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Climate change and its impact on tourism in the Alpine Space

CLIMATE ANALYSES

Climate changes over the Alps

The impacts of climate change on Alpine tourism

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Climate Analyses

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CLIMATE CHANGES OVER THE ALPS

This report aims to give an overview of some new results obtained from climate change research since the publication of the IPCC 4th Assessment Report (*Solomon et al., 2007*) for partners and pilot site stakeholders in the Alpine Space project "ClimAlpTour" .

We focus not only on long term warming due to the emission of greenhouse gases (GHGs), but also on natural factors affecting the climate system and internal climate variability. Some emphasis is put on the North Atlantic oscillation (NAO), which up to now has played an important role in the evolution of the European climate in winter (see for example figures 1 and 2).

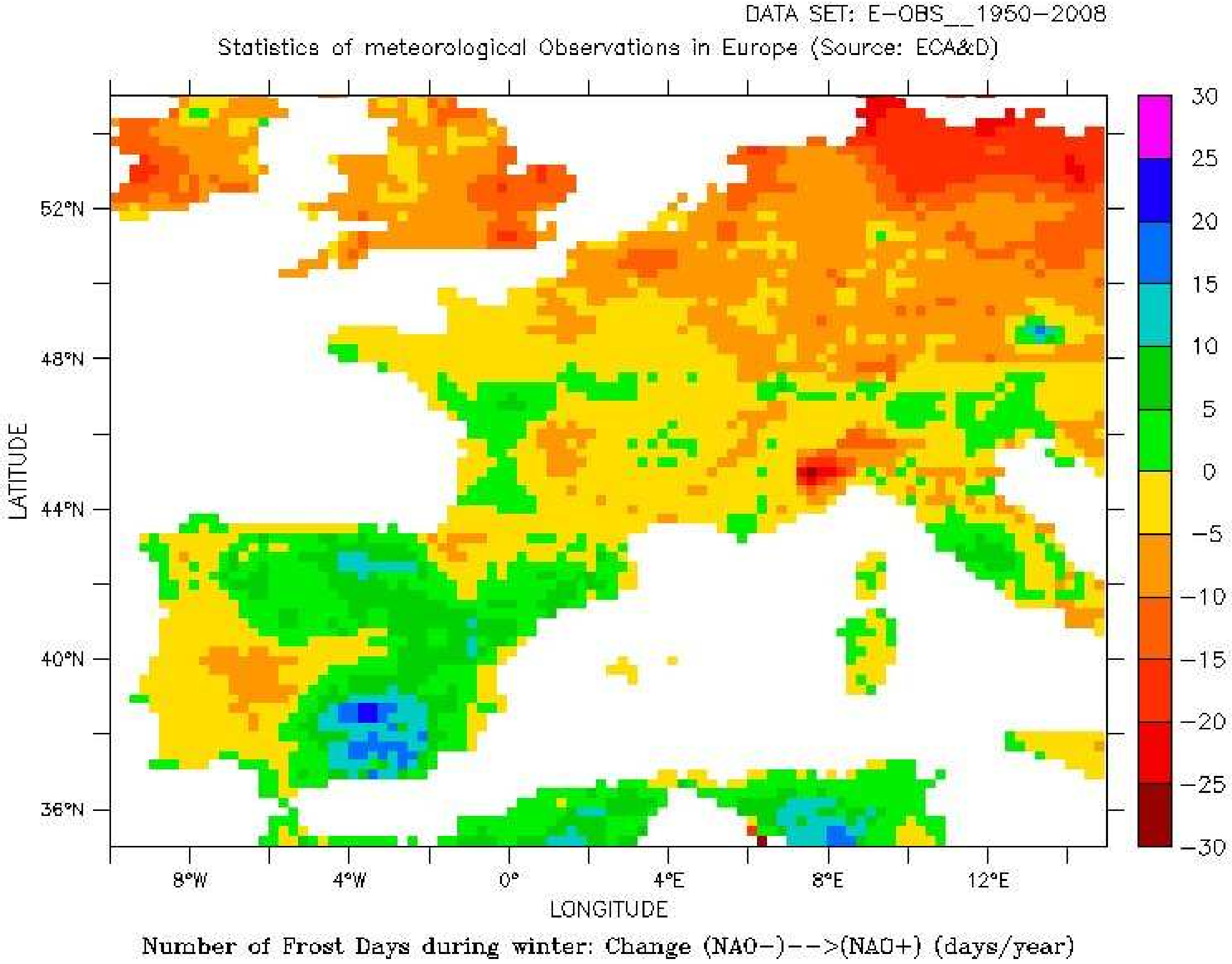


Figure 1. Observed change in the number of frost days (days/year) between winters (DJF) having a NAO positive phase (NAO+ years: 1990 – 1995) and a NAO negative phase (NAO- years: 1960 – 1965). Data from E-OBS (Haylock et al., 2008). Cooling (warming) of the Mediterranean area (northern Europe) is observed when NAO phase changes from NAO- to NAO+.

An overview is also provided on decadal climate predictions, which began a few years ago, the first results of which were published after the publication of the last IPCC report.

The climate of the Alps is strongly linked to the climate of Europe. A difficulty is that the European climate is influenced more or less with the same intensity by

i. the anthropogenic factors (emission of aerosols and greenhouse gases),
ii. natural factors (solar forcing, volcanic eruptions) and
iii. internal variability (change in the atmospheric circulation over the Atlantic ocean).

Circulation changes are probably caused by

i. changes in the NAO and associated atmospheric blocking (see figure 1), and
ii. changes in the oceanic circulation (AMOC – Atlantic Meridional Overturning Circulation).

For example, European climate change projections indicate that changes in minimum temperatures in winter for the twenty-first century will be of the same order of magnitude as the changes found by *Scaife et al.* (*2008*) and those due to the NAO between the 1960s and 1990s. This is confirmed by the recent downturn in the winter NAO from strong positive values in the early to mid-1990s to near-average values a decade later, suggesting that a significant part of the increase from 1965 to 1995 may be due to internal climate variability.

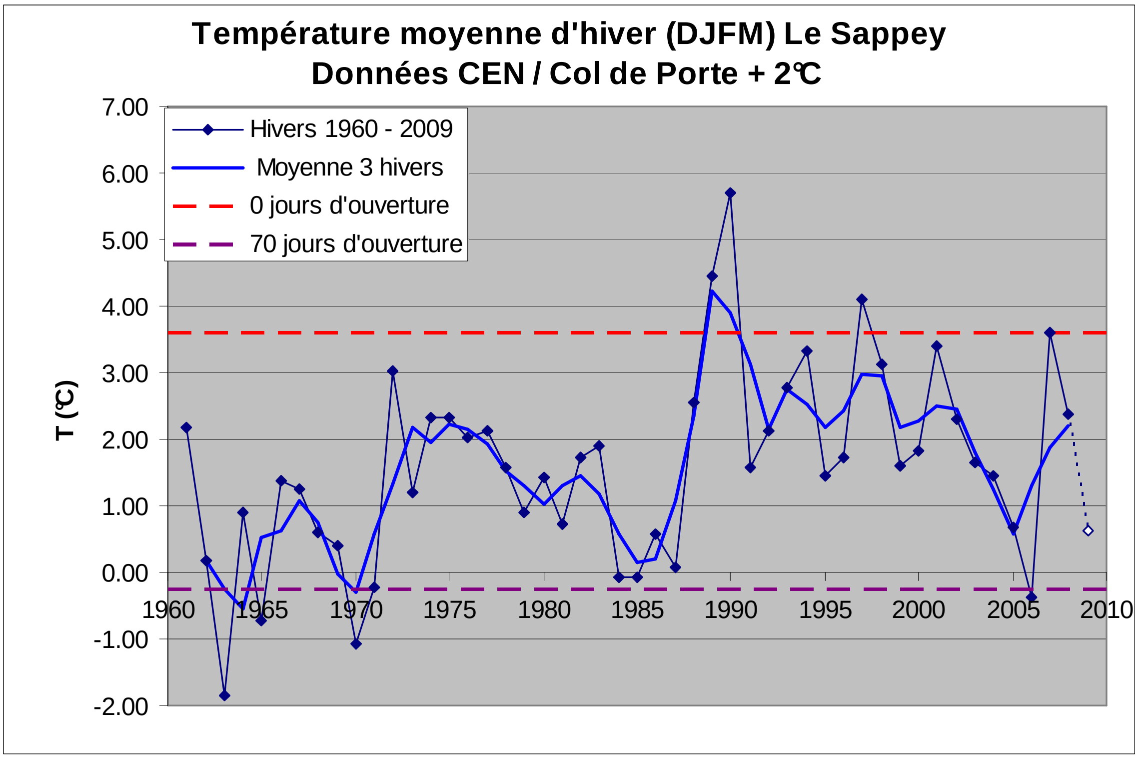


Figure 2. Reconstructed Mean Winter Temperature (DJFM) since 1961 at Le Sappey-en-Chartreuse, northern French Alps (black line). The blue line represents the 3-winter running mean. The reconstruction is made by simply adding 2℃ to the data of Col de Porte (situated 4 km away from Le Sappey) in order to correct the altitude difference (data source: CEN, Météo – France). Red and purple dashed lines are indicative thresholds of the number of opening days of the ski station, 0 and 70 days respectively.

