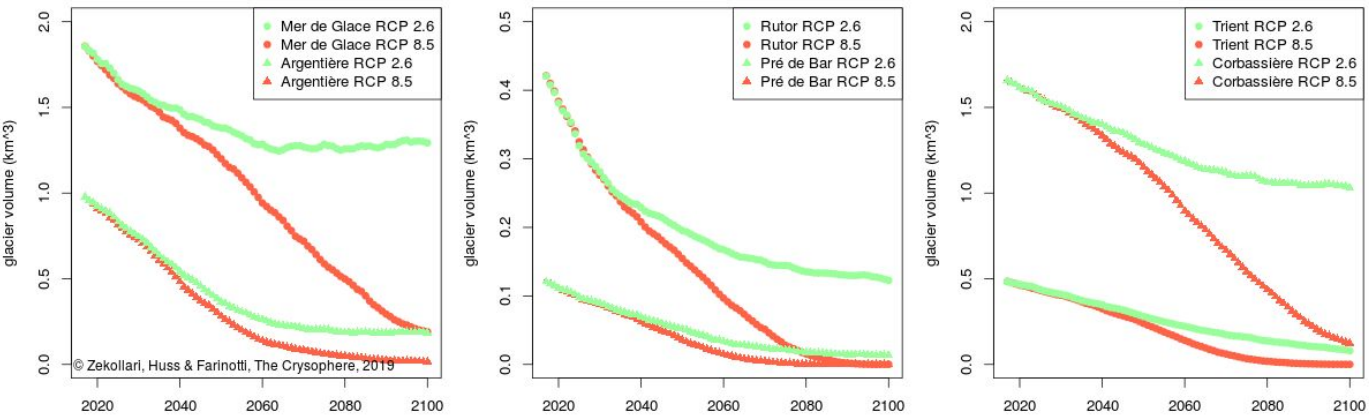


Figure 2.6. Expected change in water quantity stored in the EMB's representative glaciers. *Source:* Zekollari et al., 2019.

2.3 Permafrost degradation

Permafrost, which is defined as any substrate permanently maintained in temperature conditions below 0°C, plays a crucial role in the stability of high mountain terrain. Though it is invisible, it covers a significant area of mountain faces. Currently in the Mont-Blanc massif, permafrost can be present as low as 2,600 m in north slopes, and 3,000 m on south slopes, though it only covers entire mountainsides above 3,600 m (Magnin et al., 2015).

Rising temperatures in summer can lead to permafrost degradation and consequently, increasing instability in rock faces. Over the last 20 years, permafrost has nearly disappeared from the south faces of the Mont-Blanc massif below 3,300 m, and permafrost with a temperature above -2°C has risen from 3,300 m to 3,850 m. **By 2100, there will be no permafrost present in south faces below 4,300 m, and in the most pessimistic scenarios, it may entirely disappear from Mont-Blanc south faces** (Magnin et al., 2017). Figure 2.7 illustrates the potential degradation of permafrost at three of the Mont-Blanc massif's emblematic sites. We note a thawing of the Grand Montets (GM; 3,295 m) and the Aiguille du Midi (AdM; 3,842 m), which could destabilize these sites which are equipped with cables cars and heavily frequented by tourists (Magnin et al., 2017).

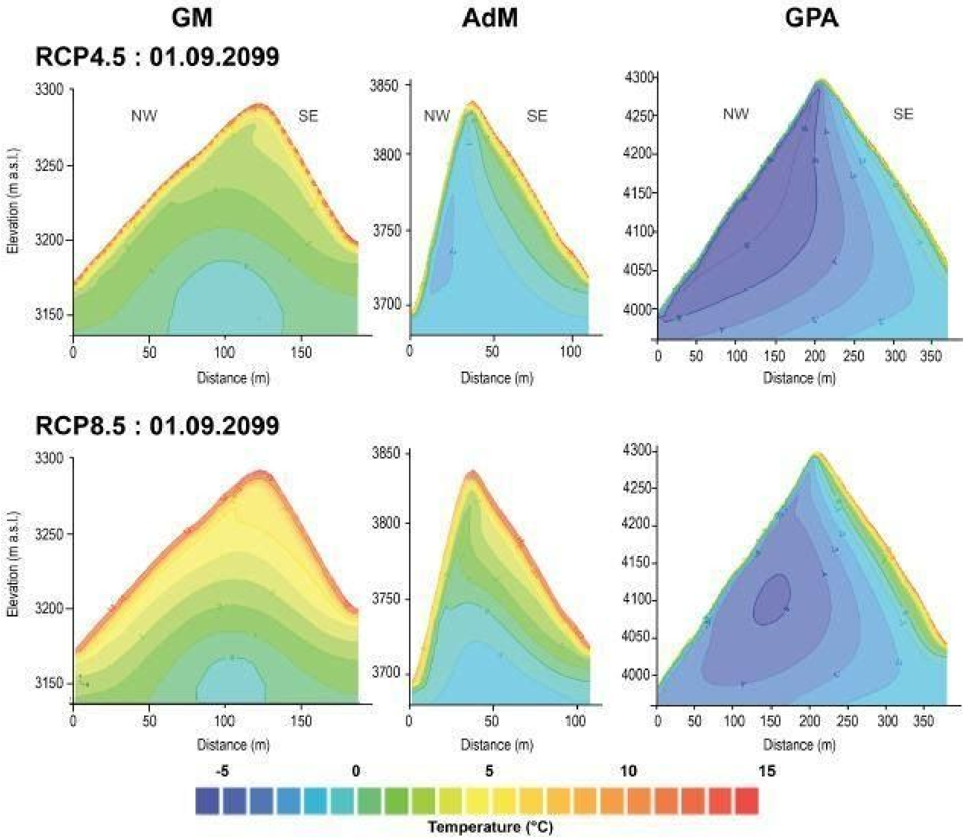


Figure 2.7. Temperature profiles for September 2099 for three sites in the Mont-Blanc massif according to RCP 4.5 and 8.5 (Aiguille des Grands Montets, Aiguille du Midi et Grand Pilier d'Angle). These diagrams show the surface and depth temperatures (negative temperatures in blue). We see an almost complete thaw of the Grand Montets (GM), with surface temperatures well above 0°C in both scenarios. The temperature of the Aiguille du Midi (AdM) is largely dependent on the climate scenario used. In the case of the Grand Pilier d'Angle (GPA), above 4,000 m, the degree of thaw on south-east facing slopes also largely depends on the emissions scenario used. ***Source:*** **Magnin et al., 2017, EDYTEM*/CNRS**

2.4 Upward shift of flora and fauna

EMB's landscapes are made up of different species that respond to climate change differently. The presence of any given species in the area, whether it is dominant (pine or larch, for example) or emblematic (ibex, mountain hare, Alpine rock-jasmine, etc.), depends on, among other things, climate conditions that are optimal for their development (Figure 2.8). As the climate warms, one of the adaptation strategies for the ensemble of alpine species is to move higher in elevation in order to find the climate conditions that are ideal for their development. However, each species has its own specific needs, meaning that species do not migrate upslope at the same speed and do not respond uniformly to heatwaves, droughts, loss in snow cover, etc. This means the landscape is changing as well.

As the climate warms, in recent decades, the **majority of animal species has migrated upslope between 30 and 100 m per decade.** For forest plant species, the upward shift observed in the Alps during the 20th century was about 30 m (Lenoir et al., 2008). Given the pyramidal shape of mountains, moving up in elevation implies a loss of available surface area. Generally speaking, **warm-weather species coming from lower elevations will gain ground as they move upslope, probably to the detriment of alpine**

species which are better adapted to extreme conditions, but are not as competitive. That said, melting snow fields and glaciers could delay the loss of alpine species as they free up new environments for those plants to colonize. Another potential protection for alpine plants is the topographic heterogeneity of mountains, which offers a wide variety of temperature and snow conditions in a relatively small area (sometimes even just a few meters apart). This varied mosaic of environments can create "micro-refuges" for alpine plants, allowing them to find favorable conditions without moving higher (Scherrer and Korner, 2011). These micro-habitats can serve as buffer-zones, curbing the loss of plant diversity in the EMB in the decades to come.

2.5 Earlier arrival of spring and prolonged growing season

In addition to changing location, species (both natural and cultivated), have another option for adaptation: changing their physiology or seasonal behavior to adapt to their environment's new conditions. We have already observed a general trend toward the **advance of seasonal events, such as flowering, reproduction and migration—from 2 to 5 days per decade for plants and terrestrial animals over the past 50 years**. For example the arrival of migratory birds has advanced by about 15 days in the last 30 years, and reproduction in amphibians like the common toad is earlier as well (a month earlier than 25 years ago, at one study site at 1,850 m in Switzerland ; Vittoz et al., 2013).

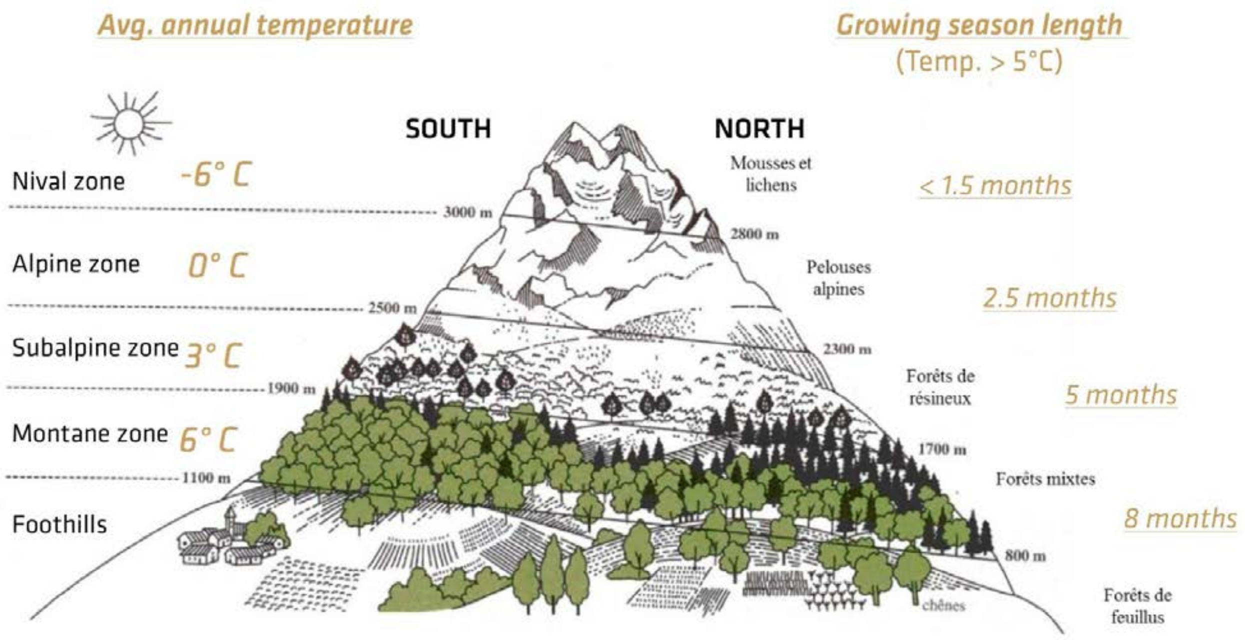


Figure 2.8. Climate conditions and favorable growing season length along the elevation gradient. Temperatures on the left indicate the average annual temperature at different elevations. As an example, trees require an average temperature above 5°C for photosynthesis, and therefore growth, to take place. The higher the elevation, the fewer days per year when the temperature is above 5°C. The length of this period, called the growing season, is represented on the right. In order to grow, the fastest-growing trees need a growing season of at least three months (Paulsen and Korner, 2014). Rising temperatures in spring and fall extend this season length, allowing trees and shrubs to move upward in elevation.

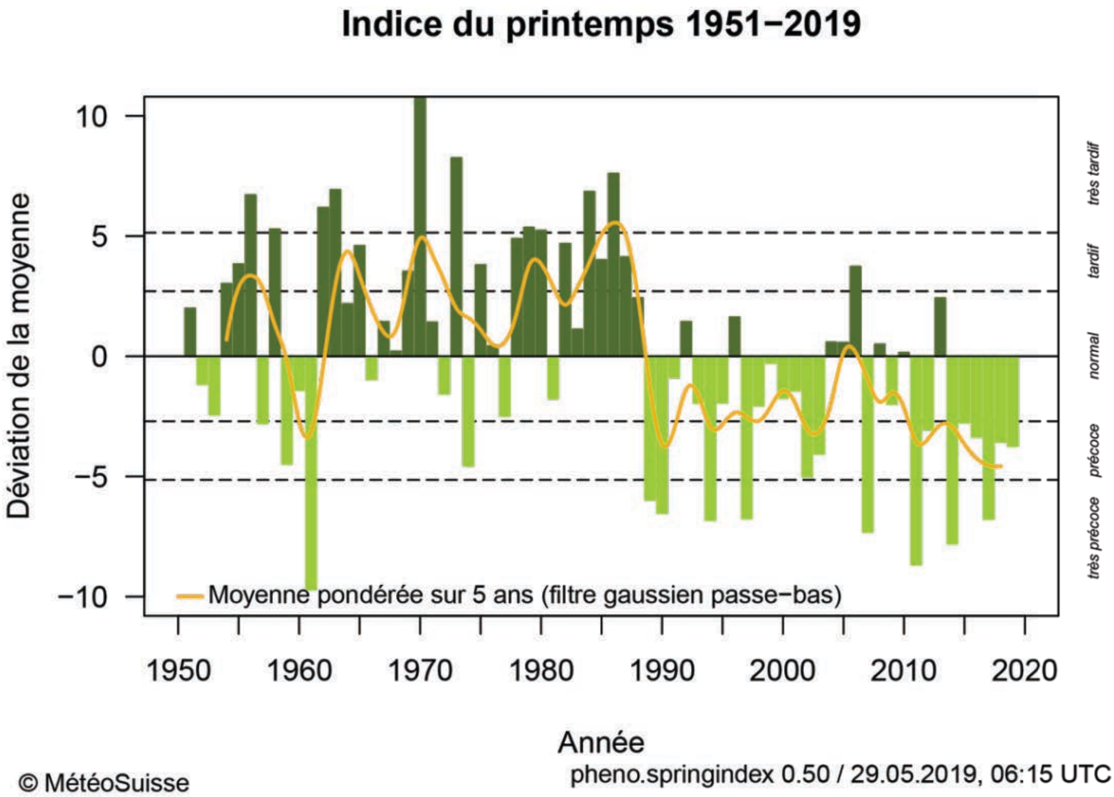


Figure 2.9. Observed change in budburst date for vegetation in Switzerland since 1951. We note a substantial advance in the arrival of spring, frequently reaching 5 days ahead of the established average. ***©MétéoSuisse***

For vegetation, the rise in spring temperatures coupled with early snowmelt allows, for the majority of species, early development (Figure 2.9). Accordingly, the vegetation growing season is longer and there is greater productivity by alpine plants, which are normally limited by temperature and snow cover. **The current length of the vegetation growing season is two to four weeks longer than in the 1960s (CH2018). Climate scenarios predict a significant increase in the duration of this growing season.** This increase (Figure 2.10) will already be significant in 2035 (7 to 38 %) and will have an even greater impact on high mountain ecosystems like alpine grasslands which are currently limited by snow cover. Several vegetation changes are expected in the coming years, in connection with a longer growing season: i) rising treeline, ii) progressive upward colonization of shrublands and heath (shrubs like vaccinium, juniper and rhododendron) and tall shrubs (green alder and willow), and iii) upward movement of alpine grasslands into screefields and snowfield areas. In addition to these impacts on species distribution and ecosystem composition, an increase in the length of the growing season will also have a significant impact on ecosystem productivity in terms of annual CO_2 balance, interactions with water and nutrient cycles, and with geomorphological processes.

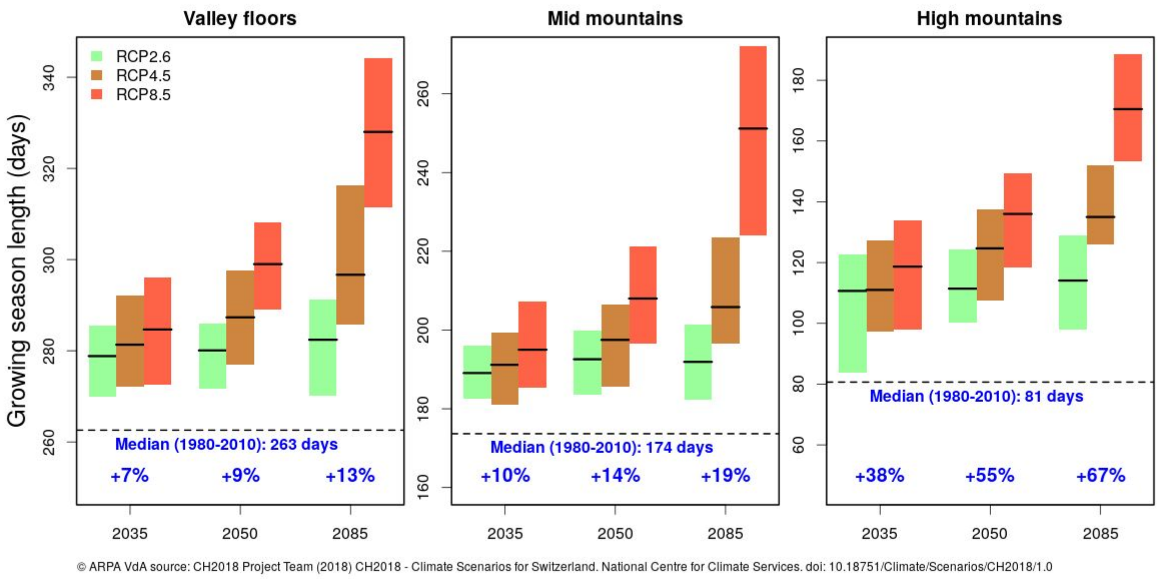


Figure 2.10. Expected change in the length of the growing season, defined as the interval between the first warm period of the year with temperatures above 5°C for six consecutive days, and the first cold period with temperatures below 5°C for six consecutive days between July and December. The color of the bars represents different emissions scenarios. The height of the bars represents the margin of uncertainty (10^{th} and 90^{th} percentile), taking into account the different climate models considered in the study.

Nonetheless, for some species, a longer growing season or earlier seasonal development is not necessarily an advantage. For the blueberry, which is very sensitive to frost, or for the dwarf willow, beginning productivity earlier can increase the risk of damage from late frost events in the spring (Wheeler et al., 2014). Likewise, for large herbivores like the Alpine ibex or the chamois, the date of the birth of kids is not related to spring conditions but rather to mating dates which occur in the autumn and do not appear to be changing. During years with relatively warm winters and/or springs, peak vegetation production occurs earlier and is thus desynchronized with the weaning of young ibex, which need tender grasses just after weaning. Because all species do not respond in the same way to climate change, **there is a significant risk of desynchronization between species within the ecosystem.**

Significant changes in high mountain ecosystem services are expected in the future. Specific studies on this subject will be necessary in order to anticipate these phenomena and manage risks and opportunities. It must also be specified that these scenarios are based on air temperature and do not take into account snow cover duration and drought, both of which may have significant and negative effects on the phenology of alpine species.

2.6 Proliferation and disappearance of species

Even without the spread of new species, the rise in elevation of species combined with longer growing seasons has led to a "greening" of the Alps, with an ever-increasing plant cover and plant diversity in the high mountains (Carlson *et al.* 2017 ; Steinbauer *et al.* 2018). Analyses carried out in the Mont-Blanc massif have confirmed this trend in the EMB, where a significant increase in the surface area occupied by vegetation between 2,500 and 3,000 m was observed between 1984 and 2017 (Figure 2.11). As a result of this trend, and combined with glacier and snow field melt, **we can expect high mountain landscapes**

to undergo transformation, even in the heart of the Mont-Blanc massif, toward more vegetated and rockier environments (where there were once glaciers).

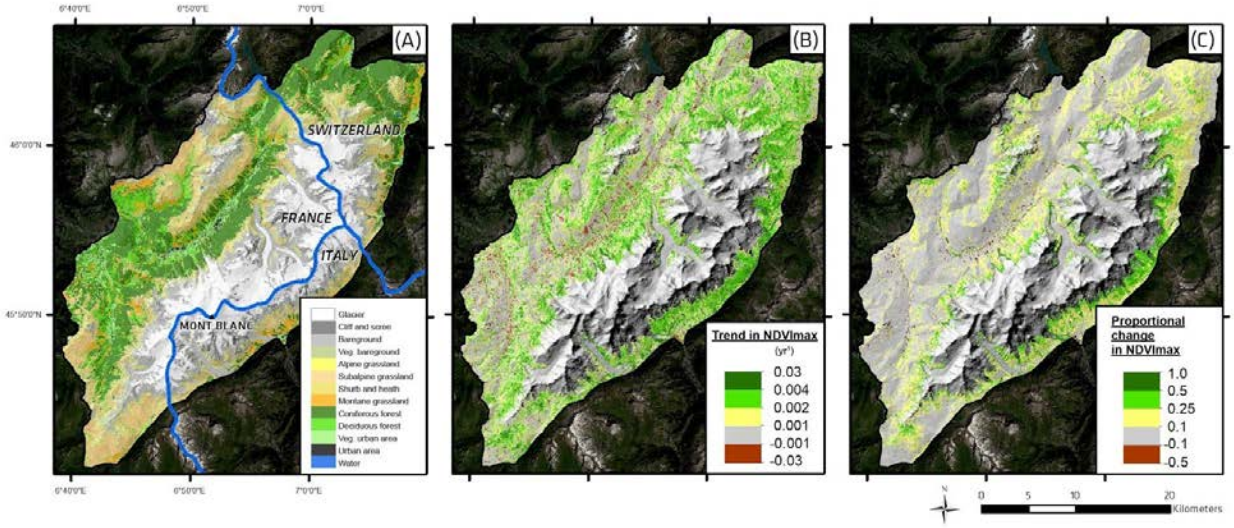


Figure 2.11. Observed changes in plant productivity (NDVI-max) from 1984 to 2017 in the Mont-Blanc massif, derived from an analysis of Landsat satellite images. Panel (A) indicates the location of different land cover classes in the massif (Source : *J. Renaud, LECA*) ; panel (B) shows linear trends in plant productivity between 1984 and 2017 and panel (C) indicates the proportional changes in productivity change over the same period. The dark green areas indicate a significant increase in plant cover, most often following the retreat of snowfields and glaciers.

Temperature variations have a direct impact on the physiology and reproductive capacity of animals, especially those that do not regulate their body temperature (pests, insects, amphibians and reptiles). This is the case with the spruce bark beetle, a small insect in the order Coleoptera, that burrows under the bark of spruce trees, feeding on wood and ultimately causing the death of the tree. **Bark beetles, like many pests (especially those found in agricultural areas), develop much faster with rising temperatures** (3 times faster at 30°C than at 15°C for the spruce bark beetle), and may be able to develop an additional generation during the summer season (CH2014-Impacts, Jakoby et al., 2019). **The proliferation of certain species weakens others, resulting in profound changes to the ecosystem.** The Norway spruce, which is currently the dominant species in the EMB's north side, is extremely vulnerable to pests (bark beetles) and summer drought. Though climate change may allow the Norway spruce to expand its range upslope, the benefit is offset by these vulnerabilities. In addition, the abundance of some emblematic alpine species will be directly impacted by climate change, in some cases leading to their disappearance. This particularly applies to so-called "arctic-alpine" species which are specially adapted to cold, snowy environments. For example, in the most pessimistic climate scenario, the rock ptarmigan may lose up to 60% of its favorable habitat in the Mont-Blanc massif by 2050, and more than 90% by 2090. Other environments like snow bed communities and wetlands that are both rich in species diversity and very dependent on temperatures and snow cover are especially threatened by climate change.

3. Impacts on socio-economic sectors

The participatory process of the AdaPT Mont-Blanc project identified, among the many sectors of socio-economic activity that will be impacted by climate change, **natural resources**, **tourism** and **natural hazards** as priority areas. Local administrators from the three countries, NGOs, technicians from regional and cantonal administrations, socio-professionals and various stakeholders contributed to the participatory approach during several cross-border workshops. The primary objective of the participatory process was to define, in the EMB, which sectors were considered as priority and in need of further study to better understand climate change impacts. The following sections of this report aim to present an analysis and overview of these impacts, based both on the development of specific indicators (carried out within the framework of this project) and a review of the available scientific literature. As such, this analysis is not exhaustive and identifies the need for specific complementary studies. However, it proposes a solid, coherent and multisectoral approach intended to inform the development of climate change adaptation strategies in the EMB.

3.1 Water

Water is a natural resource that is fundamental for life. Climate change is already impacting water cycles in the mountains. In mountain watersheds, a rise in temperatures combined with a seasonal redistribution of precipitation (cf. 1.3), a reduction in snow cover below 2,000-2,500 m (cf. 2.1) and glacier melt (cf. 2.2) will have impacts on water availability in the valleys.

More frequent summer droughts and soil water deficits will lead to more frequent water stress for vegetation during the growing season (Figure 1.20). Models predict that the soil will dry out in summer, with the water deficit zone (as defined by P-ET) rising from 600 m to 900 m depending on the scenario (Figure 3.1). In the intermediate climate scenario (RCP 4.5), water deficits will increase, with a 40-60 mm decrease in water across the entire territory. These new water deficits will have an impact not only on towns and agriculture in the valleys, but also on high mountain pastures. It is important to note that these calculations are based on summer climate (precipitation and evapotranspiration) alone, and do not take into account the water supply from snowpack or other soil properties, such as water storage capacity. We also note that due to higher rates of precipitation on the western side and cooler temperatures on the northern side, a balance of precipitation and evapotranspiration is found 1,300 m lower on the French side of the Mont-Blanc massif than on the Italian side.

