CLIMATIC CHANGE AND ITS POSSIBLE IMPACTS IN THE ALPINE REGION

MARTIN BENISTON

Department of Geosciences, University of Fribourg, Switzerland
e-mail: Martin.Beniston@unifr.ch

Le changement climatique et les possibles impacts dans la région alpine. Cet article propose un bref aperçu du changement climatique tel qu'il a été observé au cours du XX^{e} siècle dans les régions alpines ainsi que des évolutions pouvant affecter les climats moyen et extrême si l'amplitude et la vitesse de ce que l'on appelle le « réchauffement de la planète » correspondent à celles prévues par de nombreux modèles climatiques. Le changement climatique peut produire un impact significatif sur nombre d'écosystèmes fragiles en montagne, notamment par le biais de la neige, de la glace et des écoulements, sur la végétation, sur les risques naturels, et, bien sûr, sur les humains et leurs activités économiques; ceux-ci sont brièvement passés en revue. Enfin, l'aperçu est complété par quelques remarques concernant les options d'adaptation en vue du changement climatique, notamment par le biais de l'application de la Convention Cadre des Nations Unies sur les Changements Climatiques.

Key words: climate change, impacts, Alpine region.

INTRODUCTION

The geographical location and configuration of the Alps make it a particularly interesting region for many climate and environmental studies, because the mountains are at a "climatic crossroads" that include oceanic, continental, polar, Mediterranean and, on occasion, Saharan influences. The Alps are to some extent bounded by the competing influences of the Mediterranean, the Atlantic, and to a lesser extent the North Sea and the Baltic, and are located in one of the warmest areas of the Northern Hemisphere mid-latitudes as a result of the proximity of the modulating influence of the Atlantic Ocean and the heat reservoir that the Mediterranean Sea represents. The Alpine arch is subject to the influence of storms that cross the Atlantic or develop in the Mediterranean, but can also influence weather patterns in several ways, for example through lee cyclogenesis (the development of low-pressure systems resulting from the interaction between large-scale atmospheric flows and topography), contributing to the formation and persistence of blocking high pressure systems, and in the triggering of turbulent mountain waves (gravity waves) whose influence can be felt far downstream of the mountains themselves.

Rev. Roum. GÉOPHYSIQUE, **49**, p. 85–96, 2005, Bucureşti

OBSERVED CLIMATIC CHANGE IN THE ALPS IN THE 20th CENTURY

Fig. 1 shows the changes in yearly surface temperature anomalies during the 20th century for three representative Swiss stations, as a telling example of changes that have occurred in the region at various altitudes. The anomalies are computed as the difference between daily mean temperatures and the mean daily average for the 1961–1990 period, defined by the World Meteorological Organisation (WMO), as the reference period for the latter part of the 20th century. In order to remove the noisiness of year-to-year variability, the data have been smoothed with a 5-point filter for purposes of clarity. The global data described in Jones and Moberg (2003) have been superimposed on this graph to illustrate the fact that the temperature change in the Alps is more conspicuous than at a global or hemispheric scale; the warming experienced since the early 1980s, while synchronous with the warming at the global scale, is however of far greater amplitude and exceeds 1.5°C at certain sites such as Säntis or Jungfraujoch, which represents roughly a three-fold amplification of the global climate signal (Diaz and Bradley, 1997).