Note that such a change may significantly influence the number of opening days of a ski station like that of Le Sappey, which is situated at an altitude of 1000 m in the Chartreuse mountain chain on the northern side of the French Alps (see figure 2 and *Kévorkian et al., 2009*).

Among the potentially significant natural factors, volcanic activity is unpredictable while the physical processes responsible for the influence of the solar cycle on the atmospheric circulation must still be inferred (e.g., *Lockwood, 2010*). Furthermore, techniques for forecasting solar cycle intensity need to be improved as highlighted recently by the latest exceptional solar minimum and the unexpected weakness of the new solar cycle.

Global Climate Models (GCMs) including a coupled Atmosphere-Ocean General Circulation Model (AOGCM) and a carbon cycle model are able to simulate the temperature evolution at the global and continental levels sufficiently accurately to determine at these levels the effects of anthropogenic and natural factors on recent climate. In particular it has been found that global warming results from the increase of greenhouse gases in the atmosphere (see for example figure TS.29 in the IPCC AR4 report – *Solomon et al., 2007*).

I. Regionalization

Clearly there is a need to generate scenarios of climate changes at spatial levels which are much finer than the continental level. The computer-based technique used to develop these scenarios is called the regionalization. It uses either regional climate models or statistical techniques and provides results with a much finer horizontal resolution than that of the GCMs.

Nevertheless, there is an increased lack of precision in climate scenarios when one consider regions of decreasing size. This problem is due to the non-linear character in the physical behaviour of the atmosphere and it also exists in numerical weather forecasts: for example it is possible to forecast showers somewhere in a region as large as the Alps for a particular day, but it is not possible to perform the same forecast for the same day for a particular mountain in the Alps.

The climate of a region such as Europe results from the succession of several weather types which are characterized by their frequency and intensity. European weather types in winter are mainly:

i. the NAO+ regime, with a strong westerly flow reaching northern Europe resulting in milder and wetter weather than average in that area,
ii. the NAO- regime, with a weaker westerly flow reaching southern Europe,
iii. the Atlantic ridge with anticyclonic conditions over the Atlantic Ocean and
iv. the blocking of anticyclonic conditions over Scandinavia, favouring easterlies.

Climate changes result from changes in the frequency and intensity of these weather types.

Im et al. (*2010*) have performed a high resolution climate simulation over the Alpine region without modifying the frequency of weather types, in order to analyze changes in their intensity. In practice, they simply modified the observed large scale meteorological and Sea Surface Temperature (SST) forcing fields by imposing an illustrative 3°C warming. The corresponding relative humidity was kept constant, which resulted in an increase in atmospheric moisture.

Multi-year simulations of this surrogate climate change (SCC) have been completed. They indicate that in the winter season, precipitation increases consistently with the SCC approach, although this varies significantly depending on topographical elevation. Other components of the surface energy and water balances also show marked variations according to elevation, mostly related to changes in snow cover. In summer, contrary to what might be expected from the SCC forcing, precipitation decreases over the Alpine mountain range. This is due to a local surface-atmosphere feedback mechanism involving reduced snow cover and soil moisture at the beginning of summer. These results suggest that over the Alps during summer local feedback effects related to the surface energy and water balances are important factors in determining changes in precipitation as a result of global warming.

Goubanova et al. (*2010*) show that European temperature changes due to anthropogenic factors will differ from one weather type to another in winter. For example the largest warming will be associated with the NAO- regime. This is due to the fact that (i) the NAO- regime is responsible for the coldest winter temperatures over Europe for the present climate, and (ii) minimum temperatures will increase faster than maximum temperatures in a warmer climate. A consequence is that the NAO- regime will no longer be responsible for the coldest winter temperatures in Europe at the end of the century and will be replaced by the blocking weather type.

Also, a recent study (*Scaife et al., 2010*) shows that GCMs are able to simulate the variability among these weather types but that they overestimate the superimposed westerly flow. Such errors must be taken into account when describing the future European winter climate.

The French ANR (National Research Agency) project SCAMPEI (Scénarios Climatiques Adaptés aux zones de Montagne: Phénomènes extrêmes, Enneigement et Incertitudes, see web site http://www.cnrm.meteo.fr/scampei) aims to correct regionalized European climate scenarios, by removing the errors of the simulated present climate when comparing this data to observed climate data (*Déqué, 2007*). The strong assumption made here is that these data do not change in a changing climate. Nevertheless this is a first step in generating improved regional climate scenarios.

II. Anthropogenic and natural forcing of climate

It is still difficult to distinguish between the impacts of natural and anthropogenic factors on changes in atmospheric circulation over Europe. *King et al.* (*2010*) have shown that increases in the NAO are due not only to an increase in the tropical Sea Surface Temperature (SST) caused by global warming, but also to a decrease in the stratospheric temperature caused by the decrease in stratospheric ozone content.

Furthermore, melting sea ice may have an opposing influence, contributing to a decrease in the NAO. Finally changes in Total Solar Irradiance (TSI) may also play an important role. *Barriopedo et al.* (*2008*) have found that the occurrence, duration and strength of blocking events near Europe increase during periods of low solar activity. Nevertheless, the physical mechanism responsible for that process is not well understood (*Lockwood, 2010*). Over timescales longer than a single solar cycle, the NAO could be influenced by changes in the North-South gradient of surface heating in the Pacific ocean (*Swingedouw et al., 2010*).

The possibly significant influence of changes in TSI must be studied in detail, since the sun could undergo a period of weaker activity in the near future (*Agee et al., 2010*). Furthermore revised forecasts of a weaker ‘Solar cycle 24’ than previously expected could still overestimate solar activity during that cycle, as pointed out very recently (figure 3, see also http://solarscience.msfc.nasa.gov/SunspotCycle.shtml).

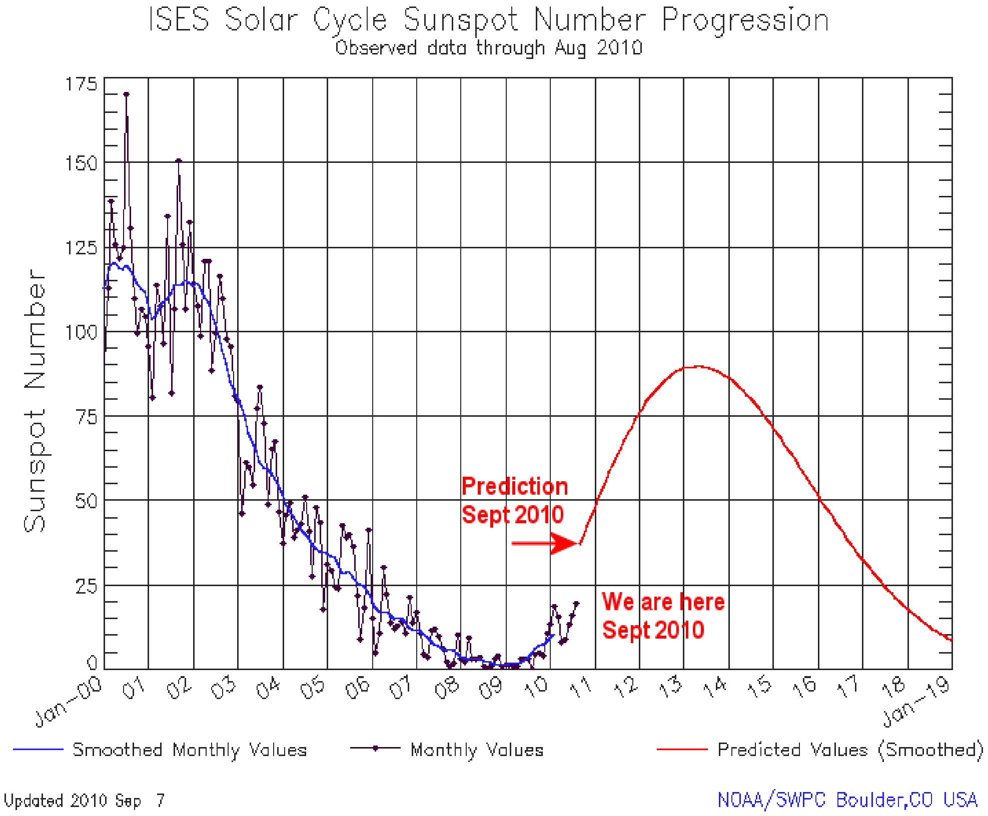


Figure 3. Recent evolution of the sunspot number (solar cycles 23 and 24, (black and blue solid line), compared to the predicted values (red line). A first prediction of solar cycle 24 gave a TSI (Total Solar Irradiance) maximum at least as large as that of cycle 23. Note that the sunspot number is positively correlated (but not necessarily proportional) to the TSI.

