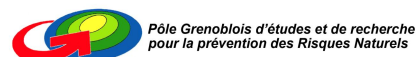


Rhône-Alpes Région



Observatoire National sur les Effets du
Réchauffement Climatique

Climate change in the Alps: Impacts and natural hazards

Rapport Technique N°1 de l'ONERC
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ClimChAlp
Interreg III B Alpine Space



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OBSERVATOIRE NATIONAL SUR LES EFFETS DU RÉCHAUFFEMENT CLIMATIQUE. *Climate change and resulting impacts in the Alps*. Paris: ONERC, 2008. 95 p.

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Temperatures



Precipitations



Glaciers



Snow cover



Permafrost



Vegetation



Floods



Debris flows and
torrential events



Avalanches



Mass movements



Glacial hazards



Storms



Forest fires



List of Acronyms

ALP-IMP : Multi-centennial climate variability in the Alps based on Instrumental data, Model simulations and Proxy data

ARPA-Piemonte: Agenzia regionale per la protezione dell'ambiente della piemonte (Regional agency for the environment protection of Piedmont, Italy)

AR4: Fourth assessment report of the IPCC (2007)

BRGM: Bureau des risques géologiques et miniers (Office for geologic and mining risks, France)

Cemagref: Institut de recherche pour l'ingénierie de l'agriculture et de l'environnement (Research institute for agriculture and environment engineering, France)

CEN: Centre d'étude de la neige de Météo France (Centre for snow studies, France)

CESR: Conseil économique et social de la Région (Regional social and economic council, France)

CETE: Centre d'étude technique de l'Équipement (Technical centre for studies of the Equipement)

CSM: Conseil supérieur de la météorologie (Superior council of meteorology, France)

CUDAM: Centro universitario per la difesa idrogeologica dell'ambiente montano (University centre for the hydrogeologic protection of the mountain environment, Italy)

DJF: December-January-February

DTM: Développement des territoires de montagne (Mountain territories development, Cemagref division, France)

EA: East Atlantic pattern

EAWR: East Atlantic West Russia pattern

ENSO: El Niño Southern Oscillation

EPA: Enquête permanente sur les avalanches (Permanent avalanche monitoring action, France)

ETNA: Érosion torrentielle, neige et avalanche (Torrential erosion, snow and avalanche, Cemagref division, France)

E & F: Eaux et forêts (Service for forest and water, France)

FOEN: Federal office for the environment

FMS: Fondazione montagna sicura (Secured mountain foundation, Italy)

GCM: General circulation model

GLACIORISK: Survey of extreme glaciological hazards in European mountainous regions

GLOF: Glacial lake outburst flooding

HH: Hydrologie-hydraulique (Hydrology-hydraulic, Cemagref division, France)

IGC: Italian glaciological committee

IGN: Institut géographique national (National geographic institute, France)

INRA: Institut national de recherche agronomique (National institute for agronomical research, France)

IPCC: International panel on climate change

IPSL: Institut Pierre Simon Laplace (Institute Pierre Simon Laplace, France)

IRMa: Institut des risques majeurs de Grenoble (Institute on major hazards from Grenoble, France)

JJA: June-July-August

KLIWA: Klimaveränderung und Konsequenzen für die Wasserwirtschaft (Climate change and consequences for water management, Germany)

LCPC: Laboratoire centre des ponts et chaussées (Public work research laboratory, France)

LGGE: Laboratoire de glaciologie et de géophysique de l'environnement (Laboratory of glaciology and environmental geophysics, France)

LGIT: Laboratoire de géophysique interne et de tectonophysique (Laboratory of internal geophysics and tectonophysics, France)

LIA: Little ice age

LST: Laboratoire des sciences de la Terre (Laboratory for Earth science, France)

LTHE: Laboratoire d'étude des transferts en hydraulique et en environnement (Laboratory for study of hydraulic and environmental transfer, France)

MEDAD: Ministère de l'écologie, du développement et de l'aménagement durables (Ministry for ecology, sustainable development and landplanning, France)

MWP: Medieval warm period

NAO: North Atlantic oscillation

NRP 31: National research program 31 of Switzerland

OAGCM: Ocean atmosphere coupled general circulation model

OECD: Organisation for economic co-operation and development

ONERC: Observatoire national sur les effets du réchauffement climatique (National observatory on the impacts of climate change, France)

ONF: Office national des forêts (National office for forest, France)

PACE: Permafrost and climate in Europe

PERMOS: Permafrost monitoring Switzerland

PGRN: Pôle grenoblois d'étude et de recherche pour la prévention et la protection des risques naturels (Grenoble research pole for natural hazards prevention and protection, France).

RCM: Regional climate model

RTM: Restauration des terrains de montagne (Mountain soils rehabilitation service, ONF, France)

SAI: Standardized anomaly index

SCAN: Scandinavian pattern

SDIS: Service départemental d'incendie et de secours (Departmental services for fire and emergency, France)

SDM: Statistical downscaling method

SLF: Institut für chnee und Lawinen Forschung (Federal institute for snow and avalanche studies)

SRES: Special reports emissions scenarios of the IPCC

STARDEX: Statistical and regional dynamical downscaling of extremes for European regions

TAR: Third assessment report of the IPCC (2001)

TORAVAL: Engineering group for hydrologic hazards in mountains (France)

UCBL: Université Claude Bernard de Lyon (Claude Bernard University of Lyon, France)

VAW: Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (Research institute for hydrology and glaciology, Switzerland)

w.e.: Water equivalent

WGMS: World glacier monitoring service

WP: Work package (in the ClimChAlp project)

Introduction

Evidence of human induced climate change has become increasingly evident as reports by the International Panel on Climate Change (IPCC, see the list of acronyms, p. 70) are giving more accurate assessments of global climate change throughout recent years (1990, 1995, 2001 and 2007).

It is now largely accepted that current warming is due to the combination of natural fluctuations and anthropogenic forcing of the climate. These changes affecting the global climate already have and will continue to have consequences on both oceanic and terrestrial ecosystems and consequently impacts on human activities and settlements.

Not all regions will be affected by climate change in the same way. Within Europe, mountain ranges and coastal areas are among the most vulnerable territories facing climate change. Natural systems and processes in the Alps (ecosystems, rivers patterns, erosion processes, etc.) are closely related to temperature and its evolution. Isotherms are crucial for the distribution of species, glacier localisation (trough equilibrium lines), snow cover extent and duration, etc.

Slight changes in the mean annual temperature may mask dramatic changes on an hourly, daily or even monthly basis which are the relevant timeframes for natural hazard triggering, permafrost degradation and many other consequences.

Increasing numbers of glacier retreats, permafrost degradation and snow cover decrease have been observed in numerous mountain ranges and particularly in the European Alps. Such evidence of climate change is quickly multiplying.

Mountainous societies are already facing difficulties because of both internal and external mutations and will have to cope with the challenge of climatic vulnerability¹ in the future. Last but not least, the consequences of climate change are also likely to impact socio-economic systems downstream, dependent on water resources provided by the water tower of Europe, the Alps.

Understanding of the impacts of climate change is closely linked to the concept of uncertainties. The origins of uncertainty are varied: it can be linked to observation, to model development and results or to the understanding of the climate sensitivity of the considered natural systems.

In general, the understanding of impacts is decreasing with the increase of parameters involved in impact assessment (as developed by Jones [2000] for the uncertainties linked to climate projections, cf. fig 1, next page). Uncertainties are sometimes very significant and it is important to identify them correctly.

¹ Climatic vulnerability is defined by the IPCC as “the degree, to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity”.

Societies must react without delay to cope with climate change, as the next years will be critical for the implementation of climate change adaptation strategies. The most threatened societies, like mountain communities must identify the changes that have already taken place, the potential changes to come and their capacity to react to new restraints. The identification of the time frame in which the expected impacts might occur, (also influencing the time frame and the priority order) represents the first step of the adaptation strategy.

The present technical report is the fruit of two years of work by different political, technical and scientific institutions collaborating in the European project ClimChAlp of the Interreg III B "Alpine Space" program. The project results are presented in this document to provide a common base of knowledge of the potential and observed impacts of climate change in the Alps.

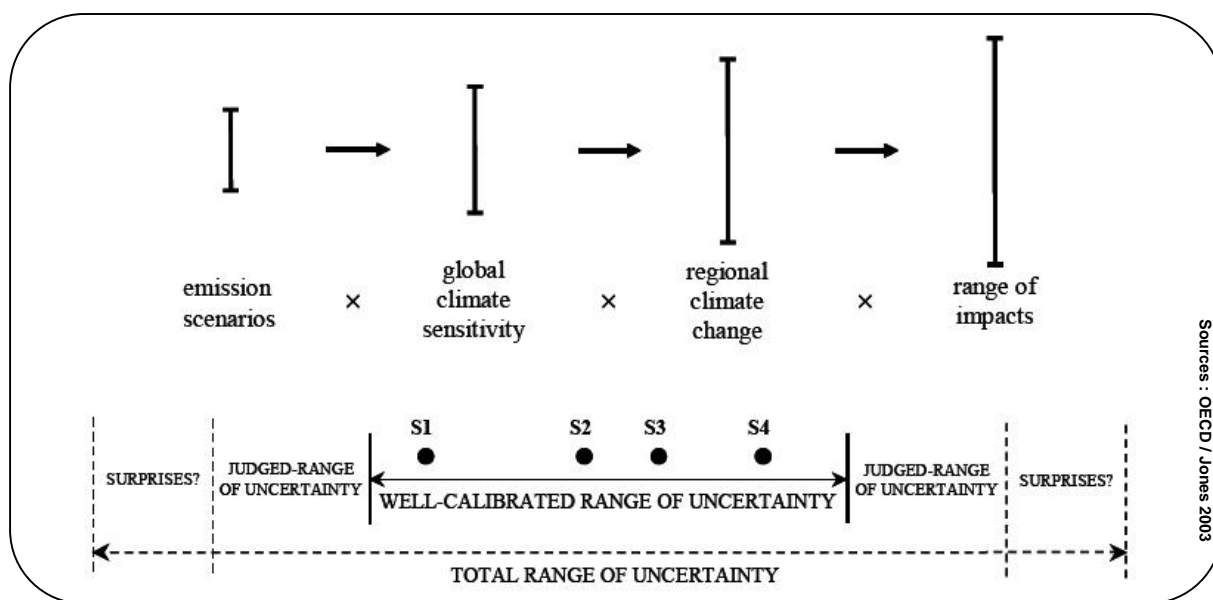


Fig.1 – Uncertainties scheme for climate change impacts assessment

The ClimChAlp project

The ClimChAlp project "Climate change, impacts and adaptation strategies in the Alpine Space" is a project of the Interreg III B program. This project is considered as "strategic" because the partnership gathers 22 institutions (mainly regional and national public authorities) of the seven alpine countries and aims to provide a strong basis for the future projects of the Alpine Space program.

The ClimChAlp project was conducted between April 2006 and March 2008. Its content is based on publications concerning observed and expected climate change in the Alps and its potential and expected impacts. The lead partner of the project is the Bavarian Ministry for Health and Ecology (Bayerisches Staatsministerium für Umwelt, Gesundheit und Verbraucherschutz Referat Klimaschutz).

The project was divided into 9 Working Packages (WP). Among these 9 groups, the WP 1 to 4 are dedicated to administrative, communication and budget issues, the WP 9 is in charge of the final report and the WP 5 to 8 were dedicated to different topics as follow:

- ☞ Climate change and corresponding natural hazards:
 - **"Climate Change"** Module: synthesis of the existing knowledge, evaluation of the historical climatic changes, evaluation of the Regional Climate Change and their uncertainties, future needs and research agenda;

- **"Natural Hazards"** Module: historical assessment of natural hazards, evaluation of the natural events modification that can be attributed to climate change, analysis of future scenarios and the potential evolution of natural events.

- ☞ WP 6. Monitoring, prevention and management of specific impacts of climate change on Nature: monitoring, tele-detection, alert systems...
- ☞ WP 7. Impacts of climate change on territorial development and on territorial economy.
- ☞ WP 8. Flexible response network: reflection on the possible adaptation of administrative and political structures.

The ONERC and PGRN (mandated by the Rhône-Alpes Regional Council) have been particularly in charge of the WP 5. The Rhône-Alpes Regional Council was also involved in the WP 8. The ONERC was in charge of the "Climate Change Module" while the PGRN was in charge of the "Natural Hazards Module". Both partners wrote reports and built up a knowledge platform on the observed and potential impacts of climate change in the Alps (described further in the report). This Technical Report is largely based on the results obtained in the ClimChAlp project.

Other French partners were also involved in different WP. The Centre d'étude technique de l'Équipement (CETE) and the Laboratoire des sciences de la Terre (LST) participated to the WP 6 and the Cemagref Grenoble contributed to the WP 7. The activities of the French partners are presented at the end of the report.

Within the ClimChAlp project, the ONERC, the PGRN and the Rhône-Alpes Region developed a knowledge platform on the impacts of climate change in the Alps, with the support from a large network of scientists which contributed with information and reviewing of the syntheses and reports. This tool is available online on the PGRN web site: www.risknat.org

This tool aims to provide critical, valid and traceable information on climate change and resulting impacts classified as follows (see below).

For each of these themes, the content is also classified according to the type of information: reconstructions (palaeo reconstitutions, historical approaches, etc.), instrumental observations, model results (such as regional climatic model or the propagation models for natural hazards) and the hypothesis.

A great part of this technical report has been realised with the information provided by the knowledge platform. For an easier reading of the report, the scientific references corresponding to the values and arguments presented in the text hereafter have not been inserted in the text. At the end of the report, the references used for each part are listed in a coloured box (see the following example).

Further detailed information concerning the themes or the references associated with a value or an argument, can be obtained by visiting the knowledge platform (www.risknat.org).

Modification of the atmospheric parameter		
Temperature	Precipitation	Air pressure / Winds

Effects on the natural systems and processes							
Surface water runoff	Snow cover	Underground runoff	Permafrost	Glaciers	Hydrology	Forest - vegetation	Erosion

Impacts on natural events						
Floods	Torrential events	Avalanches	Mass movements	Glacial hazards	Storms	Forest fires

The French Organisations involved in the ClimChAlp WP5

The ONERC

Created by the law of 19 January 2001, the French National Observatory on the Effects of Global Warming (Observatoire National sur les Effets du Réchauffement Climatique, ONERC) carries out the will of the Parliament and the Government to take into account issues linked to the impacts of climate change. The observatory collects information, research and studies about climate change hazards with the aim of informing the public and the local communities. The ONERC also proposes recommendations and adaptation strategies to face climate change. Finally, it raises awareness of climate change issues in the dialogue with the developing countries.

The PGRN

Created in 1988 within the “Isère Département Pilote” framework, the Grenoble Pole for Natural Hazards Studies and Research (Pôle Grenoblois d’étude et de recherche sur les Risques Naturels, PGRN) today incorporates 12 Rhône-Alpes institutions (such as Cemagref or Météo France) that undertake research regarding natural hazards. About 170 persons (80 scientists, 50 engineers and technicians and 40 PhD students) are involved in the study of natural hazards. The PGRN implements projects aiming to develop scientific and technical tools to help policy makers and risk managers. The PGRN focuses its activities on mountainous natural hazards, like avalanches, mass movements, torrential erosion and floods, etc.

The Rhône-Alpes Region

The second highest-ranked region in France, Rhône-Alpes accounts for 10% of the national population distributed among 2,879 communes and eight administrative “départements”: Ain, Ardèche, Drôme, Isère, Loire, Rhône, Savoie and Haute-Savoie. This dimension places it amongst Europe’s ten largest regions. The regional institution is made up of two assemblies: the Regional Council is an assembly elected by universal suffrage for a six-year term and the CESR (Regional Social and Economic Council) is a consultative assembly bringing together people/individuals from the socio-professional world. These two assemblies are backed by technical services. The Rhône-Alpes region aims to raise public awareness about the possible impacts of climate change on the territory through various actions, from European Interreg projects to small business initiatives.



Climate change and resulting impacts on natural systems and processes in the Alps



Temperature

Observations in the Alps

According to the last IPCC report (AR4) “warming of the [global] climate system is unequivocal, as it is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. Furthermore, 11 of the last 12 years (1995-2006) rank amongst the 12 warmest years in instrumental records of global surface temperature since 1850. The updated linear trend (1906-2005) of 0.74°C is larger than the Third Assessment Report (TAR) linear trend (1901-2000) of 0.6°C. The linear trend for the last 50 years (0.13°C per decade) is nearly twice that for the last 100 years. The total temperature increase from 1850-1899 to 2001-2005 is 0.76°C”. Despite the global warming trend, there are local disparities in the temperature increases and a few cases of temperature decreases. At the alpine level, most of the temperature observations converge towards a general temperature increase. The values proposed for different meteorological stations in the Alps differ in terms of magnitude but the direction is the same: warming. Moreover, this warming trend seems to have accelerated during the last decade. The positive temperature trend is also confirmed by some features common to all the alpine regions: an increased number of hot summer days and decreased number of freezing days.

Despite the important work provided by scientists and technical services, uncertainties persist even concerning observation. The temperature series are not always continuous and homogeneous.

Some meteorological stations have been displaced; some have been closed after decades of data collection and others are located in very specific places (i.e. at a summit or exposed to the winds) that blur the data quality.

Scientists have developed methods to assess the evolution of temperature prior to instrumental data collection (e.g. dendrochronology, pollinic studies, etc.). Such methods are then validated and calibrated by comparing the results with historical approaches (such as those from E. Le Roy-Ladurie in France or C. Pfister in Switzerland). For example, the ALP-IMP project proposed a temperature trend over the Alpine Space using dendrochronologic methods and data homogenisation. Using such reconstruction methods, warm periods have been identified in the Alpine space from about 1780 to 1810, 1890 to 1945, and the 1970s onward. In the Alpine area, 1994, 2000, 2002 and 2003 were the warmest years within the last 500 years (the analysis was conducted up to 2003). Over the 20th century, the mean alpine temperature is thought to have increased by up to + 2°C for some high altitude sites.

The Alpine climate is a combination of meteorological conditions at the local scale and the influence of large synoptic situations of the Northern Hemisphere. Many analyses have been undertaken to understand these large scale influences on the Alpine climate. All the results show a year-round positive correlation of temperature with the East Atlantic pattern (EA), while the North Atlantic Oscillation (NAO) shows a positive correlation in winter only. However the correlation with the NAO is considered to be intermittent and periods without correlation have been identified.

In other seasons the Scandinavian Pattern (SCAN) can affect Alpine temperatures. Thus these links are complex and highly variable and are difficult to use at the moment.

Model results for the Alps

The average global air surface warming following a doubling of carbon dioxide concentrations is likely to be in the range 2°C to 4.5°C with a best estimate of about 3°C, and is unlikely to be less than 1.5°C. Values substantially higher than 4.5°C cannot be excluded but there is a lack of consistency between models for these values. For the next two decades, a warming of about 0.2°C per decade is projected for a range of SRES emission scenarios². The likely range of the SRES scenarios is between 1.1°C and 6.4°C (for 2090-2099 relative to 1980-1999) and the best estimates are between 1.8°C and 4.0°C. Using downscaling methods, the maximum increase of the temperature (above 4.5°C) is simulated over the Western parts of the Alps for the 2071-2100 period. The warming gradually diminishes towards the North. The downscaled temperature change (period 2071-2100 vs. period 1971-2000) ranges between + 2.8°C (Bolzano) and + 4.9°C (Nice). Based on Regional Climate Model (RCM) results, the maximum temperature increase can be expected to range between 3°C to 5°C in summer and 4°C to 6°C in winter³.

Observations for the French Alps

The annual mean temperature in France increased by 0.9°C over the 1901-2000 period and the warming trend clearly accelerated during the last decade. In the French Alps the mean annual temperature also increased by 0.9°C over the 1901-2000 period, a value similar to the

increase in the annual mean of the daily minimum temperature. On the other hand, the increase of the annual mean of the daily maximum temperature was stronger and ranged between 0.9°C and 1.1°C in the French Alps.

In the Écrins and Dévoluy massifs, a significant annual and seasonal temperature increase has been observed (comparison of the 1960-1980 and 1980-2000 periods). The seasonal mean temperature has increased by 0.9°C in summer, 0.6°C in autumn and 0.7°C in winter since 1960. Since the 1980s, the five meteorological stations located in the Écrins massif have recorded an annual temperature increase, independent of the altitude considered; furthermore the number of freezing days decreased by between 12% and 14% since the 1980s, depending on the station considered. Between 1965 and 2006, a warming trend has also been observed in the Oisans and Briançonnais massifs in the French Alps with a warm year series between 1997 and 2003. The warming trend has ranged between + 0.2°C and + 0.4°C per decade.

Model results for the French Alps

The increase of the annual mean of the minimum daily temperature expected for the French Alps for 2100 (ARPEGE model) is between 2.3°C and 2.7°C for the B2 scenario and between 3°C and 3.5°C for the A2 scenario. This increase is higher than the national average. The annual mean of maximum daily temperature shows similar trends. In the simulated climate (scenario 2*CO₂) for the Écrins massif, winter temperatures are expected to increase more for the minimum than for the maximum temperature values (up to + 10°C for very low temperatures compared to + 3°C for very high temperatures).

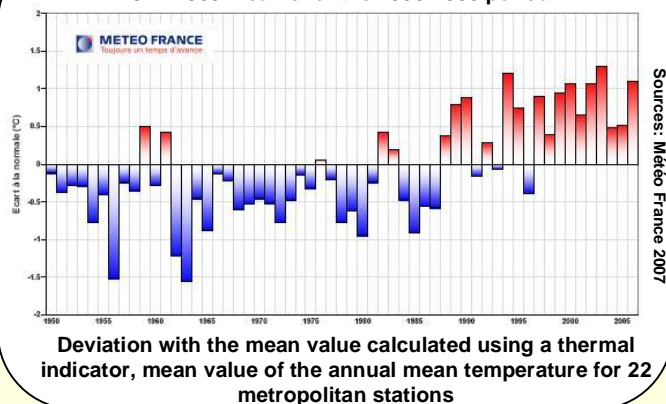
² For details about the SRES, see <http://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf>

³ M. Beniston, personal communication, 2007

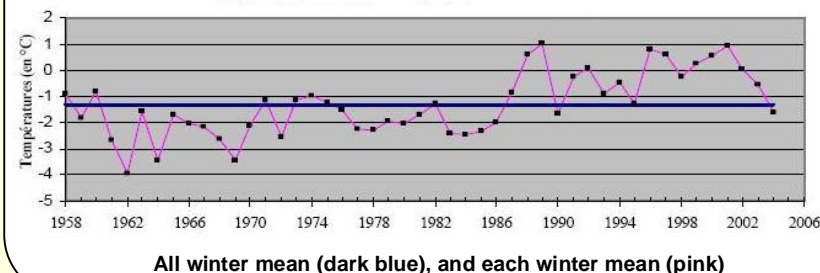
The warming is independent of the minimum and maximum values in the other seasons: + 3°C for spring, + 4°C for summer. The simulations for 3 stations (based on A2 scenario) in the French Hautes-Alpes and Isère départements show an increase of the mean temperature by + 3.79°C to + 3.85°C and an increase of the solar energy by between + 22 W/m² and + 26 W/m² between the current climate period (1969-1999) and the future climate period (2069-2099). The direct consequence of this warming is a significant decrease in the annual number of freezing days.

The model developed by Météo France to evaluate the evolution of the climate and the snow cover (SAFRAN/CROCUS) are also used to calculate past values of temperature, precipitation and snow cover in the mountain ranges. Even if this kind of data can not be technically considered as observation data, they represent a precious complement to the existing data. This is even more interesting in the mountainous area because there are usually more difficult to monitor than other kind of area. This work is still under development but some results can also be presented.