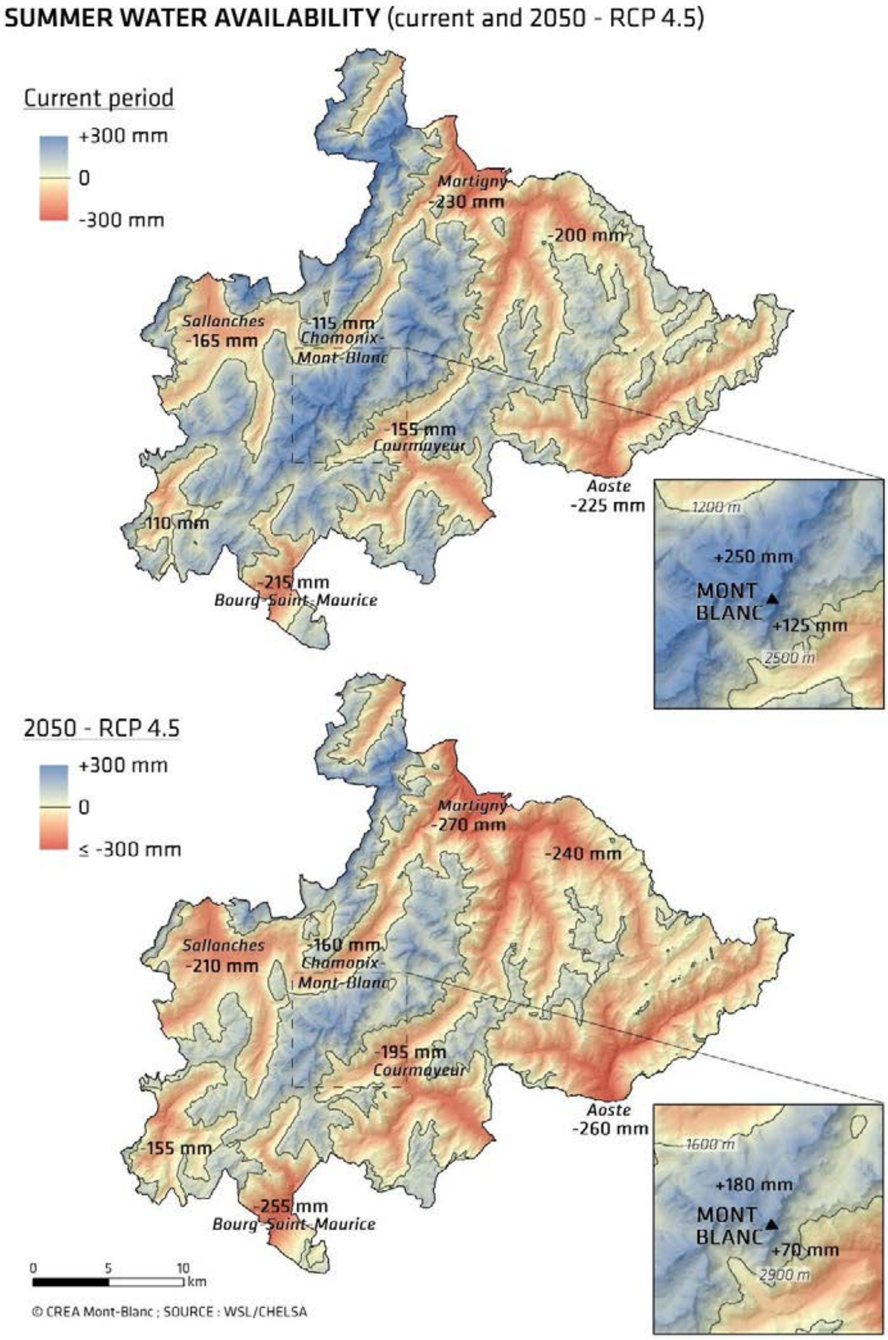


Figure 3.1. Summer water availability (P-ETP) for the current period and in 2050. A value of zero represents an equilibrium between water arriving as precipitation and water leaving as potential evapotranspiration. Positive values indicate an excess in precipitation, while negative values indicate water deficit.

In regards to **river flow rates**, Figure 3.2 shows the scenarios for expected change in stream flow on the Italian side of the EMB (Doire de Vény, Courmayeur, Aosta Valley), obtained with a hydrological model that takes into account glacier and snow dynamics. The increase in winter and spring temperatures will lead to a decrease in precipitation in the form of snow and therefore an **increase in flow towards the end of winter and the beginning of spring**. Conversely, the reduction in precipitation in summer will result in a **decrease in summer flow**. These dynamics will also interact with glacier melt: in the first half of the century, melting glaciers may offset the reduction in summer precipitation.

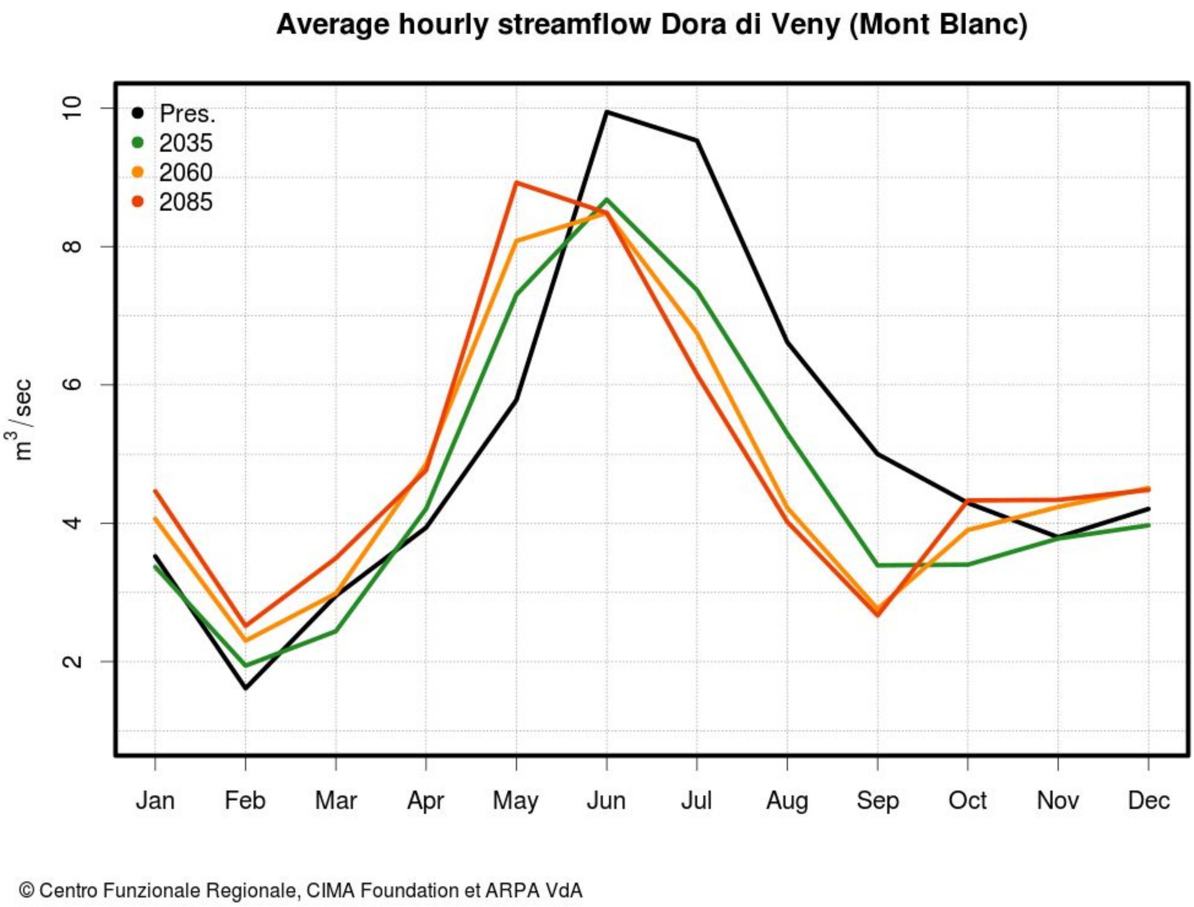


Figure 3.2. Expected change in the water regime (flow) on the Italian side of the EMB (Doire de Vény, Courmayeur, Aosta Valley). These simulations are based on a combination of the three emissions scenarios (RCP 2.6, 4.5, 8.5), a climate model (EC-EARTH-RCA4) and a hydrological model which takes into account glacier and snow dynamics. ***Source : CIMA Foundation et Centro Funzionale Regione Valle d'Aosta***.

These changes could lead to an increased risk of winter floods (cf. 3.6), as well as droughts during summer and early fall months. In years with significant reductions in river flow, we can anticipate conflicts around the use of the resource among the needs of humans, agriculture, hydroelectricity and downstream ecosystems. In order to prevent these potential conflicts, specific studies will be needed for each waterway and watershed, as well as a redefining of usage rights, the development of a culture of water sharing, improvement of irrigation techniques, and potentially, the creation of high elevation water storage reservoirs, which could compensate for the loss of glaciers and regulate water flow over time.

3.2 Agriculture

Agriculture is one of the economic sectors that could be the most directly impacted by climate change. **Rising temperatures and changes in precipitation regimes may have very large impacts on animal and plant productivity, as well as on the distribution and spread of pathogens.** Overall, these changes will impact the viability of certain crops in different parts of the territory. Impact analyses carried out both at the European and national level have highlighted both opportunities for greater productivity for crops and pastures in the context of moderate warming (1-3°C) and increased availability of CO2 for photosynthesis, as well as risks associated with more variable precipitation and increases in extreme weather events (particularly intense precipitation events, droughts and heatwaves). In the EMB, the most important agricultural activities are the **cultivation of fruit trees and grapevines** in the Aosta Valley and in the Valais, and the **raising of livestock in** all three countries.

When it comes to the production of animal feed, the pressure on farmers may be reduced in years to come. Shorter and warmer winter seasons (Figure 2.2) may mean that animals may need less feed, and that fields are more productive (5-15% higher productivity; Sérès, 2010) or can be hayed a third time thanks to a longer growing season (Chaix et al., 2017; Figure 2.10). During the cross-border meeting in Chamonix in November, 2018, several farmers from the Aosta Valley already attested to the fact that they were increasingly able to mow fields a third time at higher elevations (1,500 m) at the end of the season. However, these benefits may be limited if episodes of drought occur, especially if combined with high temperatures. In these cases, plants have a greater need for water and soil dries out more quickly, leading to a halt in primary production or a degradation in the vegetation cover during hot and dry months (Cremonese et al., 2017).
Four quantitative case studies about agriculture in the EMB are presented here. Specifically, we developed life cycle modification scenarios for different **pathogens**, an analysis of optimal conditions for **viticulture**, a projection of the risk of **late frost events,** and an index relating to **heat stress in dairy cows.**

Pathogen cycles

Pests and diseases that impact fruit trees will benefit from higher temperatures to spread and reproduce more quickly on crops. For example, the codling moth is an insect whose larvae develop inside of pome fruits like apples and pears, causing significant damage to crops. Crops in the EMB may be impacted by these phytophagous insects as a result of the following processes:

- increase in the number of generations per season (potentially affected species: *Lobesia botrana*, *Empoasca vitis*, *Planococcus ficus*, *Tuta absoluta, Cydia pomonella,* etc.)
- changes in geographic distribution with spread to higher elevations, and the arrival of new pests (example species: *Lobesia botrana, Eupoecilia ambiguella, Scaphoideus titanus, Thaumetopoea pityocampa, Leptinotarsa decemlineata,* etc.)
- modification of the wintering phase, leading to earlier activity phases in certain pests (example species: *Drosophila suzukii, Cacopsylla pyri, Cacopsylla melanoneura,* etc.)
- spread of invasive species (example species: *Halyomorpha halys*, *Popillia japonica*, *Tuta absoluta*, *Harmonia axyridis,* etc.)

All of these factors result in an aggravation of the harmful effects on crops (example species: *Zeuzera pyrina, Lobesia botrana, Eupoecilia ambiguella, Scaphoideus titanus, Thaumetopoea pityocampa, Drosophila suzukii,* etc.)

Specific phenological models (*devRate* R package, Rebaudo et al., 2017) were used to develop different life cycle modification scenarios for some of the pests mentioned above, based on the different climate scenarios. We collaborated with the Institut Agricole Régional de la Vallée d'Aoste (IAR, www.iaraosta.it) in choosing the pests to prioritize in this study.

Figure 3.3 shows that warming temperatures will be beneficial for **pear and apple codling moths (*Cydia pomonella*)**, one of the main pests of apple and pear trees. **By 2035, there will already be a significant risk of the development of a third generation per year in the valley floors during warm years.** Both this risk and the potential for significant damage are especially high for late varieties, whose fruit will still be on trees during the development of a third generation. Strategic choice of tree varieties will therefore be a key tool for adaptation (Swiss National Center for Climate Services).

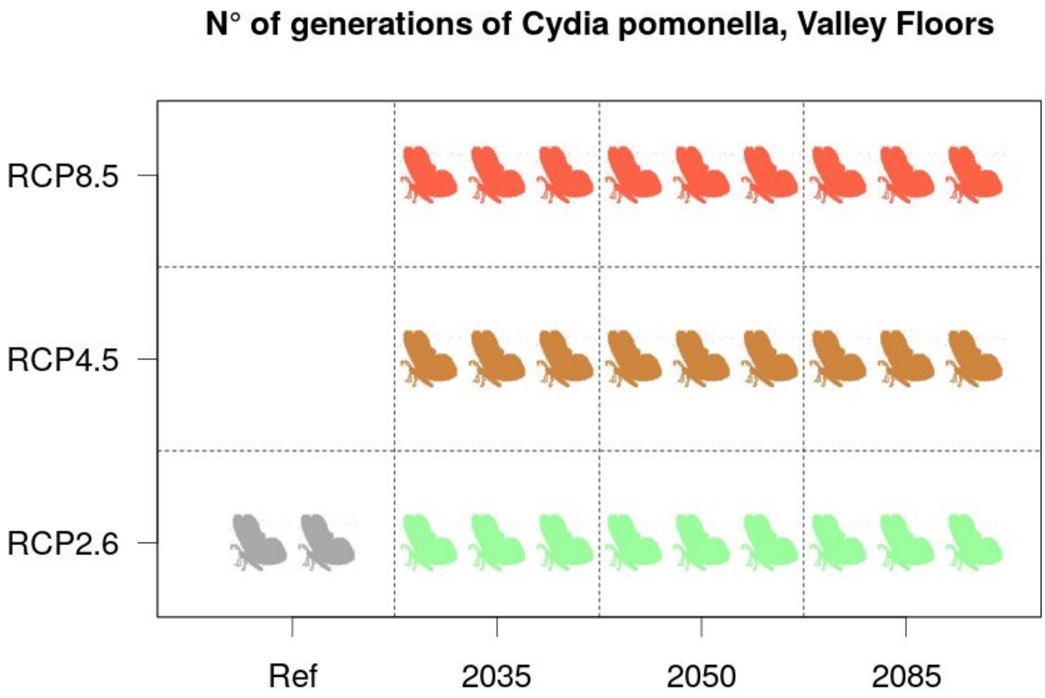


Figure 3.3. Expected change in the number of generations of *Cydia pomonella* (apple and pear codling moth) in valley floors.

Figure 3.4 shows the same analysis for the **European grapevine moth (*Lobesia botrana*)** which already produces three generations per year, making it a major pest for vineyards. As temperatures rise, the risk of a fourth generation appears in 2035, and the development of a fourth or even fifth generation becomes a risk after 2050, according to the intermediate and pessimistic scenarios (RCP 4.5, RCP 8.5).

This will have a significant impact on viticulture, especially when we consider that that caterpillars of successive generations not only puncture grapes as they are ripening but also allow for the establishment and spread of the fungus *Botrytis cinerea* (source: www.vignevin-occitanie.com/fiches-pratiques/eudemis/). In conclusion, even if we take into account factors such as humidity and precipitation, which could limit the spread of grapevine moths, we can expect a significant increase in damage.

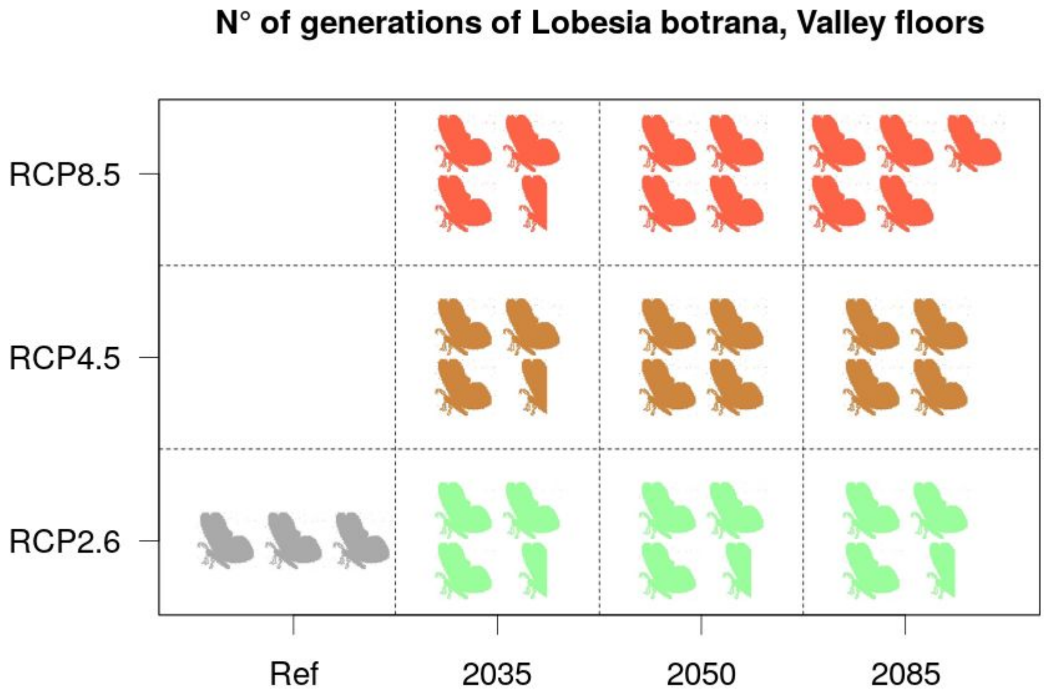


Figure 3.4. Expected change in the number of generations of *Lobesia botrana* (European grapevine moth) in valley floors.

Figure 3.5 shows different scenarios for changes in the number of generations of **tomato leafminer (*Tuta absoluta*)**, a pest originating in South America and appearing in Europe after 2000. It primarily impacts horticultural activities, in particular, tomato, potato, eggplant, pepino and pepper cultivation. This pest can cause losses of up to 80-100% of harvests. An additional generation (from five to six) is predicted by 2035, and up to eight generations are expected by the end of the century in RCP 8.5.

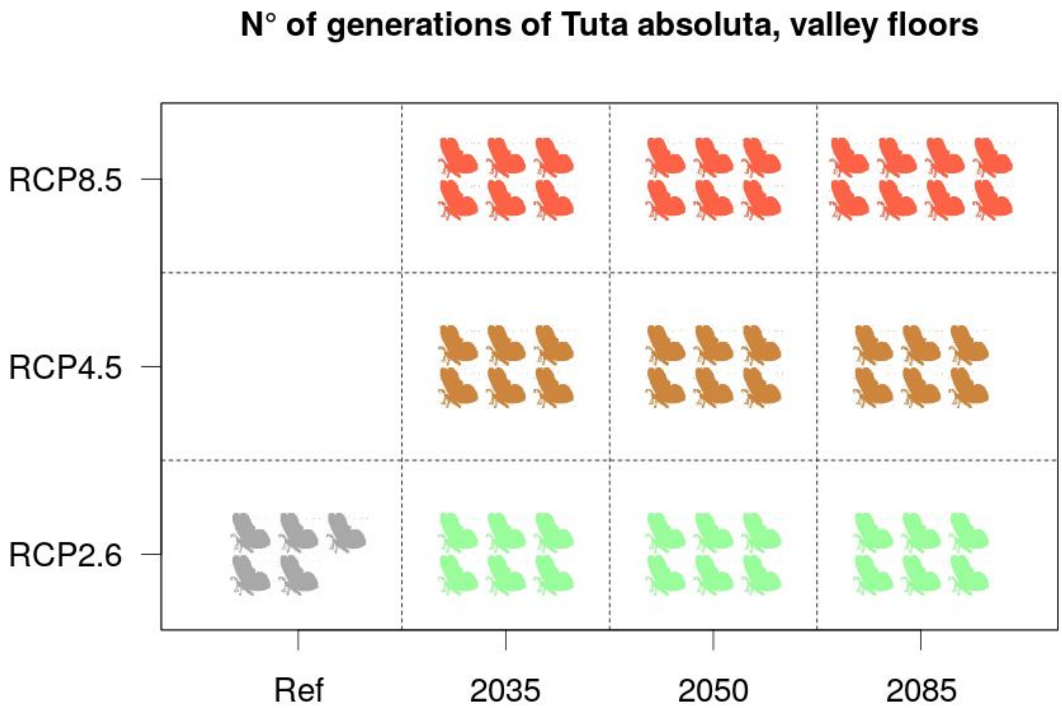


Figure 3.5. Expected change in the number of generations of *Tuta absoluta* (tomato leafminer) in valley floors.

In conclusion, by 2035, there will be an increase in the number of generations per year in valley floors for all three of the pests examined. A variety of responses and adaptation strategies will be necessary to manage these changes in pest life cycles, the most obvious being an extension of the period of active pathogen control, accompanied by an implementation of other prevention measures (CH2014- Impacts, 2014).

Viticulture

Like all agricultural activities, wine production may be significantly impacted by climate change. Observed climate change over the last few decades has already caused a significant advance in phenological stages (budding, flowering and ripening), an increase in temperatures during the maturation phase, earlier harvests and changes in the biochemical characteristics of grapes (in particular, sugar to acid ratios, differences between sugar and polyphenol accumulation, and modified aromatic components (e.g. Quénol et al., 2017, Moriondo et al., 2013, projet LACCAVE www6.inra.fr/laccave)). In the coming years, we can expect positive impacts linked to more favorable bio-climatic conditions (increased productivity of some grape varieties and an expanded range for vineyards in the EMB). However, wine-producing practices will also need to adapt in response to phenological and physiological changes (for example, anticipating earlier harvest dates for some varieties and changes in grape chemistry). It is difficult to predict the consequences on the final composition of grapes and wines because they depend heavily on the impacts of warming on yield as well as on the complex interactions between average temperatures, drought, stress and increased availability of CO2 in the atmosphere for photosynthesis (LACCAVE 2018 project).

The Huglin index was used to analyze changes in the climatic viability of wine production in the EMB (Figure 3.6, Huglin 1978). This index is frequently used in literature for viability and impact analyses (e.g. Quénol et al., 2017, Moriondo et al., 2013, Malheiro et al 2010, CH2014-Impacts, 2014) because it quantifies the ideal conditions for growth and sugar production in each grape variety. The Huglin index is based on the idea that each grape variety needs to accumulate a certain amount of heat over the course of the growing season in order to make long-term cultivation effective.

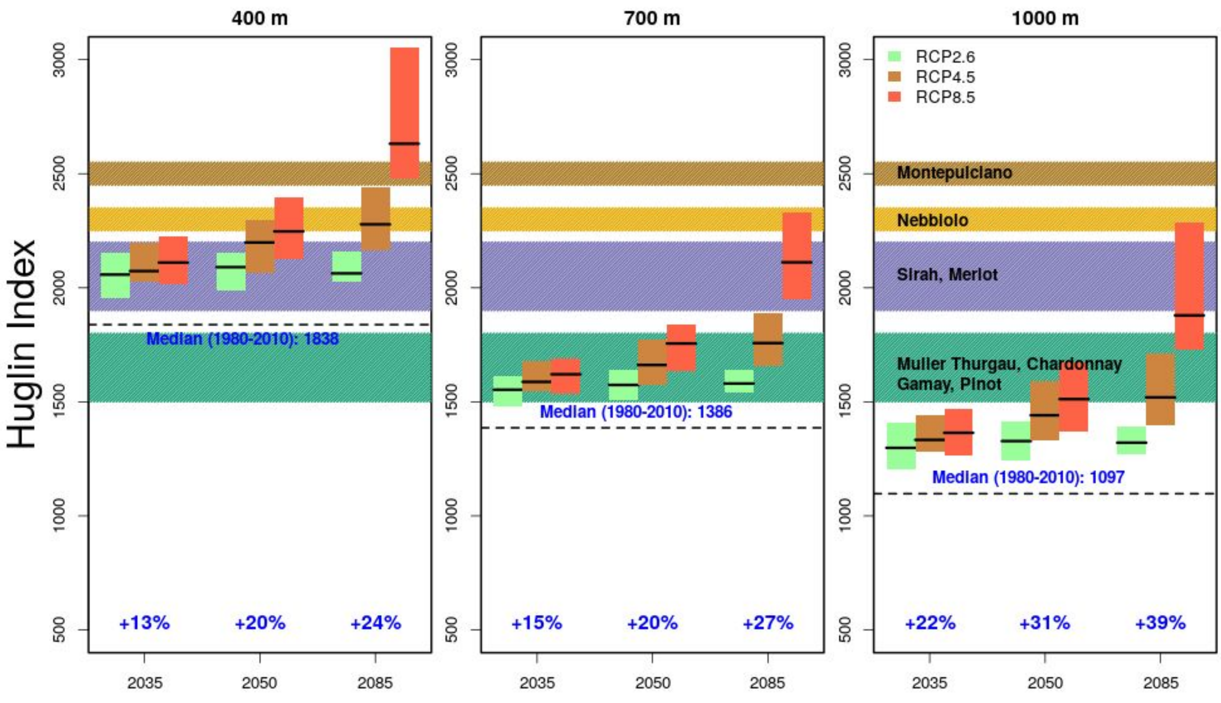


Figure 3.6. Expected changes of the Huglin index at 400, 700 and 1,000 m. The color of the bars represents the index values for different emissions scenarios. The height of the bars indicates the margin of uncertainty (10th and 90th percentile), taking into account the different climate models considered in the study. The horizontal dotted line represents the values of the established during the period 1980-2010. The colored rectangles represent the optimal index values for different grape varieties.