Natural variations of the intensity of the Atlantic Meridional Overturning Circulation (AMOC) are also assessed from SST observations made since 1850. They reveal a global mode of variation which has weakened continuously since around 1930, and an Atlantic mode, which suffered an abrupt shift (decrease) around 1970. The Atlantic mode recovered afterwards but it is expected that it will decrease again in the near future (*Dima and Lohman, 2010*). Physical mechanisms responsible for these variations are not well understood (*Frankcombe et al., 2010*).

III. Extreme Situations

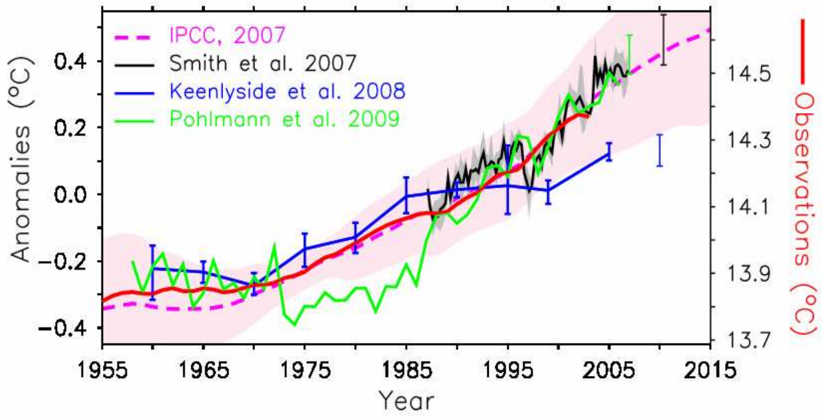
Climate changes are important not only because of changes in the mean values of the variables, but also because changes in the extremes are responsible for the strongest impacts. *Kendon et al.* (*2010*) found that predictions of increases in extreme precipitation in winter over Europe as a whole are judged to be reliable, dominated by increased atmospheric moisture with warming. A possible slowing down of the AMOC could be responsible for an increase in the land-sea warming contrast, reinforcing southerly winds over Europe and in particular over the Alps. In summer, increases in extreme precipitation over Northern Scandinavia and decreases over the Mediterranean are likely in the absence of considerable circulation change. Over central Europe, an increase in the proportion of summer rainfall falling as extreme events is likely.

Observations made during the 2003 heat wave have provided some insight into the physical mechanisms responsible for summer extremes such as summer droughts and heat waves. It has been shown that positive SST anomalies in the Arctic and/or the Mediterranean Sea are responsible for changes in the large scale atmospheric circulation, precluding precipitation over the European area (*Feudale and Shukla, 2010, a and b*). European Heat Waves may be significantly reinforced by the drying of the soils. Indeed *Jaeger and Severitnane* (*2010*) forced a regional climate model using ERA40 meteorological reanalysis and found that the intra-seasonal and inter-annual variability of soil moisture accounted for 5–30% and 10–40% respectively of the simulated heat wave anomaly. Stronger heat waves are expected in a warmer climate, but their intensities are expected on the whole to follow mean warming (*Ballester et al., 2010*).

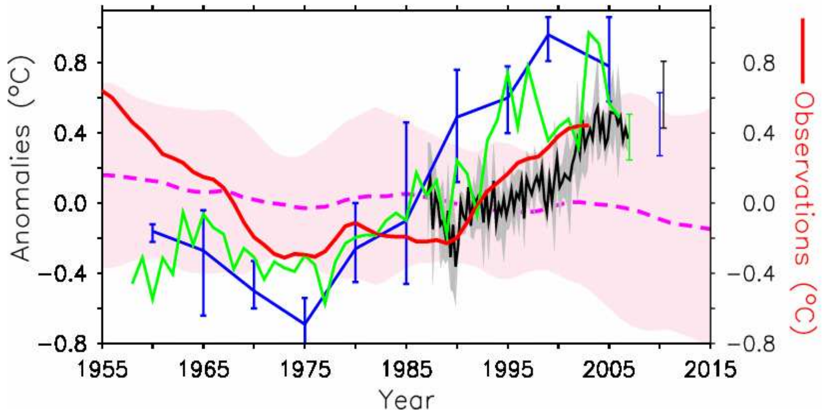
IV. Decadal Climate Prediction

Decadal climate prediction is a new area of research responding to the increased need of decision makers faced with time-evolving climate change and increasing temperatures. The decadal climate prediction is concerned typically with the near future (a time period of roughly the next 10 years) for which uncertainty about the emissions of GHGs and their impact on global warming is small. Indeed, emissions of GHGs during such a short period do not differ significantly from one scenario to the next nor does the warming due to these emissions. Furthermore, it is considered that the evolution of the climate system in the near future depends to a great extent on the present state of the climate system and in particular on the present state (in terms of temperature and salinity) of the ocean. Finally, physical processes contributing to enhanced prediction skill have been proposed (for example, the Atlantic Meridional Overturning Circulation (AMOC), the Pacific Decadal Oscillation / Interdecadal Pacific Oscillation in the Pacific). Nevertheless the mechanisms responsible for these oceanic circulations are not yet fully understood nor well simulated.

Decadal climate prediction uses the same models as those used for generating global change scenarios but in contrast with global change scenarios, initial conditions in the ocean model are prescribed from direct observations. Some examples of such predictions are shown in Fig. 4 and reveal a stabilization of the Atlantic SST dipole index, which is an indicator of the AMOC (panel B). The bottom graph of the Atlantic SST dipole indices, a proxy for MOC fluctuations, shows the SST average difference 60-10W, 40-60N minus 30W-10E, 10-40S. Hindcasts for Smith et al. (2007) begin in 1982, with one per season and four ensemble members (spread shaded); Keenlyside et al. (2008) begin in 1955, with one every five years and three ensemble members (vertical bars); and Pohlmann et al. (2009) begin in 1953, with one per year. The ensemble mean of 24 IPCC 2007 models (CMIP3, 20C + A1B scenario simulations) are shown, smoothed with a 10-year running mean; pink shading indicates ±1.65 the standard deviation of the ensemble spread. Separate vertical bars centred on the predicted period show future forecasts. The Pohlmann et al. (2009) forecast has seven ensemble members. Smith et al. (2007), Keenlyside et al. (2008), and Pohlmann et al. (2009) hindcasts have been adjusted to have the observed means over the 1979-2001, 1955-2005, and 1953-2001 periods, respectively. Observations are from HadISST 1.1 and HadCRU3, and have been smoothed with a 10-year running mean. (from Murphy et al., 2009).



(A) Global average surface temperature



(B) Atlantic SST dipole index

Figure 4: Observed and hindcast ten year mean global surface temperature (top) and Atlantic SST dipole indices (bottom).

Nevertheless significant differences exist among the available predictions, mainly because of differences between the models and their initializations. It has recently been concluded that new model developments and oceanic observations are needed (*Murphy et al., 2009*).

For example, a significant improvement in the simulation of the NAO is expected from (i) an increase of the horizontal resolution by a factor of 2 in the atmosphere and (ii) the full inclusion of the stratosphere.

V. Conclusions

The climate of the Alps is linked to the European climate. A first conclusion of recent research is that atmospheric circulation changes play an important role in changes in the European climate. Variations of the NAO influence winter extremes such as minimum temperature and precipitation while the soil moisture deficit amplifies summer heat waves.

A new feature is the unexpected weakening of the solar cycle. For the first time since anthropogenic climate change began accelerating, solar and anthropogenic trends are now moving in opposite directions. It is possible that a decrease in solar activity could influence the atmospheric circulation, causing a cooling of the European climate during winter and subsequently counteracting the global warming, but only temporarily and regionally.

Decadal predictions are a new area of research. Their reliability must be firmly determined before they can be used by decision makers. This is all the more true given that the GCMs used to perform these predictions must be able to simulate correctly the influence of solar activity on climate evolution.

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Glossary of terms

Acronym	***Full term***
AMOC	Atlantic Meridional Overturning Circulation
AOGCM	Atmosphere-Ocean General Circulation Model
GCMs	Global Climate Models
GHGs	greenhouse gases
IPCC	Inter-governmental Panel on Climate Change
MOC	Meridional Overturning Circulation
NAO	North Atlantic oscillation
SCC	Surrogate climate change
SST	Sea surface temperature
TSI	Total Solar Irradiance

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THE IMPACTS OF CLIMATE CHANGE ON ALPINE TOURISM

An analysis based on the pilot sites of the Alpine Space project "ClimAlpTour"

Determining the local impacts of climate change on mountain tourism is a complex forecasting exercise which requires both qualitative and quantitative analysis of multiple factors – environmental, social and economic factors, etc – at different levels. We are therefore constrained by the available data in meeting this objective. Nevertheless we propose an approach which is intended to offer stakeholders in the pilot sites some basic explanations and analyses of the impacts of climate change on mountain tourism, in particular ski-related activities. The characteristics of the ClimAlpTour pilot sites will be considered in turn.