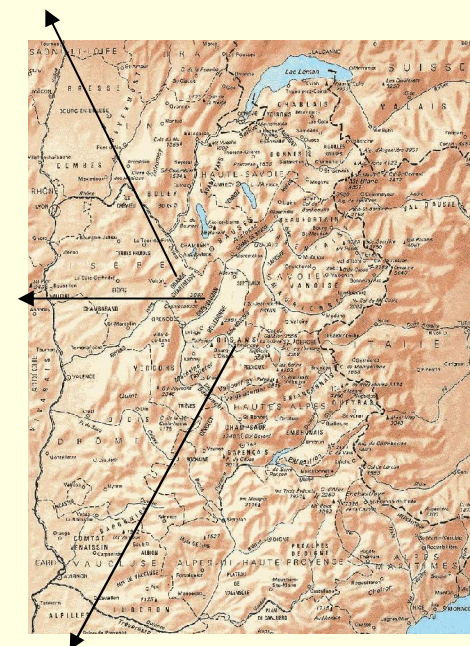
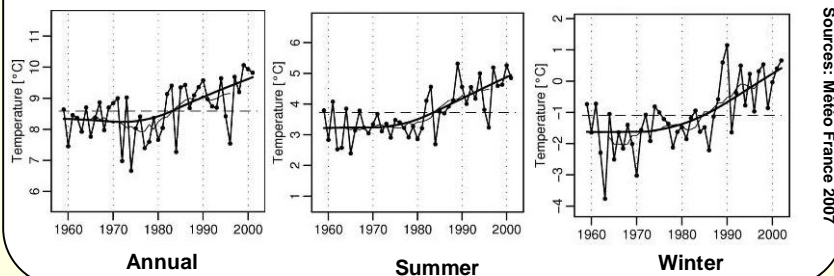
Annual temperature in France: deviation with the 1971-2000 mean over the 1956-2006 period



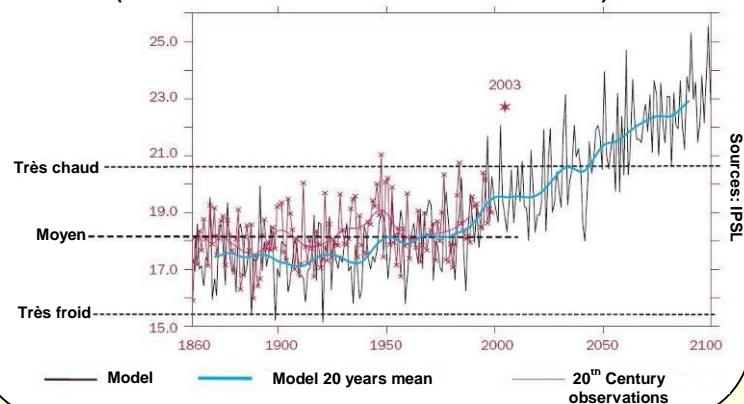
Winter temperatures in the Chartreuse massif (1800 m a.s.l) obtained with models for the 1958-2006 period



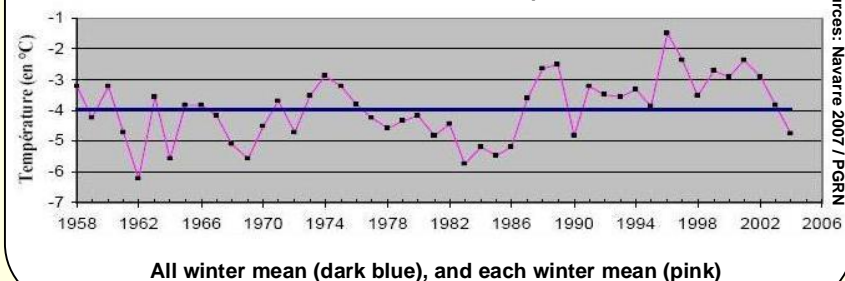
Annual, winter and summer temperatures in the Belledune massif (1800 m a.s.l) obtained with models for the 1960-2007 period



Mean summer temperatures in France from 1860 to 2100 (combination of observations and model results)



Winter temperatures in the Oisans massif (2400 m a.s.l) obtained with models for the 1958-2006 period



Observations in other Alpine countries

German Alps

In South Germany (Baden-Württemberg and Bavaria Länder), the annual mean temperature increased between 0.5°C and 1.2°C during the 20th century. This warming trend was much more significant during winter than summer: the monthly mean temperature for August increased by 0.7°C to 1.7°C, while the monthly mean temperature for December increased by 1.8°C to 2.7°C. Temperature increases were also detected for January, February, March and October, although they were less significant.

Italian Alps

In Northern Italy, a warming trend is evident throughout all seasons, with both the maximum and minimum temperatures showing positive trends. The number of freezing days has also decreased in winter and spring, although not significantly and no trend was obtained for this index in autumn. The “heat wave duration” index has also increased, with the most significant increase observed in summer.

In the Piedmont and the Aosta Valley the mean temperature increased by 1°C during the second half of the 20th century. During the 2003-2006 period, mean temperature anomalies at Lago Valsoera weather station (2,440 m a.s.l, Gran Paradiso massif) reached + 1.8°C over 1959-2002 mean values. During the winter of 2006-2007 (DJF), Northern Italy experienced the mildest temperatures ever recorded in nearly two centuries. For example, the winter temperature anomalies in Moncalieri (Piedmont) reached + 2.6 °C compared with the 1961-90 mean at the Dormais station.

Swiss Alps

In Switzerland, the years with average temperatures above the mean (1961-1990) increased throughout the 20th century, with a related rise of the mean deviation. The total temperature increase has been estimated at 1.47 °C in the period between the 1900 and 2006, with a more pronounced temperature increase in the last 40 years (0.4 °C per decade). 18 study sites in Switzerland (from 317 to 2,500 m a.s.l) show warming rates that are all significant and range from 1.8°C/century in Neuchâtel (487 m a.s.l) to 3.5°C/century in Säntis (2,500 m a.s.l). The general rise of winter minimum temperatures began in the early to mid-1960s at all the 18 Swiss monitoring sites and underwent a cooling in the early to mid- 1980s before warming rapidly thereafter.

Summer heat waves (such as the 2003 hot summer) are characterised by temperatures that significantly exceed the mean maximum temperature values. However these summer temperature anomalies remain smaller than the maximum temperature anomalies in winter (also named warm winter spells) that have been observed in high elevation sites in the Alps during the last quarter of the 20th century. Daily maximum temperature anomalies (T_{max}) during winter have been observed to exceed 15°C at sites such as Saentis (2,500m a.s.l), Grand-Saint-Bernard (2,479 m a.s.l) or Jungfrauoch (3,572 m a.s.l), , with increases of 10°C commonly occurring in the last 2-3 decades. Thus the warming trend in the Swiss Alps is particularly pronounced during winter (with a corresponding increased potentiality for more frequent, intense and long-lasting warm winter spells).

The anomalies observed were greater in winter than in the other seasons and this is even more significant for the + 10°C above the mean threshold. For example, the frequency of the winter $T_{\max} > 10^{\circ}\text{C}$ increased from 0 or 1 day/decade before 1970 to over 20 days/decade in the 1990s.

Model results in other Alpine countries

German Alps

The air temperature will continue to increase clearly in the future in Baden-Württemberg and Bavaria. The annual mean temperature increase is 1.7°C for the 2021-2050 period compared with the mean in the 1971-2000 period (using the IPCC B2 scenario). This temperature increase is higher in winter (approximately 2°C) than in summer (1.4°C).

The number of summer days (days with $T_{\max} \geq 25^{\circ}\text{C}$) and hot days (days with $T_{\max} \geq 30^{\circ}\text{C}$) will rise significantly in South Germany. The average number of summer days will increase by approximately 17 days in the future (2021-2050) compared to the current situation (1971-2000). The duration of periods with summer days should increase for most of the considered stations. A comparison of the current period (1971-2000) and the future period (scenario 2021-2050) show that the number of hot days should almost double. Over the same time period, the occurrence of extremely high temperature will also increase.

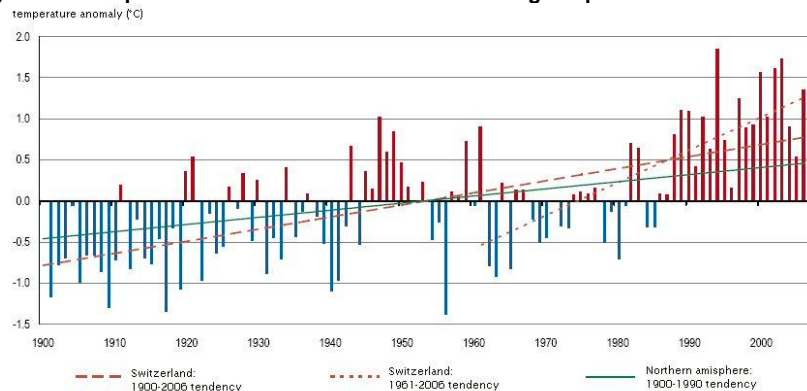
As a result of the temperature warming, the number of freezing days (days with $T_{\min} < 0^{\circ}\text{C}$) and also the number of icy days (days with $T_{\max} < 0^{\circ}\text{C}$) will decrease significantly. In the future scenario period, the number of freezing days will decrease by approximately 30 days for all the stations. The maximum

duration of the freezing period should also decrease significantly. The number of icy days in the future scenario is generally less than half the number observed for the current period.

Swiss Alps

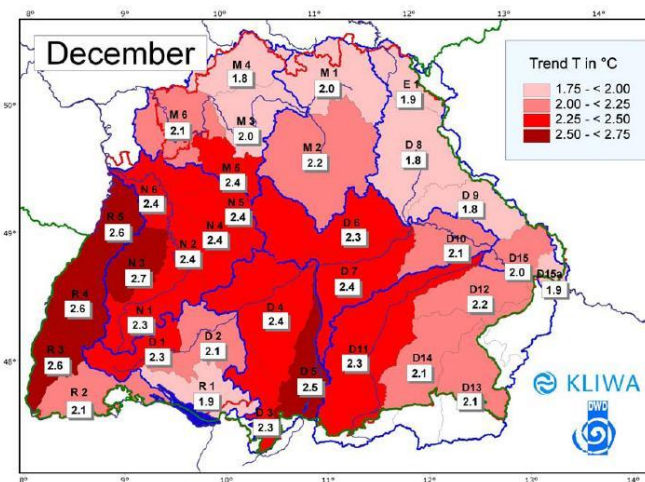
In the future climate simulation (2071–2100, A2 IPCC scenario), the mean summer temperature in the Swiss Alps is expected to increase by nearly 4.6°C (cf. fig. 3). The RCM simulations for the 2071-2100 period show similar summer climatic conditions to those observed during the 2003 summer in terms of temperature. Considering this assumption, one can expect that by the end of the 21st century (according to the given RCM results), about every second summer could be as warm or warmer (and also as dry or drier) than the 2003 scorching summer. By the end of the 21st century, the Swiss Alps might experience a temperature increase of between 4°C and 5°C (cf. fig. 3). A 2005 study also proposed a warming scenario for the Swiss Alps of $+1^{\circ}\text{C}$ (expected for 2020-2049) and two scenarios considering two different SRES for the 2070-2099 period: $+2.4^{\circ}\text{C}$ to $+2.8^{\circ}\text{C}$ and $+3.0^{\circ}\text{C}$ to $+3.6^{\circ}\text{C}$, with warming rates in summer higher than the annual averages. The climatic projection also identifies winter as the season with the strongest anomalies, with a 30% increase of the temperature exceedance for both the 5°C and 10°C thresholds, confirming trends observed in the Swiss Alps throughout the 20th century. Furthermore, winter T_{\max} anomalies should exceed 18.5°C (compared to the 1998 maximum of 16.2°C) in a climate that is simulated to warm by 4°C in winter on average (HIRHAM 4).

Temperature anomalies in Switzerland during the period 1900-2006



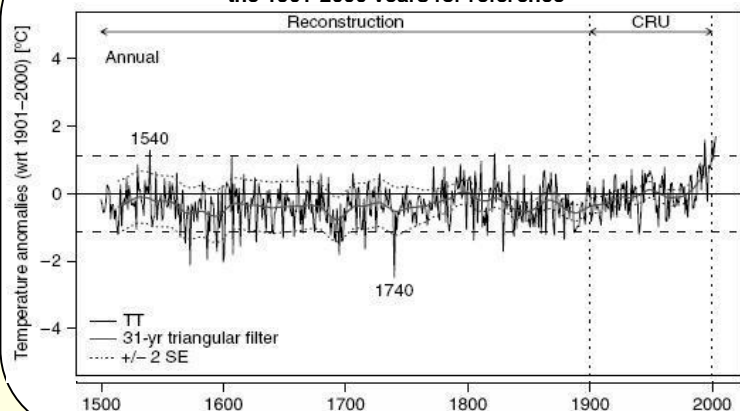
Sources: OFEN 2007

Increase in the monthly mean temperature in December in the period 1931 – 2000 in South Germany



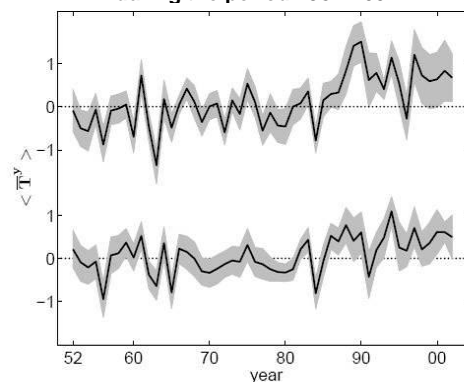
Sources: KLIWA 2006

Mean annual temperature anomalies in the alpine arc (1500-2004), with the 1901-2000 years for reference



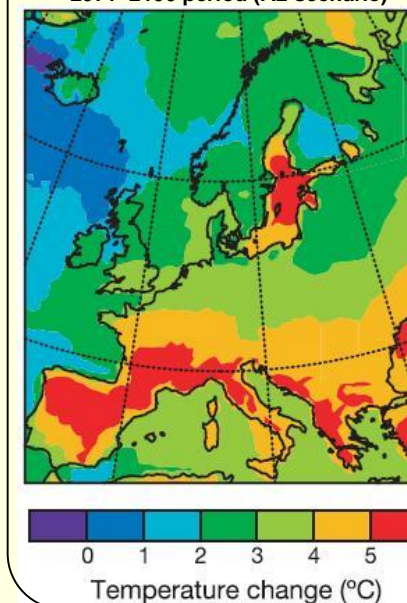
Sources: Casy et al. 2005

Temperature anomalies in Piedmont and Aosta Valley during the period 1951-2002



Sources: Ciccarelli et al. 2007

Temperature change in Europe calculated for the 2071-2100 period (A2 scenario)



Sources: Schär et al. 2004

Precipitation

Observations in the Alps

The trend and variability assessment for precipitation patterns over the Alps are clearly weaker than the Alpine temperature assessments. This is due to several reasons:

- ☞ The well known problems linked to the precipitation measure networks in mountains ranges: time and space discontinuous field with intensity distribution highly influenced by orography; changes in the measurement instruments and measurements location during the last century; feeble algorithms to correct the long time series, etc.
- ☞ Different large-scale flow regimes cause the precipitation over the Northern and Southern Alps. Thus, any weather regime modification induced by climate change can affect Northern and Southern Alps differently.
- ☞ The adjustment of precipitation series at the hourly, monthly, seasonal and even annual timescale is much more demanding than for temperature, as the spatial correlation of precipitation fields is much weaker.

Several studies on precipitation trends have been carried out at the Alpine scale, leading to a somewhat controversial picture. Recent results suggest that, as far as precipitation trends are concerned, the significance of trend results is very sensitive to the choice of the time window considered.

Despite the lack of significant trends at the alpine scale and no general direction of precipitation evolutions, local fluctuations of the precipitation patterns have been observed. Weak or non-significant trends for precipitation in the past century have been found at the Mediterranean scale, at the Alpine space scale and from the analysis of individual time series. The correlation analysis reveals weak and highly intermittent correlations with the NAO Index to the North and more robust correlations to the South of the main Alpine range. A decrease in winter and autumn precipitation to the South of the main ridge has also been observed.

Inter-annual and inter-seasonal precipitation variability is very strong. Indeed, the reconstruction of Alpine precipitation time series does not indicate significant trends. The expected precipitation increase, as a consequence of atmosphere warming, was not found at the alpine level for the 1500-2003 period. A seasonal approach enabled the scientists to identify specific winter and summer features: dry winters occurred in the second half of the 19th century, and some very dry winters occurred between 1990 and 1994. Wet winter conditions were seen in the 1670s, 1720s, 1910s and from 1950 to 1990. Interannual summer precipitation shows three prominent dry periods: around the 1540s, after 1770, and after 1860. A decrease in summer precipitation is also found after 1970. Very wet summers occurred from 1550 to 1700. 1540 was the absolute driest summer in the Alps since 1500 (anomaly of - 164 millimetres with regard to the 20th century mean summer precipitation sums of 352 millimetres), and the 2003 summer was of comparable magnitude, while 1663 was the absolute wettest summer (+ 148 millimetres).

Model results for the Alps

On the global scale, the climate models generally calculate future projections with a summer precipitation decrease and a winter precipitation increase for the mid-latitude regions and smaller changes for high-latitude regions. Despite the intensification of the global hydrological cycle predicted by OAGCM (Ocean Atmosphere coupled General Circulation Model), changes in extreme precipitation remain unconvincing. The low spatial resolution of OAGCMs precludes a realistic simulation of regional circulation and therefore of extreme precipitation. Furthermore, there is no indication of a seasonal shift of precipitation in summer and autumn.

Projections of changes in the precipitation patterns in mountain areas are tenuous in most General Circulation Models (GCM) because mountain topography is poorly resolved and, as a result, the controls of topography on precipitation are not adequately represented. It has also been recognized that there are superimposed effects of natural modes of climate variability such as El Nino/ENSO, NAO... ..which can perturb mean precipitation patterns on time scales ranging from seasons to decades. Such mechanisms are not well predicted by climate models. As mentioned above, large-scale climatic models are not adequate for climatic projections at a regional scale, such as the Alps. This is why some of the ClimChAlp WP5 partners evaluated the validity of RCM (with horizontal spatial resolution between 10 and 20 kilometres) and OAGCM (with horizontal spatial resolution of nearly 200 kilometres) for the Alpine area. The aim of this work was to prepare regional scenarios of climate change with a good resolution that might be used for impact studies at the Alpine level.

In general, the results of the RCM used in the WP5 show a mean precipitation increase in winter and a mean precipitation decrease during summer (cf. fig. 5). Most of the model results converge toward a increase in heavy precipitation in winter. As for the summer period, the model results are associated with significant uncertainties and thus cannot propose a clear picture.

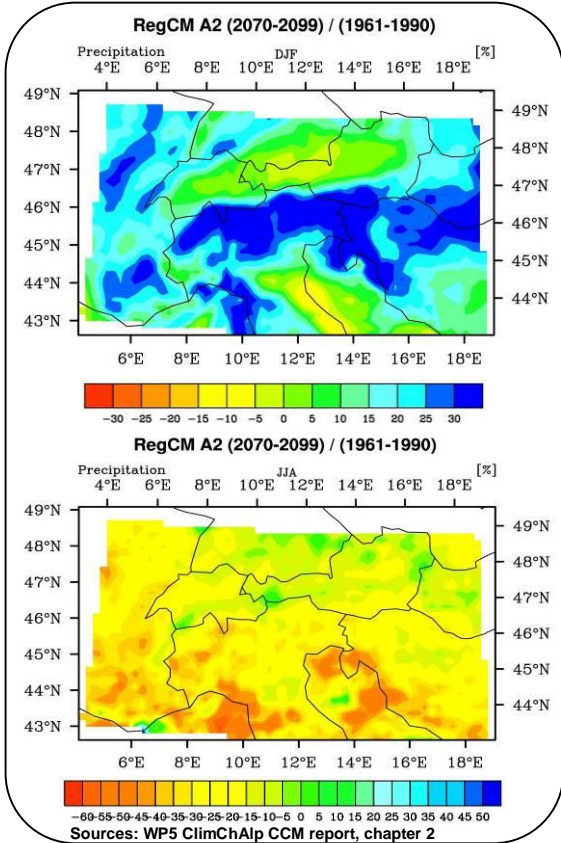


Fig. 5 – Simulated changes (in %) of the winter mean precipitation (left) and the mean summer precipitation (right) between the 1960-1991 period and the 2071-2100 period with the RegCM model and the A2 scenario

This analysis further highlights the fact there is no single best RCM for the Alpine Space. The analysed RCMs (especially the HIRHAM (Danish), RegCM (Italian), CLM (German) and REMO (German)) satisfactorily reproduce the monthly mean temperature and the daily mean precipitation. However, the models tend to overestimate the seasonal amounts of precipitation.

There is a growing need for model results of climatic extremes, particularly precipitation extremes. Indeed, changes affecting the extreme values will certainly have more significant impacts than the changes of the mean values, particularly in terms of natural hazards evolution. The WP5 analysis notably highlighted the fact that the assessment of the changes in terms of frequency and intensity is still an unsolved problem. Finally, it has been shown that it is still difficult to use the output data from climatic models as input data for the hydrological model. Despite the use of correction techniques, the biases remain significant.

A recent paper compared the results from 3 RCMs and 6 Statistical Downscaling Method (SDM) for Europe. The RCM simulations for future changes in European precipitation show a seasonally distinct pattern: in winter, regions North of about 45°N experience an increase in mean precipitation while in the Mediterranean region there is a tendency toward decreased mean precipitation. The results of the three RCMs are highly consistent. Most of the SDMs produce an increase in mean precipitation similar to that of the RCMs.

In summer, the RCMs simulate a strong decrease in mean precipitation in the entire Alpine region. This decrease is mainly due to a substantial reduction of wet-day frequency. The smaller number of wet days results in a large increase (50% to 100%) of the maximum length of dry spells. In comparison to winter, the differences model results for summer between the RCMs and the SDMs, but also between the RCMs, are much larger.

Overall the differences between the RCMs and SDMs, and the substantial biases of the RCMs in summer highlight the large uncertainties of the scenario results for the summer season.

In autumn, the region experiences a decrease in mean precipitation resulting from a strong decrease in wet-day frequency and a moderate increase in precipitation intensity. Again the results of the three RCMs are very similar. This analysis suggests that the contribution to uncertainty from downscaling is relatively small in winter and autumn, but significant in summer.

Observations in the French Alps

No significant trend of evolution of the mean values of precipitation has been detected at the French metropolitan scale. This is explained either by the absence of changes or by evolutions too weak regarding the uncertainties associated with the considered data series. The overall picture for the French Alps is not much clearer.

In the French Southern PreAlps/Alps, precipitation variability between 1950 and 2000 has been characterised by significant heterogeneity. Even if light trends have been noticed for particular characteristics and meteorological stations, no general trends could be found. On the other hand, some local and regional evolutions for extreme or heavy precipitation events have been observed (the threshold varies from one study to another). The stations located in the Northern Alps generally get more intense precipitation in all seasons except summer. Thus the increase in the extreme precipitation indices (for example in Savoie over the 1958-2001 period) was found to be highly significant, especially in winter.

In Chamonix, the annual solid precipitation mean and the extreme solid precipitation values show no trend between 1959 and 2004. Very strong interannual variations and some year cycles can be identified. It is also interesting to note that the most important daily snow falls were observed in the 1990s, even though this was one of the decades with the least snowfall overall.

In the Écrins massif, there was a significant increase in summer precipitations with intensity ≥ 30 millimetres / day over the 1986-2000 period. At the same time, there was no significant variation in the annual mean precipitation at all the weather stations studied in the Écrins and Dévoluy massifs since 1980.

In the Alpes Maritimes, many of the indices show a significant decrease in spring and summer, while they show poorly significant changes in winter over the 1958-2001 period. In autumn, only a few monitoring sites show significant positive trends.

Over the same period, in Queyras, signals of a significant increase in some heavy precipitation indices were observed in spring and winter. The total accumulated precipitation showed a slight increase in spring and autumn. The maximum number of dry days also increased in spring and decreased in autumn.

Model results for the French Alps

The relative evolution of the annual amount of precipitation predicted for 2100 with the ARPEGE model for the French Alps varies between - 0.15% and + 0.05% for the B2 scenario and - 0.6% to - 0.2% for the A2 scenario.

At the Rhône basin scale (results of ARPEGE for the 2054-2064 period with 2*CO₂ scenario), the ratio of solid precipitation over total precipitation is expected to decrease significantly (- 21%), particularly for low and medium altitude watersheds.

The climate simulated for the Écrins massif by the ARPEGE model (scenario 2*CO₂) shows an intensity increase in autumn and winter precipitation, especially for the heavy precipitation indexes (the future number of events corresponding to 45 millimetres / day may become the actual number of 30 millimetres / day events), while it will not change significantly for spring. In summer, the evolution is much more complicated. The number of days with daily values under or equal to the 50 millimetres / day threshold will decrease while the number of days with daily values above this threshold will increase. Nevertheless this situation remains largely hypothetical.

The simulations from the ARPEGE/IFS model for 3 stations in the French Hautes-Alpes and Isère départements (comparison between 1970-1999 and 2070-2099 using the scenario A2) indicate a decrease of the relative humidity (- 4.38% to - 2.35%), a contrasted evolution of the liquid precipitations (- 0.05 millimetres / day to + 0.47 mm/day) and a decrease of solid precipitations (- 0.64 millimetres / day to - 0.19 millimetres / day).