In the near future (2035) at 400 m, conditions will be too hot for grape varieties that require moderate temperatures ("cold" varieties) like Chardonnay, Muller Thurgau, Gamay and Pinot. However, climatic conditions will become ideal for Syrah and Merlot and beginning in 2050, there may be optimal conditions for new varieties like Nebbiolo and Montepulciano, which are typically found in warmer climates. By 2035, ideal bio-climatic conditions are expected at higher elevations (700 m) for "cold temperature" varieties, but also for Syrah and Merlot by the end of the century. In conclusion, grape cultivation in the EMB may benefit from climate change: **warming temperatures may allow winegrowers to plant a larger variety of grapes, potentially on higher slopes**, which is not possible in the current climate.

Nonetheless, if warming occurs at the rate of the most pessimistic scenario (RCP 8.5), negative impacts relating to heat stress, drought and extreme weather events will be felt, especially at low elevations. Interpretations of the presented results should also take into account the fact that the Huglin index is calculated at the scale of the entire territory, and does not allow for analyses of small-scale bioclimatic conditions (such as sunny/shaded slopes), the non-negligible impacts of phenomena like temperature inversions, or soil pedology and fertility – all of which will be decisive factors in assessing the viability of different grape varieties.

Late frost events

Late frost events are an example of a climatic hazard that can have an important impact on mountain agriculture. 2017 served as a clear example of the potential impact: an early, warm spring (March and April) led trees to bud and flower several weeks earlier than usual (Figure 2.9). But on April 10th, a late frost caused severe damage to young leaves and flowers, leading to crop losses of around 70-80% in the Aosta Valley and in the Valais.

We chose the "*safety margin*" indicator to help quantify crop vulnerability to late frost events in the EMB. This indicator establishes the number of days between the last frost and the budburst or flowering dates in different species. A positive safety margin indicates that budding and flowering occurred after the last frost, while a negative safety margin indicates that a frost occurred after the beginning of vegetation development, implying potential damage to the crops.

How climate change impacts the risk of late frost events is the subject of ongoing research. On the one hand, in recent decades in Switzerland (1975-2016), above 800 m, the risk of frost for fruit trees has risen from 20 and 40% (Vitasse et al., 2018). On the other hand, late frost events do not appear to have increased at higher elevations (above 2,000 m) during the last decades (Klein et al., 2018).

The hypothesis put forward is that decreases in snow cover in the mountains coupled with earlier springs may increase the exposure of plants to late frost events in the decades to come, despite the fact that temperatures, on average, will be milder. However, Vitasse et al. (2018) point out that the advance of spring may be limited by the combined impacts of photoperiod * (which could limit the development of vegetation if the length of the day is not yet sufficient) and an insufficient accumulation of cold (chilling requirement) during winter. The fact that spring plant development may be slowed down by these two factors could reduce the risks associated with late frost events.

In order to model this phenomenon at the scale of the EMB, we calculated the current and future safety margins for different representative fruit tree species. Different phenological models, which take into account the role of the chilling requirement in winter (Hufkens et al., 2018), have been optimized using the phenological and meteorological data collected by MétéoSuisse in recent decades (source: MétéoSuisse), allowing for a more precise model to calculate the current safety margin for two fruit tree species (cherry and apple). Using the same approach, future safety margin scenarios were calculated for two elevations.

Figure 3.7 shows the expected impact of these complex phenomena on apple trees. During the reference period (1980-2010), at 400 m, the safety margin was more than 20 days, and late frost events occurred in only 7% of years (displayed on the right axis of the graph). During the same period, at 700 m, the safety margin was less than 5 days, which led to the occurrence of late frosts during 35% of years. The models predict that safety margins will increase by 2035 at 700 m and in 2050 at lower elevations. **For apple trees, the risk of late frost events may remain constant at 400 m (from 7% today, to 5-7%, depending on the scenario), and could decrease at 700 m (from 35% to 24% by the end of the century)**.

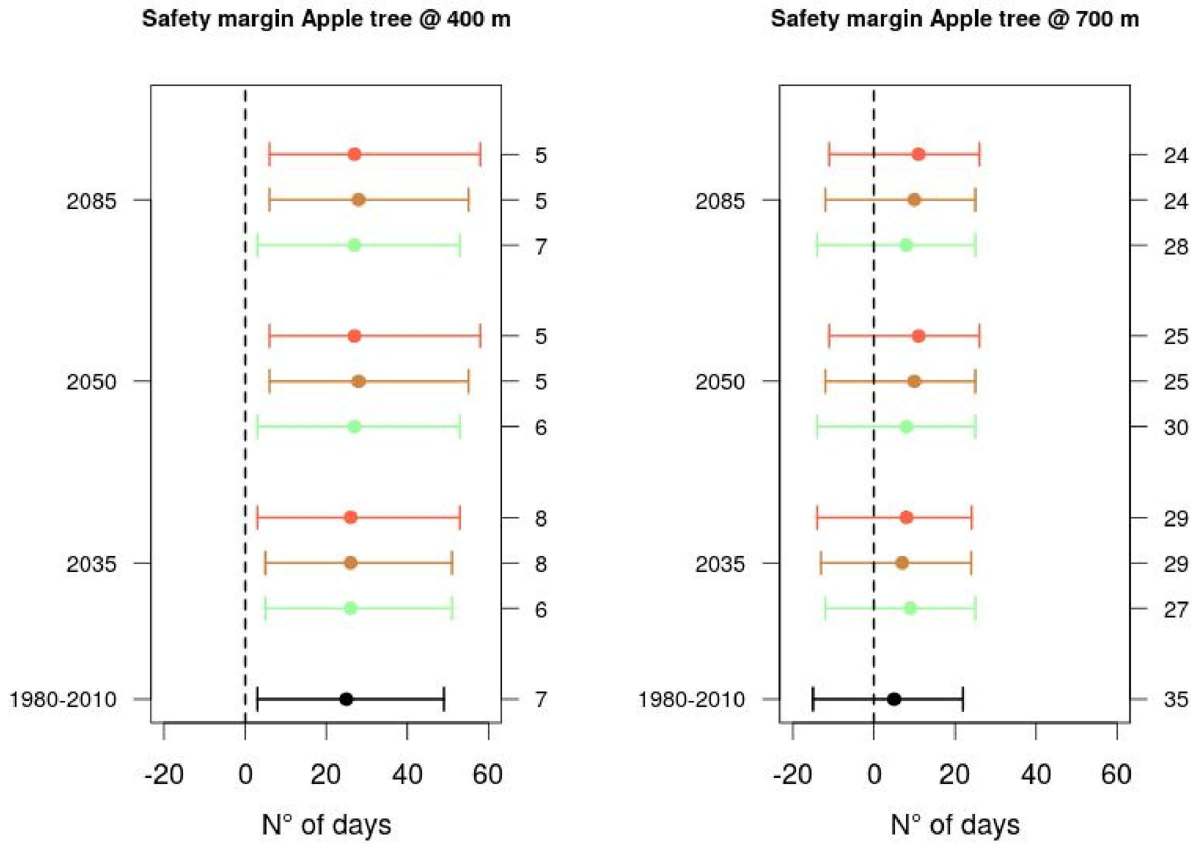


Figure 3.7. Scenarios for expected change in the safety margin for the risk of late frost events for apple trees at 400 and 700 m. The horizontal lines represent the current and forecasted variability of the margin (10th and 90th percentile) and the central point indicates the median. The color of the lines represents the different emissions scenarios (green for RCP 2.6, brown for RCP 4.5 and red for RCP 8.5). The black line represents the current reference period. The right axis shows the percentage of years with late frosts for the reference period.

Similar results have been obtained for cherry trees (Figure 3.8). Because cherry trees develop earlier than apple trees, they have a smaller safety margin and are more exposed to the risk of late frost events. During the reference period (1980-2010), at 400 m, the safety margin was less than 20 days and late frosts occurred during 15% of years (numbers located on the right of the graph). During the same period at 700 m, the average safety margin was close to zero, meaning that late frosts can occur more frequently than every other year (55%). **The models predict that by 2035, this risk may be lower for cherry trees at 400 and 700 m, but will remain higher than the risk for apple trees**. Taking into account all of the emissions scenarios and the reference period, the greatest decrease in risk is expected at 700 m (lowering from 55% to 38% by the end of the century).

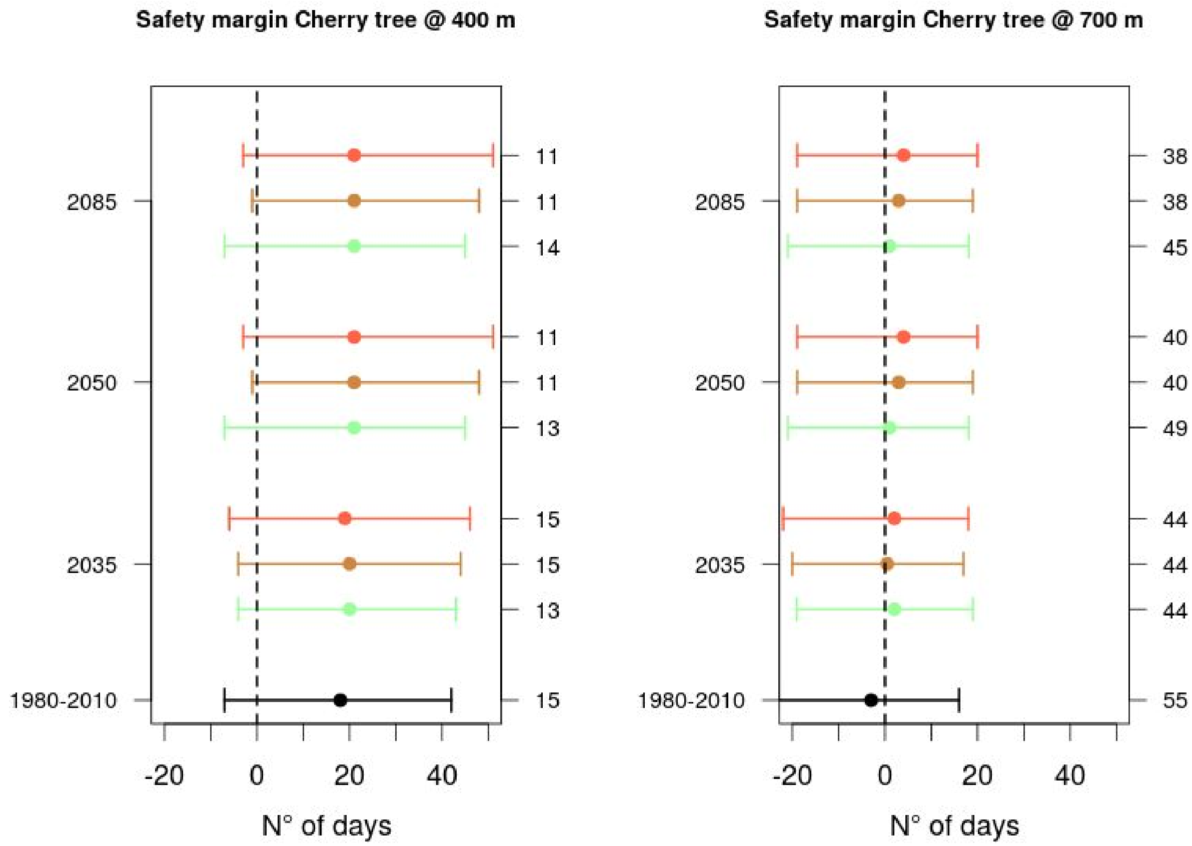


Figure 3.8. Scenarios for expected change in the safety margin for the risk of late frost events for cherry trees at 400 and 700 m. The horizontal lines represent the current and forecasted variability of the margin (10th and 90th percentile) and the central point indicates the median. The color of the lines represents the different emissions scenarios (green for RCP 2.6, brown for RCP 4.5 and red for RCP 8.5). The black line represents the current reference period. The right axis shows the percentage of years with late frosts for the reference period.

Late frost events could also be an important risk factor for pasture resources. As snow melts earlier, prairies and meadows may be able to develop earlier in the spring. However, early development increases the risk of exposure to frost which can degrade both the quality and quantity of hay (Chaix et al., 2017). Currently, there are no phenological field observations available to allow us to evaluate how the risk of late frost events is changing for meadows. Therefore, vegetation development dates for valley floors were extracted from satellite images (MODIS (2002-2018), Filippa et al., 2017). The results obtained were similar to those found for apple and cherry trees (Figure 3.9). The current safety margin is lower at 700 m (less than 5 days) than at 400 m (more than 20 days). The risk of frost is therefore greater at higher elevations (38% at 700 m versus 7% at 400 m). The scenarios predict that the risk may decrease by 2035, and that by the end of the century, the risk may be 3-4% at 400 m and 17-25% at 700 m.

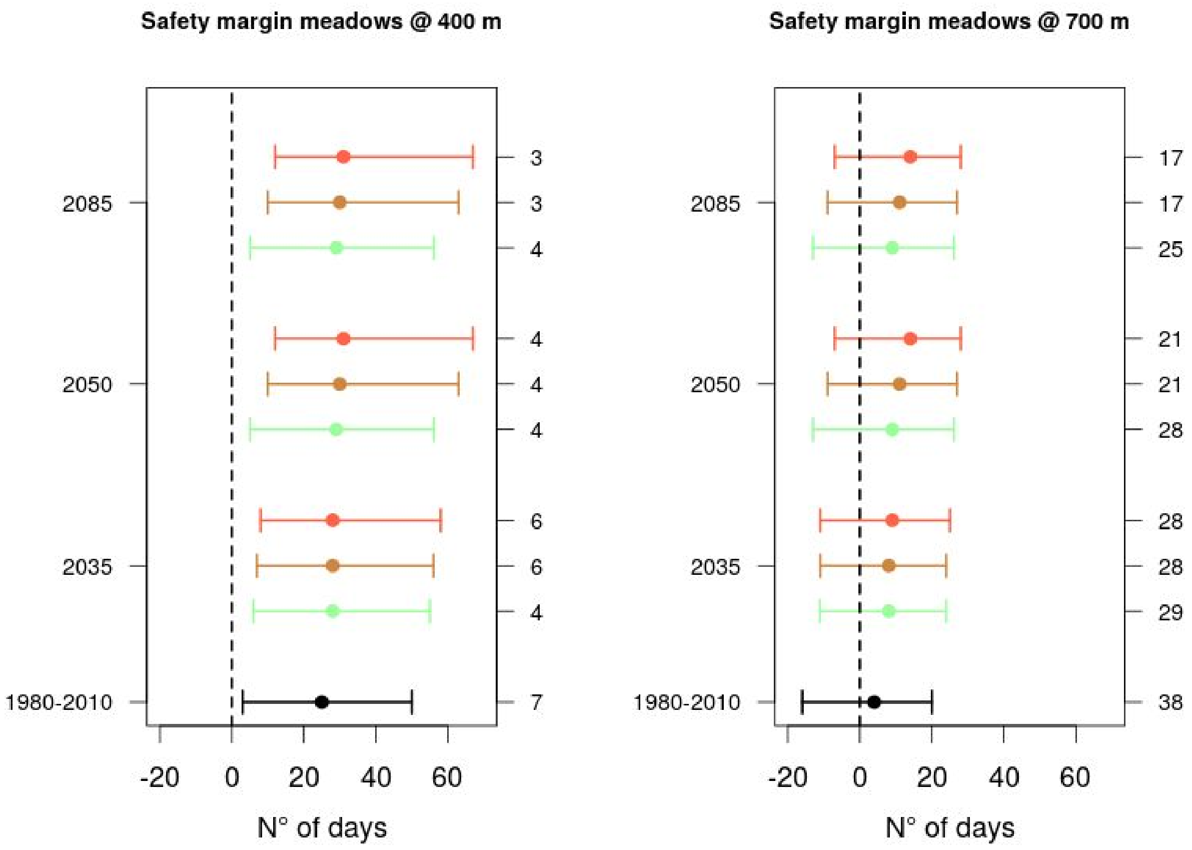


Figure 3.9. Scenarios for expected change in the safety margin for the risk of late frost events for meadows at 400 and 700 m. The horizontal lines represent the current and forecasted variability of the margin (10th and 90th percentile) and the central point indicates the median. The color of the lines represents the different emissions scenarios (green for RCP 2.6, brown for RCP 4.5 and red for RCP 8.5). The black line represents the current reference period. The right axis shows the percentage of years with late frosts for the reference period.

In conclusion, our analyses point to a **general downward trend in the risk of late frost events** for the three crops considered, with the greatest reduction expected at 700 m. The main limitations of this analysis, which merit more in-depth studies, are as follows:

- the phenological databases are fragmented: data is unavailable for some environments, they do not take into account differences between varieties; and, they are limited to Switzerland for cherry and apple trees
- data only take into account the 50% flowering phase (for trees) and end of growth (for meadows). Analyses of the early flowering phase might have rendered different results and should be one of the first additional studies carried out
- the potential genetic variability within the same species growing at different altitudes, which could induce responses adapted to the risk of late frost at each altitude (Vitasse et al., 2018). Phenological models were not optimized by separating the populations at both elevations, and therefore, the results obtained may overlook the effect of genetic adaptations within the different populations (even if this effect is surely secondary when compared to environmental controls)

Heat stress in dairy cows

Rising summer temperatures can lead to increased stress levels in dairy cows, which in turn can impact milk production. This type of heat stress can be estimated using the THI index (temperature-humidity index, Thom 1958), which takes into account the combined impact of heat and humidity on thermal comfort in animals. Heat stress in dairy cows can lead to decreased milk quality and quantity. Today, dairy cows experience an average of one day of heat stress per year (THI threshold > 72) at the valley floor (Figure 3.10). **By 2035, the number of days of heat stress may rise to 5-12 days. By 2050, that number may rise to 5-20 days, and may be as high as 5-60 days by the end of the century, leading to significant negative impacts on milk production from herds that stay at valley floor during the summer.** It may be necessary to put herd management adaptation measures in place (for example, utilizing higher elevation pastures, and bringing herds into the mountains earlier), in order to optimize the thermal and feed regimes of cows, especially in the case of hot summers (CH2014-Impacts, 2014). The quality of feed resources is also an important factor influencing the quality and quantity of milk produced. We predict that during drought years, there may be decreases in milk production. In conclusion, at the valley floor, **the number of days that dairy cows will experience heat stress will increase, leading to decreases in milk yields.**

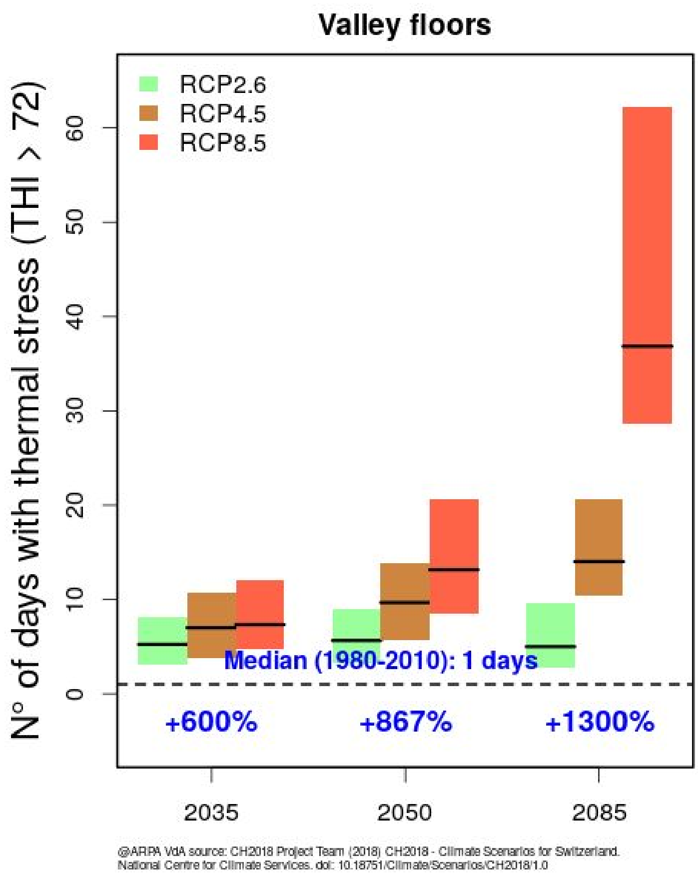


Figure 3.10. Expected changes in heat stress for dairy cows (THI index). The color of the bars represents the index values for different emissions scenarios. The height of the bars indicates the margin of uncertainty (10th and 90th percentile), taking into account the different climate models considered in the study.

In direct connection with the case studies presented above, one of the most significant challenges will be linked to the increased frequency and intensity of extreme weather events (heatwaves, drought, extreme precipitation, etc. cf. 1.3), which will increase the risk of negative impacts on the productivity of different crops. Given this context, adaptation policies should focus on risk management, including, for example, optimization and widespread adoption of irrigation, management of water use conflicts and the use of insurance instruments (CH2014-Impacts, 2014).

3.3 Forests

Mountain forests are strongly impacted by climatic conditions and human activities and are very sensitive to ongoing changes impacting the way they function in terms of physiology, growth, distribution, interactions with pathogens and exposure to disturbances (storms, fires, etc.). Forests provide many important ecosystem services for humans in mountain areas, including lumber production, water cycle regulation, CO_2 storage (carbon sinks), biodiversity conservation, and protection from rock fall, torrential flooding and avalanches. However, **the ability of forests to provide these ecosystem services is being impacted by climate change: extreme events like forest fires, droughts and storms impact the survival of trees and therefore the services they provide to humans (**Elkin et al., 2013; Linder et al. 2010).

It is therefore necessary to try to understand how forests may respond and adapt to climate change. A complete analysis of all of the impacts (stress, mortality, species distribution, etc.), risks and opportunities (changes to lumber production, reductions in the effectiveness of protection measures, forest fires, etc.) related to climate change goes beyond the scope and objectives of this report. Thus, we have chosen to focus on a few key processes: **changes in species distribution, tree line elevation rise, increase in biomass production, and risks of spread of pests and diseases impacting forests.**

Changes in forest species composition

The climatic conditions of forest environments will be affected by both the lengthening of the growing season thanks to warmer spring and fall temperatures, as well as an intensification of droughts. Some species that are unable to either adapt or colonize upslope may disappear and be replaced by new species arriving from lower elevations. Below 1,500 m, models of forest population dynamics predict the upward colonization and development of beech, maple and ash. Other thermophile species (thriving at warm temperatures) like the Scots pine could progressively take over Norway spruce forests at lower elevations. Norway spruce, which is already disadvantaged by climate change, is particularly sensitive to drought, windstorms (especially in monospecific stands of trees that are all the same age), and pathogens. We can therefore expect increased spruce tree mortality at the lower limit of their distribution in the EMB in coming years.

At the upper limit of the forest, or the tree line, the effects of climate change will vary depending on the species. By 2050, Norway spruce will find the conditions most favorable to their development higher in elevation, at the upper limit of their distribution. *Alnus alnobetula* (often called green alder) will continue to colonize hard-to-access areas, including in avalanche couloirs and steep, abandoned pastures (Anthelme et al., 2007). In the longer term, *Pinus cembra* (Stone pine) and *Pinus mugo* (Mountain pine) may expand their range, mostly in scree and talus fields, and rock walls. At even higher elevation than spruce forests, larch trees may colonize areas that have not yet developed shrub cover (Schumacher et Bugmann, 2006).

Treeline rise

Rising temperatures leading to a longer growing season at higher elevations (cf. 2.5), and combined with warmer winters that nevertheless remain cold enough for trees to accumulate the amount of cold necessary for their phenological cycle (*chilling requirement*), will allow for trees to find conditions suitable for colonizing at high elevations. **Between 1952 and 2006 in the Mont-Blanc massif, the average elevation of treeline rose by 60 m** (Martin, 2014). **Models predict that by 2050, treeline will continue to rise as much as 100 m**, depending on environmental configuration (Schumacher et Bugmann, 2006). However, warming temperatures are not the only factor contributing to treeline rise. This phenomenon is also accelerated by **melting glaciers and the abandonment of alpine pastures** because they make new space available for forest colonization. Rising treeline is not a homogenous phenomenon. In the Swiss Alps, slope orientation can cause the upper limit of forests to vary by up to 200 m (Schumacher et Bugmann, 2006). This upper limit can also vary depending on soil type, the presence of rocks and other obstacles and local-scale disturbances including avalanches and grazing. With a view to the long term, the growth of forests at higher elevations could provide additional protection from landslides, rock fall and avalanches (Lindner et al., 2010); however, these changes will significantly modify the landscape. In the Mont-Blanc massif, some alpine grasslands could be replaced by forests, greatly changing the appearance of the mountains and having potential repercussions on tourism and other local activities (cf. 3.5).