This study is based on analysis of three important elements:

- the evolution of regional climatic conditions and their impact on the natural environment;
- the analysis of the climatic characteristics specific to each pilot site; and
- the practical impacts of these changes on tourist activities according to the special features of each pilot site.

I. Preface : Limits of the study

The meteorological conditions which occur over the years at a particular site influence its tourism activities. Over the long term, this sequence of specific atmospheric conditions determines what is called its climate. Although stable over long periods of time, the climate itself evolves and changes as a result of natural factors and more recently, anthropogenic factors. These climatic changes can upset the existing socio-economic and environmental balances. It is therefore worthwhile to focus on the underlying transformations which could lead to this change and to forecast their evolution over time. In view of these changes, certain tourist activities become more vulnerable, others could be strengthened. But in what ways and for which pilot sites?

Three levels of uncertainty arise in considering these issues:

The first level of uncertainty surrounds how representative the meteorological data are to characterise the climate of a site and its past and future evolution. This point is discussed in more detail in Appendix 1.

The second level of uncertainty concerns knowledge of the full characteristics of a site: its topography, vegetation, socio-economic activities, history and so on.

Finally, the third level of uncertainty relates to knowledge of the specific features of existing tourism activities. The alteration of one climate-related parameter could have different effects on the same activity, depending on the site and its established practices.

The approach therefore needs to be simplified to achieve results that are consistent with our means.

In fact, in applied climatology, the methods are selected based on the available data and the desired goals. The aim of this study will therefore be to provide the first general observations about the vulnerability of tourism activities in the context of climate change, whilst recognising the gaps in the pilot site-specific climate data and the resulting uncertainties which arise. Knowledge of the local area is vital for this type of impact study. No scientific model can automatically generalise the impacts of climate change on mountain tourism without this knowledge. For this reason, it is down to each pilot site to tackle the problem, using first of all the results and proposals presented in this study, in order to address the issue in more depth with available experts who know the local area, the challenges and the potential impacts of climate change at the local level (university scientists, associations, etc).

Next therefore we will focus on changes in the climate and the expected impacts on certain types of tourism; then we will look at the activity of skiing, the only activity heavily dependant on a quantifiable physical parameter – snow – and on a backdrop – the topography – represented by the characteristics of the ski area. Effectively, for other activities, the natural environment has not yet had time to react to the changing climate, therefore the impact is not necessarily visible or measurable.

II. The changing climate

In order to establish past changes in the climate, long term climate data series of temperature, rainfall and snowfall (among others) must be used. In addition to the meteorological data collected by partners in the ClimAlpTour project, we will use comparable, complete data series in order to observe the changes taking place.

a) Changes in temperatures, rainfall and snowfall in the Alps

The study of alpine climate data series (Histalp data) highlighted four alpine zones for which the changes in temperatures are practically identical since 1850 (see Figures 1 to 5 at the end of this study).

Each tourist site can be pinpointed on the map (Figure 1) and we can then refer to the relevant running mean temperature change curve (Figures 2 to 5).

Generally speaking, the meteorological data measured in (or near to) the pilot sites and supplied by the ClimAlpTour partners correspond reasonably well with the longer temperature series shown in the figures below. However, the short periods of the data supplied (often around 10 years) are not long enough to enable valid comparisons. By default, and since the warming is global and reasonably uniform across the alpine area, we consider these longer temperature series as representative.

	1850/2007	1850/1975	1975/2007
NW	+1,71°C	+0,84°C	+1,63°C
NE	+1,52°C	+0,77°C	+1,5°C
SW	+1,51°C	+0,75°C	+1,53°C
SE	+1,37°C	+0.725°C	+1,62°C

Table. 1 : Increase in temperatures for each given period (linear trend)
Source:
Histalp data
http://www.zamg.ac.at/histalp

Table 1 shows a gradual temperature rise of around +0.75℃ from the end of the 19th century up to the 1980s, although the increase has accelerated since that time. Over the whole period, an increase in temperature of +1.71℃ was recorded for the NW area compared with +1.37℃ for the SE, although the latter area is now catching up.

In terms of rainfall, it remains relatively difficult to identify a significant trend. However, as can be observed on the map in Figure 6, the southern and eastern Alps have experienced a fall in rainfall since the 1960s. The Histalp data also point to the same phenomenon with a visible reduction in the south-eastern Alps.

With regards to snowfall, we can refer to the data series measured in central Switzerland and whose trend can be applied to the whole of the Alps, since it is correlated with the sharp increase in temperatures seen in the 1980s. The “snow depth” measure also follows the same trend (see Figure 7).

b) Climate outlook for the Alps

On the scale of the Alps, the climate models developed in the EU project “Prudence” formed the basis of a study using a regional scenario of temperature and rainfall calculated for Switzerland.

Two IPCC[1] average emissions scenarios (SRES[2] A2 and B2), four global climate models and eight regional climate models were combined in different ways in order to define relevant scenarios at the country level (OCCC-Proclim[3]).

Although most climate studies generally work on larger scales, this study aimed to define credible scenarios for the mountain environment. The outputs of the model are divided into two regional zones, the northern Alps and the southern Alps, and into four seasons (see Figures 8 and 9).

To refine the results between the eastern and western Alps, certain IPCC models centred on Europe are of benefit (see Figures 10 and 11). Based on the scenario A1B

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[1] Inter-governmental Panel on Climate Change

[2] The SRES scenarios are emissions scenarios named after the report in which they were published - the IPCC *Special Report on Emission Scenarios* (Nakicenovic *et al*., 2000).

[3] Organe Consultatif sur les Changements Climatiques, Proclim- Forum for Climate and Global Change (www.proclim.ch)

(which considers mixed energy supply, including fossil and non-fossil fuel sources), the model simulates the change in average temperatures in Europe between 1980/1999 and 2080/2099. We can observe that:

- winters will be 0.5℃ warmer in the eastern Alps than in the west;
- summers will be around 0.5 to 1℃ warmer in the southern Alps than in the north;
- rainfall in winter will fall sharply in the southern and western Alps.

III. Impacts of climate change on natural resources

The possible impacts of climate change in the Alps are :

- Increase in temperatures;
- Changes in rainfall patterns, with more marked droughts in summer;
- Reduction in snow cover;
- Changes in the regimes of water courses, with more dry courses in summer;
- Reduction in water resources;
- Changes in agricultural practices, biodiversity and so landscapes;
- Increase in natural hazards : rock falls, landslides, falling ice blocks, floods.

All these impacts could directly or indirectly affect tourist activities. Skiing and cross-country skiing depend on snow cover. Water activities such as canyoning depend on the behaviour of water courses. Hiking and mountain-biking will become more risky as natural hazards increase. At the same time, the increase in temperatures could also bring more tourists to the Alps in summer as they attempt to escape the higher temperatures at lower altitudes. All these impacts are described in detail in the specialist literature.

IV. Vulnerability of tourist activities to climate change

Cross country skiing

This activity is practiced for the most part at the bottom of the slopes, in the valley or in the forests. This means that the snow covering is less exposed to the sun. Techniques for packing the snow and planning the trails are also effective. On the other hand, the trails are often at relatively low elevations. The greatest risk is therefore a lack of snow or very little snow in any particular year, which would preclude the activity. Still, it does not require a great deal of snowfall to create sufficient snow cover. In the context of global warming, it is clearly not expected that snowfall will cease, rather that the rain-snow line will move higher and that temporary increases in temperature and warm periods in winter will become more common, conditions which will significantly weaken the blanket of snow at low and medium elevations.

As in the case of downhill skiing, sites which are already experiencing problems of lack of snow and which cannot extend their domains to higher altitudes will become more and more vulnerable for cross country skiing activities.

Hiking, mountaineering, high-mountain activities

The principal threat from climate change to these activities is the increase in natural hazards. The expected impacts are the melting of glaciers, leading to blocks of ice falling and to avalanches, and the melting of permafrost, causing large-scale mudslides and rock falls. The increased incidence of extreme rainfall could also lead to landslides. It is therefore important to remain alert to these hazards and to mark the trails well, providing information to the public.

Even more so with the increase in temperatures, hiking will become more and more popular as an activity in summer as holiday-makers or residents seek to escape the summer heat-waves.

White-water activities (canyoning, etc)

In the context of climate change, we can expect significant stress on water resources, with more severe low water levels in summer and so the risk of finding the rivers dried up, even if in the short term glacier melt (if there is one) will compensate for the hydrological shortage. It is important for water managers and public authorities to deal with the problem of water resources with great care, as water constitutes the cornerstone of mountain tourism. A lack of water, or at least its scarcity, will have consequences way beyond the simple practice of a tourist activity. A well-planned, global management strategy should therefore be envisaged in this regard.

Mountain-biking

Mountain-biking should not be affected by climate change.

Bathing (lakes, swimming pools)

With the increase in temperatures, we can expect an increase in popularity of these bathing spots, bringing with it potentially detrimental environmental impacts.

Hydrotherapy

In terms of the hydrotherapy industry, client management and management of the hydrothermal resources are considerably more important aspects than climate change.