Observations in the other Alpine countries

German Alps

In South Germany, there has been a significant decrease in mean summer precipitation since the 1930s especially in North Württemberg and Lower Franconia; in Eastern Bavaria the decrease shows only a low level of significance; in Southern Bavaria a slight increase has been identified. The winter precipitation increase is significant for most of the studied stations except for those located in the foothills of the Alps where the slight increase is not statistically significant.

The extreme (percentile 90) and the heavy (often designating precipitation > 30 millimetres / day) precipitation indices show a controversial picture. On one hand, the extreme precipitation index show an increase in winter ranging between 30% and 35% that is significant both for Germany over the 1958-2001 period and South Germany over the 1931-2000 period, mainly in the Black Forest, in the North-East of Baden-Württemberg and in the North Bavarian Region. On the other hand, annual heavy precipitation indices shows a significant decrease for Germany whilst no trend is highlighted for South Germany.

Italian Alps

In Italy, there is a clear distinction between the “heavy” to “torrential” categories (from 32 millimetres / day to more than 128 millimetres / day) that show an increasing trend and the other categories (from 0 millimetres / day to 32 millimetres / day) that show a highly significant decreasing trend over the 1951-1995 period. This national picture is nuanced by a more regional assessment provided within the STARDEX project; in Northern Italy, the indices related to heavy precipitation show negative trends in winter and spring, while they show positive trends in summer over the 1958-2001

period. The maximum number of consecutive dry days increased only in winter, with no change observed in other seasons.

As regards the Western Alps, a detailed analysis performed on the 1952-2002 precipitation time series, displays no significant trend for precipitation intensity or for dry period duration. A similar study conducted on the Eastern part of the Italian Alps highlights the same lack of significant precipitation trends.

These contradictions highlight the difficulty in detecting significant trends in precipitation series and the influence of methodological choices in assessing precipitation data (data series, threshold, time frame, geographical area...).

Swiss Alps

In the Swiss Alps, the increase of mean winter precipitation for the 1901-94 period amounts to 15% - 20% and is statistically significant, but no significant trend is found for other seasons. The monthly precipitation mean comparison between the 1961-1990 period and the 1931-1960 period shows a 20% increase for the December, March and April months. But the July and September months show a 10% decrease. The winter precipitation increase seems to be maximal over Western Switzerland (20%). This Western Switzerland specific feature is also consistent for the annual mean precipitation for which a general increase has been observed between 1977 and 1998.

Regional precipitation assessments in the alpine parts of Switzerland do not often propose significant trends. For example, eight Swiss meteorological stations located in four sub-regions (Jura, Swiss Plateau, Alps, Southern Alps) have been studied.

Significant variations have only been observed at the Säntis high elevation (2,500 m a.s.l.) site with a 3.3 millimetres / day increase (1961-1990 as reference period). Other regionally focused studies in Ticino and the Swiss PreAlps also reported no significant precipitation trends.

The indices related to heavy precipitation generally show significant increases in winter and autumn, while they show weak positive trends in summer and spring over the 1958-2001 period. Over the 1975-1997 period, the heavy precipitation frequency in Switzerland (considering threshold > 70 millimetres / day on a minimal surface of 500 km²) increased to two times the 1901-1974 value, to reach 3 events/year currently.

When considering the > 50 millimetres / day threshold for heavy precipitation, an increase is also identified since 1973. These results are nuanced by another publication stipulating that for extreme events, the number of stations with a significant trend was low in all four seasons and then the results must be considered poorly conclusive. It is possible to draw trends of large amplitude but they are poorly significant from a statistical point of view.

Precipitation model results for the other Alpine countries

German Alps

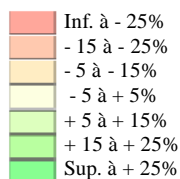
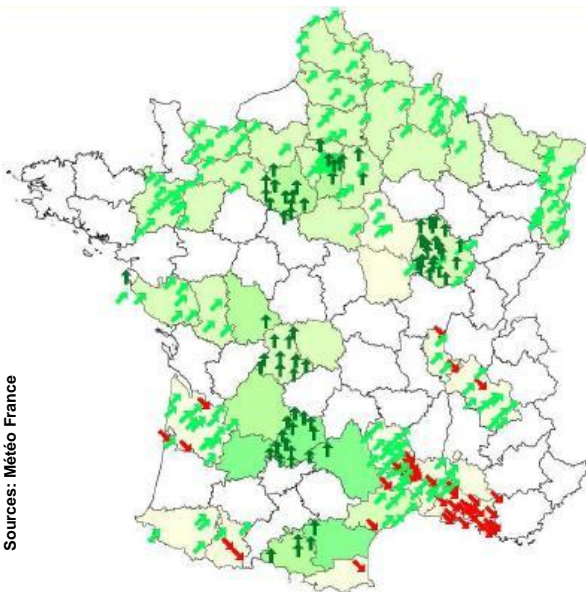
The mean annual amounts of precipitation in South Germany are expected to increase by approximately 8% with a bandwidth of 4% to 17% for the 2021-2050 period (using the ECHAM 4 GCM and the B2 IPCC emissions scenarios). Large-scale precipitation will decrease by a maximum of 4% in summer.

On the other hand, it is expected that winter precipitation will increase significantly. Depending on the region, the increase might reach 35%. However the available regional climate models currently cannot provide quantitative data for the future development of convective short-period precipitation (thunderstorms), which are of relevance to natural hazards.

Swiss Alps

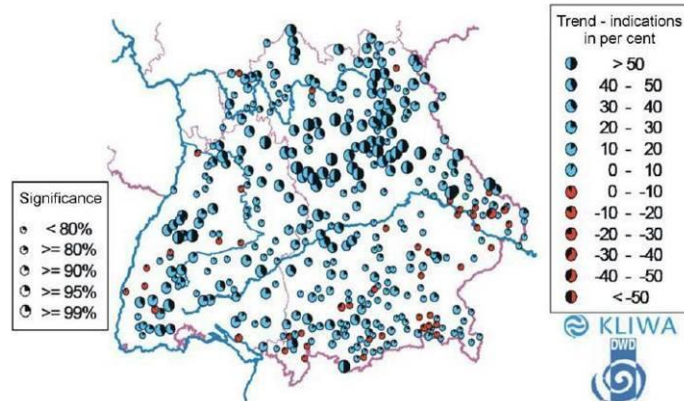
Despite the uncertainties related to regional climate simulations of precipitation in complex terrain, recent work based on 4 regional model projections for a "greenhouse climate" by 2100 suggests that mean and extreme precipitation may undergo a seasonal shift. There will be more heavy precipitation events in spring and autumn (defined here as the 99% quantile values of daily precipitation) than at present, and fewer in summer. The 99% quantile corresponds to just over 60 millimetres / day, and the increase in the number of extreme precipitation events (over 30% between the two periods) supports earlier findings by different authors.

Annual precipitation evolution over the 20th century in France (% per century)

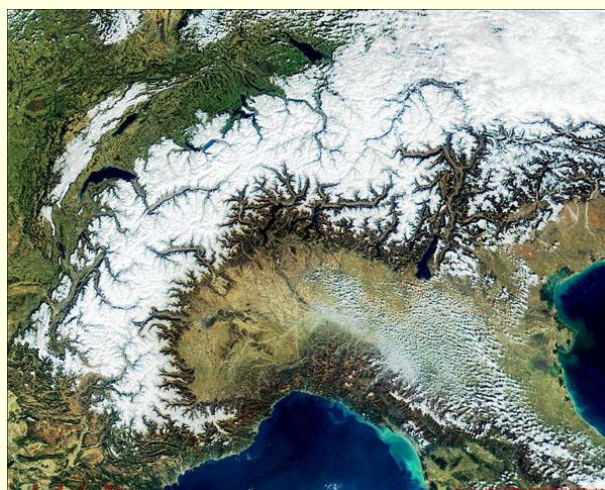


The straight arrows represent a significant trend; the oblique arrows represent non significant trends. The up arrows indicate increase; the down arrows indicate decrease

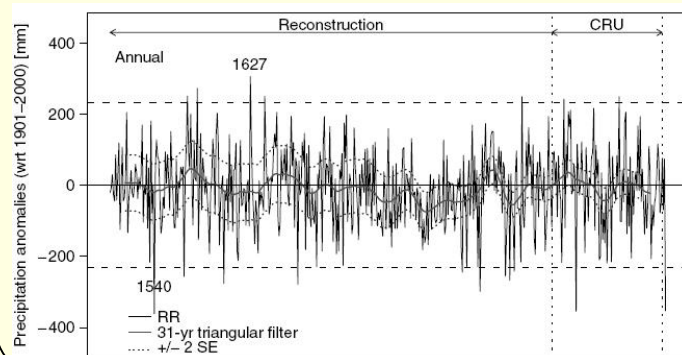
Increase in daily heavy precipitation in the winter half year in the Bavaria and Baden – Württemberg (1931-2000 period)



Sources: KLIWA 2006

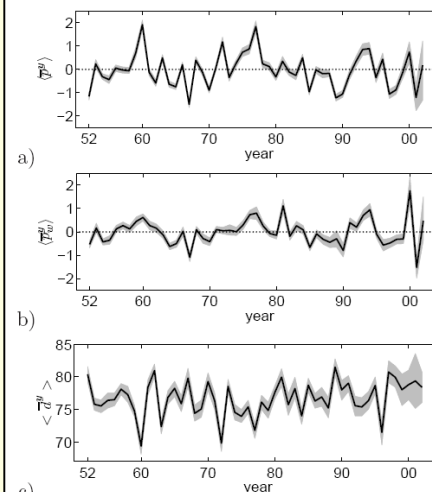


Mean annual precipitation anomalies in the alpine arc (1500-2004), with the 1901-2000 years for reference



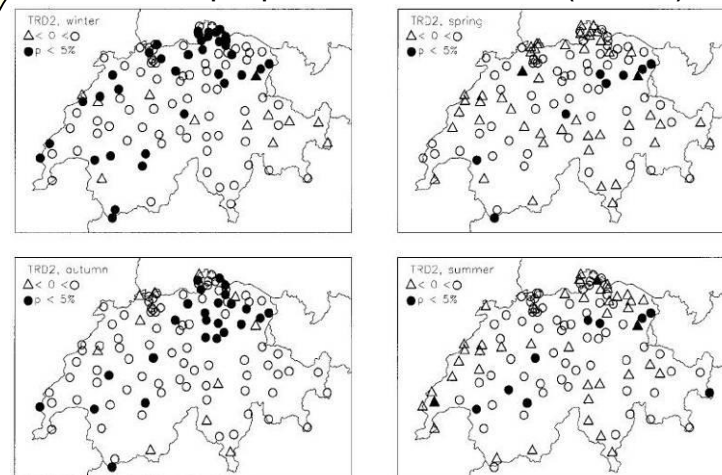
Sources: Casaly et al. 2005

Ensemble-averaged standardized precipitation statistics in Italy



Sources: Ciarrelli et al. 2007

Trend of intense precipitation events in Switzerland (1901-1994)



Sources: Frei & Schär 2001

Seasonal charts showing trend results in the frequency of intense daily precipitation (i.e., events occurring once per 30 days on average over the climatic period). Symbols represent the sign of the trend estimate (circle: increasing, triangle: decreasing) and its statistical significance (filled symbols: $p < 5\%$). Trends were estimated and tested from seasonal event counts over the period 1901–94 using logistic linear regression.

Alpine glaciers

Observations in the Alps

Mountain glaciers are sensitive not only to temperature fluctuations but also to changes in precipitation, solar radiation, ratio of solid/liquid precipitation, etc. During the last decades, the length and magnitude of glacier ablation and accumulation periods varied greatly. The glacier mass balance and the length of the glacier tongue are common indicators used to assess the evolution of glaciers. Despite the complex connection between climate and glacier reaction, glaciers are considered to be key indicators of climate change: their area, surface, elevation, thickness, volume and length are all determined by the balance between climate-driven accumulation and ablation.

During summer, alpine glacier ice is close to melting point, thus a change of temperature even over a short period can lead to a dramatic evolution. For example, the extreme 2003 summer heat wave caused record breaking glacier melting in the European Alps with a corresponding mean specific mass loss of -2.5m water equivalent (w.e.). This value is eight times the annual mean of the 1960-2000 period.

Trends in long time series of cumulative glacier length and volume changes represent convincing evidence of fast climatic change on the global scale. Mountain glaciers [...] have declined on average in both hemispheres and the secular mass loss has been considered a worldwide phenomenon (cf. fig. 7) since 1850.

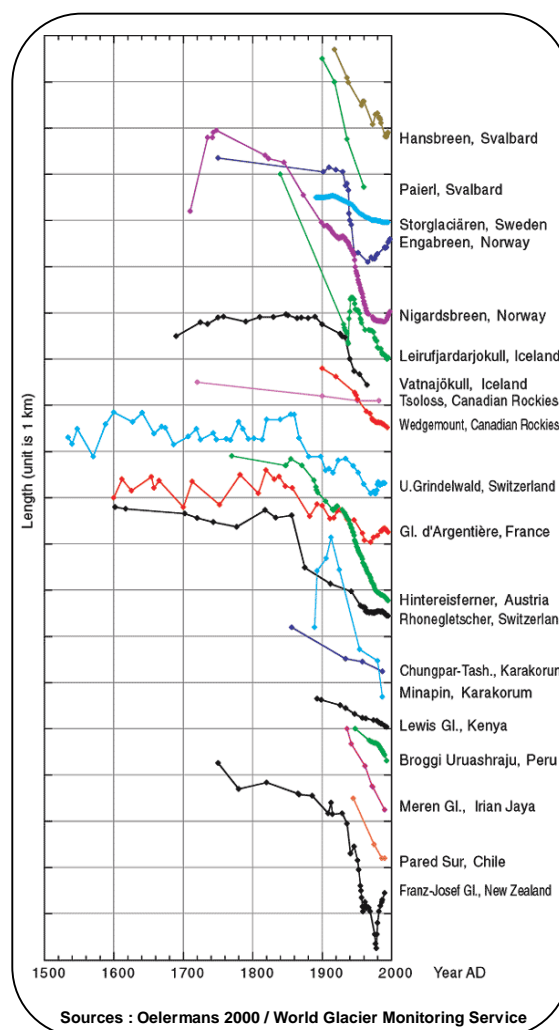


Fig. 7 – Length fluctuation of 20 glaciers worldwide

The glaciers in the European Alps have lost about 30% to 40% in glacierized surface area and about half their total volume (roughly - 0.5% per year) between 1850 and around 1975. Another 25% (or - 1% per year) of the remaining volume probably disappeared between 1975 and 2000, and additional 10 % to 15 % (or - 2% to - 3% per year) in the first five years of this century.

Even if most of the glaciers have been in general retreat since the end of the Little Ice Age (LIA, considered to end in the middle of the 19th century), there are deviations of this trend in both time and space.

Despite the apparent homogeneity of the signal on the secular time scale, contrasts appear over shorter time periods (years to decades) as a consequence of the great local/regional variability. For example, an advancing period was observed in the European Alps during the decade 1970-1980; this period of glacier advance has also been observed in other regions of the World such as the Pamir-Alai, Tien-Shan, etc.

Glacier size and its area versus elevation distribution are also critical factors when looking at its sensitivity to climate change. Smaller glaciers are most sensitive to climate change. At altitudes above about 4,000 m a.s.l. iced areas are generally cold and atmospheric temperature rises leads to ice warming rather than mass loss.

The above-mentioned retreating trend can be observed through the analysis of the mass balance of some Alpine glaciers in the period 1965-2005. In the 1960s and 1970s, the annual variations of glacier mass were balanced, but since the mid-eighties, a period of continued and accelerated loss of glacier volume has existed (cf. fig. 8). This loss is estimated to be 0.5 to 1 metre w.e. per year (with an exceptional 2.5 metres w.e. during the 2003 summer).

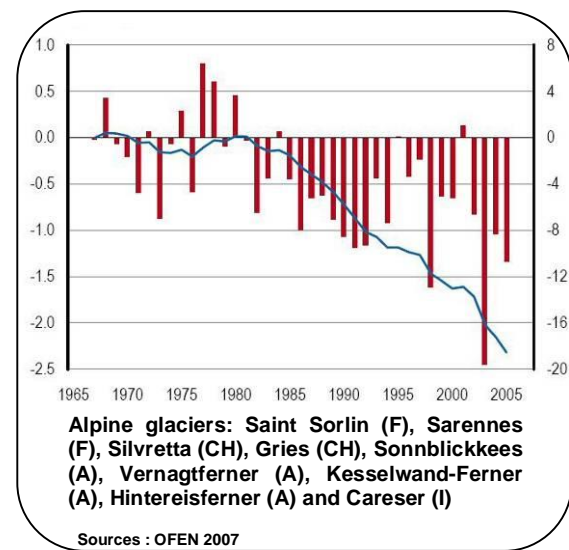


Fig. 8 – Annual (left y-axis) and cumulated (right y-axis) mass balance of nine alpine glaciers



Observations in the French Alps

The dramatic advance of alpine glaciers during the LIA might have been the consequence of more favourable than average climatic conditions during this cold and wet historical period. The general shrinking of alpine glaciers during the 20th century was therefore partially due to climatic conditions, which returned closer to the Holocene mean value. However, it is likely that recent global warming is accelerating this existing glacier retreat. For example, in 2001, the front of the Mer de Glace ended approximatively 2.2 kilometres upslope from its position of maximum extension during the LIA (cf. fig. 9), and in 2006, it retreated a further 100 metres to a point 2.3 kilometres upslope of the maximum extension during the LIA.

The 20th century French mass balance analyses highlighted four different periods: (i) between the beginning of the 20th century and 1941, the French alpine glaciers lost some mass (ii) between 1942 and 1953, the glaciers showed important deficits due to low winter precipitation and strong summer ablations (iii) between 1954 and 1981, the mass balance was generally positive and led to an important re-advance of some glacier fronts (several hundreds of meters for the la Mer de Glace, Argentière and Bossons glaciers in the Mont Blanc massif) and (iiii) since 1982, the mass balances are in deficit due to a high level of summer ablation (from 1.9 m to 2.8 m w.e. at 2,800 m a.s.l). This is due to a strong increase of the energy balance.

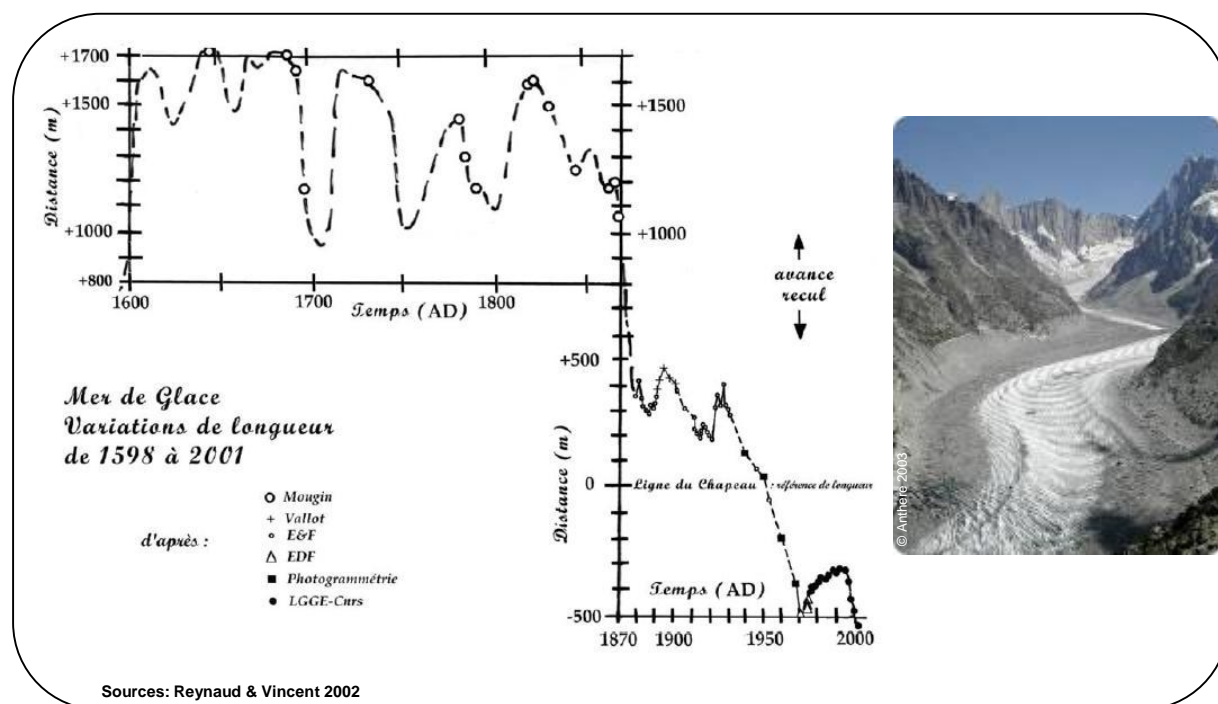


Fig. 9 – Mer de Glace fluctuations collected by Mougin (1598-1870) and completed by recent measurements

Considering cold high-altitude mountain peaks, a recent study conducted at the summit ice cap of Mont Blanc (4,808 m a.s.l) and Dôme du Goûter (4,300 m a.s.l) show that, in contradiction to the observed changes of the glacier tongues in the Mont Blanc massif, no major thickness changes have been detected over the 1905-2005 period for most of the area (cf. fig. 10).

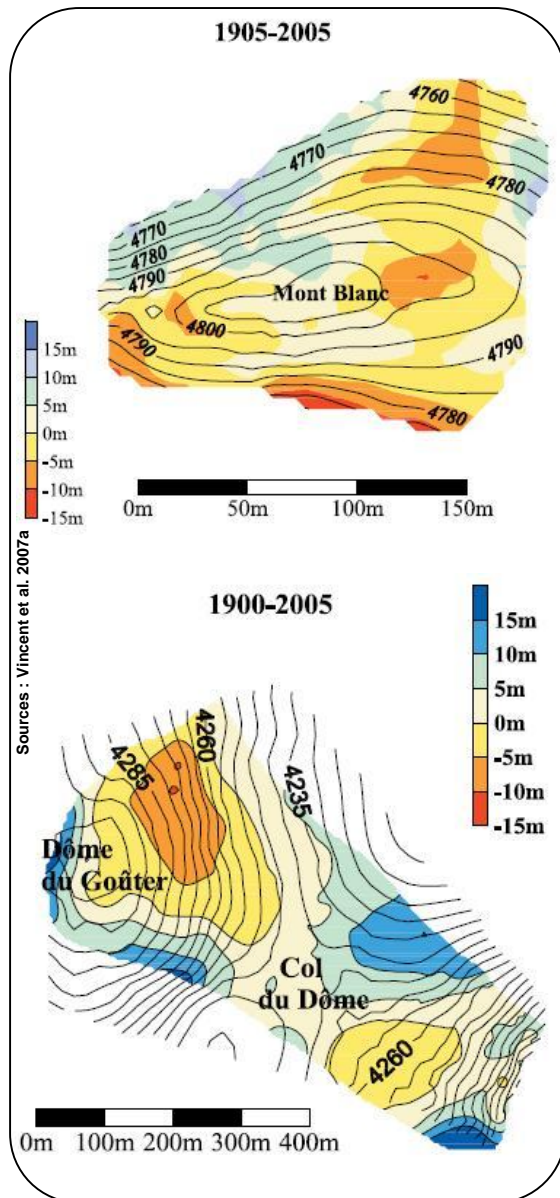


Fig. 10 – Thickness changes on the Mont Blanc and Dôme du Goûter ice cap between 1905 and 2005

On the other hand, ice temperature at the Col du Dôme du Goûter (4,250 m a.s.l) clearly increased between 1994 and 2005 (cf. fig. 10'). If this trend continues, this might lead to changes of thermal mode of some glacier from “cold” to “temperate”, with associated consequences on the long-term stability of hanging glaciers (see “glacial hazards” chapter).