Figures 3.11 et 3.12 show expected change scenarios for the distribution of different ecosystems around Mont-Blanc. These figures are based on an extrapolation of the vegetation dynamics observed over recent decades (1987-2017), projecting the changes that may be seen by 2050. We used a plant productivity index (NDVI) calculated from Landsat* satellite images. These extrapolations take into account local vegetation dynamics observed by satellites but do not take into account emissions scenarios (instead, they presuppose a continuation of the vegetation dynamics observed over the last two decades) or changes in human activity (grazing, etc.). Nonetheless this method provides us with the general trends we can expect for the future of the landscape. The projections can be considered relatively conservative given that climate change is expected to accelerate in coming years, leading to non-linear impacts linked to the complexity of natural systems. Glacier melt, which will free up new areas for plant colonization, has also been left out of this model because glacier retreat scenarios are not available at the scale of the massif. Figures 3.11 and 3.12 show the changes to the ecosystem expected **by 2050: the rise in treeline and shrub-cover is very clear on south-facing slopes, as well an increase in the areas occupied by alpine meadows, heath and grasslands which will continue to colonize areas that are currently rocky and/or snow-covered.** Unless grazing practices expand and gain in intensity, we also expect a densification of mountain forests, especially around Mégève and Les Contamines.

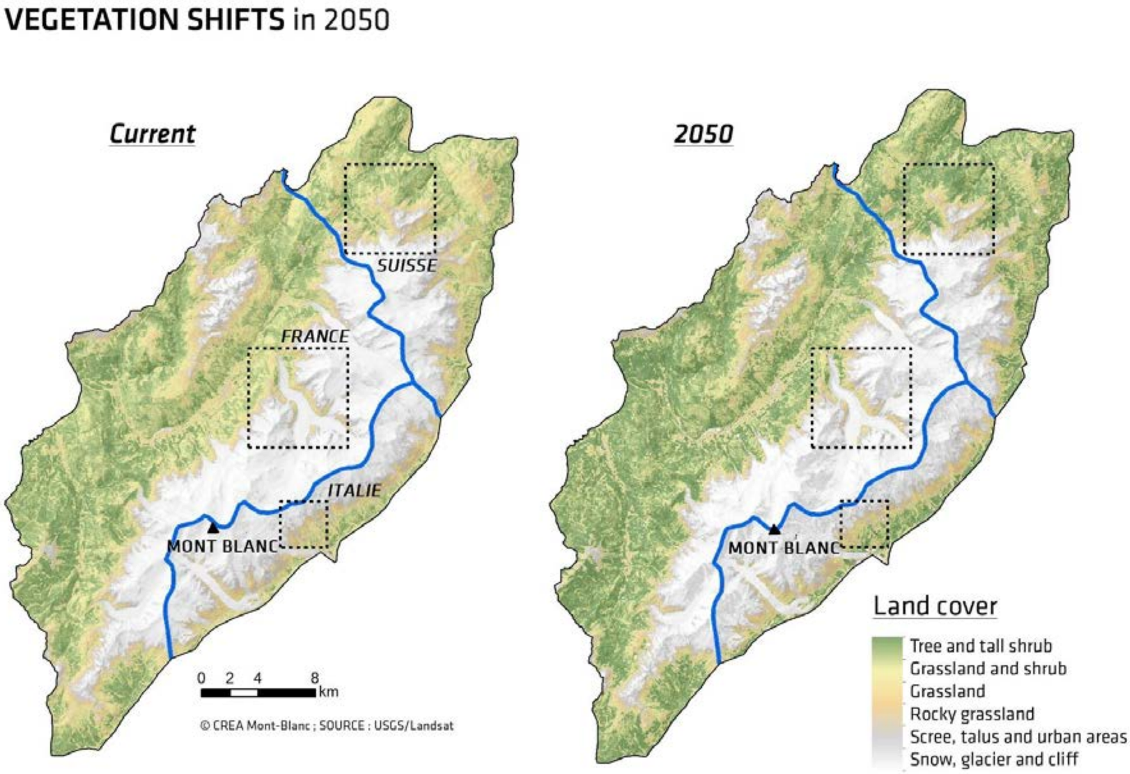


Figure 3.11. Habitat maps for the Mont-Blanc massif for the current period and for 2050, based on a plant productivity index (NDVI) detected by satellite between 1984 and 2017, and extrapolated for the future (using a linear model calibrated by pixel). On the color scale, the darker the green, the greater the plant cover and productivity. The dotted squares on the map indicate the zoomed areas illustrated in the figure below (46).

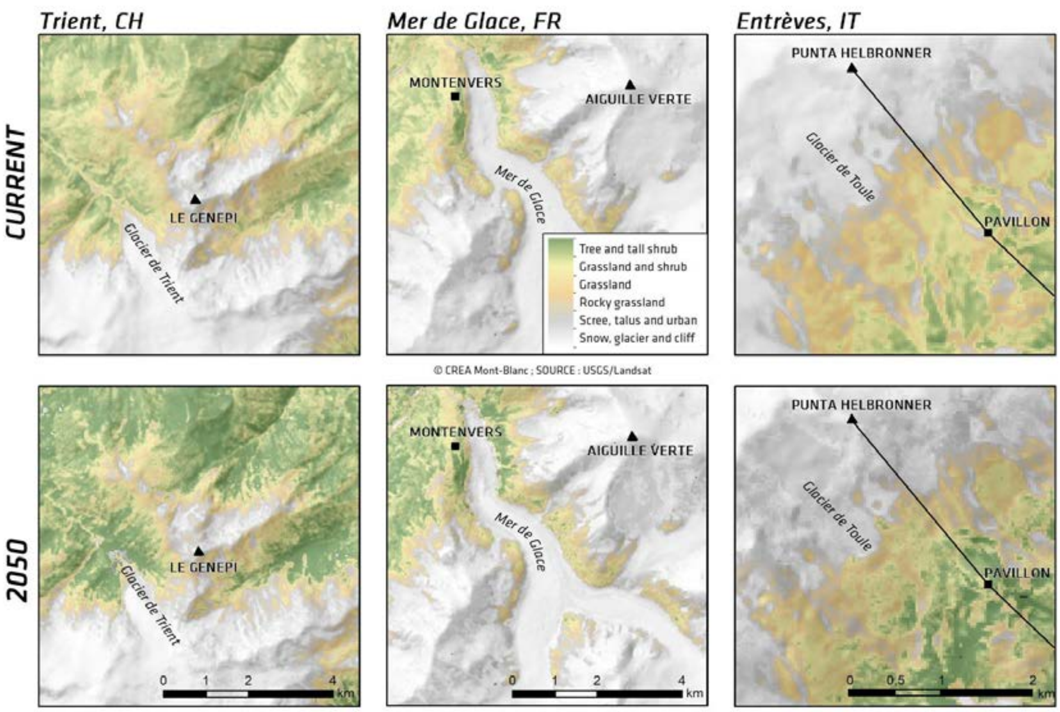


Figure 3.12. Zoom-in on different sectors within the EMB: Switzerland (Trient), France (Chamonix) and Italy (Entrèves), indicating the expected change in vegetation between the current period and 2050. In Trient, we can see significant densification and upslope colonization of trees and shrubs, especially in high mountain scree fields. At the Montenvers site, we see forest expansion both in the mid mountains and at the glacier terminus. Finally, on the Italian side, we see that the forest will likely overtake the Pavillion midstation of the Skyway.

Increase in the area and the productivity of mountain forests

In mountainous areas, where cold temperatures slow tree growth, warming temperatures will likely lead to an increase in biomass production and a densification of forests (Schumacher et Bugmann, 2006). Primary production will also be accelerated by a longer growing season, an increased concentration and availability of CO_2 in the atmosphere for photosynthesis, and an increase in nitrogen deposits linked to human activity. Forestry may benefit from faster tree growth, but only if forest managers prioritize species diversity and closely monitor forests and pests, making sure to cut trees as soon as they are contaminated (Courbaud et al., 2010).

Figure 3.13 shows the observed changes in forest area in the Mont-Blanc massif since the 1950s by aerial photos and projected in 2050 (using the extrapolation method described above). We can see a clear increase in the area occupied by **the forest, which we expect to expand from 90 km² in the 1950s to 230 km² in 2050, with the majority of expansion occurring on the French and Swiss sides of the massif.** This dynamic has already been observed between 1952 and 2006, when forest area grew about 85%, in connection with climate change, but especially with the marked agricultural abandonment during that time period (Martin, 2014). This increase in forest area and productivity will constitute an important carbon storage sink, but will also lead to major changes in the appearance of the EMB's landscape, which will have significant aesthetic, cultural and potentially tourism-related consequences (cf. 3.5)

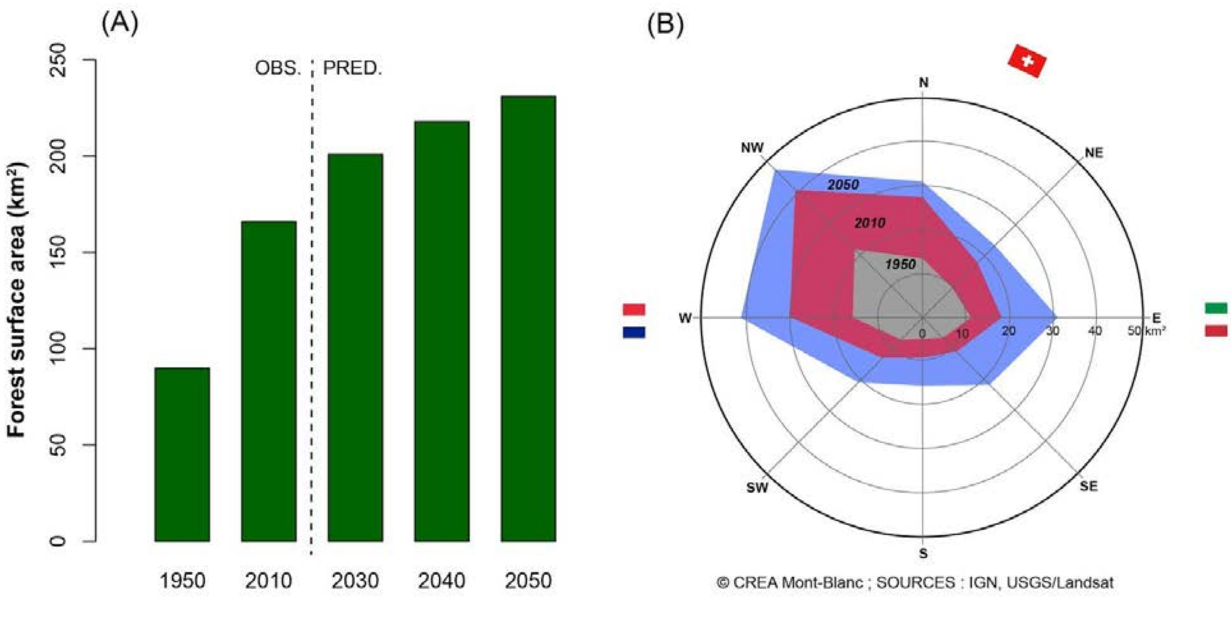


Figure 3.13. (A) Expected change in forest surface area in the Mont-Blanc massif from 1950 to 2050 and (B) distribution of forest area by slope orientation, estimated for the heart of the massif, as indicated in Figure 3.11. The area occupied by forests and high shrubs is likely to increase by about 60 km² between today and 2050. Results for 1950 and 2010 are based on aerial photographs, while estimates for the period 2015-2050 are generated by analyses of satellite images.

Risk of spread of pests and diseases affecting trees

While rising temperatures may lead to the expansion of forested area, some species may be threatened by pests and diseases which will benefit from climate change, spreading and reproducing more quickly on trees (Rebetez et Dobbertin, 2004). This is the case for the spruce bark beetle, a small insect in Coleoptera order, that burrows under the bark of spruce trees, feeding on wood and ultimately causing the death of the tree. Spruce bark beetles develop 3 times faster at 30°C than at 15°C (Wermelinger and Seifert, 1999), and may produce an additional generation in hot summers (CH2014-Impacts, 2014). **During the 2003 heatwave summer, spruce bark beetles were able to develop 3 generations, and destroyed an amount of forest equal to 2/3 of the annual conifer consumption in Switzerland. This kind of situation could impact the EMB more frequently in the future.** Spruce bark beetles are present in the EMB and already caused significant damage in 2014 and 2015; larger attacks are expected in years to come. Another example is the larch tortrix, a moth which could modify its spatial distribution with rising temperatures. Though this species' caterpillars eat larch needles, they rarely kill the trees, even in cases of complete defoliation. However, the affected larch trees are significantly weaker and produce 50-90% less wood. They are therefore more vulnerable to other pests and extreme weather events. The larch tortrix, which produces swarms every 8-10 years, will be able to spread to higher elevations (Saulnier et al., 2017). This process is a vicious cycle, because the weakened trees are less able to cope with droughts (Barros et al., 2016) and new attacks of pests and diseases.

3.4 Natural heritage, conservation and biodiversity

Mountain ecosystems are home to nearly half of the world's biodiversity hotspots (Kohler et Maselli, 2009), and are characterized by their **exceptional biodiversity in relatively small areas**. 25% of European plant species are found in the mountains (above treeline)—a zone that only covers 3% of the continent's surface (Chape et al. 2008). The relative isolation and geographic distance between these "islands in the sky", combined with the impact of glacial and interglacial periods, have led to **high rates of endemic species in the mountains** (10% for alpine flora compared to an average of 4% for European flora; Aeschimann et al., 2011). This is why the Alps, and the EMB in particular, have become home to many emblematic animal species including the mountain hare, rock ptarmigan, chamois and ibex, as well as high mountain plant species including moss campion, glacier buttercup and many others. **In addition to challenges of conserving each of these species in their own right, understanding the changes in their populations is also key because they act as a marker of the evolution of alpine ecosystems more generally,** of the alpine landscape and of the image of the Alps in our culture and imagination.

These ecosystems are extremely vulnerable to both global changes like climate change and to disturbances linked to human activity. Climate change will lead to the modification and loss of some habitats, with varying impacts on different species of plants and animals, depending on the climate scenario. **The most significant changes will occur around 2,000 m of elevation**, where the distribution of 50% of birds and 40% of animals will be impacted (CH2014-Impacts, 2014). The following sections will present an analysis of the main processes that will impact biodiversity in the EMB (these processes are illustrated schematically in Figure 3.14). These processes will necessitate adaptations of the management strategies for natural areas in the EMB.

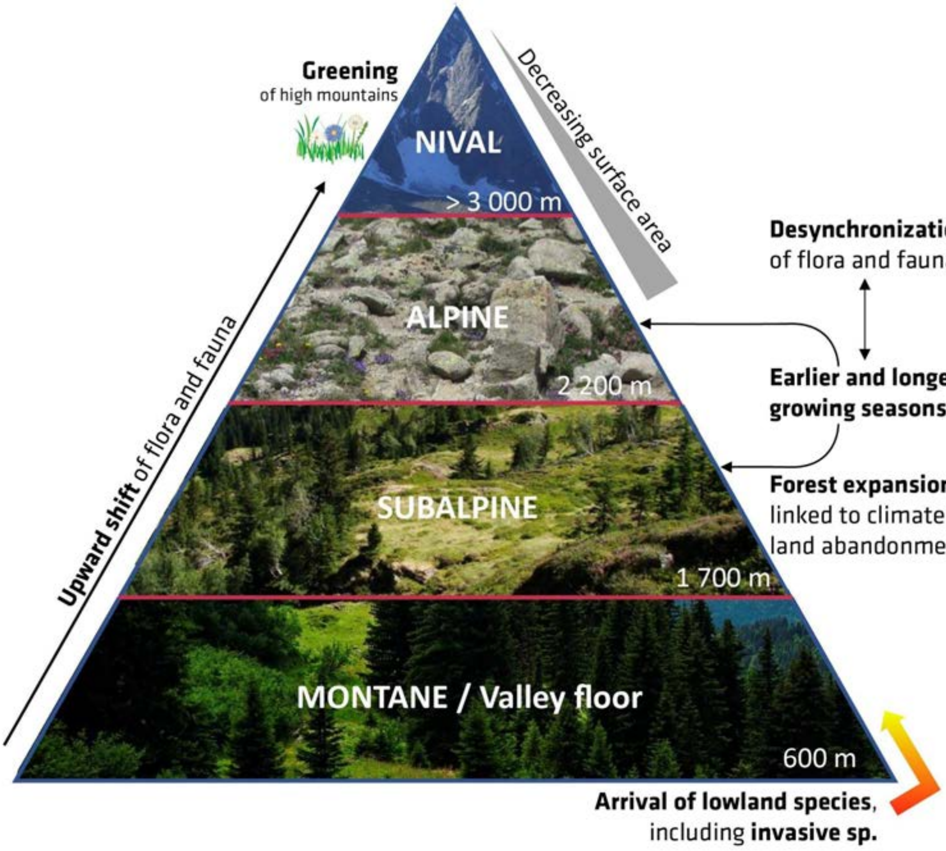


Figure 3.14. Diagram of ongoing changes (in terms of diversity and phenology) in the EMB's biodiversity along an elevation gradient. The elevations indicated on the right are approximate and designated according to current vegetation levels, which is likely to change significantly in years to come.

Impacts on flora: upslope migration

With climate change, plant species are colonizing upslope to, and even above, the upper limits of their current natural habitats (Steinbauer et al., 2018). This process is called theromophilization. In the so-called montane zone (600-1,700 m), plants will continue to colonize upslope toward treeline and into subalpine and alpine zones (Erschbamer et al., 2011). Mid mountain ecosystems will also be transformed by the arrival of more competitive plants and potentially by invasive species arriving from the valley floors (Pauchard et al., 2009). Likewise, plant species from the subalpine zone (1,700-2,200 m) will move higher and higher in elevation, reaching the lower levels of the alpine zone (e.g. Pauli et al., 2007) as a direct consequence of climate change (Gottfried et al., 2012; Steinbauer et al., 2018). As subalpine species move up in the subalpine and alpine (2,200-3,000 m) zones, we will see competition over space and resources (Gottfried et al., 2012). Alpine species may accumulate *extinction debt*, which is a delay or inability to adapt to environmental change (Dullinger et al., 2012). Conditions at high elevations (above 3,000 m) will become less extreme, allowing alpine and nival species to develop and colonize on alpine summits. A study carried out in the Ecrins National Park using NDVI (plant productivity index that measures the production of biomass) showed that productivity increased in more than half of the area of the Park between 2000 and 2015, especially in rocky areas above 2,500 m (Carlson et al., 2017). Likewise, 75% of the species studied on Switzerland's Piz Linard (3,410 m) saw increases in the number of individuals since 1835 (Wipf et al., 2013).

In general, the increase in temperatures and the lengthening of the snow-free period will favor upslope colonization and the production of biomass in mountain plants (Choler et al., 2015). However, these plants, and particularly species found in alpine grasslands, are sensitive to extreme weather events. When heatwaves are combined with decreased precipitation, a "browning" occurs and vegetation growth stops, especially for alpine plants (Corona et al. 2019). At this elevation, the short growing season (2-3 months) prevents plants from returning to a normal state after a drought (De Boeck et al., 2016, Cremonese et al. 2017).

Impacts of decreased snow cover on flora

The depth of snowpack and the length of the snowmelt period are important factors for the survival of plant species above the treeline. In particular, the duration of snow cover impacts growth, phenology and spatial distribution of alpine plants (Wheeler et al., 2014; Wipf et al., 2009). As a result of climate change snowpack is becoming thinner and spring is arriving earlier (cf. 2.1). As the snow-free period becomes longer, even in the alpine zone above 2,300 m, climatic constraints on plant growth will be lessened. So-called "specialist" alpine plant species, adapted to longer periods of snow cover, risk being gradually replaced by more generalist and competitive species. However, the impacts of a longer growing season and an **earlier arrival of spring are not uniformly beneficial to plants. Snow can provide insulation to plants, which, when they are not covered by snow, can be exposed to frost, which is still common despite rising temperatures** (Wheeler et al., 2014; Wipf et al., 2009). These late frost events occur as plant growth is just beginning after the winter, when plant tissue is the most sensitive. This can have a negative impact on plant productivity for the rest of the season (Galvagno et al., 2013). Studies show that the effects of frost on plant growth are variable: a species' resilience to frost depends on its physiological adaptations. For example, while blueberry plants are very sensitive to late frost events, alpine azalea (*Loiseleuria procumbens*) is not (Wipf et al., 2009). As we covered in section 3.3, the risk of exposure to frost may be lessened as climate change leads to warmer spring temperatures (Wheeler et al., 2014; Wipf et al., 2009; Klein et al., 2018).

Impact on biodiversity and habitats

Changes in climatic conditions for species also have an impact on the diversity of landscapes.

Paradoxically, we are currently seeing an **increase (or "enrichment") in the number of plant species found above 2,200 m**, which is a clear indicator of the effects of climate change as conditions become increasingly favorable for plants coming from lower elevations (Steinbauer et al., 2018). This study showed an accelerated enrichment of plant species on 302 summits, primarily in the Alps, five times greater during the period from 2007-2016 than 50 years ago, corresponding with the rise in temperatures. **Nonetheless, this increase in diversity can hide the anticipated dynamic of decline in alpine species as they are replaced by plants from lower elevation zones.** The delay between the enrichment period and species decline will depend on several factors including the longevity of different species, the competitive ability of local species, the dispersal capacity of species from lower elevations, and topography. The upslope colonization of species will be constrained by the decrease in available area (due to the conical shape of mountains; Dullinger et al., 2012; Pauli et al., 2007) and the presence of obstacles like glaciers and rock faces, which are common in the Mont-Blanc massif. At the same time, some alpine plants may benefit from the micro-topography found in the mountains and the new area freed up after glacier melt (Carlson et al., 2014, Fisher et al. 2019). A major consequence of the decline in specialist species (those from high elevations or snowy zones), and the upward migration of lower elevation species is the risk of **simplification of natural environments**: areas in the massif that are currently quite diverse may see a decline in their biodiversity (Figure 3.15).

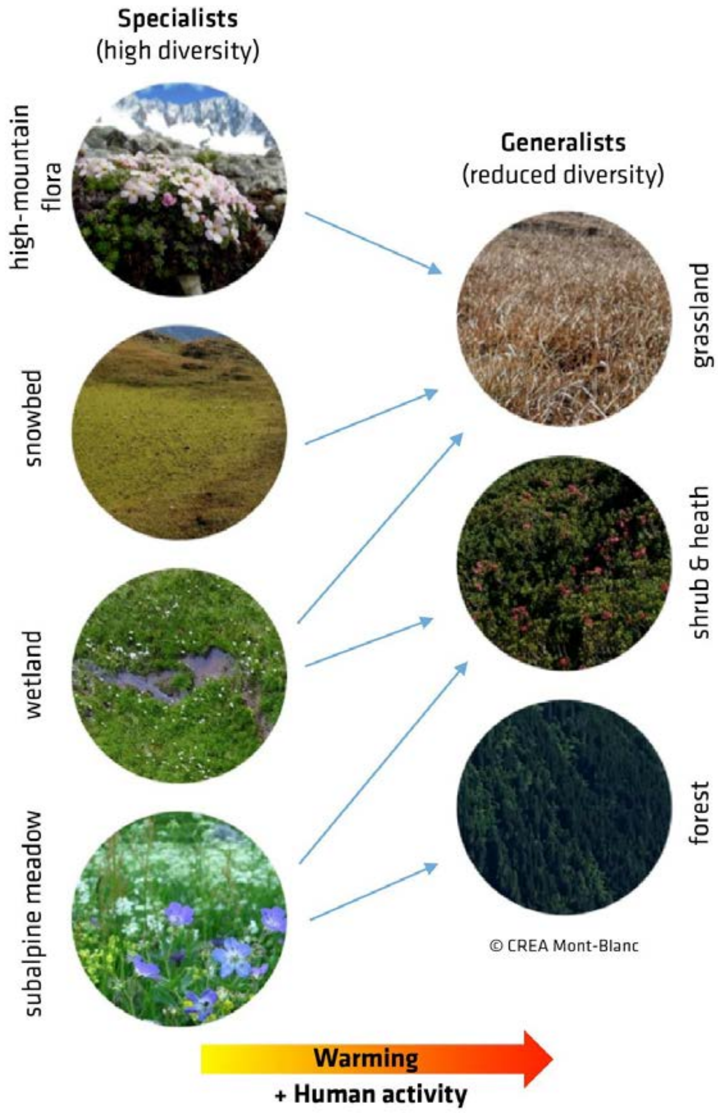


Figure 3.15. Illustration of possible shifts in plant communities (on granite bedrock) in the context of climate change. Reduced snowpack and warmer temperatures, combined with agricultural abandonment, can lead to the "homogenization" of alpine plant communities, a process in which specialist species are replaced by more competitive, generalist species. For example, decreased snow cover and summer heatwaves contribute to the drying out of high elevation wetlands, which is detrimental to the plants and animals specifically adapted to that environment. It is important to understand, however, that the topographic variability found in mountains can locally lead to climatic "micro-refuges", such as depressions on north-facing slopes, where conditions remain favorable for alpine species, even in a general context of warming.

Impacts on fauna

The depth and duration of snow cover also have an impact on all animal species that hibernate or spend the winter in the mountains. As the climate warms and snowpack is thinner, animal dens and burrows are less well insulated from the cold. Even if early springs allow animals to leave hibernation with more body mass reserves, a study in the Vanoise National Park (France) showed that alpine marmots suffer negative impacts. A thinner snow cover appeared to result in a decreased litter size (one fewer young in litters with between 1-7 babies; Tafani, 2013). Similar results were found in alpine ibex in the Grand Paradis National Park (Italy, Pettorelli et al., 2007). Other species, including hedgehogs, black grouse, snow voles and rock ptarmigans, may be impacted by decreases in snow cover (Figure 3.16).