Classic skiing

Since the 1980s, the average winter temperature (December, January, February) in the Alps has increased by 1℃ (the decade 1990-2000 recording milder winters than the decade 2000-2010, in spite of the winter 2006/7). Scientists and users alike have seen the resulting difference in snow cover, in terms of the number of days of snow and the snow depth. Inter-year variability has also become more pronounced, with winters without snow such as in 2006/7 alternating with winters with high snowfall such as in 2008/9. Moreover, it is precisely those years with a lack of snow which concern resort managers. As we can see, the impacts of climate change on the winter season are far from linear. However, over the long term, important changes in snow cover will be seen if temperatures continue to increase, the main consequences being the rise in the rain-snow limit and the rapid melting of the snow cover in anti-cyclonic weather or at the beginning and end of winter. It is therefore the aim of this study to forewarn resort managers about the vulnerability of their tourism activities, bearing in mind that technical adaptation solutions (artificial snow, etc) will never be able to compensate entirely for a lack of natural snow, unless extraordinary new technical advances are made.

In the Alps, classic skiing holds a very particular place both in tourism and in economic terms. It is distinguished by the use of a natural resource (snow) which is present only during part of the year, and more or less unpredictably. This parameter, which has an insurmountable impact on the ability to ski, has the advantage that it can be measured and compared with changes in other climate-related parameters, unlike other ‘natural services’, on which sports such as hiking or mountain-biking for example depend. Impact analyses are therefore made easier.

In addition, limitations exist in terms of the altitude of the ski area. These limitations make the impact analyses much easier because they avoid the necessity to use various series of climatological measures, which may not necessarily be representative. Indeed, various ways exist to determine the reliability of snow in ski resorts.

The technique employed in this study is that developed by the OECD based on the one hundred day rule and the altitude of the reliable natural snow limit. This limit fluctuates from one place to another in the Alpine Arc, as the climate itself varies enormously in the different areas of the Alps. These limits are shown in Table 3. Further details and supplementary information can be found in the OECD study (Climate Change in the European Alps: Adapting Winter Tourism and Natural Hazards Management, OECD 2007).

In this analysis, *a given ski area is considered to be reliable in terms of its natural snow cover if the upper half of the altitude range in which it is situated is above the threshold value for the limit of natural snow reliability*. This hypothesis is based on the fact that the essential components of a ski resort are situated in the upper part of the ski area. The majority of operators provide “aerial” connections to the highest-situated areas, with chair lifts, cable cars, etc. in order to maintain the activity, including in instances where there is a lack of snow at the bottom of the slopes.

The limit of natural snow reliability is therefore a valuable tool in situations where local data are lacking. However, if we wish to analyse in more depth a particular ski area, additional local factors should be considered in order to take into account the actual characteristics of climate, topography and use. See *Appendix 2*: The role of the orientation and the gradient of slopes.

Finally, we are obliged to make use of a climatic projection method to forecast the effects of warming on the natural snow reliability limit. According to estimates, in a warmer climate, the snow line, and also the limit of natural snow reliability, will rise by 150m for each degree Celsius increase in temperature (Föhn, 1990 and Haeberli and Beniston, 1998). As a consequence, a change in the climate could result in the limit of natural snow reliability rising by 150m, 300m and 600m respectively if the warming were 1℃, 2℃ or 4℃. With the use of climate models, it is possible to determine a time horizon depending on the anticipated temperature increase. We use the results of the modelling from the “Prudence” project described above.

V. Interpretation of the data

Table 2: Climatic characteristics of the pilot sites

The average temperatures shown are the result of analysis of the ClimAlpTour data with an indication of the name and elevation of the measurement station. These average data, and in particular the winter averages, show the level of vulnerability of the pilot site to any warming: if the average winter temperature of a low altitude site is currently around 0℃, there is a strong probability that the snow cover will be affected by significant melting in the decades to come. The snow height measures are also informative as the minimum heights measured are highly likely to be repeated in the future (unlike the maximum heights), the currently low values (minimum snow depth of less than 1m or average snow depth of less than 2m) showing high vulnerability. Finally the reference climate series allows us to ascertain the intensity of warming of a nearby measurement station.

Table 3: Analysis of vulnerability to climate change based on specific characteristics of the ski area

For each pilot site, the following parameters are considered :

- the limit of natural snow reliability
- the average elevation of the ski area
- the range of temperatures for which the snow reliability limit will move above the average elevation of the ski area, and
- the time horizon within which this rise is anticipated.

This same technique is then applied to the bottom of the ski area.

A “non-viable” situation is indicated when the current limit of natural snow reliability is close to or higher than the average elevation of the ski area. This does not mean that at present there is not enough snow for skiing, but that now or in the near future, the ski resort could experience serious problems of snow cover, for example some years without snow, which could impact the economic viability of the resort. This is why the concept of risk, or vulnerability, is expressed in terms of probability. It is also possible that the resort experience some years of very good snow cover, however in the context of climate change, resort managers should still bear in mind this vulnerability.

Vulnerability analysis criteria : a system of evaluation using stars

An evaluation system (using stars) has been developed to summarise the different parameters, both quantitative and qualitative, which have been considered in this analysis. This system is based primarily on the **limit of natural snow reliability**, and the result is then **adjusted** to take into account other parameters which can be grouped under three headings:

- Meteorological data (temperature, snow cover) provided in Table 2. Since these data are not necessarily representative (as explained above), only exceptional values are taken into account ;

- The topography of the ski area: the orientation of the ski slopes, local topography (position at the bottom of a valley, in a bowl or on a mountainside) and the geographic position (northern Alps, southern Alps, etc) ;
- Elevation of the bottom of the resort.

The assessment system comprises five values including a specific assessment for “bottom of the resort”.

* : **Not vulnerable**
** : **Low vulnerability**
b : **High vulnerability at the bottom of the resort but low vulnerability at higher elevations
*** : **Reasonably high vulnerability**
**** : **High vulnerability**

Examples :

- If a ski resort is considered ‘always viable’, it will be assessed ‘* - Not vulnerable’. If the meteorological data related to that resort show relatively low snow cover, mild winter temperatures for the altitude with ski slopes facing south, a low average elevation or if the resort is situated in an area with a high potential warming, the assessment will be downgraded to **.
- If the bottom of the resort is at a very low altitude, and so is very vulnerable to any warming, its assessment will be **b.
- If a resort is considered not viable in the event of a +1 or +2℃ temperature increase, its initial assessment will be *** , which will then be adjusted to take account of its specific meteorological and other features.

Table 2 : Climatic characteristics of the pilot sites

Country / Pilot site	Reference meteorological station	Average Temp℃ 1995 - 2007	Av. Temp℃ Winter NDJFMA 1996/2007	Av Temp℃ Winter DJF 1996/2007	Average annual snow depth (cm) 1996/2007	Nearest long-term meteorological data series
Germany Berchtesgaden	Kuehroint (1415m)	5,18	0	-1,76		Innsbruck (570m) 1961/2007 : +1.8℃ Sonnblick (3106m) 1950/2009 : +1.7℃ Source: ECA&D
Austria Stubaital	Telfes (895m)	6,71	0,94	-1,5		
	Dresdner Hutte (2290m)	0,8	-4,4	-5,9		
	Plon (1200m)				Av : 214 Max : 425 Min : 120	
Austria Wilder Kaiser	Ellmau (750m)	6,99	0,58	-2,41		
	Kitzbühler (1790m)	3,56	-1,51	-3	Av : 719 Max : 1066 Min : 483	
France Les Gets	Les Gets (1172m)	6,85	1,21	-0,91	Av : 453 Max : 886 Min : 270	Savoie 1950/2009 +1,75℃ Source : Météo France
France Les7Laux	St Colomban (1100m)	7,69	2,33	0	Av : 295 Max : 546 Min : 166	
France Montgenèvre	Montgenèvre (1850m)	4,81	-0,75	-2,8	Av : 407 Max : 633 Min : 263	
France Val d'Isère	Bessans (1715m)	3,99	-2,66	-5,73	Av : 424 Max : 558 Min : 322	
Italy Auronzo	Auronzo (849m)	6,96	0,6	-2,68	Av : 60 Max : 90 Min : 30	Cortina d'Ampezzo (1270m) +1,33℃ (1950/2002) Source: Histalp
	Misurina (1748m)	3,23	-2,32	-4,42		
Italy Entracque	Rocca dell'Abisso (2020 m)	0,92	-3,76	-5,88	Av : 263 Max : 531 Min : 68	Cuneo (536m) +1,35℃ (1950/2007) Source: Histalp
Italy Alto Tanaro C.M.	Bergalli (385 m)	11,3	4,7	2,1		
	Monte Berlino (1765 m)	4,9	0	-1,12		
	Roburent (1203m)				Av : 202 Max : 360 Min : 47	