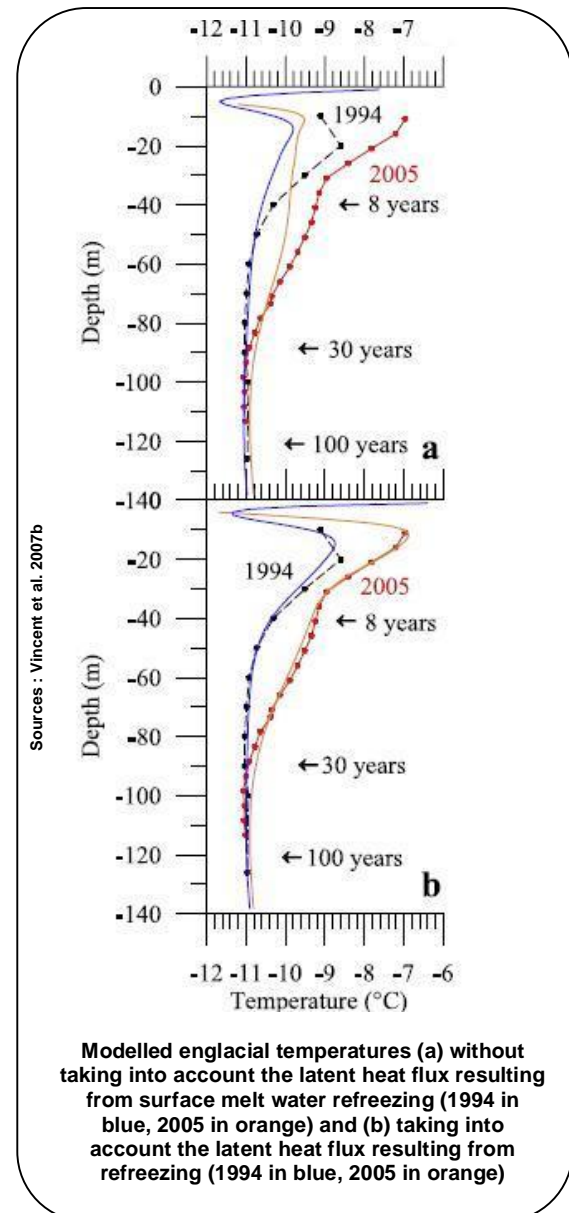


Fig. 10' – Températures de la glace mesurées dans des forages au Col du Dôme du Goûter en 1994 et 2005

Model results for the Saint Sorlin glacier (France)

As glaciers will probably continue their regression throughout the 21st century, a research team at the *Laboratoire de Glaciologie et de Géophysique de l'Environnement* of Grenoble (LGGE) developed a model to estimate glacier evolution in the context of climate change. This tool has been used to evaluate the future evolution of the Saint Sorlin glacier in the Grandes Rousses massif. Different IPCC scenarios (B1, A1B and A2) and different climatic models (CSIRO-MK3-0, GFDL-CM2-0, etc.) have been used to simulate the evolution of the glacier with a wide range of potential climatic values.

The results are varied due to the range of climatic values but the disappearance of the glacier is calculated by the end of the 21st century with the B1 scenario and the GFDLCM2-0 model (cf. fig. 12). Other scenarios expect more or less extreme glacier reaction but it is very likely that the Saint Sorlin glacier will disappear by the end of the 21st century.

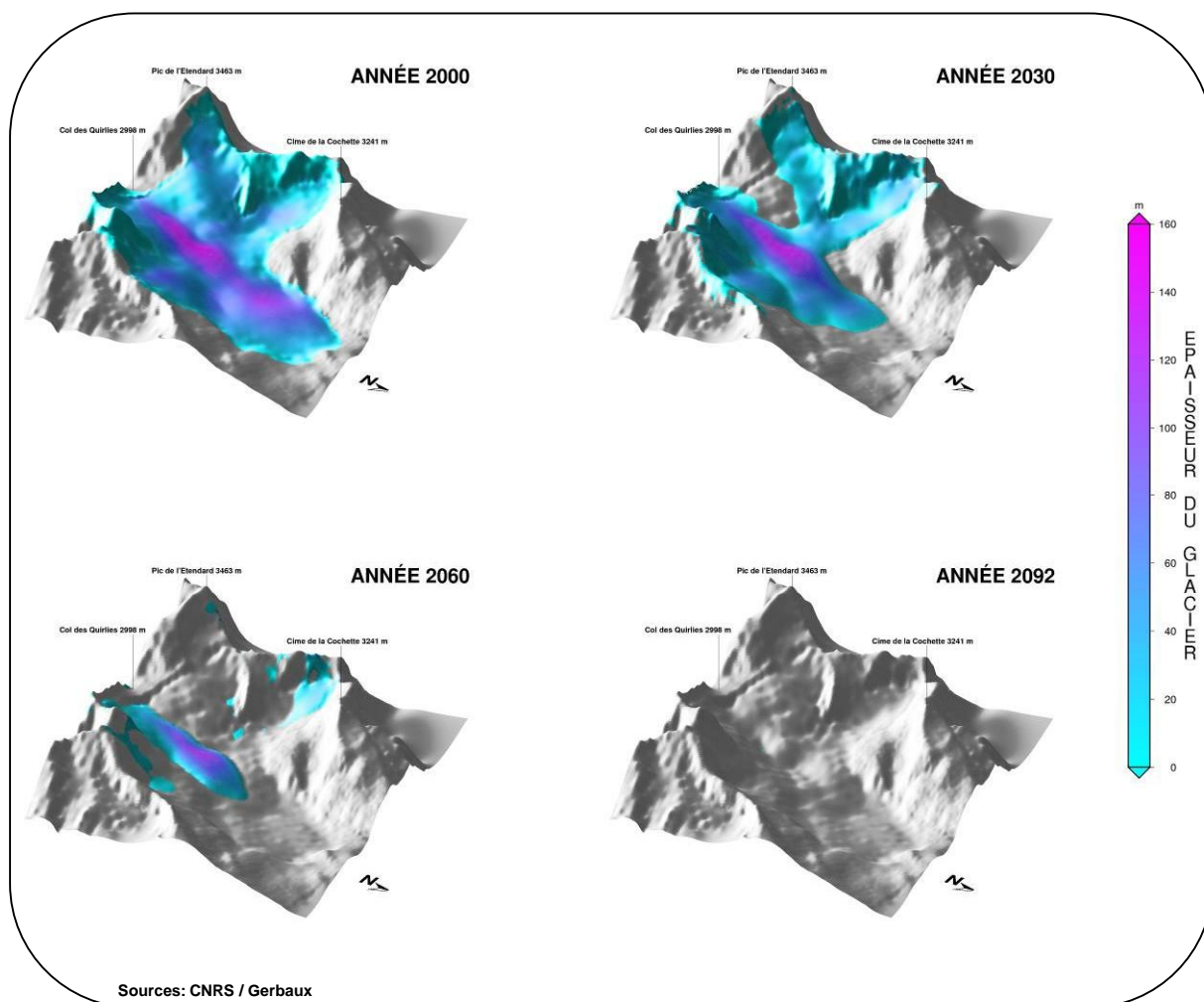


Fig. 12 – Saint Sorlin glacier evolution with the B1 scenario and the GFDLCM2-0 model

Observations in other Alpine countries

Italian Alps

There are 1,396 Italian glaciers spreading over 607 km² (21% of the glacial alpine surface). Analysis of the data from the ICG (Italian Glaciological Committee) shows that the melting phase of the Italian glaciers started in the mid-19th century with an exception in the period 1960-1980, confirming the general trend mentioned above. There has been a 40 % loss of the glacier surface in Italy since 1850. When analysing the percentage of glacier progress during the 1980-1999 period, the percentage of progressing glaciers dropped from 66% in 1980 to 4% in 1999, while the percentage of retreating glaciers increased from 12% in 1980 to 89% in 1999 (to be considered in the light of the 1960-1980 advance).

This trend is confirmed in all Italian Alpine regions. However, this kind of approach based on yearly changes has to be considered with caution as it does not show important cumulative effects. In the same period the cumulated variation of a sample of 104 Italian glaciers shows an average decrease of 4.8 metres / year. The overall decrease has been estimated to be around 95.4 metres for the 1980-1999 period. The Lombard Alps experienced the strongest retreat.

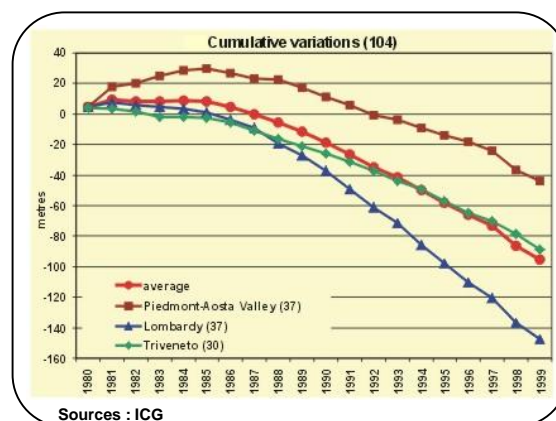
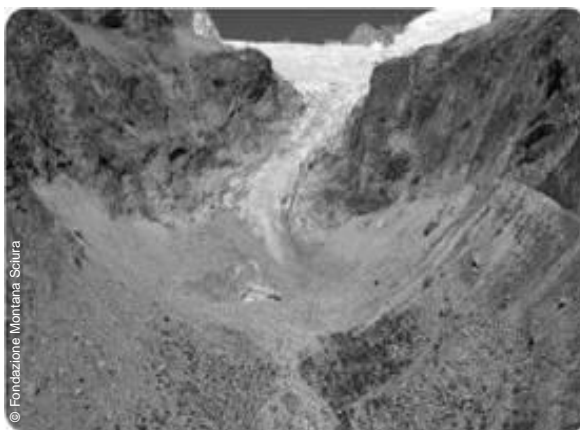


Fig – 13 Cumulative variation of a sample of 104 Italian glaciers in the period 1980-1999



Pré de Bar glacier (Aosta Valley) in 1929 (left) and in 2007 (right)

Swiss Alps

The Swiss Alps contain about half of the glacier area in the European Alps as well as the largest glaciers (Aletsch, Gorner, Fiescher, Unteraar). Since the end of the Little Ice Age around 1850, the length reduction has been about 3 kilometres for the Aletsch long valley glacier tongue, roughly 1 kilometre for the steep Trient mountain glacier and some 300 metres for the small Pizol cirque glacier (cf. fig 14).

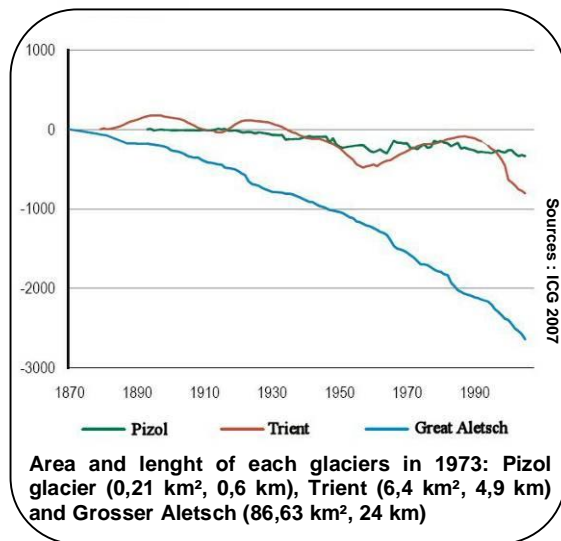


Fig – 14 Cumulated length variation (m) of the Pizol glacier Trient and Grosser Aletsch



Between 1850 and 1973, the elevation of the equilibrium line increased by an average of 70 metres to 80 metres, causing an average negative annual mass balance of a few dozen meters. The latest glacier inventory data derived from satellite imagery and corresponding comparisons with older inventories compiled and upgraded from old maps, aerial images and field mapping show that the average decadal loss in area between 1985 and 1998/99 is about seven times higher than the average from 1850 to 1973. In many cases, glaciers disintegrated into smaller units, separated from former tributaries, showed signs of collapse and started to form proglacial lakes which accelerate tongue retreat locally. This loss is particularly impressive when looking at pictures from the 19th and 21st century.



The Great Aletsch glacier (Wallis) in 1856 (left) and in 2001 (right)

Snow cover

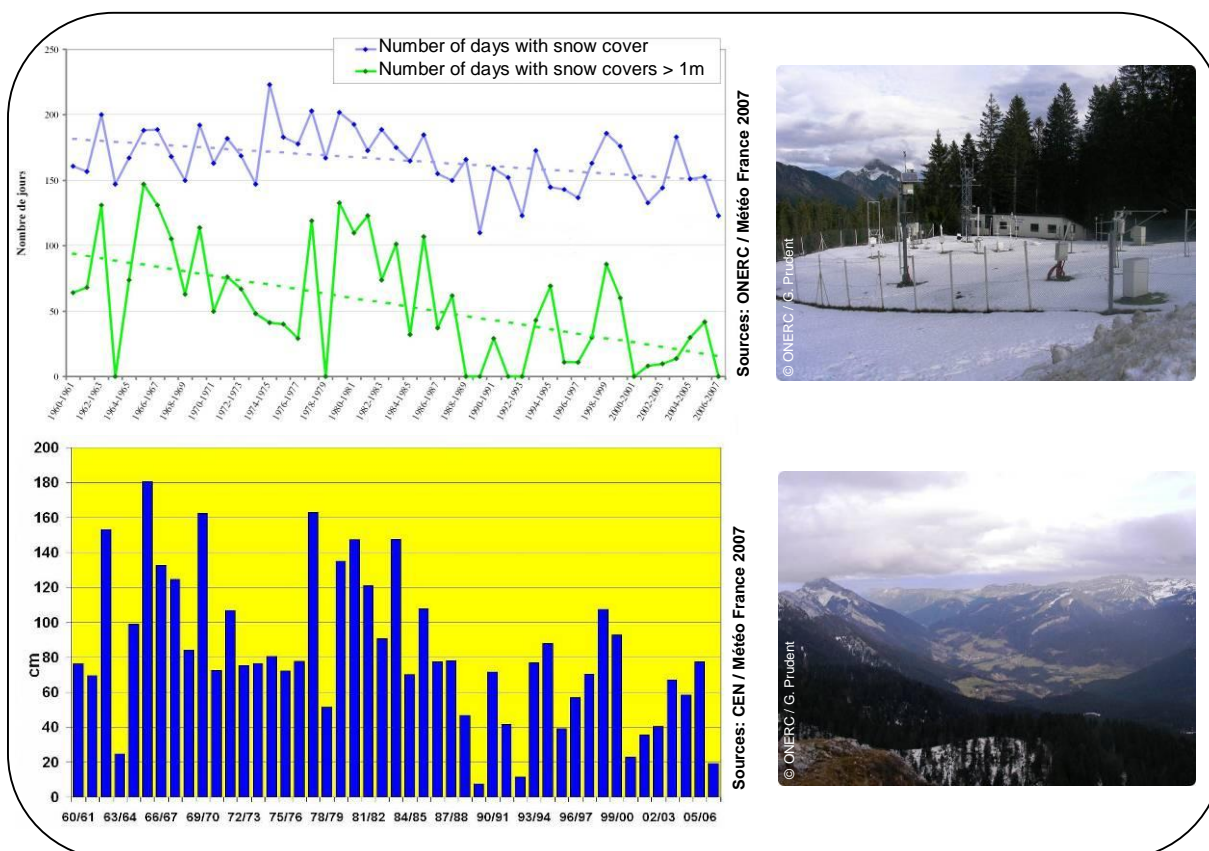
Snow cover plays a significant role in mountain systems. Besides being a primary resource for winter tourism, snow cover has a strong water storage function, insulates the ground from air temperature and hence its evolution is critical for permafrost pattern fluctuations, and it also represent an important habitat for some species. Snow cover is closely linked to both temperature and precipitation. For example, the ratio between solid and liquid precipitation directly correlates with temperature and precipitation, but many other factors also exert an influence on snow cover. The effects of shade, vegetation cover, slope and wind are some, but not all, factors influencing snow cover evolution.

Furthermore, large scale forcing, rather than just local or regional factors, plays a dominant role in controlling the timing and amount of snow in the Alps.

Observations in the French Alps

Very significant irregularity of the Col de Porte (Météo France experimental site, Chartreuse Massif, 1,320m a.s.l) snow cover for February has been observed between 1960 and 2000. Despite this strong interannual variability, the general trend is a decrease in snow height, especially due to low snow cover during the last decade (cf. fig. 13); snow height exceeded 1.5 metres only once during the 1990s, whereas it was 3 or 4 times this value for the precedent decades. Snow cover duration also decreased steadily/progressively since the 1960s (cf. fig. 15).

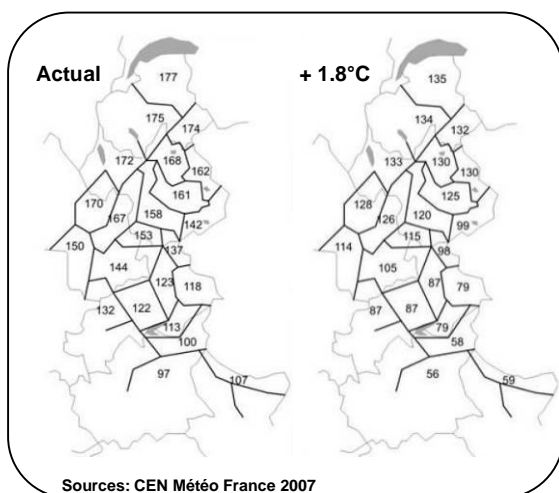
Fig. 15 – Mean snow cover duration at the Col de Porte (1,360 m a.s.l) during the second week of February (a) and mean snow cover height at the same location (b)



Model results for the French Alps

The ARPEGE global climatic model has been coupled with the snow model SAFRAN-CROCUS to calculate the snow cover reaction to a 1.8°C temperature increase. This temperature increase has much stronger impacts on low and medium elevation zones than on high altitude zones (> 2,500 m a.s.l.). At higher altitudes, the impact of climate change on snow cover can be considered as negligible. However, at lower altitudes (1,500 m a.s.l.), it is expected that the mean snow cover duration will decrease by more than one month (cf. fig. 16) and the mean snow cover height will decrease by 40 centimetres in the North Alps (from 1 metre to 60 centimetres) and 20 centimetres in the South Alps (from 40 centimetres to 20 centimetres).

Fig. 16 – Difference in mean snow cover duration between the current situation and the +1.8°C situation in the French Alps



Observations in other Alpine countries

German Alps

German scientists clearly identified a trend toward less lasting snow cover in Southern Germany. At lower altitudes (≤ 300 metres m a.s.l.) and moderate altitudes (between 300 and 800 metres a.s.l.) the number of days with snow

cover has decreased markedly (cf. fig. 17). Some distinctive regional features can be seen between the 1951-1952 and the 1995-1996 winters. In the Eastern parts of the examined region (Eastern part of the Alps and the Bavarian Forest) the decrease in the lower altitudes is from 20% to 30%. This trend weakens with increasing altitude and reverses (positive trend) at higher elevations.

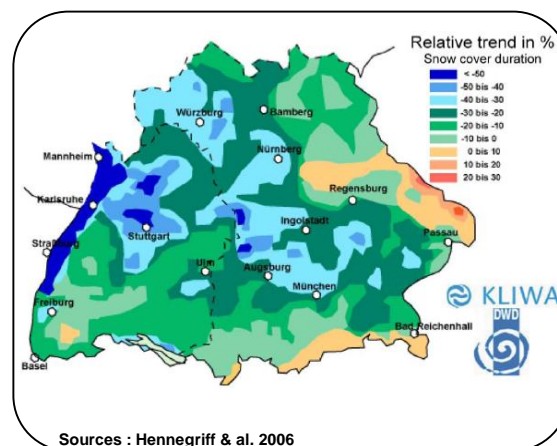


Fig. 17 – Relative trend in mean duration of snow cover in south Germany, series 1951/52 to 1995/96]

In the Western parts of South Germany (Upper-Rhine plain and the Western declivity of the Black Forest) the duration of snow cover decreased by approximately 50% and even more on lower ground whilst it decreased by 10% to 20% at moderate altitudes. In the higher regions, mean values under 10% are observed. Here, too, the trend weakens with increasing altitude.

Italian Alps

An historical analysis of snow cover over the Southern part of the Italian Alps was performed using historical data from 40 monitoring stations. The method for highlighting a snow-cover trend was based on the dimensionless index SAI (Standardized Anomaly Index). This index shows the anomalies of quantity, by means of the annual or seasonal contribution of each station. The inter-annual variability of snow cover is very significant over the 1920-2005 period but there has been a general decrease of snow cover over the Italian Alps (cf. fig. 18). During the 2003-2006 period, winter snow accumulation was even 40% below normal conditions (1959-2002 mean values) at the Lago Valsoera weather station (2,440 m, Gran Paradiso range).

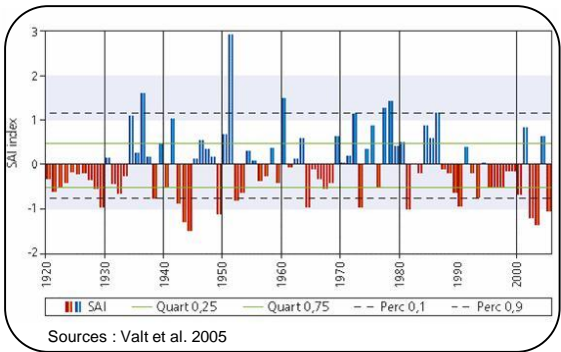


Fig. 18 – Cumulated snow cover in Italy between 1920 and 2006

Swiss Alps

The snow depth shows great short-term variability and marked long-term fluctuation. Snow coverage (number of days with more than 20 centimetres of snow) shows a similar pattern to snow depth. The variability is rather limited at the beginning of the century and increases thereafter. The greatest snowfall over 3 days and the total amount of new daily snow during the whole winter remain stable overall, but show extreme variability from year to year. Overall, both snow cover duration and height tended to decrease over the Swiss mountains (cf. fig. 19).

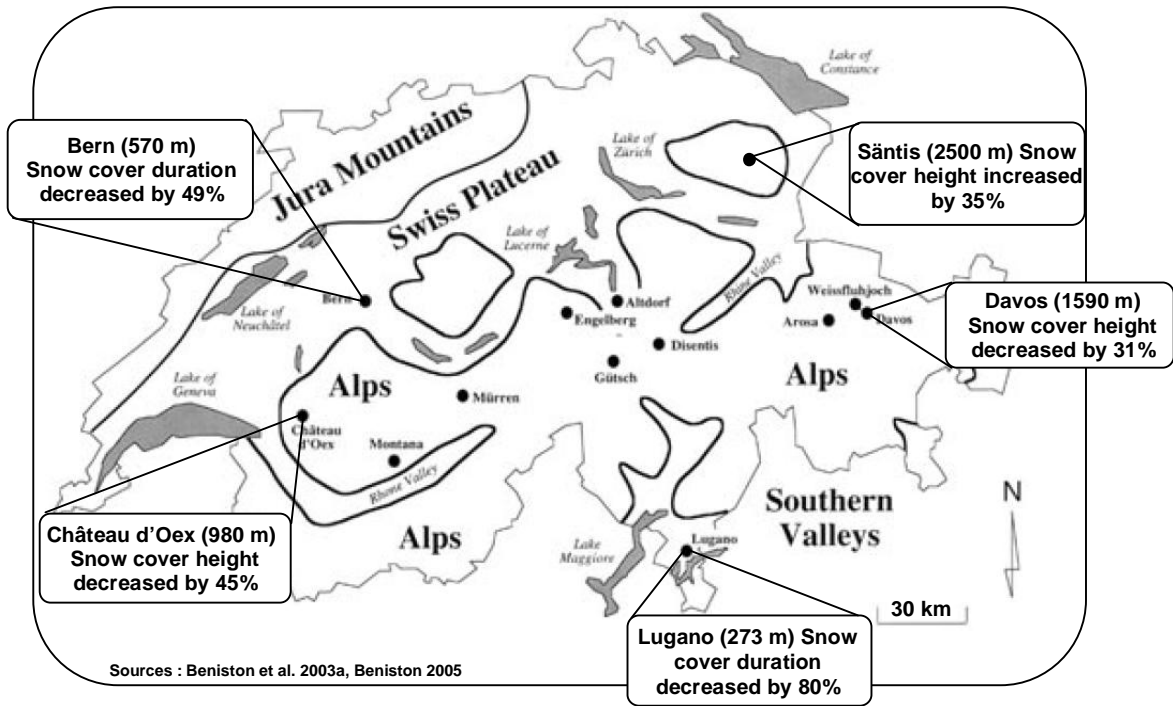


Fig. 19 – Snow cover evolution (duration and height) in Switzerland over the 1960-1990 period

Alpine permafrost

Permafrost is perennially frozen ground and defined as soil or other lithosphere material (including bedrock but excluding glaciers), at a variable depth beneath the surface of the earth, in which below freezing temperatures have existed continually for a long time, from two to thousands of years. Permafrost influences the hydrology and stability of steep scree slopes since ice-rich permafrost acts as a barrier to groundwater percolation and can imply local saturation within non-frozen debris. Additionally, permafrost thawing in non-consolidated material can lead to a loss of cohesion and to thaw-consolidation. The penetration of the freezing front into previously thawed material has the potential of intensifying rock destruction through ice formation in cracks and fissures. Such ice formation, in turn, reduces the near-surface permeability of the rock walls involved and affects hydraulic pressures inside the still open (non-frozen) fissured rocks.