Mountain animals have adapted over time to climatic conditions by **synchronizing their phenological cycles with plant growth and resource availability, and even with snow conditions.** The molting (changing color of plumage) of the rock ptarmigan, which allows them to camouflage themselves based on the presence or absence of snow, is triggered by photoperiod*. It is likely that a decrease in the duration of snow cover will occur more quickly than ptarmigans are able to adapt to the change, leading to a desynchronization with their habitat and making them more vulnerable to predators. We can also learn from the examples of alpine ibex and chamois, animals for which the quality of grass is more important than quantity (Garel et al., 2011). In these species, reproduction in the fall is also triggered by photoperiod rather than climatic conditions. With spring arriving earlier, plant growth and flowering is no longer synchronized with the birth of young, which occurs later. Mothers have fewer resources and less nutrient-rich milk for the development of their young. In the summer, drought also reduces the resources available to ibex and females are not in optimal physical condition for the rutting period and gestation. A study carried out in the Belledonne massif (France) reported a decrease in reproductive success for births following abnormally warm seasons. Another study in Ticino (Switzerland) and Piedmont (Italy) showed that **chamois populations and the body mass of individuals were greatly reduced following the 2003 heatwave. The succession of unusually hot springs and summers prevented them from being able to regain their physical condition** (Rughetti et Festa-Bianchet, 2012). In the Bauges massif (France), predictive models have estimated a 20% reduction in occupancy for chamois (Thuiller et al., 2018).

Finally, a simplification and homogenization of environments along with the expected reduction in the area of cold environments may lead to **habitat loss** for all species that require cold environments for their development and reproduction. We can once again look to the example of the rock ptarmigan, which is currently present in the Mont-Blanc massif and is an emblematic arctic-alpine species, considered a relic from previous ice ages. Although warmer springs appear to have a positive impact on rock ptarmigan reproduction (Martin et Wiebe, 2004), they are at risk of losing 60% of their favorable habitat by 2050 and 90% by the end of the century as a direct result of climate change (Figure 3.16, Reverman et al. 2012).

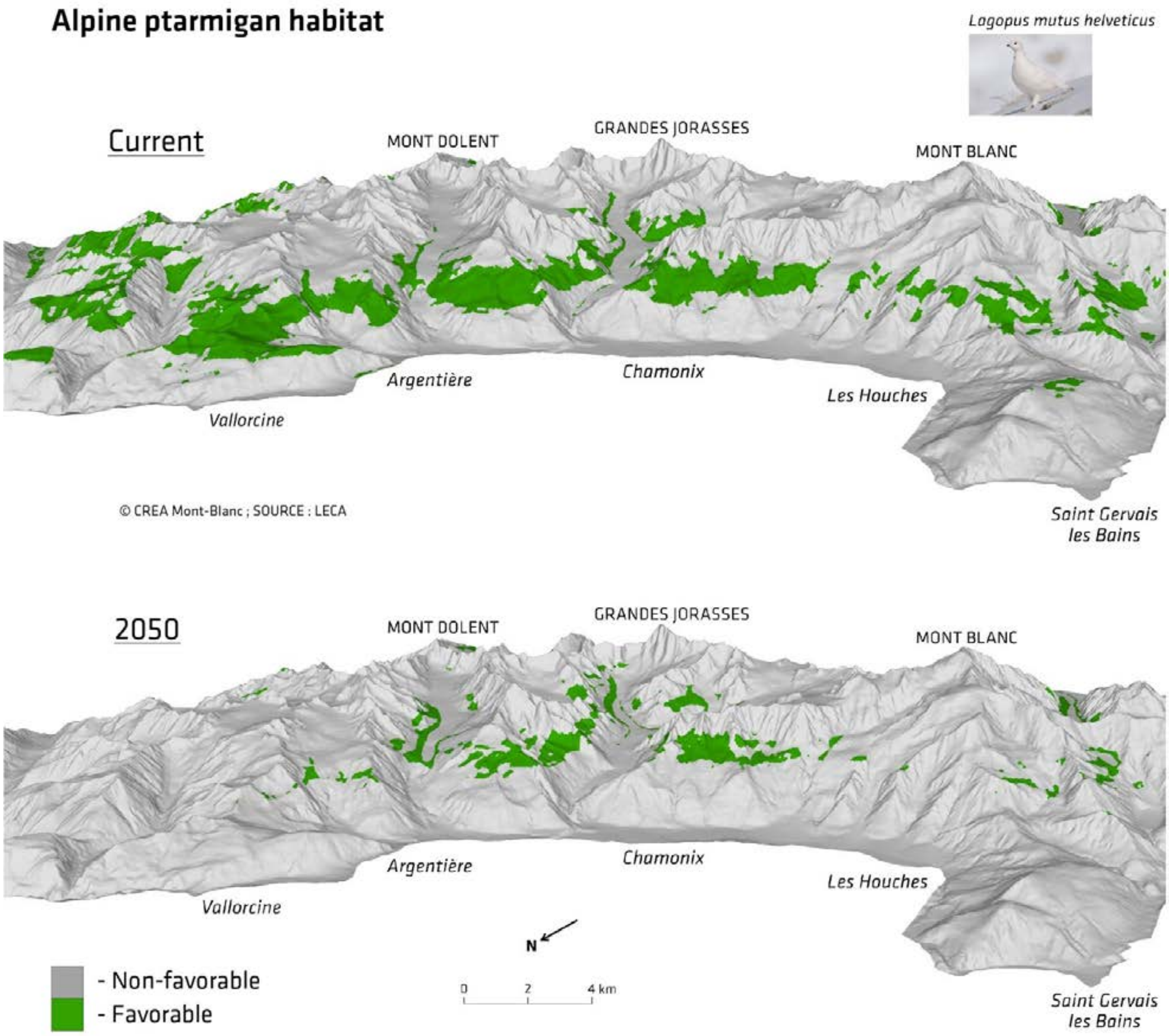


Figure 3.16. Expected change in favorable habitat for the rock ptarmigan (*Lagopus mutus helveticus*) between the current period and 2050, according to the RCP 8.5 emissions scenario. Rising temperatures will lead the species to migrate upslope where they will find a significant decrease in favorable habitat both because of the conical shape of mountains, and the extreme slope angle found above 2,500 m.

Impacts on conservation strategies

The continuous changes in these natural environments and the species they shelter generate a need to adapt existing conservation strategies for species and environments. Several elements must be taken into account in conservation strategies:

- Diverse and well-preserved ecosystems are key to the adaptation of many other sectors (forest, agriculture, tourism, and natural hazards). In addition to the value of conserving the EMB's emblematic heritage, they are often the **basis of "nature-based solutions"** to the challenges of climate change.
- Biodiversity is currently experiencing unprecedented declines due in part to climate change but also to other anthropogenic (human-caused) pressures. Conservation strategies will need to simultaneously take into account pressures related to climate change and those linked to other disturbances including tourism density (potentially rising in the EMB, cf. 3.5) and habitat

fragmentation. The impacts of all of these different pressures can be cumulative, and responses to pressure are sometimes complementary and sometimes contradictory.

- Understanding of the complexity of ecosystem function and the existence of domino effects within them remains relatively poor, with insufficient data. Therefore, **management strategies must be adaptive, highly reactive and accompanied by close monitoring.**
- Legally protected areas and relatively untouched environments are **naturally key zones for species to adapt** to the ongoing change which is happening with unprecedented speed. For many species, these areas are the only opportunity for adaptation. The loss of habitat for specialist species (Figure 3.15) could lead to a reduction to the size and the resilience (in genetic and functional terms) of these populations. The conservation of diversified natural environments will be a major challenge in order to guarantee a diversity of solutions and room for adaptation of alpine species.

Along these lines, we have identified a few guiding principles for the adaptation of conservation strategies :

- High mountains will continue to be refuges for traditionally alpine plant and animal species. In the greater European context, and due to its unique geography, the Mont-Blanc area will play an increasingly important role in the conservation of these emblematic species and ecosystems. Today, these high mountain environments are relatively uninhabited and are therefore natural refuges for flora and fauna. As the climate warms, the pressure on these areas, which until now are relatively untouched by humans, may intensify. **The scope of the challenges in managing and protecting the biodiversity of these areas will broaden and spread to higher elevations and to environments that have, until now, had little need for management** (such as glacier retreat zones and mountain wetlands).
- **Management policies and even the boundaries of protected areas should be adaptive, according to species and habitat change.** Ecological corridors and buffer zones around protected areas will be needed, and should mirror animal and plant distribution changes, in order to allow them to migrate upslope or towards micro-refuges in the topography that are more conducive to their development. The management choices made for these transition zones will need to find a balance between protecting refuges for alpine species, and limiting the arrival of invasive and thermophile species from lower elevations.
- **Decisions regarding tourism management and construction should fully take into account short- and long-term impacts on biodiversity and ecosystem services.** Tourist visitation is expected to grow overall and spread to periods of the year currently considered to be the “off season”. This will likely lead to an increased demand for infrastructure (trails, buildings, etc.) and increased disturbance. Special attention should be paid to rising visitation rates in late spring and early summer because animals are both reproducing at that time and weakened by the winter season and are especially sensitive to disturbances. Plants are also vulnerable to trampling at that time.

  - **Promote species diversity in natural environments, particularly through the use of nature-based solutions.** For example: (i) encourage extensive mountain pastures which maintain open spaces to adapt to their local environment and to prepare to adapt further as snow cover and summer climates change (drought, heatwaves in particular); and (ii) foster diversified vegetation in “cool areas” (parks, waterways) of towns.

3.5 Tourism

Tourism is one of the most important sectors of the EMB's economy. Between 2013 and 2017, it represented 6-8% of regional GDP in the Aosta Valley, taking only into account lodging and restaurants (Observatoire économique et social de la Région Autonome Vallée d'Aoste, 2018). In 2015, tourism made up 30% of private employment on the French side of the EMB (Savoie Mont-Blanc Tourisme Zoom Territoire, 2017). Winter tourism focuses primarily on skiing, an activity which is directly influenced by climatic conditions, particularly in terms of natural snow cover and planning of and management of ski resorts (for snowmaking). Summer tourism could benefit from favorable temperatures, particularly in comparison to the lower elevation plains. The mid mountains in particular may see more tourists flocking to them in search of cooler air. However, warming temperatures in the high mountains will have negative impacts on the conditions for summer mountaineering.

Winter tourism

Because it is directly dependent on temperature and snow cover, skiing is an industry that is especially vulnerable to climate change. In the Mont-Blanc massif, **the duration of snow cover (when there is snow on the ground) has decreased by 40 days between 1,500 and 2,500 m since the 1970s** (Klein et al., 2016). By **2050, a further reduction of 40-90% of snow cover duration is expected**. At 1,500 m, the snow cover period will decrease by 40 days (Verfaillie et al., 2018), with the largest decreases occurring in the spring (rather than the fall, Klein et al., 2016). The decrease is expected to be a little less severe between 1,000 and 2,500 m, and even less so above 2,500 m (5-10% decrease; Frei et al., 2018; Marty et al., 2017). Figure 3.17 shows a representation of the expected reduction in snow cover on the two different slope orientations in the Chamonix Valley. Figure 3.18 shows expected natural snow cover duration in 2050 at the scale of the entire EMB, according to the intermediate scenario (RCP 4.5). Snow pack at the valley floor is expected to disappear entirely, and decrease by 20 days in the mid mountains by 2050 (Figure 3.18).

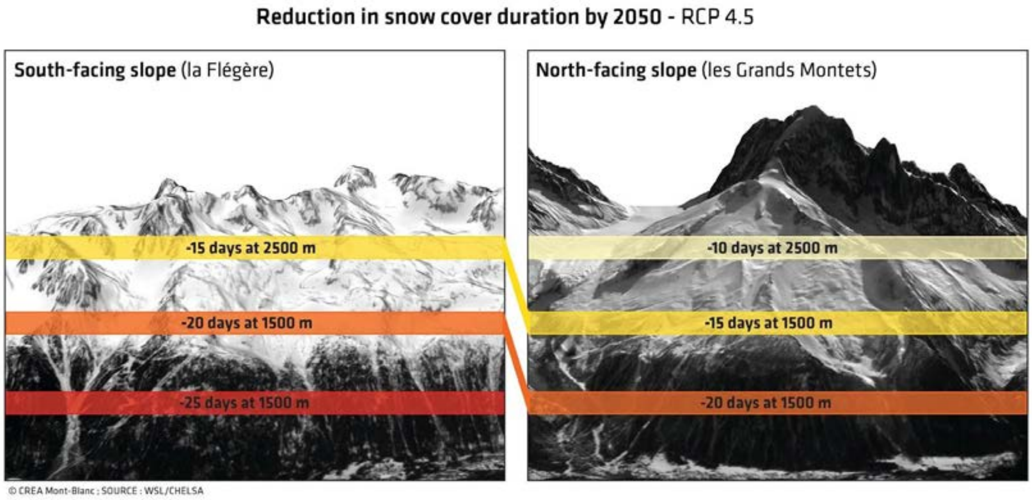


Figure 3.17. Expected reduction in snow cover duration (number of days with snow on the ground) on south- and north-facing slopes by 2050, as shown in the Chamonix Valley (France). We note that decreases will be most significant on south-facing slopes and below 2,000 m. The background images are from the Sentinel-2 satellite, in February 2016.

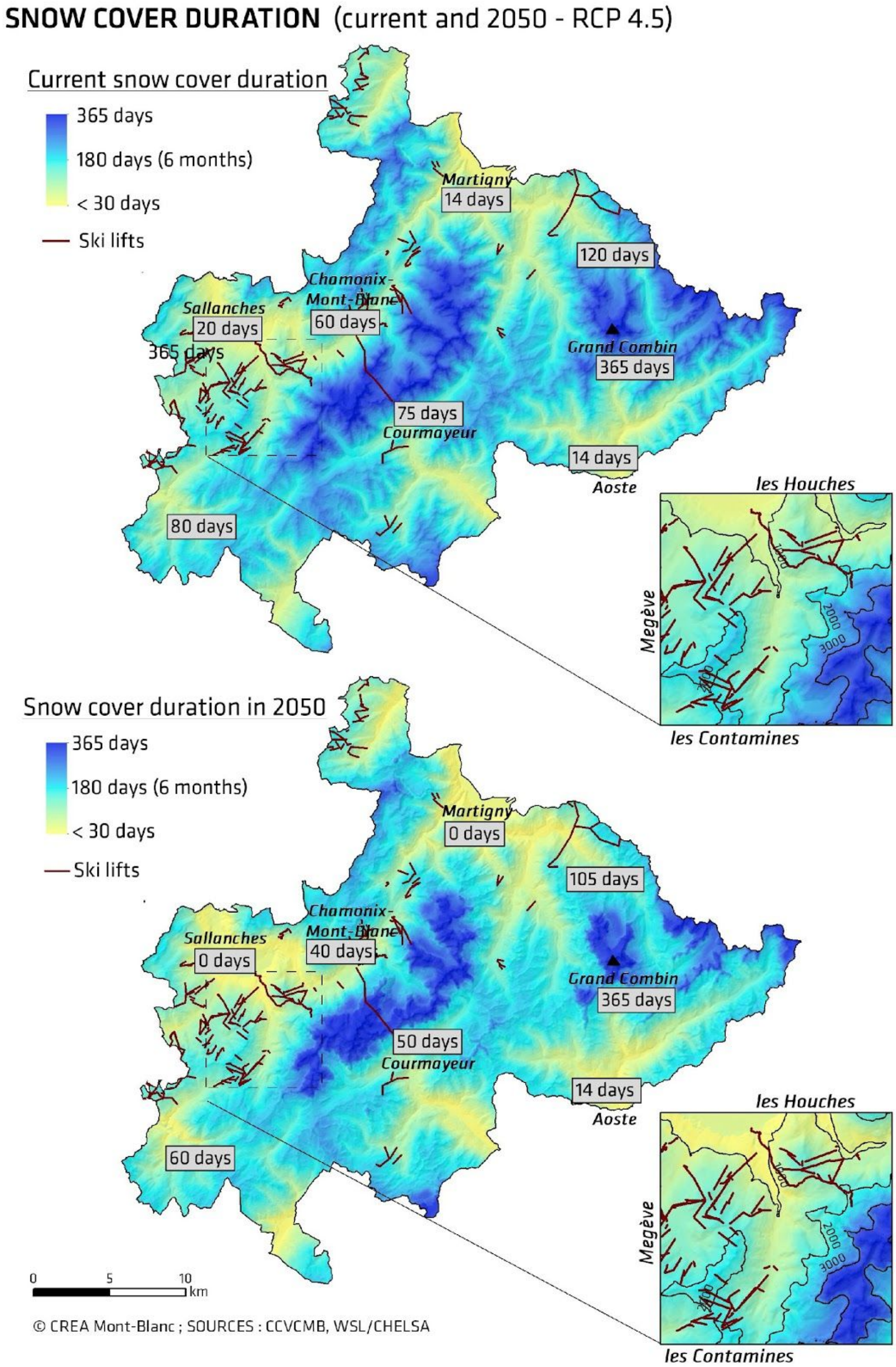


Figure 3.18. Expected change in the duration of snow cover (number of days with snow on the ground) in the EMB today and in 2050. Snow pack is expected to disappear entirely on valley floors. A general decrease is expected up to 3,000 m, including in EMB ski resorts (note: the location of ski lifts in Italy and Switzerland is neither exhaustive nor exact).

Reduction in snow cover is caused both by climatic conditions that are less favorable to the accumulation of snow (in particular, warm winter temperatures which cause precipitation to fall as rain instead of snow) and warm spring conditions that cause accelerated snowmelt. Figure 3.19 shows the reduction in the number of days with precipitation falling as snow at different elevations. At 1,600 m, we expect a 25% decrease by 2030 and a 30-35% decrease by 2050. While a similar loss is expected at 2,000 m, at

2,400 and 2,700 m, the expected decrease is less significant: at these higher elevations, only a 9-16% decrease is expected by 2030.

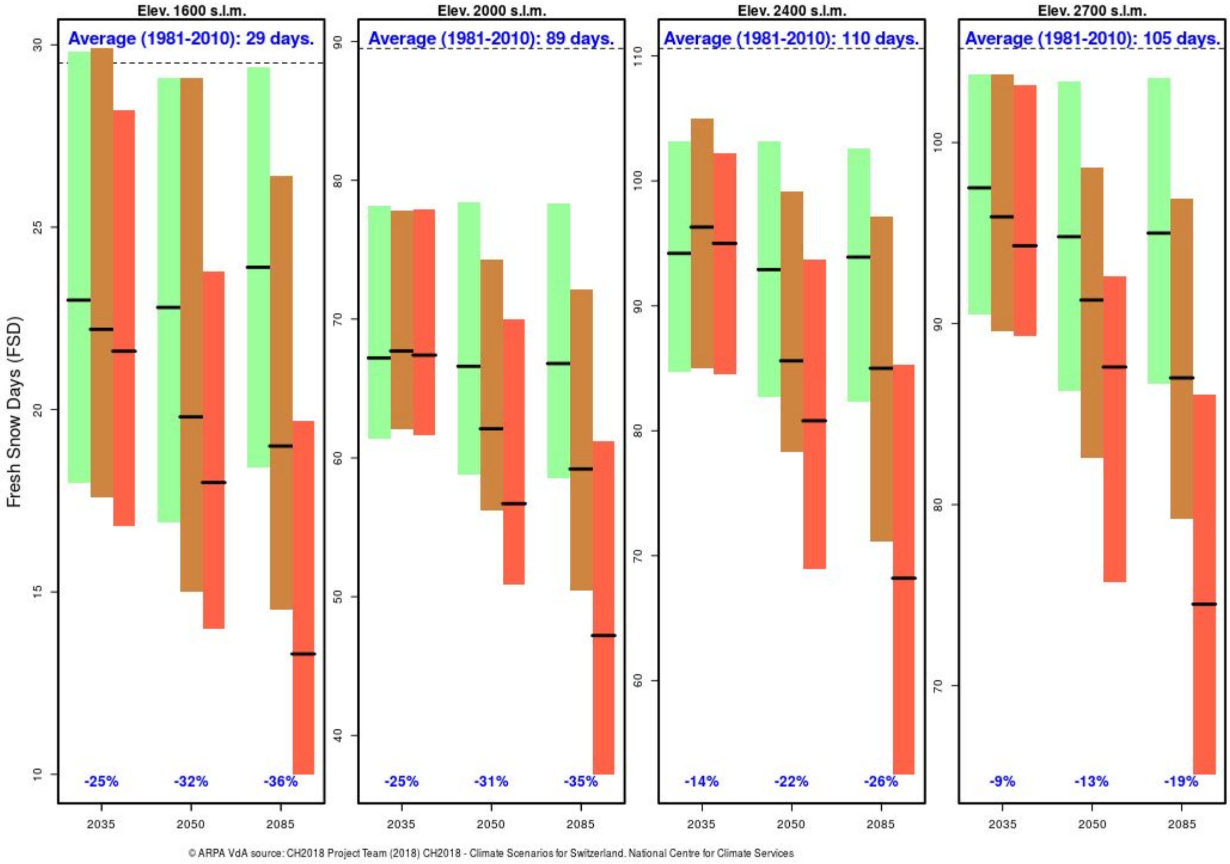


Figure 3.19. Expected change in the number of days when precipitation falls as snow, at four different elevations. The color of the bars represents the index values for different emissions scenarios. The height of the bars indicates the margin of uncertainty (10th and 90th percentile), taking into account the different climate models considered in the study. **© ARPA VdA, source CH2018**.

In order to ensure that snow cover will be sufficient for skiing and in order to reduce economic losses, ski resorts will need to adapt to present climatic hazards and future changes using snow management methods (snowmaking, piste preparation, grooming, etc.). The long-term effectiveness of these methods will depend on many different factors including temperature, humidity, water and energy availability, and the ability to invest resources and pay operating costs (Spandre et al., 2019a, Spandre et al., 2019b). **Water availability will be an important factor to consider**, given the expected decrease in water flow in the fall (Figure 3.2), which could impact the viability of diverting and storing water for snowmaking. If these snow management methods are able to be implemented in a sustainable way (from an environmental and economic point of view), resorts may be able to mitigate the negative impacts of reductions in natural snow cover.

In the near future (2035, 2050), ski resorts below 2,000 m and the lower elevation sections of higher ski resorts run the highest risk of losing viability. For resorts above 2,000, the level of risk will depend on the topographical configuration and parameters mentioned above for implementing snow management methods. Figure 3.20 shows the expected decrease in the number of days when the temperature conditions will allow for artificial snowmaking. From a technical perspective, snowmaking is only possible when the wet bulb temperature (air temperature at 100% relative humidity) is -2°C, which is equivalent to a dry-bulb (normal) air temperature of -3 to -7°C, depending on relative humidity. Optimal snowmaking temperature is between wet bulb -5 and -8°C (Spandre et al., 2019a). This figure focuses on November, which is a crucial month for resorts hoping to open in early December and for the holidays.

In 2035, at 1,600 and 2,000 m, **the number of days when snowmaking will be possible in November (JPEA)** is expected to decrease from 8 to 5-7 days. The decrease is expected to be even greater by 2050 (3-6 JPEA at 1,600 m and 4-7 at 2,000 m) and will be as low as 2-6 JPEA by the end of the century. In the near future (2035-2050), the most pessimistic scenario (RCP 8.5) projects 6 JPEA at 2,400 m in 2050 and 9 JPEA at 2,700 m. By the end of the century, the decrease will be significant even at higher elevations. According to RCP 8.5, there will only be 3 JPEA at 2,400 m and 4 JPEA at 2,700 m. However, projections based on the optimistic climate scenario (RCP 2.6), suggest that JPEA will only see minimal decreases at higher elevations. It is possible that, in the mid-term outlook, decreases in ski resort viability at lower elevations in the Alps will benefit the resorts in the EMB, which are generally located at higher elevations (e.g. the average minimum elevation for pistes at resort in the Aosta Valley is around 2,000 m; *source: Rapport Régional des Remontées Mécaniques 2018*) and may gain part of the market share (CH2014-Impacts, 2014). **In conclusion from a temperature standpoint, the effectiveness of snowmaking as a ski resort adaptation strategy will be limited in the short term (2035-2050) below 2,000 m. Risks will increase considerably in the longer term (end of the century), including above 2,000 m.**

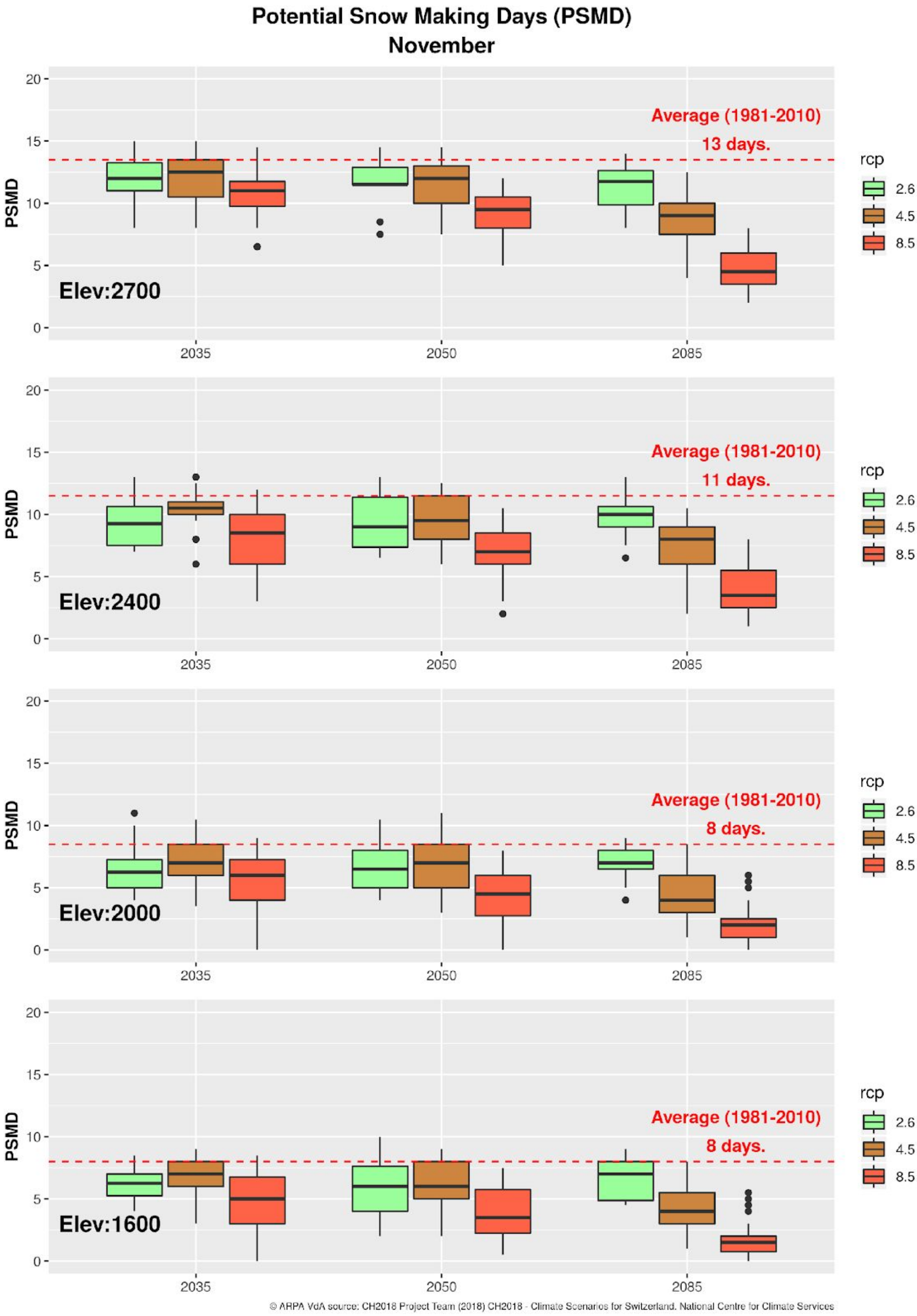


Figure 3.20. Expected change in the number of days with potential for artificial snowmaking (JPEA) in November at different elevations. The color of the bars represents the index values for different emissions scenarios. The height of the bars indicates the margin of uncertainty (10th and 90th percentile), taking into account the different climate models considered in the study. The dotted red horizontal line shows the current levels, as a reference. The number of potential snowmaking days was determined using a minimum daily wet bulb temperature of -8°C.