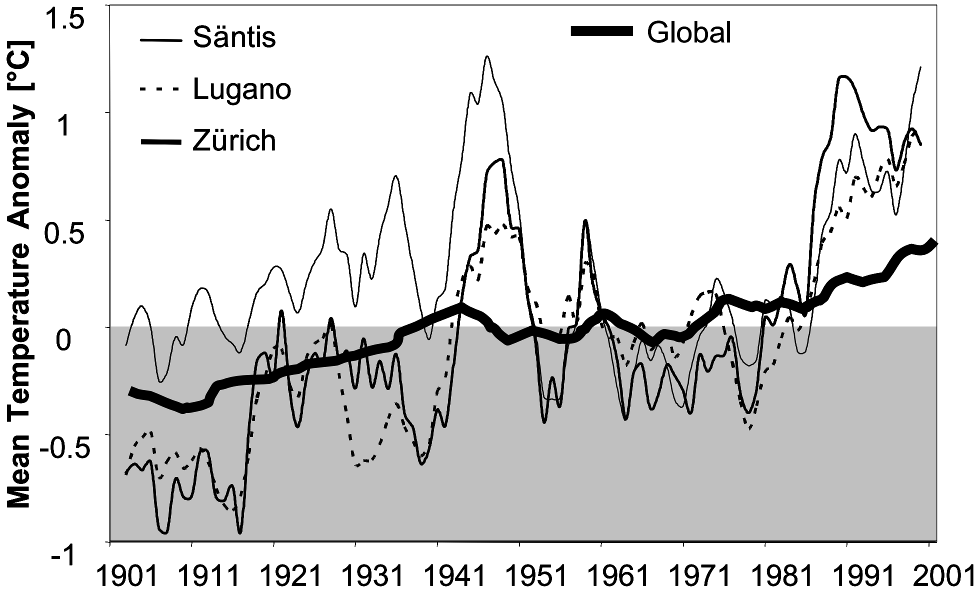

Fig. 1 – Temperature departures from the 1961–1990 climatological mean for three sites in Switzerland compared to global temperature anomalies.

Beniston (2004), among others, concludes that climatic change in the Alpine region was characterized during the 20th century by increases in minimum temperatures of over 2°C in some locations, a more modest increase in maximum temperatures with the exception of the sudden jump in maxima resulting from the 2003 heat wave that affected much of western and central Europe, and a small trend in the average precipitation data. Several periods of warming are observed during the instrumental record, with the 1940s exhibiting a particularly strong warming and then a cooling in the 50s, possibly associated with increased solar energy fluxes.

The most intense warming occurs in the 1990s, however, a behavior that can be explained in part by the influence of the North Atlantic Oscillation (Beniston and Jungo, 2002). During the last decade of the 20th century, persistently positive values of the North Atlantic Oscillation (NAO) index were observed. The NAO index is based on the pressure difference between the Azores and Iceland and is an indirect measure of the intensity of the atmospheric general circulation over the North Atlantic; its behavior accounts for over 60% of the variability of climate in both the eastern third of North America and a major part of western and central Europe (Hurrell, 1995). When the NAO index is high, Alpine climate tends to respond through lower-than-average precipitation and higher-than-average temperatures. Fig. 2 shows the relationship between the NAO index and minimum temperatures at Säntis (eastern Swiss Alps, at 2,500 m above sea level), and especially the strong synchronous behavior since the 1970s. Beniston and Jungo (2002) have computed that the bias on minimum temperatures due to the highly positive NAO index since the early 1970s exceeds 1°C (about 0.7°C bias for maximum temperatures). In other words, if the NAO index had not exhibited such strongly and persistently positive behavior, the observed amplitude of warming in the Alps would have been probably lower than recorded.