Country / Pilot site	Reference meteorological station	Average Temp℃ 1995 - 2007	Av. Temp℃ Winter NDJFMA 1996/2007	Av Temp℃ Winter DJF 1996/2007	Average annual snow depth (cm) 1996/2007	Nearest long-term meteorological data series
Italy Monterosa	Eselbode (1642m)	6,2	1,2	-1	Av : 260 Max : 512 Min : 130 (1637m)	Col du Grand St Bernard (2472 m) 1959/2009 : +1,88℃ Source : Météo Suisse
	Gabiet (2379m)	2,3	-2,43	-4,9		
Italy Presolana Monte Pora	Clusone (303m)	Data error				Milano (122m) +1,77℃ 1950/2007 Source: Histalp
	Barbelino (1900m)				Av : 410 Max : 750 Min : 148	
Italy Valgrisenche	Valgrisenche (1664m)	4,8	-0.6	-2,7	Av : 290 Max :428 Min : 200	Col du Grand St Bernard (2472 m) 1959/2009 : +1,88℃ Source : Météo Suisse
Slovenia Kranjska Gora	Ratece - Planica (864m)	6,79	0,3	-2,8		Kredarica (2514m) 1970/2008 : +1,56℃ Source : ECA&D
	Kredarica (2514m)	-0,85	-5,75	-7	Av : 374 Max : 700 Min : 195	
	Kranjska Gora (804m)				Av : 186 Max : 385 Min : 106	
Slovenia Upper Soca Valley	Bovec (441m)	9,95	3,79	0,68		
	Vogel (1535m)				Av : 50 Max : 136 Min : 6	
	Sella Nevea (IT) (1190m)				Av : 353 Max : 707 Min : 93	

Table 3 : Analysis of vulnerability to climate change based on specific characteristics of the ski area

Country / pilot site	Ski resort	Snow reliability limit	Average altitude of ski area	Orientation of ski slopes	Ski resort not viable at :	Time horizon	Base of the station not viable at :	Time horizon	Vulnerability assessment
Germany Berchtesgaden	Jenner	1050m	1500m	N	+3℃	2070/ 2100	+1℃	2030	**b
Austria Stubaital	Skigebietschlick	1100m	1700m	N	+4℃	2100	+1℃	2030	**b
	Serles Bahnen	1100m	1350m	N	+1℃ / +2℃	2030 / 2050	+1℃	2030	***
	Elfer Skigebiet	1100m	1500m	N	+2℃ / +3℃	2050 / 2070	+1℃	2030	***
	Stubaier Gletscher	1100m	2800m	E	Always viable	-	-	-	*
France Les Gets	Les Gets	1100m	1600m	SW / NW	+3℃ / +4℃	2100	+1℃	2030	**b
France Val d'Isère	Val d'Isère	1300m	2600m	E / N / S	Always viable	-	+4℃	2070/2100	*
France Les 7 Laux	Les 7 Laux	1200m	1900m	W / E	+3℃ / +4℃	2100	+1℃	2030	***
France Montgenèvre	Montgenèvre	1400m	2200m	N	Always viable	-	+3℃	2070	*
Italy Alto Tanaro Communita Montana	Garessio	1500m	1550m	N	+1℃	2030	Non fiable	-	***
	Viola St Gree	1500m	1350m	N	Not viable	-	-	-	****

Country / pilot site	Ski resort	Snow reliability limit	Average altitude of ski area	Orientation of ski slopes	Ski resort not viable at :	Time horizon	Base of the station not viable at :	Time horizon	Vulnerability assessment
Italy Auronzo	Auronzo di Cadore	1400m	1200m	N	Not viable	-	-	-	****
	Misurina	1400m	1850m	NW	+3℃	2070/ 2100	+2℃	2050	**
Italy Entracque	Sciovie del Viver	1500m	1050m	SW	Not viable	-	-	-	*****
Italy Monterosa	Antagnod	1300m	2000m	SE	Always viable	-	+3℃	2070	**
	Gressoney la Trinité	1300m	2400	E/W/S	Always viable	-	+3℃	2070	*
	Gressoney St Jean	1300m	1700	NE	+2℃/+3℃	2050/ 2070	+1℃	2030	**b
	Champoluc	1300m	2100	W	Always viable		+3℃	2070	**
Italy Presolana Monte Pora	Presolana	1400m	1300m	NW	+1℃	2030	Non fiable	-	** *
	Monte Pora	1400m	1650m	NW	+2℃	2050	+1℃	2030	**b
Italy Valgrisenche	Valgrisenche	1300	1800	-	+3℃ / +4℃	2070/ 2100	+2℃	2050	**
Slovenia Kranjska Gora	Kranjska Gora	1300m	1000m	N	Not viable	-	-	-	****
Slovenia Upper Soca Valley	Kanin	1300m	2000m	SE	+4℃	2100	+3℃	2070	**
	Sella Neva (I)	1300m	1500m	NW	+2℃	2050	+1℃	2030	* *b

VI. Conclusion

The impacts of climate change will have both direct and above all indirect repercussions on tourism. Thus, changes to biodiversity – flora and fauna –, to agriculture, glacier melt and the transformation of landscapes are so many factors which could modify the behaviour and needs of the clientele. The mountain is a relatively isolated system within which everything is related. An impact on one sector will necessarily have repercussions on others. In order to anticipate these problems, specific, localised studies which identify the full range of possible impacts of climate change on a territory would allow these different interrelationships to be identified. A concrete example of this exists in Savoie, France in the form of the "*Livre Blanc du Climat en Savoie*" (The White Book on Climate in Savoie, 2010).

The climate is but one more factor which comes on top of the huge complexity of tourism mechanisms and its development. However, in the context of increasing temperatures and the foreseeable consequences on territories and social, economic and environmental spheres, an element of forecasting can be made. This is what this study aims to provide - a clearer vision of the challenges of tomorrow.

Analysis also available in French.
Translation to English by Sarah Rutter.

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APPENDICES

Appendix 1 : Problems in interpreting climate data

The data available through the ClimAlpTour project were in most cases measured several kilometres from the pilot site, the series are often incomplete and many cover only a short period of time (around ten years). The use of a series of temperature data from one location to understand the unique thermal features of another location is problematic since, in the mountain environment, the climate varies significantly from one place to another (the same is true for the other parameters used in the study). The geographical relief of the landscape influences the climate, whether on a fine scale (micro-climate) or on a scale of several kilometres (topo-climate). There exists therefore a multitude of different climates in the mountain area, depending on topography, altitude and position in relation to the general atmospheric circulation.

In addition, the short-term local data series available reveal more the meteorology year by year than a long-term trend which could bring to light a particular specific sensitivity to climate change.

What we can find however in a long-term climate series is a trend. And these trends are broadly all the same over the last 100 years or so across the entire Alps, or at least across large areas. The local data do nothing but follow this underlying trend, at the same time highlighting particular features (a site at the bottom of the valley will be colder and less sensitive due to temperature inversions than a site on the mountainside, well exposed to the sun).

Appendix 2 : The role of the orientation and the gradient of slopes

The daily energy received by a mountainside facing south is four times greater than that received by a north-facing side and twice more than an easterly or westerly-facing side (for these last two orientations we assume that the west-facing slope, exposed to the sun in the second half of the day, is more at risk from warming than the east-facing slope). In conclusion, the snow cover on a south-facing slope and to a lesser extent a west-facing slope is far more at risk of melting than that on north- and east- facing slopes.

The gradient of the slopes can also play an important role in determining the thickness of snow. Thus, at the end of March, the depth of snow on a north-facing slope with a gradient of 20° is twice that on a flat surface, while on a south-facing slope with a gradient of 20°, the snow depth is only 30% of that found on the flat surface.