Summer and off-season tourism

As temperatures rise, tourists may flee from heatwaves in the plains in favor of cooler areas (Bourdeau, 2009). Figure 3.21 illustrates the concept of temperature conditions along an elevation gradient: as climate changes and temperatures warm, mountains allow us to find current climatic conditions by moving up in elevation. However, increases in tourism density will lead to challenges in territorial planning and adaptation of the tourism offering, especially as high elevation environments experience their own challenges of adaptation, as described in this report.

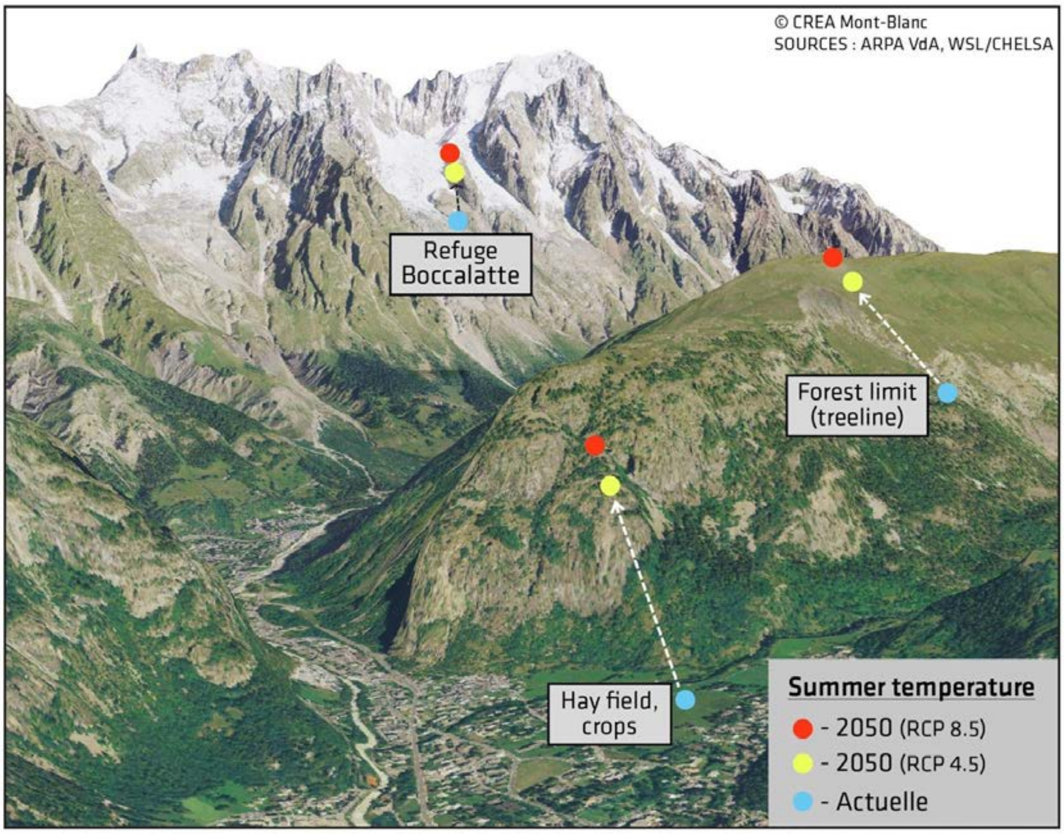


Figure 3.21. Cool zones in summer. As tourists flee from heatwaves in the plains and in the cities, summer tourism in the EMB may expand, even if it is necessary to go higher and higher in elevation in order to find those cool zones.

The lengthening of the summer season may also help the expansion of tourism, especially during spring and fall which are currently considered to be the "off season" (CH2014-Impacts, 2014). The **Tourism Climate Index** (TCI Mieczkowski, 1985) is a comfort index that combines the different meteorological parameters (temperature, wind, solar radiation, and humidity) that determine the climatic comfort necessary to carry out outdoor tourism activities. This index defines comfort categories including "excellent" and "pleasant". Figure 3.22 shows that in June, hotter temperatures will lead to a decrease in climatic comfort on valley floors, while at 1,000 m, changes in comfort will be limited. At 1,600 and 2,000, the number of days considered excellent or pleasant will increase.

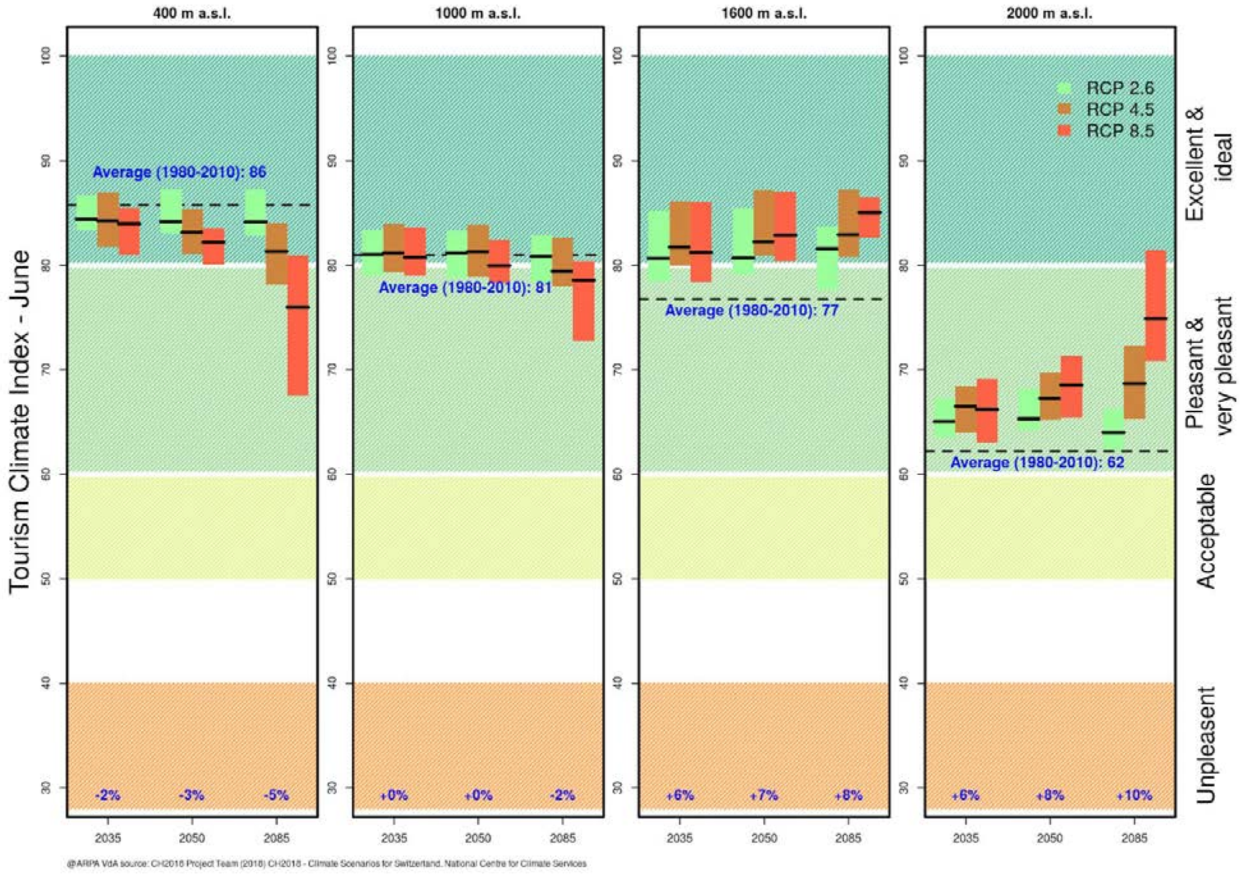


Figure 3.22. Expected change in the Tourism Climate Index for the month of June, at four different elevations. The color of the bars represents the index values for different emissions scenarios. The height of the bars indicates the margin of uncertainty (10^{th} and 90^{th} percentile), taking into account the different climate models considered in the study. The black horizontal dotted line indicates the index value for the reference period from 1980-2010. The colored rectangles represent the different categories of climatic comfort.

The TCI values for June can be understood by analyzing the variation in the **number of expected pleasant or excellent days** compared to the current reference period. Figure 3.23 shows that, in the near future (2035-2050), the number of excellent days should increase by 4-8 days between 1,500 and 2,000 m, and should continue to rise to 8-10 more excellent days by the end of the century. This increase will be less significant at 2,500 m where there will be 2-3 more pleasant days in the near future, and 4-6 more by the end of the century. However, at 1,000 m any change is expected to be negligible. If we look at **October** (Figure 3.24), we begin to see greater **opportunities for the prolongation of the "summer" season:** in the near future (2035-2050), there will be 2-5 more excellent days between 1,500 and 2,000 m, and 6-8 more days by the end of the century. At 2,000 and 2,500 m, there will be 2-4 more pleasant days in the near future, and 4-6 more days by the end of the century.

In conclusion, **in the near future (2035-2050), we expect an increase in the number of excellent or pleasant days at all elevations in June and October, with as much as an additional week in certain zones.** The development of "off-season" tourism may constitute an important opportunity for the tourism sector to adapt to a changing climate, especially for lower-elevation locations that may be negatively impacted by decreases in snow cover. It follows that, in order to fully benefit from these new opportunities, proposed tourism activities and infrastructure will need to be adapted to the latest environmental conditions.

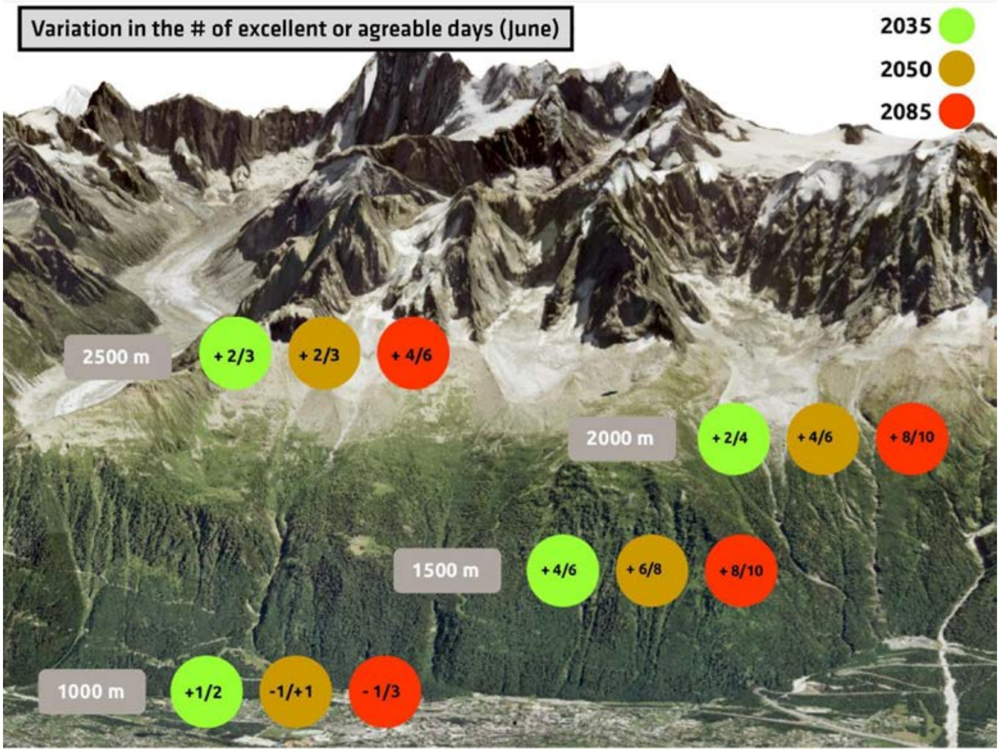


Figure 3.23. Expected change in the number of excellent or pleasant days at different elevations in the month of June. The values in the circles indicate the increase in the number of days with pleasant or excellent climatic conditions for different elevations (1,000; 1,500; 2,000 and 2,500 m), for the month of June. Pleasant and excellent climatic conditions were defined based on the Tourism Climate Index (Mieczkowski, 1985).

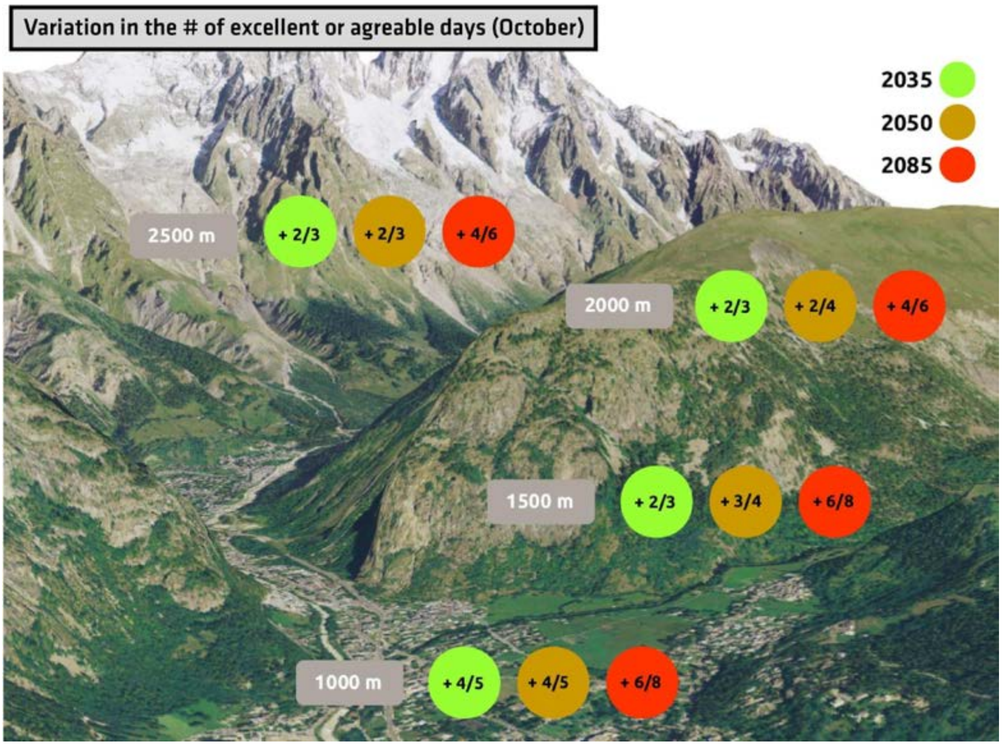


Figure 3.24. Expected change in the number of excellent or pleasant days at different elevations in the month of October. The values in the circles indicate the increase in the number of days with pleasant or excellent climatic conditions for different elevations (1,000; 1,500; 2,000 and 2,500 m), for the month of October. Pleasant and excellent climatic conditions were defined based on the Tourism Climate Index (Mieczkowski, 1985).

At the same time, it is important to consider that the attractiveness of mountain tourism may change as a result of increased risk of natural hazards, and as emblematic high and mid mountain landscapes evolve away from our current cultural perceptions and expectations of high mountains.

More specifically, in the high mountains, glaciers are retreating and often take on a grey aspect during the summer. The colonization of glacier moraines by forests and other plants may have a positive effect on the stability, and therefore attractiveness of post-glacial landscapes.

In the mid mountains, the rise in vegetation (treeline in particular) and changes in biodiversity will impact landscape appearance and their visual appeal in the long term. Treeline rise may also get in the way of both mountain infrastructure and popular tourist sites, many of which currently offer impressive viewpoints, unobstructed by trees. Figure 3.25 shows this process above Chamonix, indicating areas that will most likely be colonized by the forest by 2050—most notably, the Plan de l'Aiguille hut and the Balcon Nord trail. Above Courmayeur (Figure 3.26), it is possible that the mid station of the Skyway (Pavillon) will be surrounded by forest by 2050. These predictions raise important questions about management strategies: to what extent should these sites be left to follow a 'natural' trajectory? Or, should management practices be put in place in certain sectors to limit the rise of treeline?

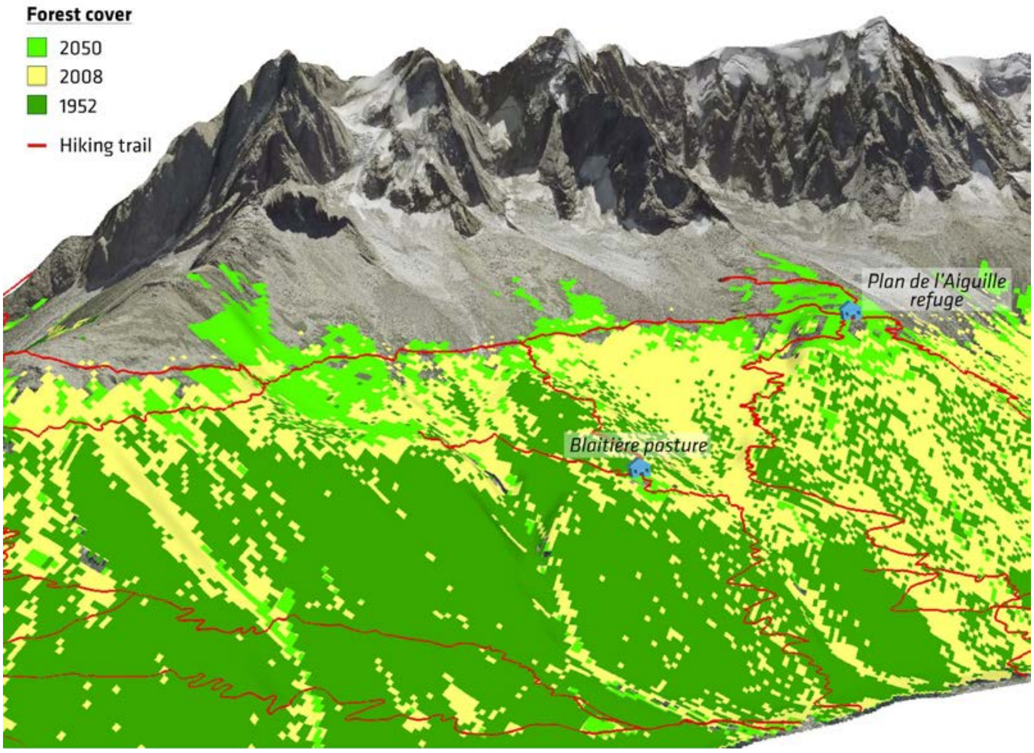


Figure 3.25. Expected and observed change in forest cover from 1952 to 2050 on the French side of the Mont-Blanc massif, at the Plan de l'Aiguille. The yellow areas indicate the expansion and densification of forest observed between the 1950s and 2000, in connection with rising temperatures and agricultural abandonment. The light green areas show the areas that the forest is expected to occupy by 2050, including the Plan de l'Aigulle hut and the Balcon Nord trail.

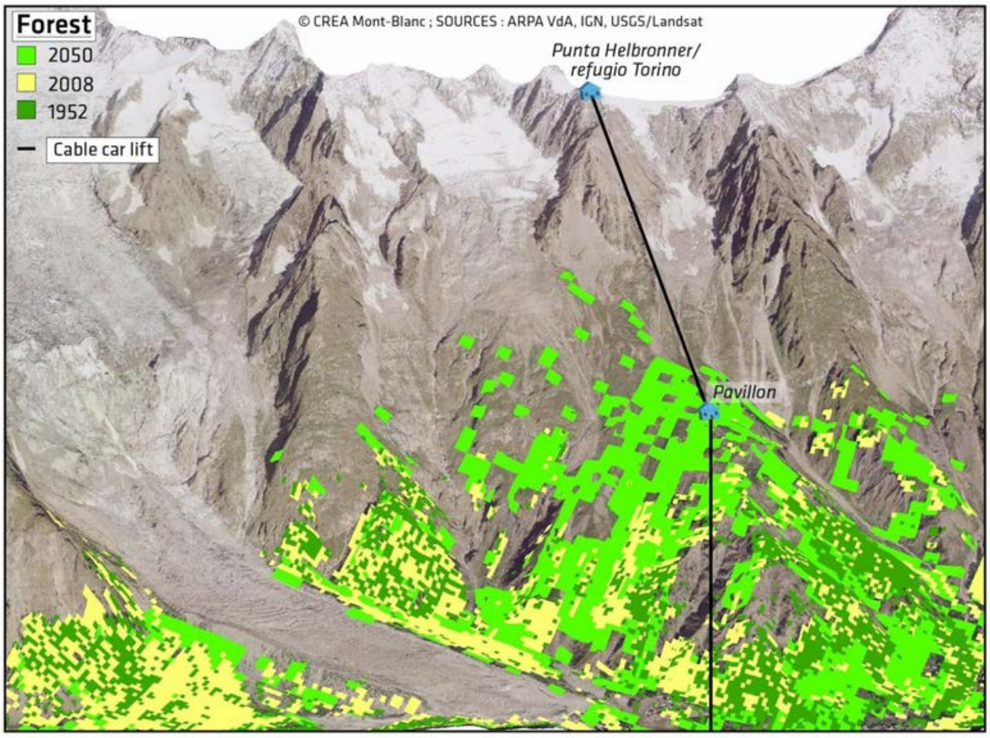


Figure 3.26. Expected and observed change in forest cover from 1952 to 2050 on the Italian side of the Mont-Blanc massif above Courmayeur. The yellow areas indicate the expansion and densification of forest observed between the 1950s and 2000, in connection with rising temperatures and land use change. The light green areas show the areas that the forest is expected to occupy by 2050, including the Skyway midstation (Pavillon)

BOX 7: Tortin Glacier case study

The Tortin Glacier, located at the base of Mont-Fort between 2,900 and 3,300 m, is the high point of the 4 Vallées ski resort and has been managed by Téléverbier and NVrm (Télénendaz) since 1980. The area has infrastructure allowing easy access to the glacier via ski lift from the Verbier and Haute-Nendaz resorts. The Tortin Glacier no longer has any sufficient accumulation zones and is decreasing both in surface area and thickness. Because of its high elevation and accessibility, the viability of skiing is not called into question. Operators manage to adapt to glacier movements (crevasses) and changes in terrain (scree/moraines that replace ice). Barring the appearance of a major topographic change (such as the appearance of rock bars or a massive destabilization of permafrost), winter activity can reasonably continue and even be expanded, given its competitive advantages.