The climate is influencing permafrost, particularly the active layer, which is melting throughout summer and the transition periods. Snow cover plays an important role in permafrost pattern by insulating it from low winter temperatures, and, as a consequence, the extent and duration of the snow cover is a critical factor for permafrost evolution. If snow falls in late autumn, then the low surface and air temperatures will effectively cool the permafrost – if snow falls in early autumn, the snow cover insulates the ground, preserving more of the summer heat deep within. Similarly, early melting of snow cover exposes the permafrost to long summer warming while the late disappearance of snow cover will reduce ground warming.

For example, during the 2002-2003 winter in the Swiss Alps, there were snow falls late in autumn but early melting of the snow cover in spring. Thus, the permafrost had already experienced a “bad winter”, with ground temperature anomalies, when the 2003 summer heat wave occurred. Similar events were observed in France at the rock glacier of Laurichard during the 2003-2004 winter. The effect of snow is much less important for permafrost at steep summits and in bedrock. The warming and degradation of permafrost in ridges, peaks and spurs is quicker and stronger because the heat front comes from several sides.

Based on observations, theoretical considerations and model simulations, permafrost degradation is likely to be of critical importance for natural hazards such as rock falls, mudslides and debris flows, as well as interactions with other phenomena such as hanging glaciers. These issues are developed further in the natural hazards chapters.

Observations in the Alps

Permafrost in the Alps occupies an area that is comparable in extent to the glacierized area but its secular evolution is less understood due to a lack of measurements. Gradual melting of Alpine permafrost has already taken place since the end of the Little Ice Age. Alpine permafrost in debris slopes is typically several decametres to more than 100 metres thick and has a characteristic mean annual surface temperature between melting point and about -3°C . Permafrost at steep bedrock summits can reach temperatures well below -10°C . Rock glaciers are also reacting to the rise in air temperature. The melting of ice within rock glaciers is leading to increased speeds of deformation.

The movement of rock glaciers is a common feature in the Alps, indicated by an increase in recent years from 20% to 100% of movements in the French, Swiss and Austrian Alps. Measurements in the upper 60 metres of ground show a more or less stable surface temperature between 1950 and 1980. As a consequence of the exceptional warming in the 1980s, the annual rate of thaw settlement due to melting ground ice in Alpine permafrost may have doubled since the 1970s and reached the decimetre range per year. Borehole observations also indicate that permafrost temperatures are now rising at a high rate although they can be drastically influenced by snow cover conditions in early winter that may lead to cooling phases.

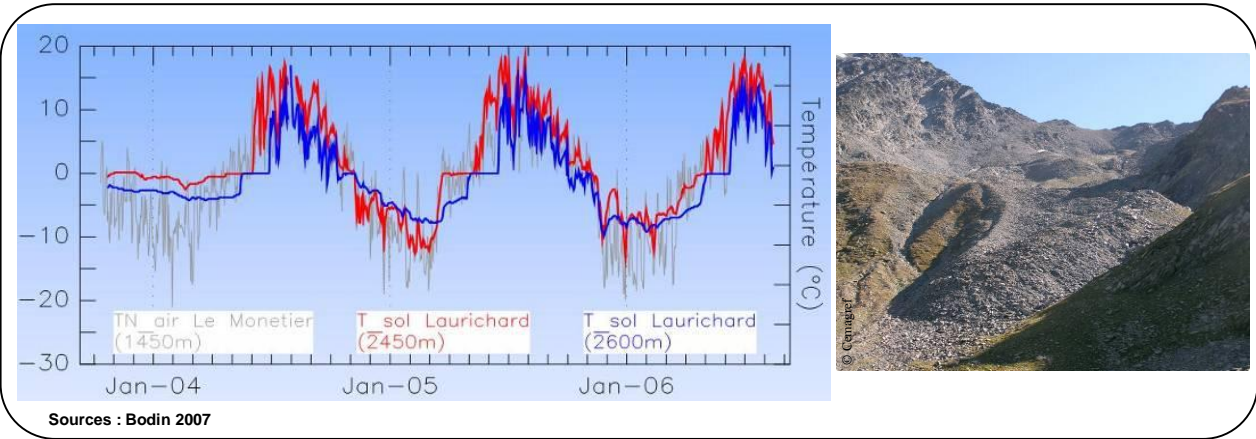
A rapid warming of 0.5°C to 0.8°C during the last century in the upper decametres of Alpine permafrost has been confirmed by borehole measurements. Researchers in the PACE project (Permafrost and Climate in Europe) have found temperature increases between + 0.5°C and + 2.0°C over the past 60-80 years in permafrost soils in European mountain regions, from the Sierra Nevada in Spain to the arctic archipelago of Svalbard. The 2003 summer was of critical importance in demonstrating the reaction of permafrost to high summer temperatures.

For example, the active layer at the monitored Swiss site of Schilthorn dropped from 3.7 metres to 4.2 metres in depth during the 2003 heat wave. By 2004, the active layer had still not recovered its initial position at 4 metres.

Laurichard Rock glacier (France)

In detail, the flow speed of the Laurichard rock glacier (Hautes-Alpes) shows successive acceleration and deceleration during recent decades. Between 1979 and 1997, the speed was roughly 25 centimetres / year with a slight inflection since 1986. Thereafter the flow accelerated together with other rock glaciers in the Alps, to reach a maximum speed in 2001. The speed values then became similar to those of the 1980-1990 period. The snowy winter of 2003-2004 clearly prevented the ground from cooling by keeping the heat trapped within the rock glacier throughout the 2003 summer (cf. fig. 18). This might explain the high speed and the surface subsidence of the glacier (through permafrost top melting) that were observed in 2004.

Fig. 20 – Ground temperature at Laurichard (2,450 and 2,600 m a.s.l) and air temperature at Monetier between October 2003 and September 2006



Permafrost and rock glaciers in the Swiss Alps

The longest continuous series of temperature measurements within European mountain permafrost is from the 58 metres deep borehole at Murtèl–Corvatsch (Engadin, Switzerland) which was drilled in 1987 through slowly creeping ice-rich debris. Long-term monitoring of ground temperatures at Murtèl–Corvatsch in Switzerland has clearly demonstrated the sensitivity of mountain permafrost to changes in both air temperature and the amount and timing of winter snow cover.

Rapid warming of the uppermost 25 metres of permafrost was observed between 1987 and 1994. The mean annual ground surface temperature is estimated to have increased from -3.3°C (1988) to -2.3°C (1994). At a depth of 11.6 metres (inside the active layer), the permafrost warmed by nearly 0.6°C . At 20 m (under the active layer), the warming was only by 0.2°C .

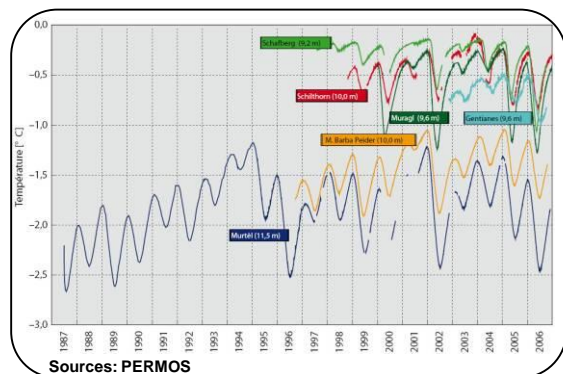


Fig. 21 – Ground temperature (10 m deep) at different monitored Swiss sites (PERMOS)

However, low snowfall in December and January during the 1994-1995 winter followed by moderate snow fall in 1995-1996 caused intense cooling of the ground and permafrost temperatures returned to values similar to those in 1987. Early winter snow was thin in 1998-1999 and winter ground temperatures remained low in 1999, 2000 and 2001.

The analysis of this long data set, combined with more recent measurements at other Swiss monitoring sites confirms that the permafrost has been warming since the beginning of the measurements. This warming took place in three steps interrupted by a cooling during the 1995-1996 winter and a cooling since 2002 (cf. fig. 19). These decelerations of the warming trend are mainly due to winters with limited snow cover.

Climate change seems also to have strong impacts on Swiss rock glaciers. At the vallon des Yettes Condjà (Wallis), the speed of surface movement of one rock glacier increased by 200% between 2000 and 2004 and by 76% for the other rock glacier (cf. fig. 22).

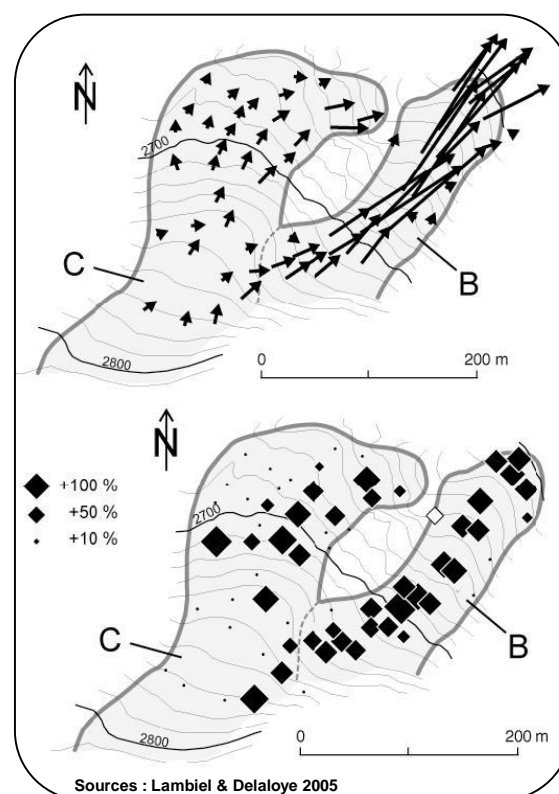


Fig. 22 – Rock glaciers of the vallon des Yettes Condjà (Wallis, Switzerland): Surface horizontal speed 2003-2004 (left) and surface horizontal speed variations 2001-2004 (right)

Alpine vegetation

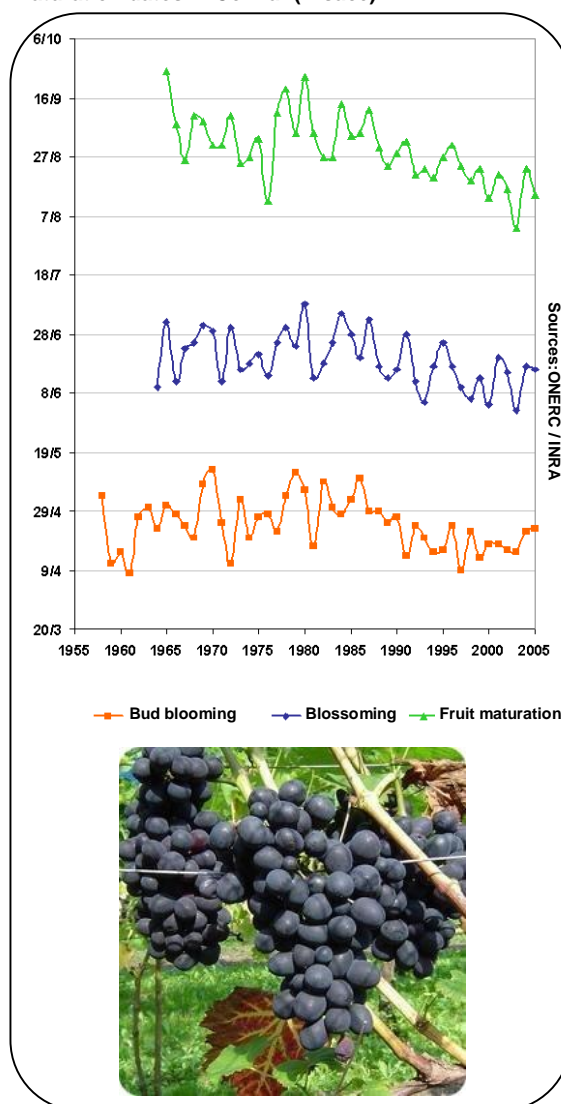
Vegetation observations in France and other alpine countries

Climate change has already impacted on vegetation, through direct and indirect impacts. For example, climatic parameters have direct impacts on species physiology whereas the changes in repartition of parasites and insects, which are disease vectors (closely linked to climate evolution), are an indirect impact. Furthermore, evaluations of the influence of climatic parameters on vegetation evolution remain difficult. Indeed, Alpine vegetation has been suffering for over a millennium from various modifications due to human activities (wood exploitation, agricultural changes, species introduction, use of water resources, etc.).

A direct impact of climate change that can be readily observed is the extended vegetative period (not only in the Alps), with earlier bud blooming and later leaf shedding (cf. fig. 23).



Fig. 23 – Bud blooming, blossoming and fruit maturation dates in Colmar (Alsace)



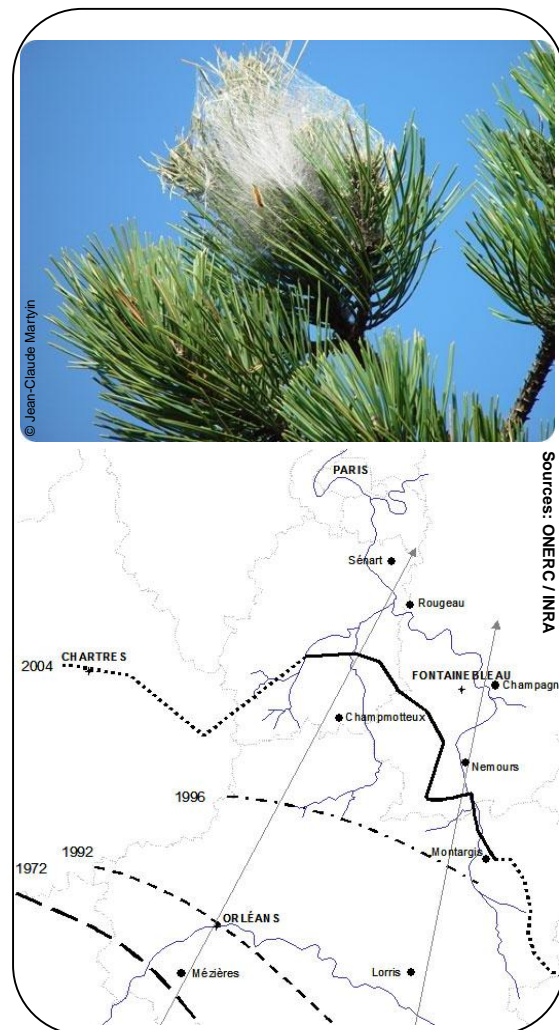
Since the end of the 19th century, an increase in forest growth has been observed in Europe. This phenomenon is quite general with some marked regional differences. For example, beech tree height increased by 25% in North-Western France, and 50% in North-Eastern France during the 1900-2000 period. Climate change is one of the hypotheses to explain this increase in forest growth but it is still difficult to determine the respective roles of the CO₂ concentration increase and climate evolution.

The evolution of the repartition area of species has also been observed both for altitude and latitude. For example, a general extension of *Lauryphilles* (species with large, persistent and tough leaves) has been observed, as well as the altitude rise of some species (+ 200 metres for the mistletoe in the Valais between 1910 and



“Negative” impacts have also been observed. Parasites and their hosts are developing due to warmer temperatures (cf. fig. 24, this figure illustrates the propagation of a parasite in the Parisian Basin but the mechanism is the same for Alpine regions, with an additional propagation in altitude). The temperature increase also has negative impacts on water availability. For example, the 2003 drought was the most severe drought for the broad-leaved tree population in France over the last 50 years and caused a significant death rate peak.

Fig. 24 – Pine processionary caterpillar progression in the Parisian Basin between 1972 and 2004



Vegetation evolution projections in France

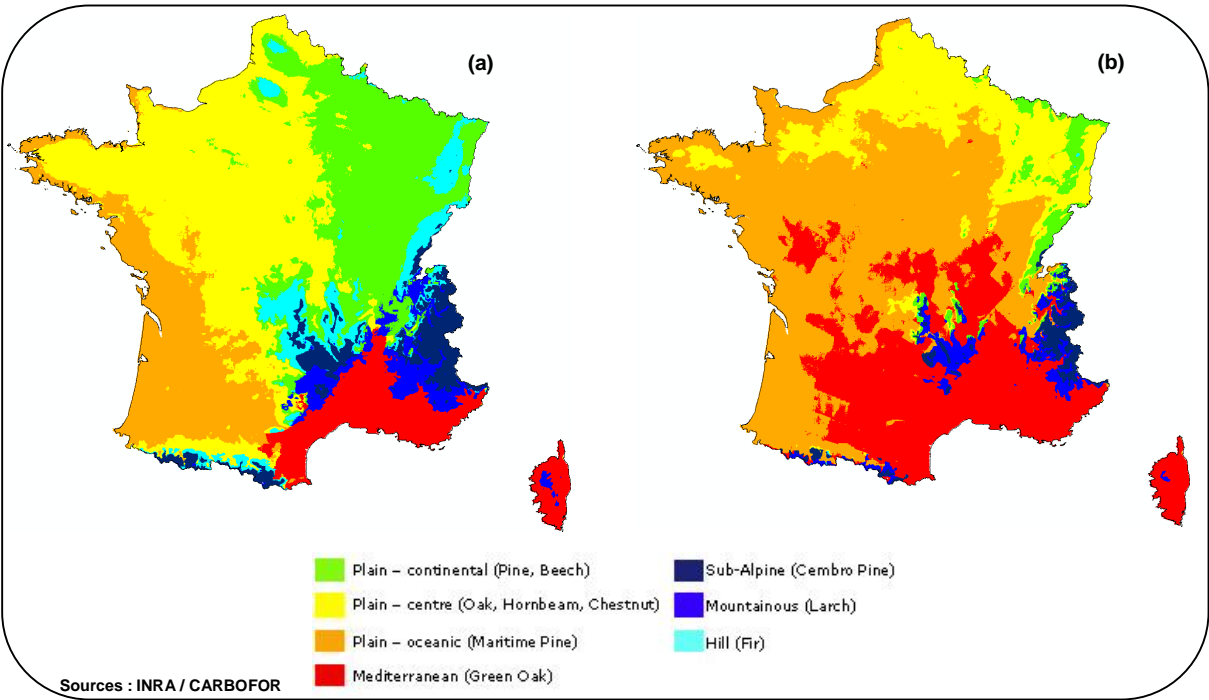
Projections follow the observed impacts of climate change on vegetation, but the “positive” impacts of climate change should continue to occur until a threshold is reached. Beyond a limit, the increase in vegetation production should be counterbalanced by a lack of water for the vegetation. Again, the balance between positive and negative impacts of climate change on vegetation is difficult to assess. By using models, scientists can give directions about future evolution of vegetation.

For example, bud blooming would occur earlier by 6 to 10 days for broad-leaved trees and 15 to 20 days for the Maritime Pine. For the Pine and the Spruce (species needing cold periods), the earlier bud blooming would only occur in altitude. For all species, the risk of freezing would be reduced. However these models do not correctly integrate all the parameters (e.g. diseases and parasites are poorly represented in these models). As regards forest cover, there would be a general progression of the Oceanic and Mediterranean bioclimatic areas while the mountainous bioclimatic area would be in regression (cf. fig. 25).



Fig. 25 – Geographic repartition of 7 chorologic groups for the current climate (a) and 2100 climate projections with the ARPEGE model (b)

Forest evolution is important for forestry but also has consequences on the landscape and natural hazard protection. For example, the progression of broad-leaved trees against conifers might increase protection from rock falls but at the same time decrease protection from avalanches; broad-leaved tree trunks are more resistant to shock but coniferous trees provide better protection against avalanches through better stabilisation of the snow cover. Biodiversity in mountains is expected to diminish with climate change. The natural response of vegetation to a temperature increase will be to migrate in altitude. For each degree of temperature increase, the species might migrate 150 metres in altitude. However, for species which are already on the edge of their bioclimatic area, there might be nowhere to migrate. Endemic species also have a limited climatic tolerance, while alien species have very good climatic tolerance. Thus climate change will increase the pressure of alien species as well as biological competition.





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The influence of the climate and climate change impacts on natural phenomena in the Alps



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Floods – historical processes and projections regarding climate issues

Definition

Floods are a rapid and long-lasting increase of the water level that can lead to inundations (through infiltration, dike bursting, etc.). Floods are part of a river's natural cycle. The implementation of human stakes within major riverbeds puts these stakes into potential flood situations.

Data concerning floods in the Alps

Floods are relatively well observed in both time and space. Monitoring and observation networks are implemented along most of the alpine and peri-alpine rivers. The Alps represent an important part of the big European rivers catchment area. Indeed, 20% of the Rhône waters and 67% of the Rhine waters originate in the alpine area. Rivers like the Rhône and the Rhine have long flow chronicles. Furthermore, historic reconstructions (like that carried out by C. Pfister in Switzerland) can give an idea of river activity for the period preceding instrumental records.

Flood sensitivity and links with the climate

The link between climatic parameters and river floods is obscured by many human factors (this is even more perceptible than for torrential events). Land-use changes greatly modify the surface flows and the stream. Today there are no catchment areas in the Alps with “natural” flow processes. Water used for agriculture also represents an important part in the flow balance. Hydraulic works can have a strong influence on river characteristics. Dams radically change the flow patterns, whilst protective buildings and micro power plants represent “noises” in

frequency and intensity analyses. Moreover, many “hazard-reducing” measures (dikes, protection forests, etc.) were implemented in the first half of the 20th century, while “hazard-aggravating” measures (ground waterproofing, concrete banks, etc.) have generally increased in the second half of the 20th century.



The following hypothesis is generally proposed: in a warmer climate, the situations that could lead to floods would increase (with the postulate that with more energy in the climatic system, the water cycle would be enhanced). However, there is a lack of “transfer” between climatic model results and the possible effects on hydrological balance and river runoff. Up till now, the proposed impacts were mainly qualitative. Hydrological models aimed at obtaining quantitative results are currently under development in Germany and Switzerland.

Climate models calculate a precipitation increases for some seasons and precipitation decreases for other seasons. Thus it is expected that the evolution of floods will follow that of precipitation. However the non-linear nature of precipitation/runoff relations and various buffer effects might attenuate the impact of precipitation on large-scale catchment areas. As regard to the torrents, the buffer effect on the catchment area is more reduced and so it is more sensitive to fluctuation in precipitation.

Observed impacts of climate change on floods

Flood intensity: On the world scale, around 70% of rivers flows do not show any significant trends related to climate change. When these trends are significant, they are divided equally between an increase and decrease in flood volume. In France, different studies converge on the fact that there are no significant trends concerning flood volumes since the middle of the 20th century. These findings are also valid for Central Europe (Elbe and Oder rivers).

However, in Southern Germany, the examined runoff time series demonstrate a regional increase in flood runoff for some stations in the last 30-40 years; but no significant changes were detected when examining the annual series for 70 to 150 years time series duration.

Flood frequency: An increase in the frequency of « extreme » floods in the Alps has been observed over the past 20 years, compared to the 20th century mean. In Southern Germany, the KLIWA project stated that the frequency of winter floods increased since the 1970s with the exception of Southern Bavaria (i.e. North edge of Alps). Significant floods occurred in Switzerland in August 1987, September 1993 and October 2000, particularly in Ticino in 1978, 1987, 1993 and 1994. However this frequency increase seems to be within the natural range of variability. The same kinds of conclusion have been proposed for floods in Central Europe (Oder and Elbe). In France, statistical studies do not show any significant flood frequency increase.

Floods intensity/frequency and seasonality:

An increase in summer flows for rivers fed by glaciers, due to increased glacier melting, has been observed in the Alps, with favourable impacts (on a short-term scale) on low waters, but no direct impact on floods. In Southern Bavaria, the KLIWA project stated that monthly runoffs during winter are higher since the 1970s (compared to preceding values, available since 1931). In France, the only detected changes concerning floods and low water patterns are found in mountainous areas (Alps and Pyrénées). In these mountain ranges, a temperature rise lead to earlier melting of snow cover and strong low water events (depending on whether there was snow cover or not).