FIGURES

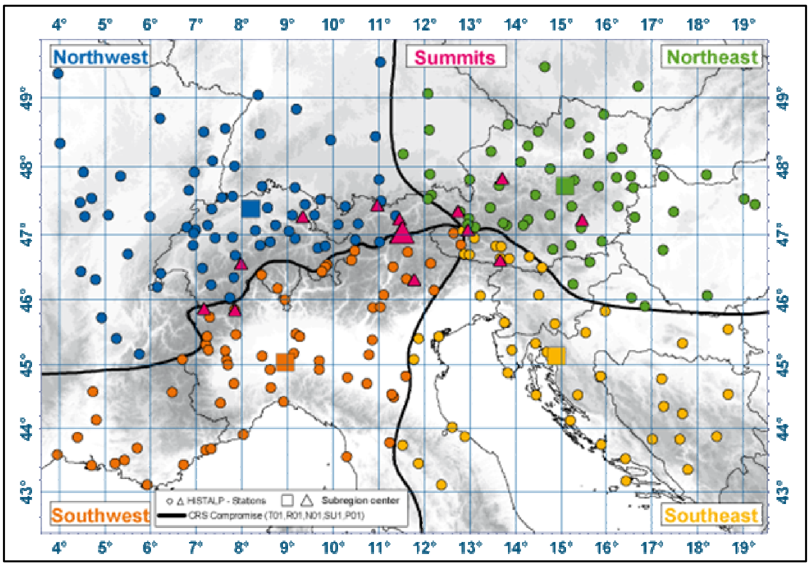
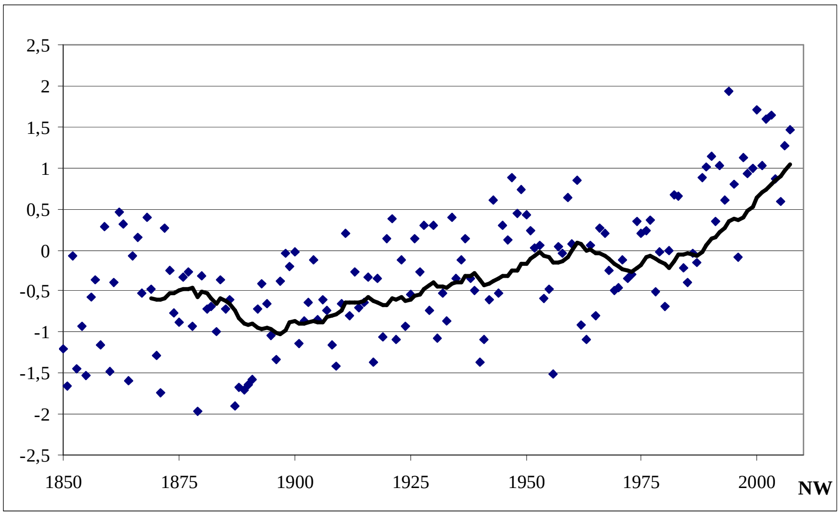
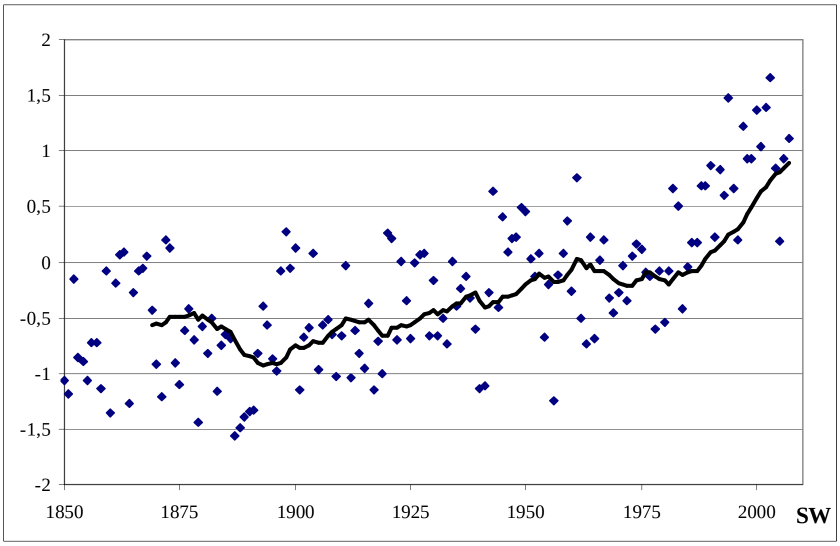
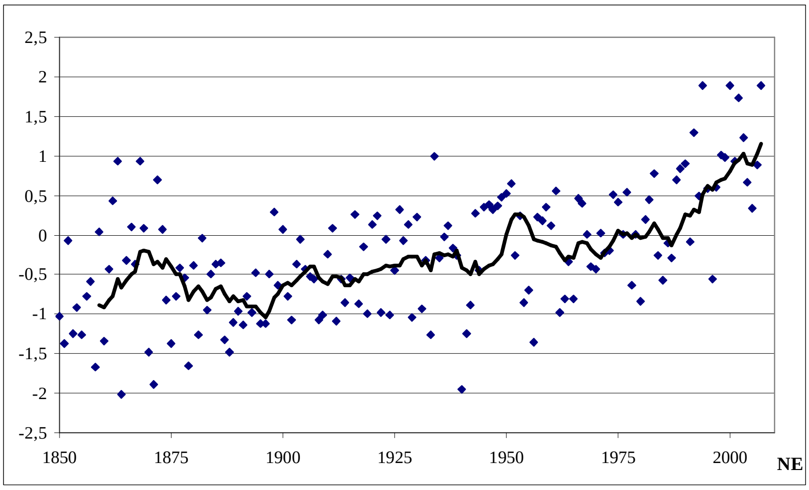


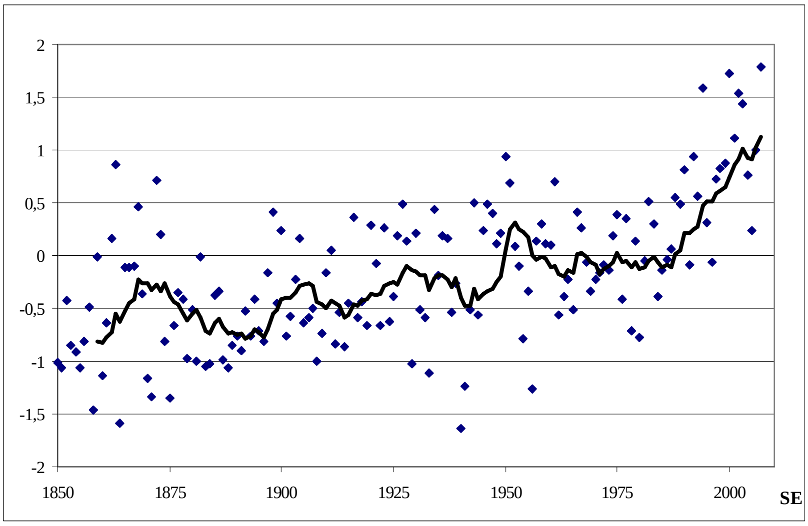
Fig. 1 : Map of position of measuring points used in the Histalp project. Division of the Alps into four climatically homogenous sub-regions (NW, SW, NE, SE). *Source :* http://www.zamg.ac.at/histalp



Figs. 2, 3, 4, 5 : Average annual differences in temperatures for the four identified areas of the Alps (NW, SW, NE, SE) from 1850 to 2007 (compared with the period 1961-1990).
Black curve : moving average.
Source : http://www.zamg.ac.at/histalp







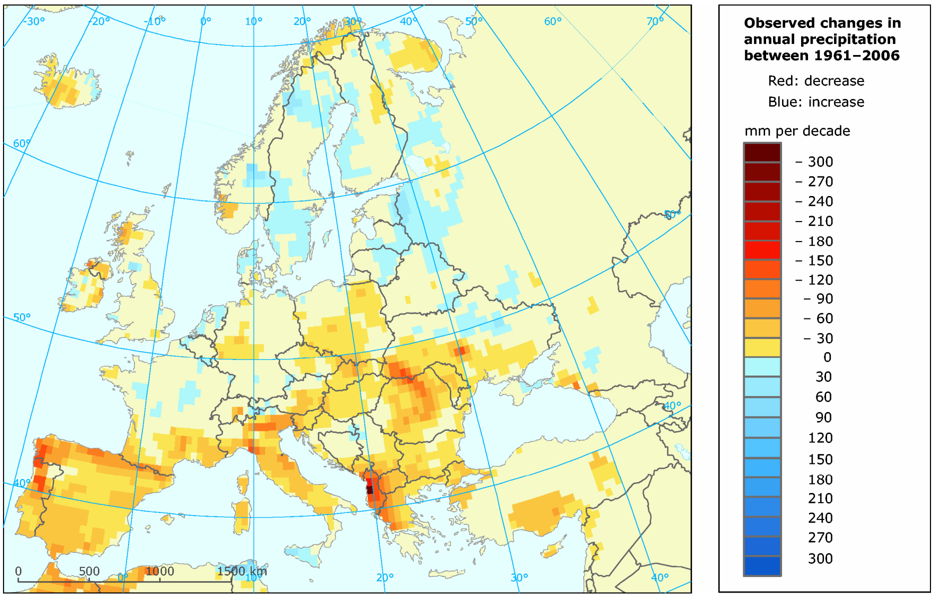


Fig. 6 : Observed changes in annual precipitation between 1961 and 2006.
Source:
EEA Report, Impacts of Europe's changing climate – 2008 indictor-based assessment.