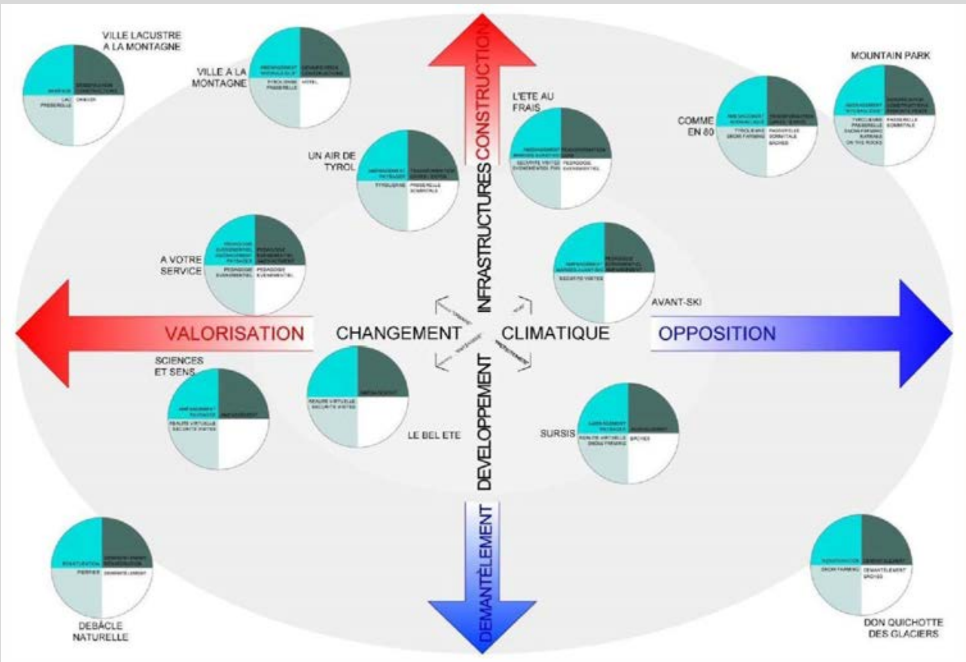
Summer activities are being called into question. In the current state, summer skiing is no longer possible. In good weather, the site draws people in for its panoramic view and (limited) hiking opportunities. The lower-elevation sectors are more attractive (more varied activities) and much cheaper to operate. Nonetheless, the high elevation area is accessible and could be more effectively used. Ski lift managers have to make choices today. The aim of this pilot project is to propose a new methodology that will allow local actors (operators) to develop strategies and make informed decisions. The resulting projects will be submitted to local authorities (municipalities and cantons) for validation (especially for building projects). This method is comprised of the following steps:

Step 1:

As a first step, all ideas are recorded, including utopic ideas which will never be carried out but will help frame the reflection. These possibilities are then represented graphically along two axes: **dismantlement/construction** and **opposition/promotion** in relation to climate change.

The vertical axis represents dismantlement/construction. Along this axis, possibilities are positioned according to the perspective of the operator. The scale goes from total abandonment of the site, to small and then measured actions, and finally intensive operations.

The horizontal axis represents opposition/promotion. This scale situates the ideas in terms of climate change and ranges from attempting to maintain current practices to using climate change to develop new opportunities.



This first tool does not include decision making or critiques, and rather provides an overview intended to situate both projects and attitudes.

Step 2:

In addition to the traditional approach of "weighing" interests based on attitudes towards the mountains, economic interests, environmental impact, social opportunity, etc., we must **take into account the question of resilience in the face of glacier retreat.** This is especially emphasized to avoid blindly ignoring this crucial question. It also requires approaching the process with a critical eye in order to avoid the temptation of reproducing the strategies put in place by competitors, or one-upmanship (higher, more beautiful, more impressive). The second step of the method is comprised of this multicriteria analysis and accompanied by critiques and examples.

ENVIRONMENTAL CRITERIA							
IMPACT / CLIMATE CHANGE			EXPOSURE TO NATURAL HAZARDS	CHANGES OF THE IMPACTS OVER TIME	ADAPTABILITY OF THE PROJECT		
CLIMATE FEEDBACK	ENERGY PRODUCTION	WATER-ICE RESERVE	AVALANCHES FLOODS LANDSLIDES	REVERSIBLE IMPACTS	CHANGES IN GROUND STABILITY OVER TIME	FLEXIBILITY – CLIMATE CHANGE	WEATHER DEPENDENCY
=	=	=		-		+	-

Step 3:

The final step is decision-making and submission of the choice to local authorities. The choice should be made consciously and justified as the product of broad and comprehensive reflection. For the pilot program, the choice of project rests with the operators. The goal is not just to present an idea, but also to explain why certain measures were chosen over others. This approach requires clearly stating a position to shareholders, authorities and the public, ensuring that the choice will be made with full awareness of its sustainability and the risks taken.

Consulting company: BFN architectes
Follow-up: Foundation for sustainable development in mountain regions (FDDM)
Valais government: Service de la mobilité (SDM)
Valais government: Service de l'économie du tourisme et de l'innovation (SETI)
Summary author: Gilles Délèze, SDM

The impacts of climate change on alpinism

Warming temperatures lead to profound modifications of the high mountains, including glacier retreat, permafrost degradation and decreases in snow cover. In turn, these phenomena cause decreases in glaciated areas and increases in the frequency and size of rockfalls (more than 550 rock falls with a volume greater than 100 m^3 between 2007 and 2015 in the Mont-Blanc Massif; Mourey et Ravanel, 2017). These changes have a direct impact on trails used to access high mountain huts. In the Mont-Blanc massif, 81% of hut caretakers reported that the safety of the access routes to their huts had changed in the last 10 years. In 96% of cases, routes had to be redesigned, often at significant cost. As an example, the construction of the footbridge to access the Conscrits hut cost 130,000 €. Access routes to all five huts above the Mer de Glace are at risk due to profound changes that have become visible since 1960: melting ice has exposed rock slabs and decreased the stability of moraines. The routes have had to be modified multiple times, and new ladders are installed every year to compensate for decreased glacier thickness. Some glacier moraines remain unstable, and even with these modifications, landslides can lead to human injury. For example, in 2002, multiple people were injured in a landslide on a lateral moraine while on the access trail to the Requin Hut. All eight access routes studied by Mourey et Ravanel (2017) have been impacted by glacier melt and the erosion of lateral moraines, **raising questions about the future of access to the huts and the corresponding impact on visitation rates.**

High mountain environments where alpinism is practiced are undergoing massive changes due to climate change (Deline *et al.*, 2012). The result is significant changes to climbing routes and to the frequency with which they are climbed. Despite recent increases in awareness about this problem, research on the topic remains limited. For this reason, J. Mourey undertook a doctoral thesis within the framework of the AdaPT Mont-Blanc project to look at this issue. His PhD took a multidisciplinary approach to studying how climate change is changing the practice of alpinism, focusing on three main areas of study, described below.

As a first step, the study sought to reconstruct how high mountain climbing routes have changed over time, and how that may have impacted how much they were climbed. Results showed that access to high mountain huts, situated at an average 3,020 m, are principally impacted by glacier melt (the Mer de Glace is an emblematic example; Mourey et Ravanel, 2017). While significant work is done to ensure that the huts remain accessible, the routes tend to become more dangerous and technically demanding, which calls future visitation rates into question. The findings are similar for the mountaineering routes themselves, even if they are located at higher elevations. A comparison of the current state of 95 mountaineering routes with the descriptions in Gaston Rebuffat's emblematic guidebook, *Le massif du Mont-Blanc, Les 100 plus belles courses* (*The Mont-Blanc Massif's 100 Most Beautiful Routes*), published in 1973, showed that 26 routes were substantially impacted and rarely practicable in summer, and 3 had completely disappeared (Mourey *et al.*, 2019 ; Figure 3.27). In addition, as a result of their increased technical difficulty and dangerousness in connection with the numerous geomorphological processes impacting them, "good conditions" for mountaineering are becoming more and more uncertain in the summer, and are shifting to springtime and even sometimes autumn.

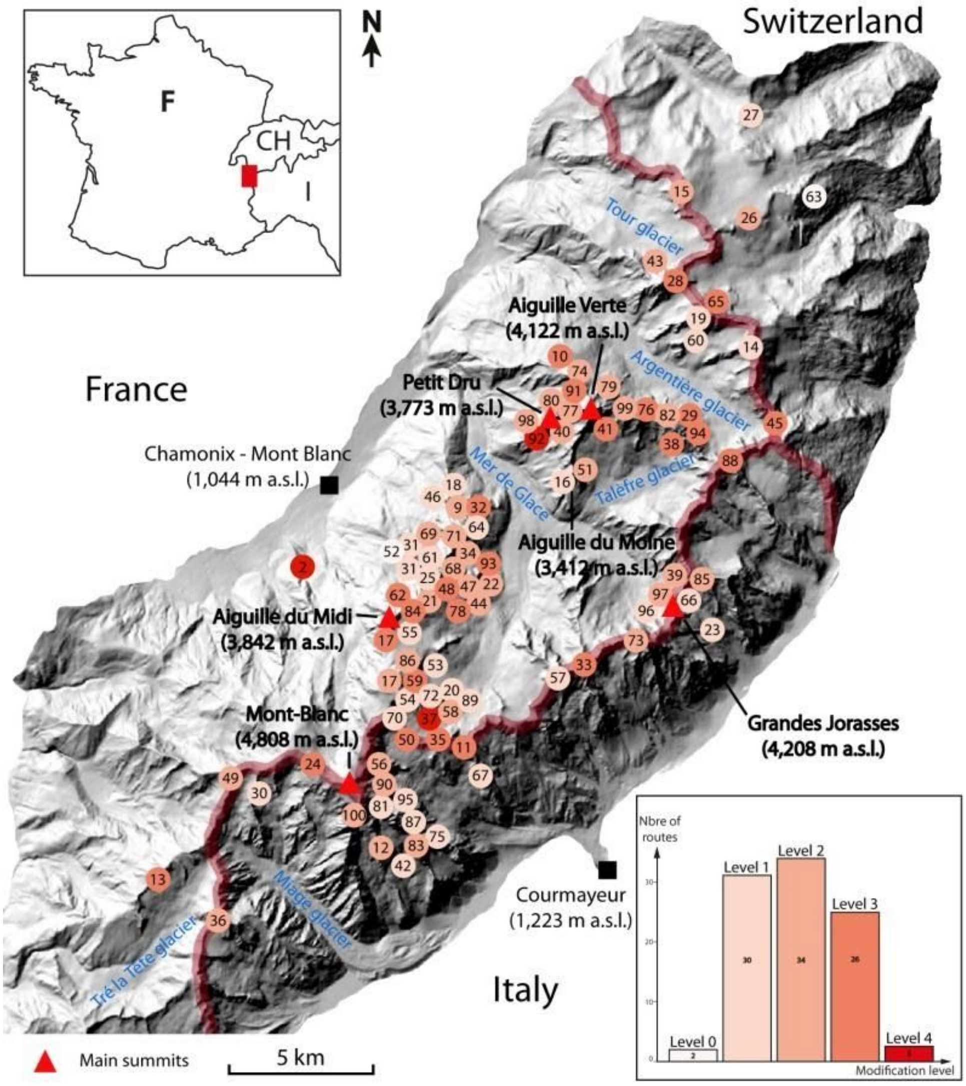


Figure 3.27. Location of routes and level of change observed (Mourey et al., 2019). Level 0 refers to no change, while Level 4 means the route has disappeared. The numbers correspond to the number of the route in Gaston Rebuffat's guidebook *Le massif du Mont-Blanc: les 100 plus belles courses* (Denoël, 1973).

This first finding led the project to study the way in which high mountain guides, revered alpinism professionals, are impacted by these changes and how they adapt to them, focusing on a comparison between France and Italy. About 30 semi-directive interviews were carried out with high mountain guides, guide union leaders and directors of guiding companies. Questionnaires were also distributed to guides. The results showed that, overall, the guiding career can evolve and mountain guides can adapt their practice to changing conditions (largely thanks to the wide variety of activities they are qualified to practice), and in so doing, maintain their economic activity. However, responses varied widely from one guide to another, depending on their clientele and level of personal motivation to diversity their activities.

The study focused much attention on one climbing route in particular that is significantly impacted by climate change: the regular route up Mont Blanc (4,809 m). In order to better understand the high rate of accidents in the Goûter sector of the route, in connection with rockfall in particular, the study put a multidisciplinary monitoring system in place (Mourey *et al.*, 2018; Figure 3.28). The system will allow researchers to gain a better understanding of the origin of rockfall and a better assessment of alpinist vulnerability, thanks to counters measuring the number of visitors. Initial results have identified particularly risky practices, and will allow for accident prevention and adaptation proposals to be developed.

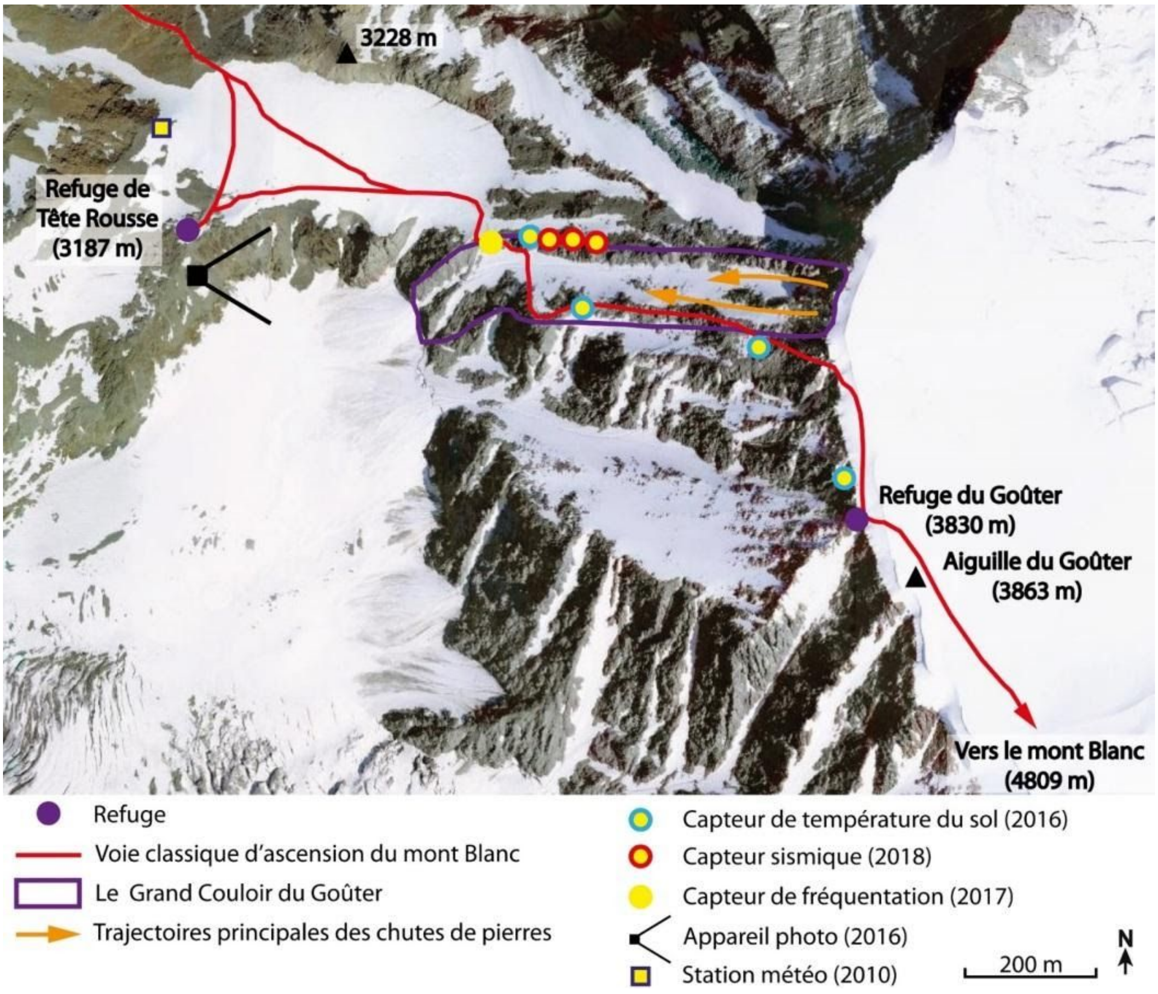


Figure 3.28. Multi-disciplinary monitoring system put in place in the Goûter sector of the regular route of Mont Blanc

The future of glacier tourism in the Alps

Beginning in 1741, the Mont-Blanc massif became recognized as one of the birthplaces of "Glacier" tourism. Today, the massif is still an exceptional place for those who wish to see or walk on a glacier. For this report, a glacier tourism site is defined as any site for which the main attraction is a glacier, the geomorphological forms associated with a glacier, or the evidence left by a glacier on the landscape. Using this definition, the Mont-Blanc massif (in France, Italy and Switzerland) is home to 10 of the 51 "important sites" identified within the Alpine arc by E. Salim, as part of his doctoral thesis (2018-2021), which is also associated with the AdaPT Mont-Blanc project. Four of those sites are mountain huts, hotels or small sites near glaciers. The remaining six are major tourist sites such as France's Aiguille de Midi (3,841 m) and Montenvers – Mer de Glace (1,913 m), which are two of the Auvergne Rhône Alpes Region's most important sites in terms of tourist visitation (*source: Savoie-Mont-Blanc-Tourisme*). Access to Italy's Punta Helbronner (3,462 m) via the "Skyway" cable car is also an important tourist site.

In the face of observed and ongoing glacier retreat, the future of these sites is called into question. Even if the high elevation sites (Aiguille de Midi and Punta Helbronner, in particular) seem to be, at least for now, sheltered from current cryospheric changes, sites located at lower elevations are in a much more worrisome situation. In the last 150 years, the thickness of the ice at Montenvers, which currently sees 400,000 visitors per year (*source: CMB*), has decreased by more than 200 m (Figure 3.29). Every year, the site managers have to install new staircases (534 steps in 2019) in order to reach the glacier, and soon the ice cave, which has been dug every year since 1946, may no longer be viable. In addition, the changing visual aspect of the site presents new problems as well, both due to glacier retreat and the development of a dark, sedimentary cover (layer of rocky debris) over the ice. In this context, infrastructure managers need to better understand the perceptions and decision-making of their customers in order to implement adaptation procedures.

Figure 3.29. Repeat photography of the old Mer de Glace cable car station (Ravanel et Moreau, 2018). Above: views looking uphill, into the heart of the massif. In 1985, the abundance of crevasses is evidence of the quick movement of the glacier. Today, the glacier is flat and slow, and covered in sediment. Below: views downslope, looking toward the valley. In 1986, the glacier reached the counterweights of the old cable car. Today, the surface of the glacier is 120 m lower in elevation.

These issues are not limited to the Mont-Blanc massif. Other sites across the Alps are undergoing similar changes (see Switzerland's Rhône Glacier, Austria's Stubaï Glacier, or the Theodule Glacier which provides important tourism revenue for both Switzerland and Italy). In this context, the research that will be carried out around Mont-Blanc in the coming months will be principally focused on the following:

- Changes in the motivations of the current visitors to glacier sites
- their perceptions of landscape evolution and its impact on their aesthetic judgements
- changes in the sites from the point of view of site managers, including challenges encountered and adaptation needs

During the summer of 2019, the first phase of fieldwork was carried out at six emblematic glacier tourism sites in the Alps. Three of these sites were located in the Mont-Blanc massif, while the other three were located in other French and Swiss massifs, allowing for a comparative approach. This phase of fieldwork allowed for the collection of nearly 1,000 responses to a quantitative survey focused on visitor motivation, and 50 semi-directive interviews aimed exploring this question in depth, while exploring their perception of the landscape. The responses collected are currently being analyzed.

3.6 Natural hazards

In the EMB, like the rest of the Alps, is particularly sensitive to natural hazards linked, in particular, to the intensification of the water cycle (Huntington, 2006) and to changes in the cryosphere (snow, glaciers, and permafrost), which is an important factor in maintaining the stability of rock walls and slopes (IPCC, 2019). Compared to other mountainous regions, the EMB is especially vulnerable due to its i) high population density, ii) high tourism rates (Huggel et al., 2019), iii) high elevation and iv) large are affected by glaciers and permafrost. The climatic conditions that will increase the risk of natural hazards in the EMB were described in the previous sections and are primarily linked to the interaction between rising temperatures, changes in precipitation regimes and the intensification of extreme weather events (cf. 1.3) and the geomorphological processes that act on mountain environments.

The following sections will present a summary of the principal natural hazards encountered in the EMB, providing an overview of the observed changes over the course of recent decades and the changes expected in the different scenarios for the future. The primary source of information for this analysis was the latest IPCC report, "*Special Report on the Ocean and Cryosphere in a Changing Climate*" (IPCC, 2019).

Permafrost degradation, which is directly linked to rising surface temperature, can lead to slope instability (especially in cases of ice-rich soil, rock glaciers, cracks in rock walls filled with ice and nearby moraines) and impact infrastructure stability in the high mountains (cable car stations, huts and buildings). This phenomenon is well documented in rock faces in the Mont-Blanc massif, where the frequency and volume of rockfalls have increased in recent decades due to the degradation (warming) of permafrost (Ravanel et al., 2011) and heatwaves (Ravanel et al., 2017). Increased slope instability can also be caused by glacier retreat, which can leave unstable lateral moraines and rock walls. This process, sometimes called "post-glacial decompression", can be mitigated by plant colonization in newly deglaciated areas (IPCC, 2019).

Ice avalanches and serac fall are processes linked to the interaction between climate change that natural evolution of some glaciers. It is therefore difficult to link individual events directly to climate change and predict their occurrence in the future (Faillettaz et al., 2015). Nonetheless, there is a strong consensus that collapse of the fronts of hanging glaciers and glaciers on steep slopes will be exacerbated by warming basal glacier temperatures (IPCC, 2019).

Changes in snowpack may impact probability and type of **snow avalanches** seen in the EMB. As temperatures warm and snowline (where precipitation falls as snow rather than rain) rises in elevation, the frequency of wet slide avalanches will increase, even in mid-winter. Unlike the mid mountain elevations, for the high mountains, models predict an increase in the number of wet or mixed avalanches, similar to what has been observed since the mid-1970s in the Mont-Blanc massif (Naaim et al., 2016). In recent decades, across the Alps, an increase in the number of wet slide avalanches and decrease in the volume of individual avalanches (at least in certain sectors) have been observed (IPCC, 2019). It is important to note that wet slide avalanches can cause major damage to mountain infrastructure. As an example, in 2012 at Saint François-Longchamps (Savoie, France) a wet snow slide destroyed a chairlift. Scientists agree that the observed trends will continue and intensify in the years to come. To summarize, we can expect that **avalanche risk will decrease at low elevations and the characteristics of avalanches will change in the high mountains.**

Phenomena like river floods and debris flows triggered by the **sudden burst of glacial melt pockets or glacial lakes** are generally linked to recent glacier change. They are one of the most well-documented high mountain risks, largely because they have the ability to impact large swaths of the region. Across the Alps and in the EMB, glacier retreat has produced many new glacier lakes and increased volume in existing lakes (Magnin et al., 2019). Meltwater is sometimes trapped by terminal moraines formed by glaciers, which can burst suddenly in the event of overflow, or rock or ice fall from surrounding walls. As glaciers melt more quickly in coming decades, these phenomena are likely to intensify and may represent a major risk for the valleys below.

Permafrost degradation and snowmelt and can also interact with flood risks, debris flows and mudslides, in particular, when **rain falls onto snow pack**, accelerating snowmelt and mobilizing substantial bodies of water and causing significant damage in mountain areas (Pomeroy et al., 2016). Scientists agree that this kind of events have become more frequent in recent decades, particularly at high elevations and especially at the change of seasons from fall to winter and winter to spring. We should note, however, that these events will decrease in frequency at lower elevations as the length of snow cover decreases. A recent study (Beniston et Stoffel, 2016) predicts that, in the Swiss Alps, these events will be more frequent in the future in the intermediate warming scenario (+2 to 4°C, RCP 4.5) and less frequent in a more extreme warming scenario (RCP 8.5). These events could therefore interact in a differentiated way with flood risk, in particular during the beginning of spring and the end of the fall.
In conclusion, in the coming years in the EMB, risk of **flooding and debris flows**, either as a result of changes in the cryosphere presented in the previous sections or as a result of the increase in the frequency of extreme precipitation events (Figures 1.21 et 1.22), will almost certainly increase.

Based on emissions scenarios combined with a hydrological model taking into account glacier and snow melt (Silvestro et al., 2013), figure 3.30 presents the expected increase in the number of days when flood risk alert thresholds (alert, pre-alarm and alarm) are surpassed for the Doire river, just above Courmayeur (Italy). The number of days exceeding alert thresholds are expected to increase by 70-100% (i.e. passing from 1.5 to 3.2 days per year) in the short-term (2035-2050), and 150% by the end of the century. An increase from 1.3 days to 2.2 days is also anticipated for the pre-alert alarm threshold by 2050.

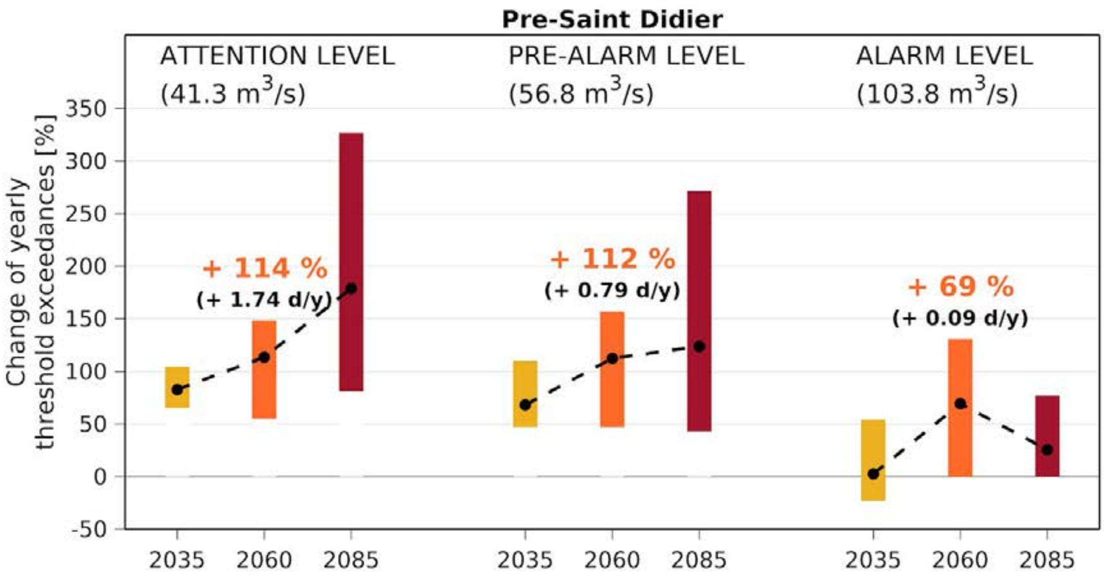


Figure 3.30. Expected change in the number of days when flood alert thresholds will be met or passed for floods on the Italian side of the EMB (Doire de Vény, Courmayeur, Aosta Valley). These simulations are based on a combination of three emissions scenarios with a hydrological model that takes glacier and snow melt into account (Silvestro et al., 2013). The height of the bars represents the margin of uncertainty in the models. The numbers in parenthes below the alert thresholds indicate the flow for the given alert. ***Source : CIMA Foundation, Centro Funzionale Regione Valle d'Aosta.***

It is extremely important to keep in mind that the natural hazards presented above, especially in a high mountain context like the one found in the EMB, can interact synergistically and lead to a domino effect. For example, an ice avalanche can cause a glacial lake to burst or trigger a bigger avalanche. All risk adaptation strategies for the EMB need to take into account the possibility of interactions between hazards. Given these scenarios of permafrost melt, glacier retreat and bursting of glacial lakes, there is a strong consensus that the frequency and magnitude of these cumulative events will increase in the future, and that the territory facing these risks will expand.