Potential impacts of climate change on floods

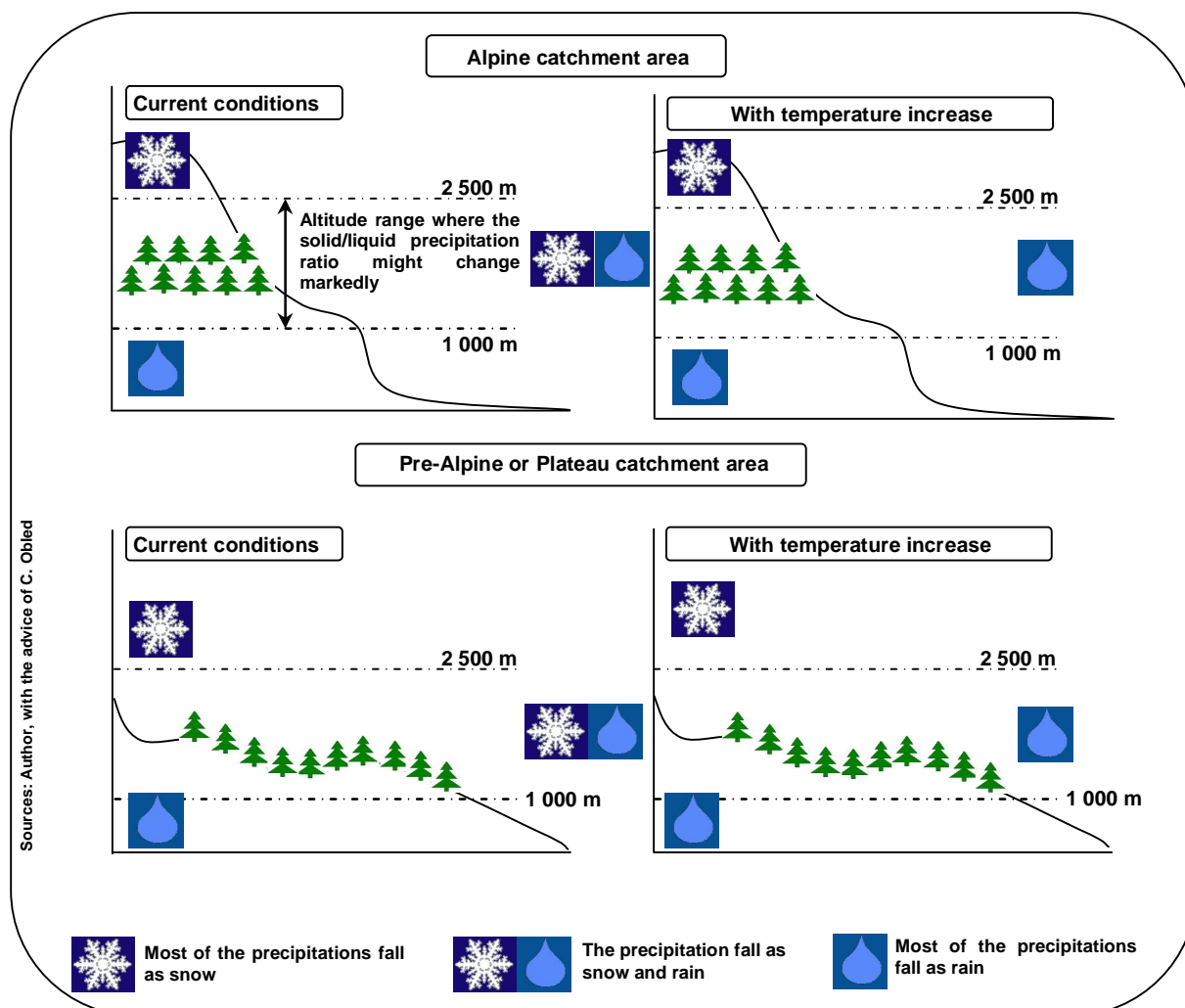
Floods intensity/frequency and seasonality:

The simulated winter precipitation increase and the expected limited buffer effect of snow cover (due to a higher rain/snow limit) should lead to favourable situations for floods in winter (both for intensity and frequency).

Depending on the topography of the basin, these impacts might be of major importance if it incorporates a large zone at medium altitude ($\approx 1,000\text{--}2,500$ metres a.s.l.) with a consequent snow cover (cf. fig. 24). On the other hand, the intensity of spring flood peaks would be reduced as a consequence of the gradual melting of snow cover.

The river flood peak due to snow cover melting could occur a month earlier in the year. On a global scale, diminished low waters and even droughts should be more frequent during summer because of reduced summer precipitation and stronger evapotranspiration. Nevertheless, the rivers fed by glaciers (which represent important water stocks) may experience a flow increase in the short-term with stronger glacier melting in summer. In the long-term, once the glaciers would have lost most of their volume (and/or surface), and thus their potential water stock, the flow of these rivers would decrease. The increase in summer flow has already been observed while the long-term decrease remains a strong assumption.

Fig. 26 – Schematic evolution of the winter solid/liquid ratio for Alpine and Pre-Alpine catchment areas



Debris flows and torrential events – historical processes and projections regarding climatic issues

Definition

Torrents are mountain rivers characterised by small length, a steep slope ($> 6\%$), with sudden and violent floods. Downstream of these torrents are torrential rivers with a gentler slope (between 1% and 6%), with sudden floods and an important solid transport linked to the slope. Depending on the percentage of solid materials, sediment transport in torrential floods can be either suspension, bed load or debris flows. Debris flows are generally triggered by extreme precipitation, when a liquid flow in a torrent bed is moving a large amount of non-consolidated materials (e.g. scree, mud, etc.). These flows constitute more than 50% solid materials of different sizes, from very small materials to rocks of several cubic metres. Even when they are quite slow, debris flows can be very powerful.

Data concerning torrential events in the Alps

Debris flows and other torrential events are relatively difficult to observe. The same is true of the predisposition, triggering and aggravating factors related to torrential events. There are insufficiencies in the rain cover network, i.e. a precipitation measure network that is adapted to the torrential phenomenon. With the exception of some experimental basin catchments, measure stations are rarely located in close vicinity of hazard zones and the data have to be extrapolated from distant stations. The precipitation data provided by meteorological stations also have limits when trying to assess the link between torrential events and climatic parameters.

Indeed, the significant precipitation gradient on the mountainous relief makes the data from permanent measure stations located at the piedmont or valley floor unusable. For example, during the August 2005 floods in the Belledonne massif (France), 278 millimetres of rain was been recorded in 48 hours at the La Pra refuge (2,100 metres a.s.l.) whilst only 32 millimetres was recorded at the Versoud automatic station (220 metres a.s.l.). To correctly assess the meteorological conditions associated with the triggering of torrential events in a particular location, it would be necessary to have measure stations in these locations or at least to have a network representing the massif with a good altitudinal distribution. The implementation of automatic flow monitoring stations is not feasible as these installations would most likely be carried away during each torrential flood. Even direct observation during an event is difficult as it is hard to correctly estimate torrent flows during a flood. Automatic monitoring systems exist in Switzerland but they are used to give the alert and cannot provide instrumental data that could be used for studying the events.

Indeed, torrents have a very limited observation potential. This does not mean that no data exists for torrents and associated natural phenomena, but the data are too heterogeneous or too rarely synthesised at the regional scale to propose a complete analysis of the evolution of torrential events. In France, these observations are realised on the field by the RTM service (Special Office for the Restoration of Mountain Soils) in the Alps and the Pyrénées. These specific studies of some torrential catchments usually provide long event chronicles but with the difficulties mentioned above, especially concerning volume estimation.

However it is easier to evaluate the volume of carried materials, especially coarse debris (e.g. those exceeding 1 metre in diameter).

Furthermore, even if bed load and suspension are important in terms of the operational management of natural hazards, the impact of climate change on these events has not actually been assessed in the available scientific literature, unlike debris flows. Thus the next paragraph will concentrate on debris flows. This should not obscure the importance of the other torrential events.



Debris flows sensitivity to climate change

Debris flows are principally triggered by violent water release on areas where available materials will potentially be carried away by the rush of water. Precipitation and the availability of the non-consolidate materials are the two main components that might be affected by climate change. The threshold values for triggering of debris flows can differ from one massif to another, and even between two hazard areas within the same massif. This violent release of water can be characterised as follows:

- ☞ Spring / early summer thunderstorms (May, June and July) with very confined and short (one to four hours duration) events but at a period when the mountainous catchment

areas are still moist from recent snow melting.

- ☞ Generalised autumn events (end August, September, October) when water is falling on drier ground, but with high intensity, longer duration (six to 18 hours) and over a wider area. Autumn events show greater intensity due to their origin in the Mediterranean Sea which is warmer during this period of the year.



At Ritigraben (Wallis, Switzerland), an increase in precipitation events with the potential to lead to debris flows has been observed during the past three decades. However, the precipitation data available are on a daily scale while for a more precise assessment, hourly precipitation data would be required. Indeed, hourly precipitation intensity is an important parameter, and for a given daily precipitation value, the hourly precipitation distribution can vary greatly.

Many hypotheses propose links between permafrost degradation and an increase in debris flow intensity and frequency through the increased availability of non-consolidate materials. The degradation of frozen grounds concerns the periglacial area⁴ in its entirety. Permafrost thawing diminishes cohesion inside unstable or metastable structures and can potentially increase the future material availability for debris flows. Glacier retreat also exposes large amounts of freshly uncovered materials presenting very low cohesion.

All these phenomena, which could lead to debris flows, are potentially influenced by climate change through changes in the freezing/defreezing cycles, changes in heavy precipitation seasonality and frequency, changes in glacier patterns as well as changes in the available materials for debris flow triggering. However, debris flows are phenomena characterised by very significant spatial and time variability which leads to difficulties in assessing the impact of climate change on these natural events.



⁴ Area where freezing/defreezing and snow cover alternation play a predominant role



Observed impacts of climate change on debris flows

Debris flows intensity/frequency: Despite the important number of hypotheses proposing an increase in debris flow intensity with climate change, no trends have been observed or modelled. The available studies mention a decrease in the occurrence of debris flows. Correspondingly, the debris flow frequency in the Swiss Wallis seems to be the lowest in the last 300 years and a significant decrease in the number of debris flows has also been observed since the mid 1970s in the Écrins and Dévoluy massifs (France).

The evaluation of events considered “extreme” when they occurred (this is especially true concerning the Ritigraben torrent in Switzerland in 1987 and 1993) has been moderated by recent publications. Early analyses which interpreted these events as the first signs of climate change have been attenuated because further investigations on the site showed that such intense events occurred with the same frequency in the past.

Debris flows seasonality: Debris flows mainly occur during summer, generally between June and October. A seasonal shift has been observed between the 1800-1950 and 1950-2000 periods at Ritigraben (Swiss Wallis) where the debris flows shifted season from June/July (linked to local thunderstorms) to August/September (linked to regional heavy precipitation).

Debris flows localisation: An altitude increase has been observed in the triggering areas of debris flows for some massifs, such as the Écrins (France), where their altitude rose by more than 100 metres between 1952 and 2000. The triggering areas located under 1,800 metres a.s.l. have remained inactive since 1976. However no variations have been observed above 2,200 metres a.s.l. The temperature increase and the decrease in freezing days are assumed to explain these altitudinal shifts. Another study at the Mont Rose, which also mentions a spatial shift, proposes glacier retreat as an explanation.

Nevertheless today, no changes in debris flow activity directly caused by changes in the volume of available materials in these areas have been detected. Given the limited number of studied sites and the fact that existing studies do not focus on the material availability; it cannot be assumed that no changes have occurred as yet.



Potential impacts of climate change on debris flows

Debris flows intensity: Despite the large number of hypotheses proposing an increase in debris flow intensity with climate change, no trend has been modelled. Material availability is the critical factor that could lead to a change in future debris flow intensity. This intensity variation could lead to increased volume and stopping distance. Thus, even if debris flow intensity can be assessed in a general manner, it is important for policy makers and technical services to also understand the evolution of particular sites. Particularly, hazard areas linked with periglacial areas may potentially experience marked intensity changes (even if such changes have not yet been observed).

Debris flows frequency: Model results simulating a decrease of debris flow events for a warmer climate are in accordance with observations at low and medium altitude. However, on the Alpine scale the frequency could increase in particular regions and decrease elsewhere depending on local situations and driving parameters (altitude, occurrence of permafrost...).



Debris flows seasonality: Some hypotheses also propose the evolution of debris flow activity if precipitation were to increase during spring and fall (as suggested by climatic models). However this seasonal shift in precipitation should not have any effect on debris flows because the mean temperature during these periods would remain lower (from 4°C to 7°C) than the mean temperature during summer (summer is the main season for debris flow occurrence).

Debris flows localisation: Deglaciating areas (moraine, scree slopes) and permafrost degradation (including rock glacier dismantlement) are expected to furnish more available materials for future debris flow activity. Moraines and active talus slopes can furnish debris flows; some dismantled rocky glaciers can also be affected by this kind of phenomenon. Debris flows could be triggered more easily if the slope is steep in these areas. High mountain areas in the periglacial zone could be more favourable to debris flows events than in the past.



Avalanches – historical processes and projections regarding climate issues

Definition

An avalanche is the rapid movement of snow cover on a slope. This is a gravity movement triggered by a loss of balance of the snow cover. Depending on the snow settlement, ground temperature, existing vegetation cover, air temperature and humidity, this movement can occur at the ground level (wet snow or slab avalanches), or as an aerosol. These types of avalanches result in different propagation characteristics inducing various levels of damage and protection possibilities.

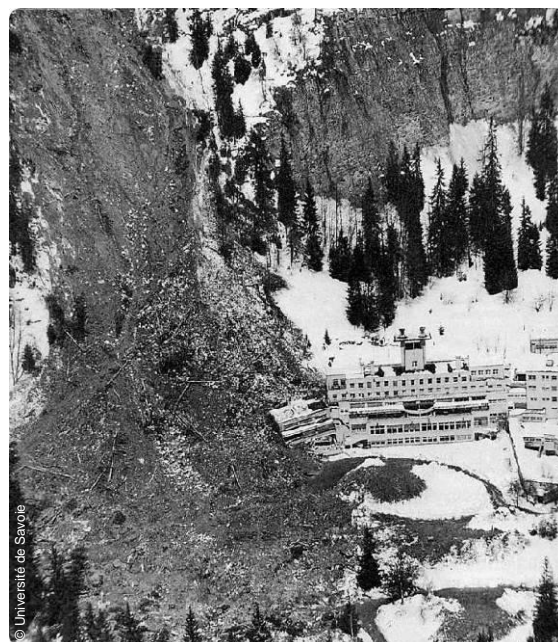
Data concerning avalanches in the Alps

Past avalanche activity reconstructions are realised by using historical documents reporting damages to buildings and inhabitants, some of these chronicles date back to the 16th century. However this kind of analysis cannot be used to assess the evolution of natural events because only catastrophic events, which lead to damages, are reported and detailed. Some dendrochronology and lichenometry techniques have also been used to characterise past avalanche activity in very precise locations. These techniques are still being developed and many limits still exist: the limited number of available studies hinders a critical view of the method used. Some problems concerning time calibration can also be found.

Furthermore, even if avalanche activity in a precise location can be reconstructed using these techniques, the link with climatic parameters is not easily discerned. Even if it is possible to assess the link scientifically, the

researcher must extrapolate data from meteorological stations often located quite far from the observation site.

Avalanche observation is compiled in avalanche atlases, databases which are often maintained by the forest services or their equivalent in the alpine arc. This observation work is carried out from identified avalanche locations on maps. Technicians observe the events and describe their characteristics using a data form; all these data forms represent a database describing the avalanche activity of the monitored avalanche area.



Some cooperation networks with ski resorts provide information about avalanche activity within the ski resorts or in their vicinity. The data analysis is not able to propose a clear evolution of avalanche hazards and even less to provide links between avalanches and climatic parameters. However, these data are used to evaluate the avalanche risk with “closest neighbour” methods. These methods are used by the meteorological services and ski resorts in Anglo-Saxon countries (United States, New Zealand, Canada...).

Data concerning avalanches in France

The « Enquête Permanente sur les Avalanches » (EPA) started in Savoie before 1900 and has been carried out systematically in the Alps and Pyrénées since 1965, leading to a database which now includes over 80 000 events. For a long time, this monitoring was dependent on the initiative and availability of the ONF (National Office of Forestry) personnel and particularly the RTM services. Despite these limits, exhaustive data series are available for various territories, especially since 1945.

Since 2002, the « Ministère de l'Écologie et du Développement Durable » (today MEDAD) aimed to give an official frame for this action (following a recommendation of the back analysis commission set up after the catastrophic avalanche of Montroc in 1999). A protocol has been developed to homogenise all the information for the sites: observations are always conducted from the same location, indications on the map help the observer to estimate the event's magnitude and the periods without avalanche activity are also detailed so as not to be considered periods without observation. All these recommendations are detailed in an instruction book. This new regulation of avalanche observation should enable a scientific analysis of the avalanche evolution for particular locations.

The snow-meteorological network was implemented in the 1980s through cooperation with Météo-France. This network provides daily information on avalanche activity in ski resorts and their vicinity during the tourist period. These data are not exhaustive in terms of area covered or in terms of time covered.

They are of very poor quality when the meteorological conditions do not enable the personnel to make direct observations (e.g. due to fog).



Like floods, avalanches are highly monitored (in the critical area) and many prevention/protection measures exist. The implementation of protection buildings (protection dikes, snow fences, avalanche mounds, etc.) or changes in forest cover for example have strong impacts on avalanche activity. All these measures represent “noise” in the signal of the natural event itself, making its interpretation more difficult.

Despite the importance of the data collected and its compilation within a homogeneous database, it does not represent a systematic and instrumental chronicle of avalanche activity enabling a complete statistical analysis on the phenomena evolution. Thus it is important to choose a representative sample for the considered massif. The difficulty of collecting data with a standard protocol (as the EPA method) is a crucial problem for the study of avalanches. Methods aiming to account for these insufficiencies (using automatic monitoring with seismic captors or satellite data for example) are currently in development or undergoing testing but they face technical limits.

Avalanche sensitivity and links with the climate

Avalanche situations often results from a combination of an extreme meteorological situation (massive snow falls, intense melting) and a significant existing snow cover. It is therefore necessary to know the evolution of such extreme meteorological situations to be able to assess the evolution of avalanche activity.



Nevertheless the understanding and integration of extreme meteorological events into the climatic model is still in process. Approaches based on “closest neighbour” methods which are used to assess avalanche danger can also be used for scientific purposes. These probabilistic approaches enable scientists to associate a climatic situation to probabilities for corresponding avalanche activity. Some studies have also studied the potential correlation between avalanche activity and large-scale climatic circulations such as the North Atlantic Oscillation, but no links have been found.

It is also important to precisely characterise the evolution of snow cover conditions for a wide range of altitudes. Avalanche characteristics (stopping distance, volume in movement, etc.) are closely linked to snow cover conditions.

All types of avalanches are dependent on the presence of snow cover; hence a potential decrease (in duration, height or extent) of the snow cover and a possible altitudinal shift of the snow/rain limit will have impacts on avalanche activity. Depending on the type of avalanche, other factors are also involved. Whilst aerosol propagation is relatively independent of the local topography, the propagation of the wet snow and snow-slabs avalanches is sensitive to the relief, forest cover and whether the area is prone to erosion. All these factors are obstacles to providing a direct link between avalanche activity and climatic parameters on one hand and between avalanche activity and snow cover on the other. Even with good snow cover observations showing clear trends for its evolution and efficient models of snow cover evolution in a warmer climate, this information would not be sufficient to assess the potential evolution of avalanche activity. Some hypotheses can be proposed but they encounter the limits mentioned above.

No complete model currently exists for assessing the predisposition, the triggering and the flow of avalanches, but some partial models have been developed. To fill these gaps, Météo France has developed an approach based on snow cover modelling in 2001. The scientists exploited the Safran-Crocus-MEPRA coupled model that is usually used for the assessment of snow cover stability on a slope from observed and predicted meteorological conditions. With this tool, it is possible to test snow cover sensitivity to the evolution of a meteorological parameter, e.g. air temperature or precipitation increase. The Cemagref also developed a numerical tool to understand the propagation of avalanches.

Observed impacts of climate change on avalanches

The climate does not seem to have evolved enough to have significant consequences on avalanche activity. Indeed, no trends have been observed regarding the frequency and the localisation of avalanches in the Alps. However, the number of studies is limited: the data series are limited and not all the research possibilities have been explored. Intensity and seasonality are the least studied parameters. Thus it is difficult to propose an impact assessment for these factors.

Catastrophic avalanche situations, such as that which occurred in the Alps in 1999, are the consequences of extreme snow falls. In the current climate, such situations are encountered around once every ten years and no changes concerning this kind of situation have been detected so far.



Potential impacts of climate change on avalanches

Some authors propose a potential increase in wet-snow avalanches due to more frequent and intense melting periods and an elevated snow/rain limit, but the same authors also believe that, looking at the annual mean, these changes would be almost imperceptible. Other hypotheses propose that avalanche activity would decrease at low and middle altitudes because of reduced snow-cover, while it could increase at high altitudes (> 2,500 metres a.s.l.), because of an expected snow cover increase at high altitudes, as a consequence of increased strong precipitation falling as snow.



A 2001 Météo-France study showed that snow cover stability would tend to increase in a warming climate. The number of “fresh snow” instabilities would tend to decrease partially because of a higher snow/rain limit. Preliminary results from the Cemagref confirm this hypothesis. It seems that the altitude of the stopping area of the avalanches referenced in the EPA moved toward higher altitudes. Avalanches have tended to stop higher in the past 30 years. This reduced propagation is explained by a greater number of wet avalanches and a smaller number of fresh snow avalanches.

Consequently, it seems quite difficult to provide a general overview of the evolution of avalanche activity in regards to intensity, frequency, location and seasonality in a climate change context. Many hypotheses have been proposed but the evolution suggested is not quantitative and could not actually be detected in the available data. Nevertheless, a decrease of avalanche activity at low and medium altitudes and an increase of the proportion of wet snow avalanches are the most plausible hypotheses considering current knowledge.

Different research methods have been explored to develop this point: improvement of the observations, development of statistical methods designed to assess available data sets, development of numerical tools for better understanding of avalanche activity and the link with meteorological parameters, regional application of climatic scenarios for mountainous area.



Mass movement – historical processes and projections regarding climatic issues

Definition

A mass movement is a brutal gravity movement of the ground dependent upon the structure of the geologic layers, the type of soil and underground water pressure. These movements are due to alteration and erosion processes of different kinds: freezing/thawing cycles, water erosion. Human activities can also influence shallow landslides (for example through ploughing) or even deeper landslides in particular cases (concentration of drainage waters, underground cavities, mining...). In this report, the considered mass movements are shallow landslides, deep landslides and rock falls.

Data concerning mass movements in the Alps

There are many databases in the Alps that inventory mass movements. In France, there are two main databases. One is the BDMvt, held by the BRGM (Office for Geologic and Mining Risks), with the contributions from the RTM services and the public work research laboratory (CETE/LCPC). For each movement data form, the precise location (both geographic and administrative), date, volume, width and the possible damages are detailed. However, all the parameters that could lead to these movements (geologic, precipitation, chemical, etc.) are not recorded. The second database is the BD-RTM database which comprises observations of forestry agents working on estate, communal or State lands. This database references avalanches, mass movement, torrential events and erosion in the 11 “départements” of the Alps and Pyrénées.



Generally only events leading to damages are recorded in these databases, contrary to systematic instrumental inventory (e.g. seismic monitoring data network). These databases are strongly influenced by the evolution of vulnerability and thus need to be used with caution in the evaluation of natural event evolution.

Precise information is only available from experimental sites (“observatories”), monitored by laboratories or observatories. Even if these sites have a good temporal cover, they are limited geographically. An extrapolation based on these data for wider territories is not possible as each movement is strongly conditioned by local parameters.

Radiocarbon dating methods enable scientists to re-construct the temporal distribution of landslides for various locations in Europe during the Holocene. Some dendromorphology methods are also used to reconstruct past rock fall activity by studying the impacts of rock falls on trees. This process is still in development and many limits exist: rock falls may impact only a single tree, several trees or none at all. As it is impossible to determine, scientists make the postulate that “each impact corresponds to a rock fall event”.

The impacts can make scars or “trauma” in the resin duct, but these signs are difficult to study. Furthermore, the correlation test with climatic parameters is based on measures from far-away meteorological stations (from a few to dozen of kilometres). The limits are numerous and the proposed results have to be considered carefully.