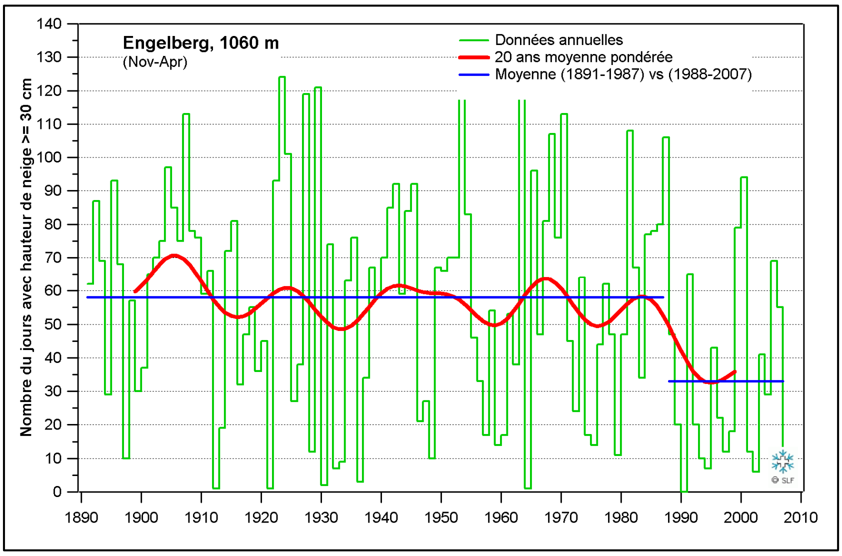
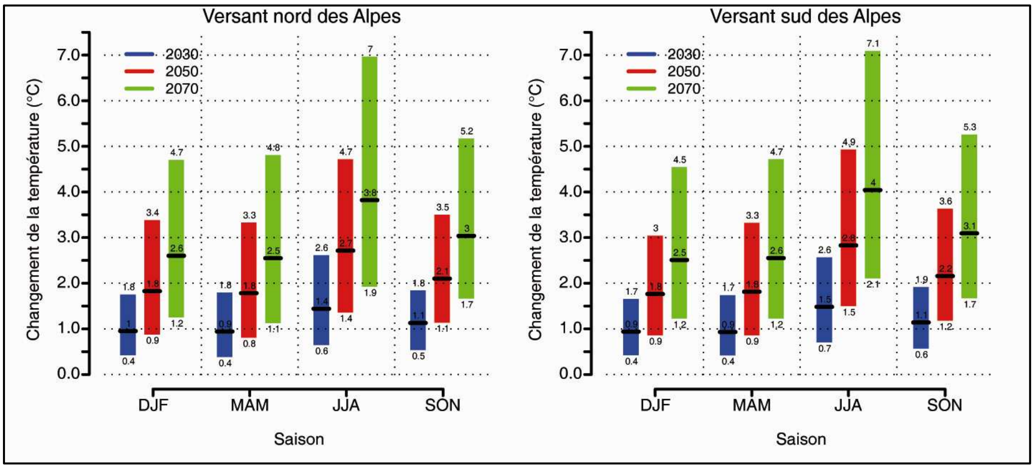


Fig. 7 : Number of days with a snow depth over 30cm in Engelberg (Switzerland) between 1891 and 2007. *Courtesy of SLF. Seiz, G., Foppa, N., 2007. Système national d'observation du climat (GCOS Suisse), Publication de Météo-Suisse et de ProClim, 92p.*



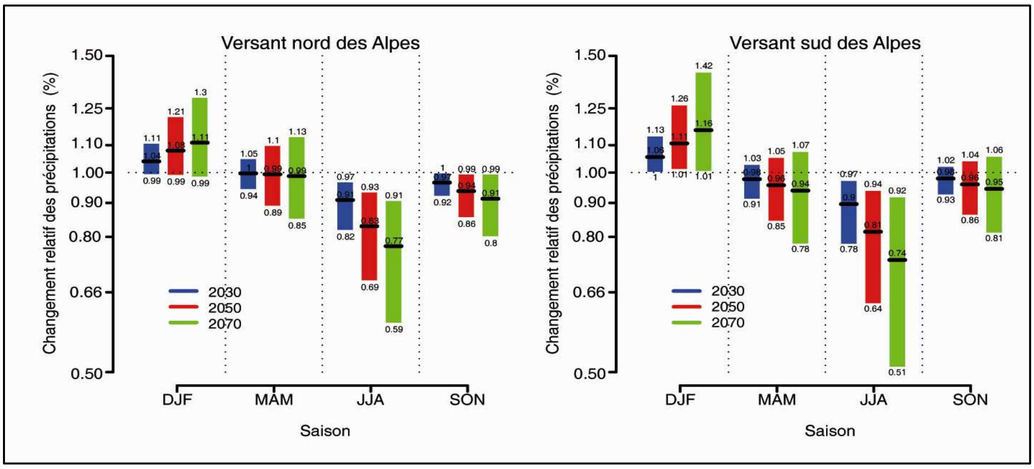
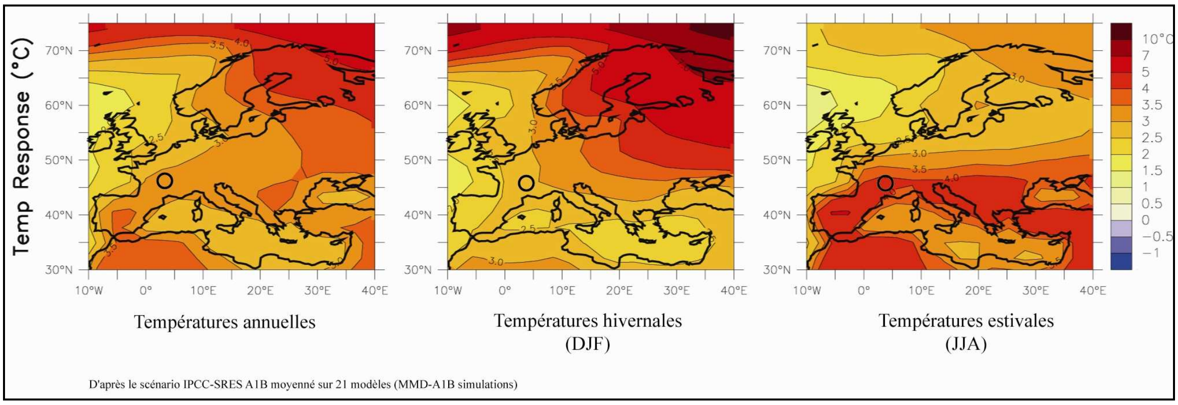


Fig. 8 : Differences in **average temperature** in winter (December, January, February), spring (March April May), summer (June July and August) and autumn (September October November) on north-facing slopes (versant nord) and south-facing slopes (versant sud) of the Alps in 2030, 2050 and 2070 compared with 1990. http ://www.proclim.ch/4dcgi/proclim/en/Media?794
Fig. 9 : Differences in **average rainfall** in winter (December, January, February), spring, summer and autumn on north-facing and south-facing slopes of the Alps in 2030, 2050 and 2070 compared with 1990.
Source : OCCC, Proclim

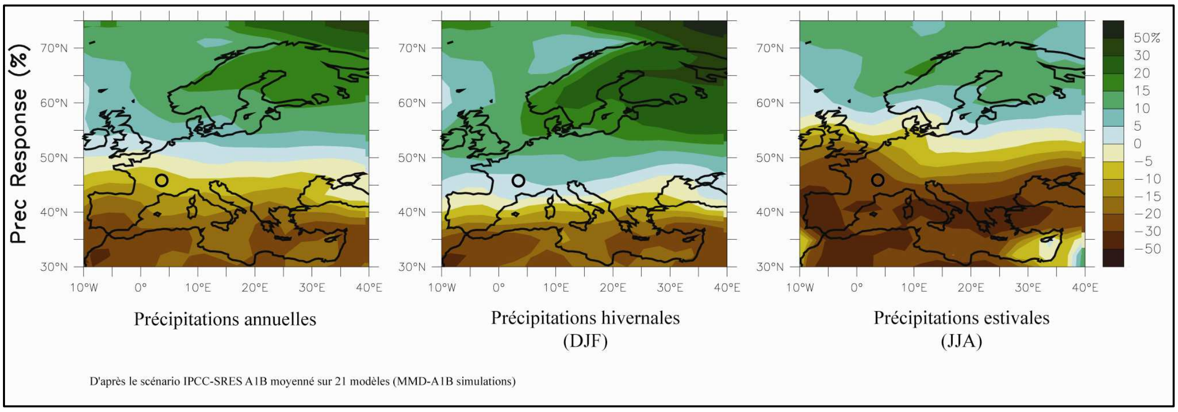


Températures annuelles

Températures hivernales
(DJF)

Températures estivales
(JJA)

D'après le scénario IPCC-SRES A1B moyenné sur 21 modèles (MMD-A1B simulations)



Précipitations annuelles

Précipitations hivernales
(DJF)

Précipitations estivales
(JJA)

D'après le scénario IPCC-SRES A1B moyenné sur 21 modèles (MMD-A1B simulations)

Fig. 10 – Changes in average temperatures in Europe between 1980-1999 and 2080-2099.
Fig. 11 – Change in average precipitation in Europe between 1980-1999 and 2080-2099.
Source : IPCC, Christensen et al, 2007

Data sources :
Histalp : http://www.zamg.ac.at/histalp/content/view/35/1/index.html

European Climate Assessment & Dataset (ECA&D) :
http://eca.knmi.nl/dailydata/datadictionary.php

OCCC-Proclim
www.occc.ch/Products/CH2050/CH2050-Scenarien.pdf

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Tofane, Cristallo et Col di Lana vus depuis les pentes de ski du Col de Padon, Italy ; Un bateau sur le lac d'Achen, Austria ; Lac de Garde et des skieurs du Mont Paganella, Italy ; Le tourisme balnéaire au bord du lac de Molveno, Italy. All photos © Andrea Bianchini, Italy