BOX 8: Changes in the stability of infrastructure built on permafrost

Over the last four decades, the winter sports industry in the Western Alps has undergone substantial development with the construction of several hundred infrastructure projects (ski lifts, huts, avalanche control, etc.) on permafrost in the high mountains. In the last thirty years, a general increase in the temperature of permafrost has been observed.
In the larger context of climate change and the degradation (thawing) of permafrost, infrastructure is becoming vulnerable to changes and potential instability in the ground that it it is built on. In the French Alps, research is currently being carried out within the framework of the EU-POIA PermaRisk project (by P.-A. Duvillard, in particular). This project aims to i) identify all of the infrastructure built on permafrost, ii) use surveys of site managers to carry out the most exhaustive inventory possible of damage to infrastructure, and iii) identify the principal geomorphological processes responsible for the geotechnical problems. The inventory of infrastructure built on permafrost (for example, pylons) via GIS was carried out using different sources of information, including permafrost distributions maps (at the scale of a massif or the French Alps, e.g. Magnin *et al.*, 2015) for rockwalls and surface formations. A total of 947 infrastructure elements are built on permafrost and 74% of them are ski lift components (Duvillard *et al.*, 2015).

The surveys carried out with the managers and operators of infrastructure sites built on permafrost made it possible to create an inventory of the damage to these sites. According to the information collected, more than 15 infrastructures in the French Alps have experienced damage most likely related to permafrost changes in the last 30 years. Damaged infrastructure, which generally saw problems like subsidence, tilting, and deterioration of foundations or anchors, has generally been restored with adjustments, consolidations or reconstructions, but sometimes there is no long-term geotechnical solution. A relative increase in the number of structures damaged has been observed in the last two decades (9 cases reported between 2000 and 2010, versus 20 cases between 2010 and 2019; Figure BOX 8.1), as well as an increase in maintenance costs (Duvillard *et al.*, 2019). While a lack of information about some resorts means that this inventory is not exhaustive, it provides important revelations about the changes occurring in the Alps.

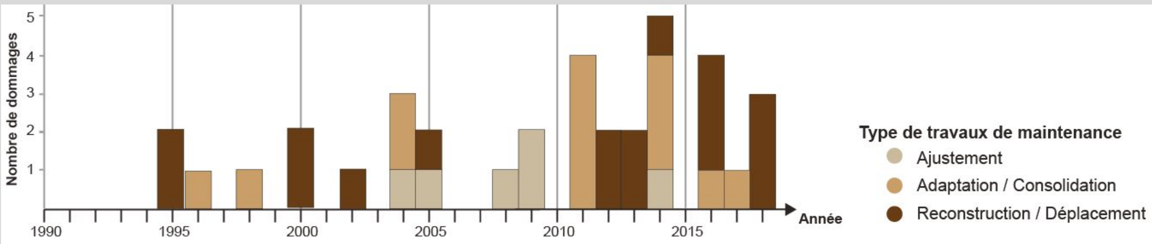


Figure BOX 8.1. Observed change in the amount of damage and maintenance work on the infrastructure built on permafrost in the French Alps, for which information has been gathered (Duvillard *et al.*, 2019).

The majority of damage occurred on ice-rich terrain, such as rock glaciers. Many of the incidents could have almost certainly been anticipated and/or avoided with diagnostics, more detailed geotechnical studies, or by taking permafrost into account. The geomorphological processes that impact infrastructure stability are mostly slow, and sometimes human-caused. Anticipating future instability requires determining how much ice is present in the ground and what temperature it is at. This represents a real challenge for guaranteeing high mountain infrastructure stability, especially when it is built on rock faces. Even if there is a relatively small amount of infrastructure built in such a context in the French Alps, much of it is particularly sensitive. For example, the Cosmiques Hut (located at

6,613 m in the Mont-Blanc massif, Figure BOX 8.2) is built onto a rocky ridge and collapse of 600 m² of rock from the southeast side caused instability in part of the building and required substantial reinforcement work (Ravanel et al., 2013). Today, the sector around the hut is the subject of geophysical and thermal monitoring in order to determine changes to the permafrost.

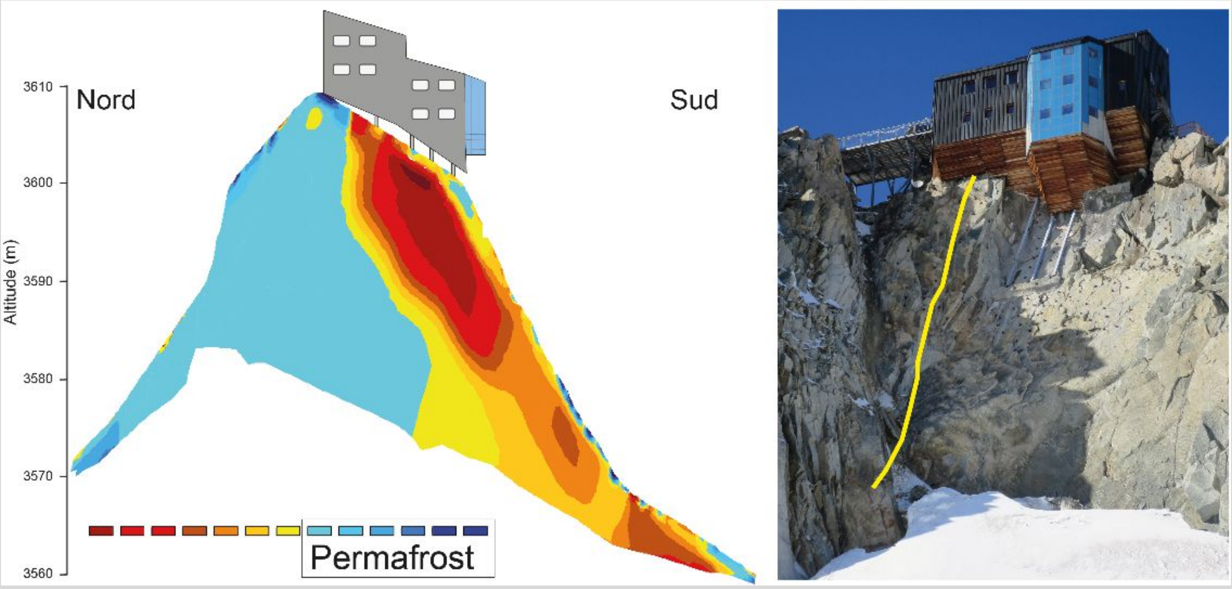


Figure BOX 8.2. Permafrost distribution in the ridge below the Cosmiques hut, determined using electric tomography in 2016.

In the context of rapidly changing high mountain environments (Bodin et al., 2015), two research areas should be investigated to continue developing the knowledge necessary for effective management of high mountain infrastructure. In particular, it is necessary to i) continue to inventory infrastructure damage to broaden geotechnical knowledge about permafrost terrain. These reports and experiences will allow experts to ii) propose concrete technical solutions, technical maintenance recommendations and construction suggestions for infrastructure managers.

The EMB therefore finds itself in a general context of increasing risk. However, the changes to come remain difficult to predict and model with precision, given the chaotic nature of the processes causing them, and the complexity of their interactions with climate change. It's crucial to understand the levels of risk depend on localized conditions and specificities and it is therefore difficult to make generalizations. When considering **adaptation strategies**, it will be key to implement different policies at different administrative levels, allowing local communities to adopt effective, localized approach. It is also important to help create a **culture of risk management in the mountains,** promoting interactions between technical and scientific experts, and integrating a social science approach (awareness campaigns, promotion of local knowledge, collaboration with media and implementation of communication and alert strategies to increase social acceptance of adaptation practices). In this context, it is a priority to integrate the concept of "sustainable risk", where protection of the population (both current and future) becomes a primary objective and is considered for all future development and sustainability projects (cf.: Alcotra RISKNET project).

One specific goal should be the development of a shared, cross-border culture when it comes to evaluating natural hazards, and taking into account a shared set of global, economic and socio-economic aspects. The implementation and long-term management of observation networks and territorial monitoring of natural processes (integrating monitoring, adaptive monitoring, management of early warning systems, etc.) will be essential. In parallel, financial and socio-political support for research and studies focusing on the interaction between the cryosphere and natural hazards will be key in filling in gaps in the current knowledge—a point highlighted by the IPCC in their last report on the cryosphere (IPCC, 2019). The EMB's well established cross-border collaboration will be advantageous and help with the **sharing of knowledge and experiences between countries** and different actors within the territory (researchers, municipalities, local and regional administrations, professionals, etc.). From a governance perspective, it will also be key to promote the integration of themes linked to the interaction of climate change and natural hazards throughout the **territorial planning process.** The creation and frequent updating of natural hazards maps should be a priority as we gain knowledge and better understanding of these processes.

Finally, given the challenges of putting in place common adaptation and management measures for territories in a cross-border context, the EMB should promote exchanges about best practices. In so doing, it could become a **platform for collaborations between managers and legal experts to examine the responsibility and the application of the self-responsibility concept** with regard to ongoing changes in mountain conditions.

4. Conclusion

The findings presented in this report call for adaptation policies that are themselves adaptive and consistently updated to mirror the pace of change, which is already fast and accelerating. The report identifies important challenges in the face of rising temperatures, increasingly extreme weather events, which will require major socio-economic and cultural changes. A number of strategic opportunities are also becoming apparent for the EMB, a territory which will undoubtedly become a place of refuge for animals, plants and humans seeking cooler temperatures.

This report represents a first step in our understanding of the changes underway and in the development of adaptation strategies. In the writing of this report, certain knowledge gaps were identified and should be the focus of future studies:

I. Deepen the understanding of the impacts on certain sectors, currently limited by lack of data or time available for this report, including.

- *Agriculture:*
    - analysis of the impact of summer droughts on pastures in the mid and high mountains
    - addition of other pathogens into the evaluation of changes in pest life cycles
    - analysis of the risk of late frost events on earlier phenological stages
- *Water:*
    - Specific analyses of the seasonal distribution of water stress, taking into account the different uses at a watershed scale
    - Modeling of different scenarios of stream and river temperature change, and the potential impacts on the ecosystem
- *Forests:*
    - Improvement of predictive algorithms for future landscapes, using, in particular, non-linear approach and integrating explanatory variables like grazing pressures and climate
    - Expansion of analyses to the whole of the EMB (currently limited to heart of the massif)
    - Modeling of future change in ecosystem services (e.g. carbon sinks, protection from natural hazards, etc) and potential impacts of extreme weather events, fires and pests.
- *Natural heritage and conservation:*
    - Species distribution modeling across the whole EMB, as a function of glacier retreat and the latest emission scenarios, and integrating, where possible, human activity as a co-variable (tourism, grazing, etc.)
    - Studies examining the role of glacier retreat zones as potential refuges for species
    - Study and monitoring of the adaptation capacity of key species in mountain ecosystems
    - Studies carried out in collaboration with managers of protected areas, aiming to integrate climate change into environmental management strategies
- *Tourism:*
    - Cultural and socio-psychological studies on the cultural representations of mountain environments and whether or not this representation can evolve in the eyes of visitors and mountain professionals, especially in the natural environments most strongly impacted by climate change
    - Evaluation of the economic impacts of planned modifications to summer and winter tourism

- *Natural hazards:*
    - Studies focusing on the interactions between the cryosphere and natural hazards in mid and high mountain with a special focus on compounding factors
- *Health and wellbeing:*
    - Specific analyses of this theme

II. **Better take into account interactions between sectors**, in order to identify possible positive synergies or, on the other hand, cumulative negative impacts of change to consider in planning. For example, summer/off season tourism and the conservation of specific natural environments, or water and agriculture and winter and summer tourism.

III. **Incorporate the cumulative effects linked not only to climate change but also to other impacts of human activity on the environment** (covering ground with artificial surfaces, tourism visitation rates, pollution, future demography, etc.) which, depending on the strategic choices made on these other parameters may either reinforce or weaken climate change adaptation policies.

IV. **Analyze the current state and develop future scenarios of the main ecosystem services** at the scale of the EMB using a multi-disciplinary approach across the elevation gradient but with a **special focus** on pivotal zones like the area between 2,000 and 2,500 m.

V. Better **incorporate socio-cultural aspects in the analyses to encourage** the general public, the various stakeholders and decision-makers **to recognize the importance of climate change adaptation actions and policies** in the EMB, and also improve the transmission of the results of scientific studies.

The Mer de Glace landsacpe in **2015**

The Mer de Glace landscape in **2050**

Figure 3.31. Watercolor paintings of the Mer Glace and surrounding mountains in 2015 and 2050, by the artist Claire Giordano, according to glacial retreat and plant colonization models for 2050. ***Data source: IGE, Landsat/USGS*** **© CREA Mont-Blanc**

Annex 1: Selection and processing of climate data

Among the different datasets available, we chose to use two different data sources: 1) CHELSA data (Karger et al. 2017) to map climatic changes at the EMB scale, and 2) data from the CH2018 (CH2018) scenarios to quantify the evolution of certain climatic parameters that require daily observations. Below, we will explain the methodology used to produce the analyses presented in this report.

CHELSA Spatial Data

Available since 2017, CHELSA (Climatologies at High resolution for the Earth's Land Surface Areas; Karger et al., 2017) is a climate database derived from the ERA-Interim physical model, developed and maintained by the European Center for Medium-Range Weather Forecasts (ECMWF). The CHELSA project responds to the recurring need of scientists in ecology and natural sciences to have high spatial resolution climate data for current and future periods. The algorithm, developed by D. Karger at WSL in Zurich, takes large-scale climate drivers (80 x 80 km) from ERA-Interim to estimate with a statistical downscaling approach temperatures and precipitation at a resolution of 4 x 4 km for the entire terrestrial surface of the planet. The model was designed for use in mountainous areas, and takes into account prevailing winds and orographic effects when estimating precipitation. The basic dataset therefore consists of monthly temperatures and precipitation, over a grid cell size of 4 km.

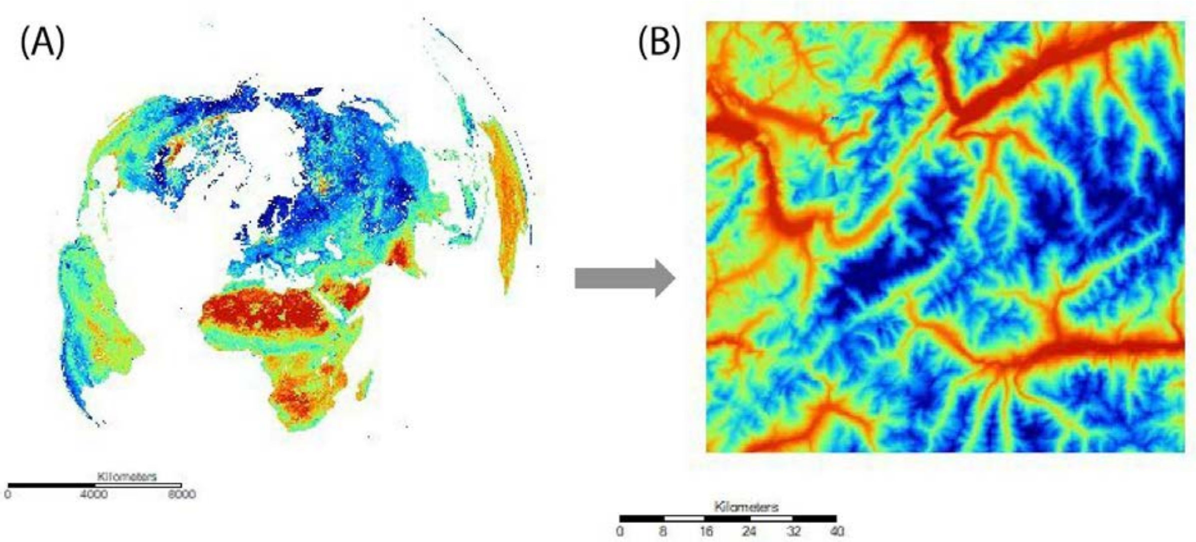


Figure A1. (A) Example of CHELSA raw data (temperatures), available globally at a resolution of 4 x 4km. (B) The methodological approach was to adapt the raw data to the EMB relief, taking into account altitude and solar radiation. The resolution of temperature and precipitation maps produced for the EMB is 25 x 25 m. ***Source : WSL/CHELSA © CREA Mont-Blanc***

The current reference period for CHELSA runs from 1979 to 2013. Karger et al. (2017) producted a climatology for this period, which provides the average temperature and precipitation for the period 1979-2013 by month. As an example, in this report, the summer temperature map is the average of the months June-July-August from this climatology. This project then required a further downscaling from the 4 x 4 km grid cell size to the topography of the EMB, which is to say a gridcell of 25 m x 25 m (Figure

A1). This spatial downscaling was done using a "geographic weighted regression" algorithm to predict local temperatures and precipitation as a function of altitude.

Regarding temperatures, further analyses allowed for the translation of air temperatures into surface temperatures, which are more representative of the alpine environment experienced flora and fauna, as well as by humans. For this, it was necessary to calculate the total monthly solar radiation for the EMB, taking into account the topographic relief and the average cloudiness estimated by the MODIS satellite (https://www.earthenv.org/cloud). The total solar radiation was then combined with the air temperature map using the "Land Surface Temperature" tool in the SAGA GIS software. Details about the algorithm can be found in Boehner and Antonic (2009). We used this methodology to estimate the monthly minimum, maximum and average temperatures for each month.

From the four future emissions scenarios available, we chose the intermediate scenario (RCP 4.5) and the pessimistic scenario (RCP 8.5; (Figure A3). We then selected five climate models from the fifth IPCC Report (CMIP5) that are representative of the variation among the many models available (for more information:: http://chelsa-climate.org/future/). We averaged the results of the five models to estimate temperatures and precipitation for each scenario and for each month through 2050. Then we applied the same spatial downscaling method described previously.

Several modules have been developed in the SAGA GIS software to estimate various environmental parameters from CHELSA data: evapotranspiration, soil moisture, duration of snow cover and duration of the growing season. According to D. Karger, these tools are "research grade" and being validated. Nevertheless, the algorithms are based on existing scientific publications and constitute powerful tools for estimating parameters of great interest in a territory such as the EMB.

The main limitation of the CHELSA data is the monthly temporal resolution, which did not allow the calculation of climate indices requiring daily observations (frost days, heatwaves, etc.; see Annex 2).

Temporal station data: CH2018

The CH2018 (CH2018) scenarios are based on EURO-CORDEX climate projections, which combine simulations of global (GCM) and regional (RCM) climate models. In particular, we used 68 EURO-CORDEX simulations (12 for RCP2.6, 25 for RCP4.5, and 31 for RCP8.5). These three scenarios are based on very different greenhouse gas emission rates: on one end of the spectrum, RCP 2.6 requires a strong mitigation of emissions, a transition to decarbonation which would also respect the Paris Agreement (temperature increase at the end of the century < 2°C) and on the other end of the spectrum, continued emission (comparable to what historically was defined as “business-as-usual” scenario and a temperature increase at the end of the century of 4-5°C, RCP8 .5). The intermediate scenario (RCP 4.5) implies a 2.5°C rise by 2100. The names of the three scenarios are based on the corresponding radiative forcing expected by the end of the century.

The dataset used (DAILY-LOCAL) is made up of time series of daily data points between 1981 and 2099. Five variables are used: minimum, maximum, and average temperature, precipitation (daily cumulative) and relative humidity. The continuous time series over the entire period (“transient scenarios”) make it possible to quantitatively address the indices linked to extreme events, which was not possible with the CH2011 scenarios used before (“delta change approach”).

Data are available for 86 stations in the MeteoSuisse network. From those 86, we chose eleven for climatic indices calculations. Table A1 shows the characteristics of the selected weather stations. The choice of stations was based on climatic analog criteria (Dahinden et al., 2017). We calculated a combined dissimilarity index for temperature and precipitation between each Meteo Suisse station and the reference stations in the Espace Mont-Blanc, and identified the stations most similar (climatically speaking) to the stations in the Mont-Blanc area (table A1). For most of the analyzes, the stations were organized into three altitude ranges: valley floor (400-1000m), mid mountain (1000-2000m) and high mountain (2400-2700m).

ID	Full name	Elevation	latN	lonE	Elevation zone
PUY	Pully	455	46.51	6.68	Valley floor
SIO	Sion	482	46.22	7.33	Valley floor
VIS	Visp	639	46.3	7.85	Valley floor
LAG	Langnau	745	46.94	7.81	Valley floor
GST	Gstaad	1045	46.47	7.29	Mid mountain
GRC	Grächen	1605	46.20	7.84	Mid mountain
ZER	Zermatt	1638	46.03	7.75	Mid mountain
MLS	Le Moléson	1974	46.55	7.02	Mid mountain
GRH	Grimsel Hospiz	1980	46.57	8.33	Mid mountain
GSB	Col du Grand St-Bernard	2472	45.87	7.17	High mountain
WFJ	Weissfluhjoch	2691	46.83	9.81	High mountain

Table A1: characteristics of Swiss weather stations which were used to calculate climate change indices.

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Annex 3: Definitions and acronyms (definitions indicated by an * in the text)

Albedo: proportion of solar radiation that is reflected by the earth's surface (e.g. snow, which is white, has a greater albedo than rock, which is darker in color)

CHELSA: International high resolution (4km grid) climate data set for the earth's land surface; CHELSA = Climatologies at High resolution for Earth's Land Surface Areas - http://chelsa-climate.org/

CH2011: Daily climate data from Swiss weather stations, available for different scenarios through 2100. http://data.c2sm.ethz.ch/dataset/CH2011plus/seasonal_regional/

CH2018 : Daily climate data from Swiss weather stations, updated for new models and emissions scenarios. Available through 2100. https://c2sm.ethz.ch/research/ch2018.html

CNRS: French National Centre for Scientific Research **-** *Centre National [français] de la Recherche Scientifique*

EDYTEM: *Environnements, Dynamiques et Territoires de Montagne* – research laboratory specializing in geosciences and social sciences in Chambery, France

Elevation gradient: Elevation variation which corresponds to climatic variations (e.g. decrease in temperature, increase in precipitation and cloud cover as elevation rises)

EMB: Espace Mont-Blanc – a cross-border cooperation initiative http://www.espace-Mont-Blanc.com/

Evapotranspiration (ETP): The amount of water transferred to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants

Extremely hot day: day with maximum temperatures above 32°C

Frost day: day with minimum temperatures below 0°C

Greenhouse gases: Gaseous components that contribute to the greenhouse effect on a planetary scale (water vapor, carbon dioxide, methane, etc.)

Growing season: Period of the year favorable for plant growth, without snow and with daily temperatures above 5°C (for trees; the threshold for alpine plants is 0 °)

Ice day: day with maximum temperatures below 0°C

0° Isotherm: Freezing limit, which can be mapped as a line, below which temperatures are above 0°C and above which temperatures are below 0°C

IGE: Institute of Environmental Geosciences - *Institut des Géosciences de l'Environnement* – research laboratory specializing in glaciology and hydrology, based in Grenoble, France

IGN: *Institut national de l'information géographique et forestière,* national provider of maps and aerial imagery in France

IPCC : Intergovernmental Panel on Climate Change – United Nations body for assessing the science related to climate change – http://www.ipcc.ch/

Late frost event: Frost events that occur in the spring after the growing season has begun (see definition of growing season)

Little ice age: Climatic period in the Alps between 1500 and 1850 characterized by wet and cold conditions

Landsat: Series of satellites launched in the 1970s by NASA to observe Earth's land surfaces

Nature-based solutions (UICN definition): actions to protect, sustainably manage and restore natural or modified ecosystems to directly address societal challenges in an efficient and adaptive manner, while ensuring human well-being and producing benefits for biodiversity

Permafrost: All terrain or substrate (soil, rock, scree, etc.) that stays frozen all year long

Phenology: Seasonal biological events (budburst, flowering, egg-laying, etc.)

Photoperiod: Day length, which varies throughout the year

ppm: "Parts per million", expresses the concentration of greenhouse gases * in the atmosphere, ie the number of molecules of greenhouse gases * (CO2, methane, etc.) considered per million molecules of air

RCP: "Representative concentration pathway" term from the 5th IPCC report which corresponds to a socio-economic scenario and the corresponding concentration of greenhouse gases *

Snowbed: Alpine environment characterized by a long snow cover duration, and specialized flora that is able to take advantage of an extremely short growing season*

Snow cover duration: The number of days in a water year (beginning in September through the end of August) with snow present on the ground

Summer day: day with maximum temperatures above 25 °C

Tropical day: day with maximum temperatures above 30°C

USGS: United States Geological Survey, provider of Landsat satellite images used for the study of plant dynamics in the EMB

WSL: Swiss Federal Institute for Forest, Snow and Landscape Research