Mass movements / Shallow landslides – historical processes and projections regarding climatic issues

Definition

Landslides are slow movements of terrain (from some millimetres / year to metres / day) occurring on a slope. They are characterised by the existence of a discontinuous surface easily identified (flat or circular), separating the stable part from the moving part. Shallow landslides are generally some meters deep.

Shallow landslides sensitivity and links with the climate

Increases in intense precipitation could lead to increases in the frequency of shallow landslides, which are often triggered by peaks of pore pressure. This response depends on the water infiltration characteristics of each site. Shallow landslides can also be indirectly impacted by climate change, through effects on glaciers, permafrost or forest fires.

Glacier retreat and permafrost degradation should lead to large areas of unstable slopes (especially because of cohesion loss due to the melting of ice particles in these slopes). These voluminous materials could potentially become debris flows at high altitudes; this is also relevant for very steep slopes.

With a temperature increase, some hypotheses are also proposed concerning a possible re-colonisation of scree slopes because of longer vegetative periods. Such re-vegetation should enhance slope cohesion. This stabilisation as a result of vegetation cover could also be limited by the appearance of acidifying species (such as Ericaceae s.l. on grassland) limiting the growth of plants with a wider root system. The vegetation conditions can also be very harsh at high altitude and re-vegetation in this case will be quite slow



Forest fires cause the ground to lose a great part of its protection previously provided by the vegetation cover. Furthermore, small particles (such as ash and coal) can act as lubricants, which would favour surface erosion. All these conditions aggravate the aggressive effects of intense precipitation and could lead to more superficial mudflows.

The multiplication of forest fires (plausible in a climate change context) is a supplementary aggravating factor for the increase of shallow landslides. This type of aggravating circumstance has been observed following the forest fire in the Chamatte massif on the 6th July 1982 (Alpes-de-Haute-Provence, France). On 18th July of the same year a thunderstorm reactivated slopes (considered inactive) leading to mudflows on Angle village.

However this degradation of ground conditions is only temporary and after some years, re-colonisation by vegetation will again exert a protective effect on the slope. Similar features can also be observed after heavy storms, when wide parts of the forest cover are destroyed.

Observed impacts of climate change on shallow landslides

In the “Romandie” and Ticino cantons (Switzerland) an increasing number of landslides have been observed in simultaneously with increased precipitation suggesting a link. However the available literature does not propose any analysis of the impacts of climate change on shallow landslides. Indirect impacts via forest fires and storms are often mentioned or locally observed, though observations are limited both in terms of time series and geographical extent. Thus, despite the lack of significant trends, these indirect impacts have to be considered as potential emerging risks.



Potential impacts of climate change on shallow landslides

Shallow landslides intensity: Some hypotheses propose that increased heavy rainfall, permafrost degradation and marked glacier retreat may increase the intensity of shallow landslides (especially mudflows through increased available materials). These hypotheses only concern high altitude areas and have neither been confirmed nor disproved by observations in the Alps.

Shallow landslides frequency: The hypotheses developed in the intensity chapter (based on glacier retreat and permafrost degradation) are also valid for event frequency at high altitude. For low and medium altitudes, there are hypotheses concerning the destabilising effect on the first layers of the ground of the disappearance of vegetation cover after a forest fire or a storm. Combining this multiplication of soil degradation and the expected increase of precipitation, scientists propose an increase in shallow landslides.

The progressive re-vegetation of slopes (moraines, scree slopes, rock chaos...) may lead to decreased slope instability in the long-term through better slope cohesion. However there are currently no observations that validate this hypothesis.



Mass movement / Deep landslides – historical processes and projections regarding climatic issues

Definition

A landslide is a slow movement (from some mm/year to m/day) of the ground occurring on a slope. They are characterised by the existence of a discontinuity surface easily identified (flat or circular), separating the stable part from the moving part. Deep landslides are generally some dozen to hundreds of meters deep.

Deep landslide sensitivity and links with the climate

Deep landslides often occur on “dormant” landslides (e.g. Val Pola 1987). The assessment of such old inactive features as well as of slow creeping slopes is possible with geomorphological studies, but the forecasting of their reactivation is difficult to assess. Different scientists propose mean annual precipitation and even pluri-annual means as the key-parameters for deep landslides, through the influence of deep infiltrating waters and underground waters. Thus, any marked change in the precipitation pattern may have consequences on deep landslide activity. In particular, slopes with stability controlled by foot erosion seem to be more sensitive to surface water runoff linked with intense precipitation. A dendrochronologic study has highlighted a link between climate and landslide activity on the geological timescale in the Fribourg Pre-Alps (e.g. Hohberg and Falli-Hölili sites), where warm periods led to increased deep landslide activity in the Flysch area under 1,500 metres a.s.l. This re-activation seems to be linked with the 0°C isotherm position. However, these links between warm periods and increased deep landslide activity cannot be extrapolated for the Alps.

Observed impacts of climate change on deep landslides

No observed impacts of actual climate change on deep landslides are currently available in the referenced literature.

Potential impacts of climate change on deep landslides

Deep landslides intensity: Each deep landslide has its own characteristics (lithology, hydrogeology, topography, vegetation, etc.) and regime of deformation. Some might react to increases in precipitation with an acceleration of their movement. This reaction might not be systematic and may be strongly influenced by local conditions.

Deep landslides frequency: For movements presenting sensitivity to short-term meteorological parameters, an increase in the acceleration phases can be expected (as a consequence of the expected increase in intense precipitation).

Deep landslides localisation: As a consequence of the new climatic conditions, and particularly changes in precipitation patterns, a re-activation of old deep landslides rather than an activation of new deep landslides is expected.



Mass movement / Rock fall – historical processes and projections regarding climatic issues

Definition

Rock falls are an instability phenomenon that implies rocks or blocks breaking off a cliff or a rock slope and subsequent movements (free fall, rebound, rolling, sliding) along the slope until an equilibrium is reached. Rocks usually refer to a volume of dm^3 , and blocks to a volume of m^3 .

Rock fall sensitivity and links with the climate

Positive correlations between rock falls and days with freezing/defreezing events have been highlighted; however a link with precipitation has not been established. In France, a study on 46 rock falls in the Chartreuse and Vercors massifs has shown no correlation between rock fall activity and precipitation; but a correlation has been shown for days with freezing/defreezing events. This link is valid for small to medium scale rock falls. For very large events (millions of cubic meters, e.g. Randa 1991), the importance of climatic factors becomes negligible in comparison to geological patterns.

During the 2003 summer, many rock falls were observed in high mountain areas. This rock fall activity increase could be the consequence of permafrost degradation induced by very high summer temperatures. The permafrost thaw depth reached values 10 to 50 centimetres deeper than the mean for the preceding 20 years. It is interesting to note that these instabilities occurred between June and August, i.e. not when the thawing phenomenon was at its deepest point but when the heat flow in the superficial layer was at its maximum.



Many studies propose the hypothesis of a link between permafrost degradation in steep bedrock and rock fall activity. This permafrost degradation may have consequences on the intensity, the frequency, the seasonality and the localisation of the natural event.

After the immediate response of the superficial permafrost layer to increased temperature, the lower limit of permafrost may rise in altitude and several instabilities may develop at high altitude where there are usually no freezing/defreezing cycles. The penetration of the freezing front in previously thawed materials may lead to important constraints through ice formation in cracks.



The disappearance of forest and vegetation cover following forest fires would have potential consequences for the rock fall triggering (thermal constraints and stabilisation because of the roots system) and the stopping distance (decrease of the protective layer of the forest): the multiplication of forest fires (likely to happen in a climate change context) may be an aggravating factor for the evolution of rock falls. These negative consequences were observed following the fire at Argentière-la-Bessée in 2003 (Hautes Alpes, France) and at the Néron and Pont en Royans, also in 2003 (Isère, France).

Observed impacts of climate change on rock fall

Rock fall intensity: A study using dendromorphology in the Swiss Pre-Alps did not show any evolution of intensity in rock fall activity in the studied area in the last decades.

Rock fall frequency: Rock fall frequency seems to have increased in the Swiss pre-Alps during the 20th century. Many rock fall events were observed during the 2003 summer. However due to a lack of observation, it is hard to determine if the number of rock falls during this scorching summer was higher than during a “normal” summer. A statistical study proposed that the probability of occurrence of rock fall events is 2.5 times higher for the days with freezing/thawing cycles than for the days without these influences (evaluation for the Chartreuse and Vercors massif, France).

Rock fall localisation: During the 2003 heat wave, numerous rock falls were observed on the North face of the alpine mountains. This increase in frequency may be explained by more important permafrost surface in these slopes. A

study on the Monte Rosa (Swiss Wallis) observed an altitudinal rise of the triggering area. This spatial shift has been explained (as for the debris flows) by glacier retreat.

Potential impacts of climate change on rock fall

Rock fall intensity: Some hypotheses propose a link between permafrost degradation and an increase in future rock fall intensity in the zones affected, but it remains difficult to propose trends for future event intensity.

Rock fall frequency: The assumptions for the evolution of rock falls propose a frequency increase in the permafrost area influenced by freezing/thawing cycles. Thus it is very likely that the frequency would increase in these zones but that it would also decrease in lower zones.



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Glacial hazards – historical processes and projections regarding climatic issues

Definition

Generic term representing all kinds of hazards originating from glaciers and corresponding water pockets and lakes.

Data concerning glacial hazards

The last catastrophe due to a glacier in the Alps occurred in 1965, in Switzerland. The terminal part of the Allalin glacier tongue broke off and devastated the Mattmark dam building site (Swiss Wallis). As few glacier catastrophes occurred during the second half of the 20th century, the attention given to this hazard has decreased.

However, some potentially dangerous situations have existed in the Alps during the last few years, such as the pro-glacial Arsine lake (Hautes Alpes, France), the supra-glacial lake on the Rochemelon glacier (Savoie, France) or the Lago Effimero on the Belvedere glacier (Piemonte, Italy).

The GLACIORISK program (2001-2003) aimed to propose a homogeneous database concerning glacial hazards in Europe. This database provides data forms for 166 alpine glaciers considered as “hazardous” and located in France, Switzerland, Austria and Italy.

The glaciers characteristics (length, altitude, type, surface, slope, orientation and localisation) are detailed as well as known glacial events that occurred in the past. However all the glacial events are not reported and the data quality is not homogeneous for all the events;

some have been provided by technical services observers, others are quite old and based on various historical documents. Thus although this database is a unique for glacial hazards, it does not allow for assessments of glacial hazard evolution.

Up till now, glacial water pockets have been impossible to observe and despite some attempts using remote sensing, there are no data for this class of glacial hazard.



Glacial lakes and ice avalanches are observed punctually by research institutes (e.g. the French LGGE or the Swiss VAW) at experimental sites (which can also correspond to hazardous areas threatening human stakes). These punctual observations enable scientists to develop models (especially an ice avalanche prevision model with a precision of 1-2 weeks range) and trends for some specific sites although general trends cannot be proposed.

Glacial lakes Outburst Flooding – Historical processes and projections regarding climatic issues

Definition

As a glacier front advances or recedes, some natural dams (mainly moraines) can be created, leading to glacial lake formation. As these natural dams are made of heterogeneous materials with limited cohesion, they can burst easily, leading to significant inundations and debris flows in the valleys downstream. These lakes can be located at the glacier front (proglacial lakes), above the glacier (supraglacial lakes), between the glacier and the slopes (gutter lakes) or between two glaciers (confluence lakes). The term GLOF (Glacial Lake Outburst Flooding) is used to name the hazard linked to glacial lakes.

« GLOF » sensitivity and links with the climate

Climatic conditions and glacier dynamics explain these lake formations. Pro-glacial lake occurrence is closely linked to glacier retreat with different possible typologies. When a glacier retreats, moraines can become dams, creating pro-glacial lakes. These dams are often constituted with unstable materials and very low cohesion (some of these moraines can also be partially frozen). Furthermore, the over-digging ice-free basin following the glacier retreat can be filled with liquid precipitation and water released during glacier and snow cover melting, eventually becoming a pro-glacial lake. Finally, pro-glacial lakes can appear behind glacial rock bolts, e.g. at the Rhône glacier (Swiss Wallis). If dike bursting is a threat for the first two cases, it is far less plausible for lakes behind a rock bolt.

Supra-glacial lakes can also be the consequence of glacier dynamics, as supposed at the Belvedere glacier (Piemonte, Italy) in 2002.

This lake is thought to be the consequence of the strong advance of this glacier since 2000⁵. Climatic conditions can also lead to the formation and extension of supra-glacial lakes. These types of lakes need further study to better understand the conditions that lead to their creation as well as the method of safe drainage of the lakes (there were uncertainties during the Rochemelon Lake draining concerning the ice channel behaviour during the operation).



Ice avalanches in glacial lakes can also create waves (as the 50 centimetre wave observed at the Arsine pro-glacial lake on the 14 September 1996), which can potentially cause dikes to burst. Research on the stability of moraines which act as natural dikes for glacial lakes needs to be developed.

⁵ Even if glacier retreat is general, some particular glaciers can be advancing.

Observed impacts of climate change on « GLOF »

No observed impacts of climate change on Glacial Lakes Outburst Flooding are currently available in the referenced literature.



Potential impacts of climate change on « GLOF »

Some hypotheses propose that climate warming (with accelerated glacier retreat and increased heavy precipitation at high altitude) may lead to a potential increase in glacial lake formation, without distinction. These conjectures are based on weak arguments because the influence of climatic conditions on supra-glacial, peri-glacial, gutter and confluence lakes is not clear. Only the evolution of pro-glacial lakes is clear and there would be a multiplication of these lakes with strong glacier retreat.



Glacial hazards / Glacial water pocket – Historical processes and projections regarding climatic issues

Definition

Glacial water pockets can be either intra-glacial, i.e. within the glacier or sub-glacial, i.e. between the glacier and the bedrock (cf. fig. 27). The conditions leading to glacial water pocket formation and bursting are not well known. However, it seems that sub-glacial water pockets often occur where there is a morphologic projection.

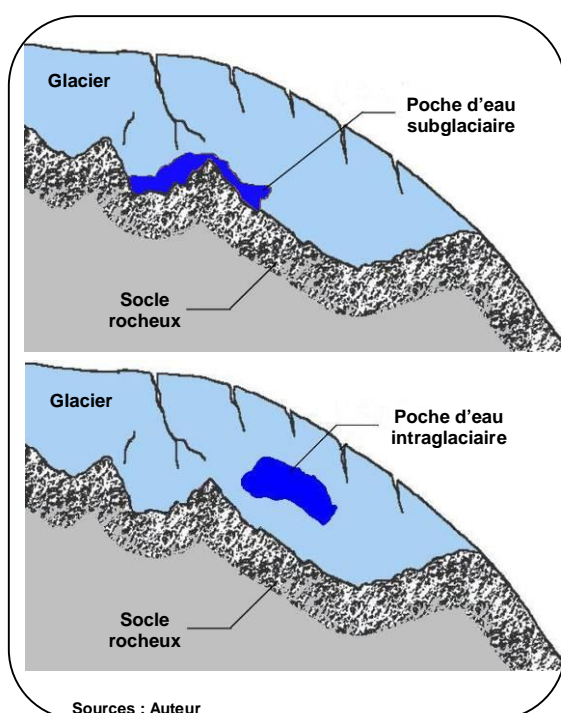


Fig. 27 – Glacial water pockets

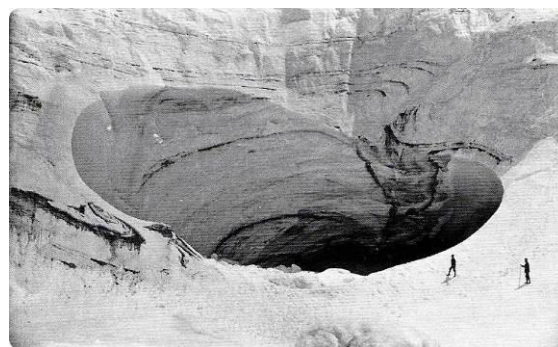
Glacial water pockets sensitivity and links with the climate

The formation and bursting of glacial water pockets (both intra-glacial and sub-glacial pockets) remain unknown processes. Liquid water flows inside glaciers are also quite unknown today. In the Mont Blanc massif, some water release and its consequences have been observed at the Trient glacier, at the Mer de Glace and at the Tête Rousse glaciers (1995).

These observations of liquid water release cannot yet be linked with clearly identified causes: they could be the consequence of accelerated melting of some part of the glacier, the bursting of small glacial water pockets, the flow of precipitation falling on the glacier or also unknown intra-glacial liquid water flows.

Observed and potential impacts of climate change on glacial water pockets

Considering the lack of knowledge mentioned above, the evolution of glacial water pockets is impossible to assess (with or without considering climate change).



Glacial hazards / Ice avalanches – Historical processes and projections regarding climatic issues

Definition

Ice avalanches are large blocks breaking off from the glacier and falling into the downstream slope, fracturing into smaller blocks. In some extreme cases, the whole terminal tongue might break off.

Ice avalanche and sensitivity with the climate

Ice avalanches are quite a frequent phenomenon for glaciers and constitute a part of their natural ablation process, particularly for hanging glaciers. The link with climatic conditions is mainly indirect because ice avalanches are influenced by glacier movements and dynamics, themselves influenced by climatic parameters. A glacier with a strong dynamic experiences frequent ice avalanches. A mean temperature increase would lead to an ablation increase and an accumulation decrease (unless the precipitation increase hypothesis for high altitude is confirmed and is strong enough to counterbalance the effect of the temperature increase). This would result in a negative mass balance and glacier flow should decrease, along with ice avalanche flows. This evolution should be experienced in the long-term and the evolution of ice avalanches for the next 20-30 years is quite uncertain.

In some extreme cases, the entire terminal part of the glacier tongue that can break off from the glacier and fall downstream. This kind of phenomenon occurred, for example in 1949 at the Tour glacier (Haute Savoie) and in 1965 at the Allalin glacier. Hanging glaciers can effectively break off from their anchorage site if the “freezing conditions” at their base are no longer guaranteed.

The switch from a “cold” glacier thermal mode (the glacier sticks to the bed rock because of the low ice temperature of its base) to a “temperate” glacier thermal mode (many liquid flows can lubricate the glacier at its interface with the bed rock) would thus be the main consequence of climate change affecting hanging glaciers and their stability. This is even more worrying because warming of cold glaciers located at high altitudes has already been highlighted in the Alps (for example at the Col du Dôme du Goûter, refer to the “glacier” chapter of this report). Some “hazardous” sites have been identified: Dôme du Goûter and Taconnaz (Haute Savoie, France) where ice avalanches on a voluminous snow cover lead to snow avalanches; Grandes Jorasses (Aosta, Italy) or Randa/Weisshorn (Swiss Wallis).



Observed impacts of climate on ice avalanches

Ice avalanches localisation: A study carried out at the Monte Rosa (Swiss Wallis) has shown that more new ice avalanche triggering zones have developed at higher altitude than were present before. This is the only source mentioning a spatial shift of the ice avalanche triggering zones and it is premature to draw general conclusions.

Potential impacts of climate change on ice avalanches

Ice avalanches frequency and intensity: Ice avalanche frequency should not increase. There are few direct observations of this phenomenon and the evolution of predispositions for this natural event is mainly hypothetical. Even if a local short-term increase in ice avalanche frequency can be extrapolated on some sites, the ice volume decrease and general glacier retreat should attenuate this increase. However, as mentioned above, the evolution of hanging glaciers might be critical with a temperature rise. If these glaciers switch from a cold mode to a temperate mode, then it is likely that there would be an increase in ice avalanche frequency and also an increase in the volume involved in each event, or even the breaking off of voluminous parts of hanging glaciers.



Storms – Historical processes and projections regarding climatic issues

Definition

When winds are stronger than 89 km/h (corresponding to 10 degrees on the Beaufort scale), they are considered a “storm”. Most storms approach Europe from the Atlantic, between 35° and 70° latitude North. These storms occur mainly during the European autumn and winter (especially between November and February).

Data concerning storms

In France, there is no exhaustive inventory of storms for the past centuries as wind measure networks were only implemented at the beginning of the 20th century. It is possible to use air pressure data, available since the end of the 18th century for thirty stations, to extrapolate storm activity. Exceptional events leading to important damages (remembered by the local population) are generally well documented. However these extreme and punctual events alone are not sufficient for assessment of storm evolution.



Storm sensitivity and links with the climate

Winds are the direct consequences of pressure differences. The influence of climate and global warming on storm activity remains unknown. Storm creation is closely linked to barocline instability (which is preponderant in depression formation). However the link between the North Atlantic Oscillation and storms is blurred. It is premature to propose a storm evolution assessment based on available knowledge and modelling.



Observed impacts of climate change on Storms

Storm intensity: There is no significant trend for the evolution of storm intensity in France between 1950 and 2000

Storm frequency: There has been a slight storm frequency increase over the North Atlantic during the 20th century, but the intensity of the events remained unchanged. Around 15 storms are recorded in France each year. The interannual variability of storms is significant, for example, 25 events in 1962 against 7 in 1968. One in ten is usually considered “strong” (i.e. at least 20% of the departmental stations record an instantaneous maximum wind above 100 km/h), the frequency of such events is around 1.4 event/year over the last 50 years.

There has been a slight decrease of the number of storms over the past 50 years in France, but this trend is not significant (cf. fig 28).

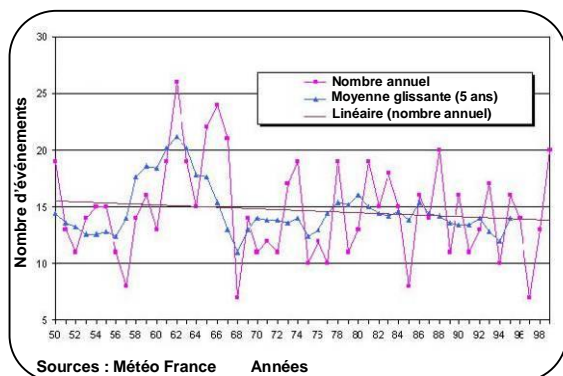


Fig. 28 – Annual number of observed storms in France from 1950 to 1999

Potential impacts of climate change on storms

Storm intensity: The increase in water steam may have two divergent impacts: it may facilitate water steam condensation during cloud and precipitation formation, or help the energy storm transfer to high latitudes. So, the hypotheses for the evolution of storm intensity are contradictory for the moment..

Storm frequency: The warming of the atmosphere may have contradictory consequences with a North-South gradient increased or decreased (depending whether the warming impacts the high or low atmosphere to a greater extent) and thus a storm frequency increase or decrease.

Forest fires – observations et projections dans un contexte de variations climatiques

Definition

Forest fires are hazards triggered in forest or sub-forest areas that propagate at least on 1 hectare. Forest areas are organised or spontaneous vegetal formations that are dominated by trees of various ages and densities. Sub-forest areas are constituted by bushes and small trees.



Data concerning forest fires

Since 1973, there is a forest fire database for 15 South-East French “départements” called “Prométhée”. This database references all the fires occurring on forest or agriculture lands since 1973. The location, date and surface are always referenced and for larger fires, more details are included, such as the kind of vegetation and forest cover, the vehicles and human forces involved in the fire fighting, the means of propagation, etc.

The Alps are not covered by this database, except for the southernmost parts of the range. However, since the 2003 heat waves and resulting forest fires, the SDIS services implemented a database for some of the Alpine “départements” (e.g. Isère département) on the same scheme as the “Prométhée” database. This database aims firstly to improve the

efficiency of the emergency and fire services through experienced feedback analysis but can also be used to assess the evolution of forest fires regarding climatic parameters. However, the fact that this method has been implemented after 2003 does not allow long-term evolution assessment and a longer period of observation would be relevant for scientific assessment.



Forest fires sensitivity and links with the climate

Forest fires are linked to the climate via various direct and indirect parameters. Forest fire dynamics are strongly influenced by climate, which determine fire prone conditions: the mean and extreme temperature, the amount and frequency of precipitation, the intensity, duration, type and direction of the wind and sunshine duration have direct impacts on forest fire proneness. One scientific paper studied the links between forest fires and climate by identifying 6 climatic parameters: temperature maximum and minimum, precipitation, sunshine duration, Foehn wind events and relative humidity (measured at 7 am, 1 pm and 7 pm).

Furthermore, the climatic conditions also have impacts on vegetation, real vegetation vaporous transpiration, the dryness of the grounded vegetation, etc.

Forest fire triggering can be linked to both human (various causes) and natural (thunder) actions. However human triggering is the most common and can be intentional or not:

- ☞ Accidents linked to infrastructure: electric installations, railways, vehicles (trucks and cars) and garbage storage (official or clandestine).
- ☞ Unintentional accidents linked to professional activities: forest works, agriculture work such as “écobuage” and industrial activities.
- ☞ Unintentional actions linked to citizen activities: work such as garden vegetation burning, recreation such as barbecue, fireworks and disposal of burning objects (mainly involving cigarette butts or ashes).
- ☞ Intentional actions: conflicts linked to land occupation and hunting problems, interests linked to hunting, agriculture and land occupation, pyromania. liés à la chasse, à l'agriculture, pyromanie.

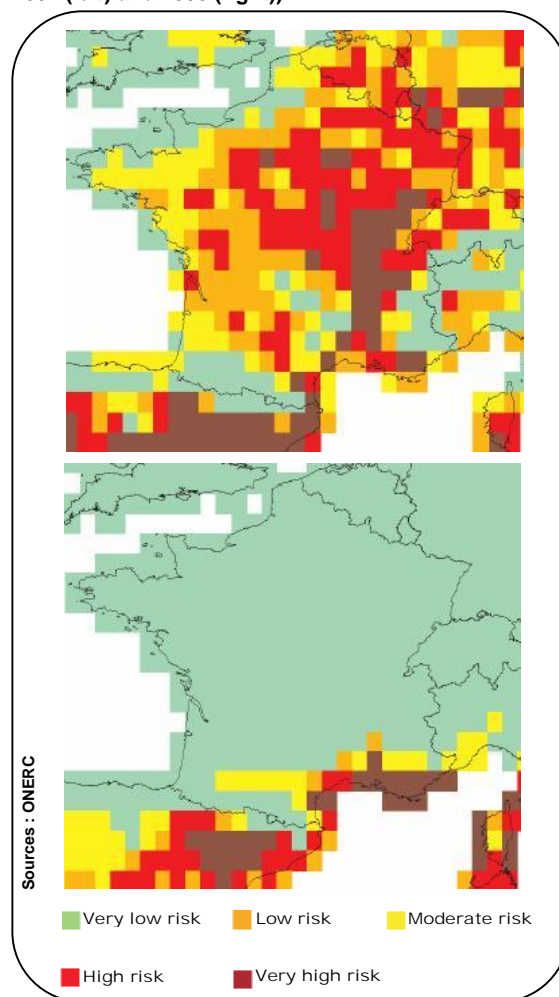


Observed impacts of climate change on forest fires

There is no scientific assessment of forest fires in France regarding climate change impacts. However, during the 2003 heat waves, numerous forest fires occurred in mountain ranges that are usually not affected by such events (such as the Chartreuse massif). The following maps (cf. fig. 29) show the forest fire index for the same day in

2003 and 2004. The situation during the heat wave is one of general fire potential. The Alpine region was almost exempt from forest fire potential during the 2004 “normal” summer while it was a zone of high forest fire risk during the hot 2003 summer.

Fig. 29 – Forest fire risk index on the 13th of August 2004 (left) and 2003 (right))



Some results from scientific analyses in the Ticino canton in South Switzerland showed that fire potential evolved with climatic drought and that the annual value of the climatic parameters is of little use for assessments of forest fire proneness. Indeed, forest fires proneness can vary greatly at smaller timescale, i.e. season or months. However, the interannual values of climatic drought conditions are likely to exert an influence on forest fire potential.

Potential impacts of climate change on forest fires

At the moment, there are only assumptions concerning the future evolution of forest fire proneness in the context of climate change. The evolution of the climate toward drier conditions in summer might potentially increase the forest fire danger in mountain ranges. Situations of very high forest fire risk like the one experienced during the 2003 heat wave may become more common by the end of the 21st century. However, considering the important human element involved in forest fire triggering, the future evolution is also strongly linked to human behaviour and laws regarding forest fires (regulation of agriculture and forestry work, banning fires for recreational use, etc.).

Conclusions and contributions from the other French partners



Conclusions

Climate change

- ☞ The observations converge toward a general increase of the temperature in the Alpine arc. The amplitude of the warming varies depending on the regions considered. In the French Alps, the mean warming reached 0.9°C during the 20th century. The model results show that this trend should continue throughout the 21st century. The mean temperature in the Alps might increase by between 3°C and 6°C by 2100.
- ☞ Precipitation observations do not indicate particular trends in the Alps, for any season and threshold considered. Climate models have difficulties representing precipitation in mountain areas. However, some general trends can be proposed with a precipitation increase during winter and a decrease during summer

Impacts on natural systems

- ☞ The duration and height of the snow cover have both decreased in the entire Alpine arc. The model results of snow cover evolution in a warming climate show a decrease in the duration and height of snow cover throughout the 21st century.
- ☞ Most Alpine glaciers have been in a retreat phase since the end of the Little Ice Age (middle of the 19th century). This natural retreat accelerated strongly with the rise in air temperature during the 20th century. Some Alpine glaciers might disappear by the end of the 21st century.
- ☞ Observations show a degradation of Alpine permafrost and an increase in the deformation speed of rock glaciers in the Alps. This

degradation seems to be stronger in complex topography such as ridges and peaks.

- ☞ Observations show few trends concerning Alpine river hydrology (mean runoff, floods and low waters). However, the evolution of snow cover and glaciers will certainly exert an influence on river patterns and induce a decrease in water resources in the long-term after a temporary increase following enhanced melting rates.
- ☞ Some species have tended to migrate toward higher altitudes, while parasites and disease vectors have migrated toward higher latitudes. The evolution of vegetation in the future in comparison to current conditions will depend on the balance between “positive” (less freezing days, increase of the vegetation period, etc.) and the “negative” effects (less available water, development of new diseases, droughts...).

Impacts on natural hazards

- ☞ An increase in the intensity and frequency of floods has only been detected for some Alpine regions (such as South Germany). In the French Alps, some signs of changes have been detected but a more detailed analysis is needed to confirm and develop these early findings. In the future, the flood peaks linked to the melting of snow cover should be weaker and occur earlier in the year. An increase in winter floods and summer droughts is likely to occur. Enhanced melting of glaciers may compensate the summer deficit of rivers fed by glaciers in the short-term.

- ☞ During recent years, the triggering areas of debris flows have tended to move toward higher altitudes in some massifs (like at the Ritigraben or in the Écrins massif). An increase in non-consolidated materials in the vicinity of glaciers and the increase of heavy precipitation might induce increased intensity and frequency of debris flows locally.
- ☞ Avalanche activity does not seem to have evolved in a significant manner in terms of frequency and seasonality. The assessment of the intensity and localisation of avalanches has been limited up till now. In the future, avalanche activity should be closely linked to snow cover evolution. A decrease in the frequency of avalanches at low and medium altitudes is likely to occur as well as an increase in the number of wet snow avalanches. Generalised situations of avalanches (such as the one that occurred in the Alps in 1999) remain probable in a warmer climate.
- ☞ An increase in rock fall frequency was observed at high altitude during the scorching 2003 summer. With a temperature rise and a corresponding degradation of the permafrost, an increase in rock fall frequency should be expected for high altitude areas. On the other hand, a decrease in the number of freezing/thawing cycles at low and medium altitudes might induce a decrease in rock fall frequency. Furthermore, an increase in precipitation (mainly heavy precipitation) might lead to increased mass movements, particularly shallow landslides.
- ☞ In regards to the complexity of glacial hazards and their limited occurrence, it is difficult to detect trends from the observations. A decrease in the stability of hanging glaciers and an increase in the number and size of proglacial lakes, due to an increase in ice temperature and glacier retreat should be the two main impacts of climate change on glacial hazards.
- ☞ Storm activity does not show any significant trend in France during the past 50 years. Storm evolution in a climate change context is very difficult to assess because of the uncertainties regarding warming of the high or low atmosphere and latitudes, and the consequences of the increased concentration of water vapour.
- ☞ During the 2003 summer, many forest fires occurred in mountain ranges that are not usually concerned by such hazards. A multiplication of droughts and hot summer might increase the forest fire proneness in areas considered at low-risk up till now

Contributions of the French partners to the WP6, WP7 and WP8

Contribution of the WP6: Monitoring, prevention and management of specific impacts of climate change on Nature

This contribution has been written by Pierre Potherat, Johann Kasperski and Jean-Paul Duranthon (CETE Lyon), Pascal Allemand (LST Lyon) and Didier Hantz (LGIT Grenoble).

In the climate change context, the observation of the territory evolution, and more especially the slope monitoring, is a key element to prepare adaptation strategies. A method comparison enables scientists and technical services to select the most relevant method to detect changes in the territory and then to study the link with climate fluctuations.

The aim of the WP6 was to perform comparisons, assessments and enhancement of ground motion prevention by monitoring and management techniques to, finally, propose common response strategies against natural hazards. These objectives were divided in two modules and different activities. Among these activities, a state of the art of the monitoring methods and a comparative analysis of new existing remote sensing techniques (laser scanning, satellite based methods, radar interferometers...) in situ have been performed.

The activities of the CETE de Lyon and UCBL were focused on the evaluation of potentials and limitations of optical remote sensing data for

deriving surface displacement maps on three different active mountainous alpine sites: Sedrun (Grisons, Switzerland), Séchilienne (Isère, France) and Gorges de l'Arly (Savoie, France). The work was also aiming to estimate the complementarities between optical imagery and conventional geodetic measurements. The remote sensing data used for this analysis are either from aerial and HD-satellite images or from terrestrial scanner Laser and LiDAR.

Contrary to traditional techniques, the remote sensing techniques enable the monitoring of the global evolution of large scale landslides and cliffs. An evaluation of some of those techniques has been realized on the three unstable sites mentioned above. Using optical imaging techniques to study the kinematics of these instable zones, it has been shown (1) that terrestrial laser scanner allows acquiring data in small areas undergoing higher sliding rates, often not accessible to aerial survey; (2) and that multitemporal image correlation is a fast way to derive surface displacement maps:

✎ The terrestrial Laser scanning technique applied to the study of landslides permits to achieve irregular 3D point clouds of land areas in a very short time and with a high accuracy (few centimetres on objects at distances of some hundred of meters). Then, scanning a landslide at different time can shows quantitative changes in topography. One limitation of this technique is the difficulty to reconstruct a general picture from focused scanning that is due to the local topography. Despite this patchwork, the resolution and the precision of data are about two centimetres for a scanning distance smaller than 80 metres. In order to correctly use these data, one of the easiest

way consists in creating and comparing multitemporal profiles in the different clouds of points;

- ✎ Images correlation is used to derive displacement map from multitemporal images acquired over the same area. This technique is based on the automatic research of same structure. Then, the shift between the positions of the same structure on two images can be associated to surface displacements which occurred between the two dates. Then correlating images of different epochs gives a synoptic view of displacements. Different types of images can be used:

- 1) The aerial images obtained from national geographic institutes associated with images correlation are very useful for scientific studies. The archive of images covers fifty years with an average time span of five years. Their spatial resolution is about (or better than) one meter and the detection threshold is around two or three pixels;

- 2) High optical resolution satellite images (IKONOS and QuickBird: images resolution < 1 metre) associated with correlation techniques can be used for both scientific and hazard purposes. Although time span of these images can be adjusted, the lack of archives prevent from the study of slow landslides (< 2 metres / year). These images should be reserved to landslides with high velocity;

- 3) Regular acquisition of transversal images acquired on site provides a fast, efficient and low-cost way to follow the evolution of a landslide.

Limits of optical correlation are mostly due to the change of vegetation, the change in the length of shadows due to either different time acquisition or different angle of sight and other radiometric differences: that can lead to problems with the image matching, especially in the case of studying landslides.

Here are some of the results obtained for the CETE/UCBL case studies

- ✎ The Sedrun landslide (Switzerland) has been regularly slowing down since 2002, following a 150% increase in speed between 1990 and 2002. The detailed description of its kinematics combined to field geology allows predicting the future evolution of the site.
- ✎ As for the frontal zone of the Séchillienne landslide (France), it slides horizontally rather than it subsides vertically: using scanner-laser data set, the scientific team shows that the structural blocks the zone is composed of are tilting downhill.
- ✎ Lastly, at the Arly Gorges study site (France), the Cliets tunnel undergoes pressure releasing difficult to track using imaging methods.

To conclude, the methods based on image analysis are shown to be a very powerful tool. Furthermore, they are complementary to the traditional techniques used to follow the evolution of the motion of specific mountainsides.

The activities of the Grenoble LGIT concerned the slope evolution survey at the temporal scale of the climatic changes which occurred in the post-glacial period (last 10 000 years), and at the spatial scale of homogeneous mountain ranges like Vercors (limestone) and Écrins (crystalline).

This survey consisted firstly in assessing the rock fall frequencies in different homogeneous ranges or valley slopes. This assessment has been done by using historical inventories covering some decades up to some centuries. These inventories make it possible to know the frequencies associated with different rock fall volumes (more than 100 m³, 1,000 m³, 10,000 m³, etc...), in a given area (massif or valley slopes). Fitting a frequency-volume law makes it possible to assess the frequencies of very large rock falls, which did not occur during the historical period covered by the inventory.

In order to detect the influence of the passed climatic changes, the frequencies corresponding to the different climatic phases of the post-glacial period have to be determined. These frequencies can only be determined for rock falls which are still visible nowadays, i.e. those of more than 106 m³. As these events are relatively rare, an inventory must be made at the scale of the Alpine Arc. Then an Alpine database is being achieved, including at least the location, volume and date of each rock fall.

Determination of a rock fall volume needs to know the initial surface, on which the fallen rocks settled. For that, different geophysical prospecting methods have been tested.

From the first results (Lauvitel rock fall), electrical prospecting appears to be the more appropriate method.

In order to estimate the date of a rock fall, the more used method up to now consists in dating vegetal debris found in the rock fall deposit, but this is not always possible. That is the reason why another method based on the rock surface exposure to cosmic ray has been developed. This method made it possible to date the Lauvitel rock fall at about 3,600 years.

Presently, the number of dated rock falls in the Alps is not yet sufficient for assessing the influence of passed climatic change. For a better knowledge of the occurrence probabilities of large rock falls and a better evaluation of the influence of the present climatic change on these probabilities, pre-historical rock falls must be better studied. To do so, an Alpine rock fall database should be achieved and dating methods should be further developed.

Contribution of the WP7: Impacts of climate change on territorial development and on territorial economy

This contribution has been written by Émanuelle George-Marcelpoil and Vincent Boudières (Cemagref DTM Grenoble)

Climate change from the threat questioning to the reaction ability

Today climate change is incontestable. The last IPCC report (AR 4) refined the uncertainties associated with the projections of temperature. However, the assessment of climate change impacts is less accurate, especially for the local level. Indeed, the uncertainty concerning the direction and magnitude of climate changes is already strong at the global level but it increases exponentially when looking at the local level. And this local level is precisely the relevant one for the implementation of adaptation actions; this is even truer for tourist mountainous territories.

Thus, the research on the response to face climate change should be focus on the level of action. In a general manner, the knowledge of the hazard "climate change" can not solely be undertaken as the phenomenon understanding. In a strong uncertainty context the focus given to the natural phenomenon tend to eclipse the knowledge and the debate on the vulnerability. The development of scenarios about the potential evolution of the natural phenomena maintains a determinist vision of climate change. This determinist vision is an obstacle for differentiated responses to climate change. Climate change is generally considered as an external threat and is less looked at from the angle of the local adaptation ability.

Considering this point of view, the climate change problem can be fundamentally seen as the ability of local territories to face climate change.

To answer this research questioning, it is very important to identify and understand the existing strategies and actions concerning tourism diversification but also the kind of obstacles that may slow down the adaptation to climate change.

Climate change and active factors of vulnerability

Firstly, the following definition of the hazard has been considered: Risk = F (unknown factor, vulnerability), where F is a function depending on means of analysing the problem. Considering this approach, responses to face climate change are possible under the condition that the territorial vulnerability is integrated to the analysis. This territorial vulnerability and more precisely the vulnerability factors are closely linked to the different actors and their state of mind. This approach also highlights the coherence (or lack of coherence) between the various actions implemented in the winter resorts. In fact, winter resorts are relevant territories for such kind of analysis because of their high population density, their environmental and socio-economic importance and the complexity of their management.

There are various vulnerability factors. Some of them are linked to the kind of development of the ski resort but most of them are rather linked to its management. Thus, the following questions have been considered: How climate change is apprehended by the different actors? What are the strategies developed and implemented to face climate changes?

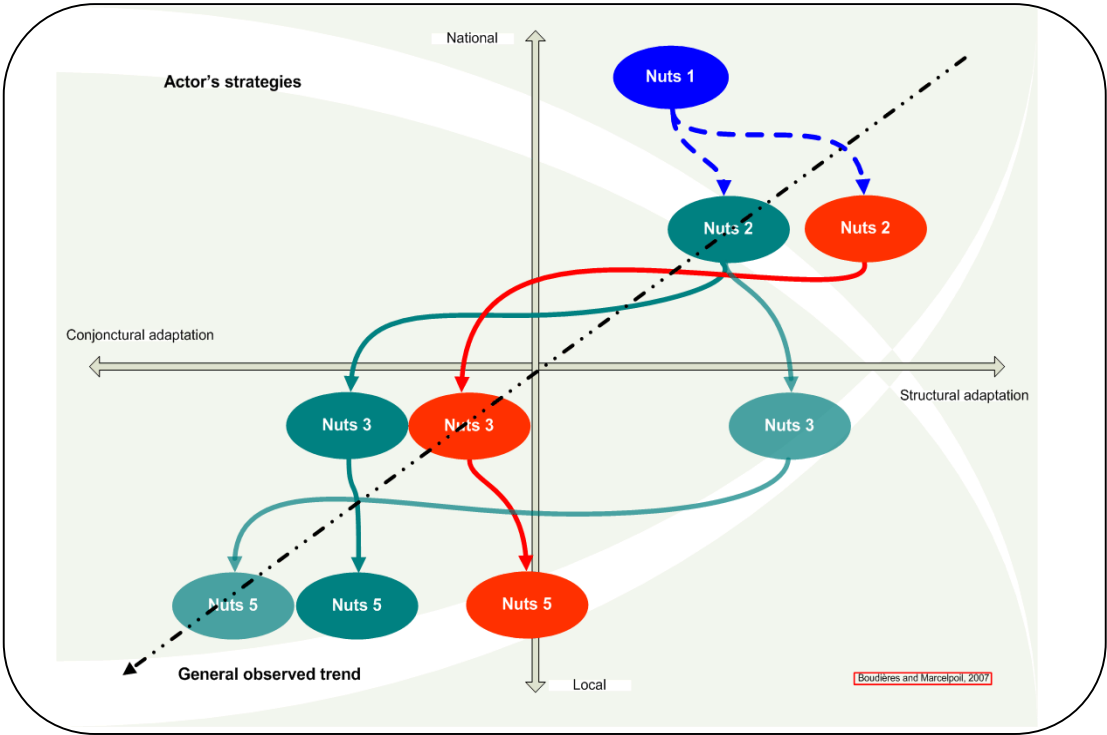
Are these strategies coherent with other politics implemented at different intervention levels?

All these questioning highlight the importance of the organisational and political factors in the assessment of the vulnerability of ski resorts. These factors have been identified trough comparative analysis of the different strategies. Based on an empirical approach, the analysis concerned the structuring between the public actors strategies (Nuts⁶ 1, 2, 3 and 5) and the economic actors of the mountain tourism industry (cf. fig. 30).

This analysis that is considering climate change not as an external threat but rather from the angle of the internal weakness reveals the strong stakes for the French tourism territories in the mountains.

Fig. 30 – Scheme of the strategies of the tourism actors to face climate change

It also highlights the importance of the management where the crossing of competences and strategies increases the existing uncertainties about climate change impacts. Beyond the external threat of climate change, the future territorial management will have to improve the thinking on coordination, shared project and collective strategies. The wide range of solutions implemented, the divergences and crossings are obstacles for the implementation of a relevant and long lasting adaptation strategy. Indeed, to face climate change the purpose is to look at the active factors of vulnerability in terms of structure and organisation. Thus it is important to not impose a uniform view of the hazard but rather to take into account the way each level understands and formulates the problem. In this context, the adaptation should not level the divergences but rather build in the existing plurality common strategies in a way to contribute to the durability of the tourist destinations.



⁶ Nuts: Nomenclature d'Unités Territoriales Statistiques. This European nomenclature is used to facilitate the comparison between countries or regions. For France, the Nuts 1 corresponds to the State, the Nuts 2 to the Region, the Nuts 3 to the Department and the Nuts 5 to the Commune.

Contribution of the WP8: Flexible response network - reflection on the possible adaptation of administrative and political structures

This contribution has been written by Jean-Marc Vengeon (PGRN) and Sandrine Descotes-Génon (Rhône-Alpes Region)

The objective of the WP8 was to provide recommendations toward policy makers and administration of the Alpine Space to help them to design common actions to straighten an integrated natural hazards management and to face climate change.

In particular, the WP8 aimed to assess the interest and the feasibility of an alpine institutional network to promote and exchange quickly the ideas and the know-how of integrated management of natural hazards and adaptation to climate change. The Rhône-Alpes Region participated actively to the different activities of this group.

Firstly, each national or regional system of natural hazards management has been described and documented: institutional actors, rules and procedures. A specific tool has been developed to facilitate the access to this information: the PLANALP-DB data base is available online on the project web site www.climchalp.org. Some best practices examples for each State or Region have also been referenced and added to the data base.

Secondly, an investigation on the effective and non-effective practices of natural hazards management has been performed to the manager of different regions. The analysis of these contributions provided the base to realise a “state of the art” of

the natural hazards management in the Alps and to formulate the expected recommendations.

Finally, an international expert hearing on the impacts of climate change on river floods and torrential events has been organised in Bolzano (Italy) in May 2007. The conclusion is that a common adaptation strategy for the Alps is highly recommended. To help the alpine territories to be “ready for the unexpected”, it is proposed to increase locally the integrated management of natural hazards while taking into account the scenarios of climate change impacts and to develop exchange network for an interregional cooperation.

The recommendations for the integrated management of natural hazards consists in the development of the collaboration between sectors, the best use of the existing resources and local network, the generalisation of the hazard maps, the straightening of the awareness and the responsibility regarding hazards, straightening of the maintenance program for the protection buildings, the development of tools to deal with extreme events (such as alert systems)...

Regarding the interregional collaboration, it has been proposed to establish a “Flexible Response Network” gathering the managers of the natural hazards and territories at the alpine level. This network should enable the permanent and fluent exchange of information on the climate change impacts and the best practices within the Alpine Space. Various actions such as common training, expert hearings and the development of a common tool providing information are proposed.

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References used for each thematic

This technical report is greatly based on the knowledge platform described page 9. To facilitate the reading of the document, the scientific references corresponding to the mechanisms exposed are not inserted in the text.

If the reader wants to explore in details a thematic and find the references associated with a value or a mechanism, he can visit the knowledge platform (www.risknat.org) to obtain this detailed information.

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Abstract

Mountain ranges are very sensitive to climatic variations. The impacts of climate change on these territories can be various, from the modification of the biodiversity to the permafrost melting and the evolution of natural hazards. The assessment of temperature rise and its impacts on mountains constitutes an important issue considering the strong uncertainties and the specific sensitivity linked to these areas. The territorial manager – policy makers and technicians – have to deal with this questioning for the implementation of short term actions as well as for strategic choices in terms of land planning and spatial development. This is why 22 public institutions from seven Alpine countries were involved in the European ClimChAlp project. The ONERC participated actively to this project in collaboration with the Rhône-Alpes Région and the Pôle Grenoblois Risques Naturels. This report is based on the synthesis realised by the French partners to propose a common base of knowledge about climate change and its impacts in the Alps.

Résumé

Les milieux de montagne sont des espaces particulièrement sensibles à des variations climatiques. Modification de la biodiversité, dégel du permafrost, évolution des risques naturels sont autant d'impacts possibles du changement climatique. L'évaluation du réchauffement climatique et de ses impacts en zone de montagne constitue un enjeu autant par ses incertitudes que par la sensibilité caractéristique de ces milieux. Cette question s'impose donc aux gestionnaires - décideurs et techniciens - tant pour la conduite de leurs actions à court terme que dans le choix d'orientations stratégiques d'aménagement et de gestion des territoires. C'est pourquoi 22 institutions publiques de sept pays alpins se sont mobilisées pendant deux ans dans le cadre du projet européen ClimChAlp. L'ONERC a activement participé à ce projet aux côtés de la Région Rhône-Alpes et du Pôle Grenoblois Risques Naturels. Ce présent rapport expose la synthèse réalisée par les partenaires français pour proposer une base de connaissance commune sur les changements climatiques et leurs impacts dans les Alpes.

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