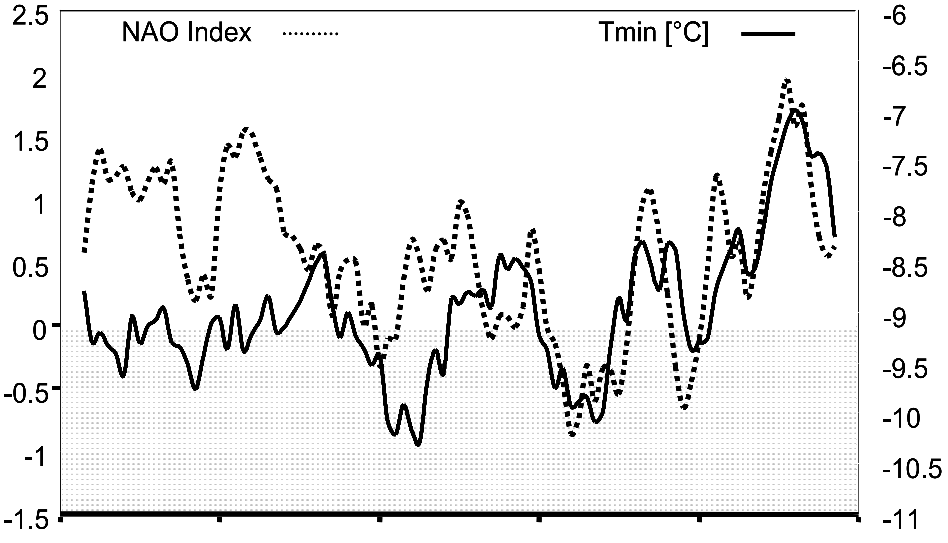

Fig. 2 – 20th century time series of the wintertime (DJF) NAO index and winter minimum temperature anomalies at Säntis (2,500 m above sea-level). A 5-point filter is used to eliminate high-frequency oscillations in the series.

The importance of snow in terms of environmental (*e.g.*, hydrology, vegetation) and economic systems (*e.g.*, tourism, water management) has been stressed in numerous studies (*inter alia*, Beniston, 2004). A quantification of the amount of snow in the mountains and the changes that occur with shifts in climate is crucial for assessing the amount of water that will ultimately run off and be routed into the numerous river systems originating in the Alps in the spring and early summer. The Alps in general, and Switzerland in particular, are frequently referred to as "the water tower of Europe". Any substantial changes in the mountain snow pack would have a significant impact on the flow of many major river basins, not only because of changes in the amount and timing of run off, but also because of the potential for enhanced flooding, erosion, and associated natural hazards. The timing of snow melt is also a major determinant for initiating the vegetation cycle of many Alpine plant species, and hence its quantification is necessary when assessing the response of vegetation to climatic change (*e.g.*, Keller and Körner, 2003; Myneni *et al.*, 1999).

Fig. 3 illustrates the manner in which the Alpine snow-pack has responded in the past decades to the degree of climatic change experienced in the Alps (Beniston *et al.*, 2003). The data for each of the selected sites show that while there is a strong interannual variability, the overall trends in snow amount have not changed substantially; this is because the rate of warming that occurred in the course of the 20th century is still relatively modest compared to what is envisaged to take place in the future, so that snow still falls during the winter months at most locations. At elevations below about 1,200 m, there has been a reduction in the total amount of snow and also in the duration of the snow season since the mid-1980s, but this remains well within the bounds of annual variability despite the strong warming that has intervened particularly in winter since about 1985.

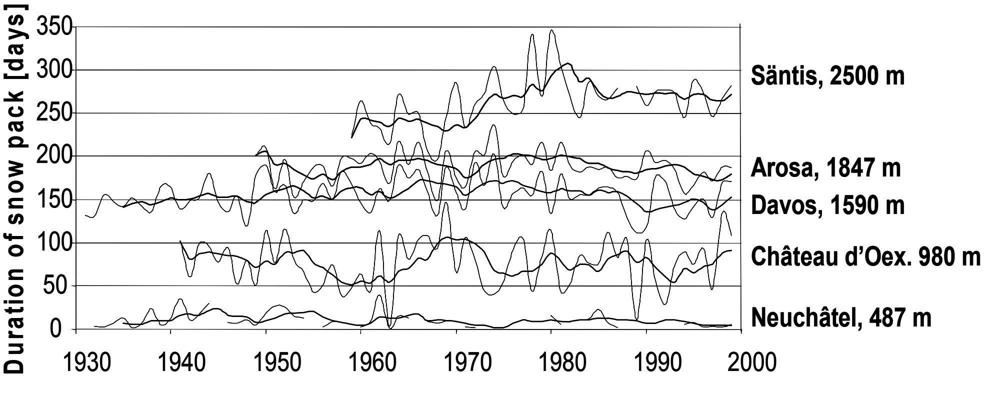

Fig. 3 – Time series of the duration of the snow season for a number of Swiss observing sites located at different altitudes, for a threshold of snow depth of 10 cm or more. Bold lines are smoothed series where a five-year filter has been applied.

Säntis, like other sites above 2,000 m, has experienced an increase in the amount of snow; this could indeed be related to warmer temperatures and certainly more precipitation in the last two decades that has fallen in the form of snow at high elevations (thus accumulating more snow over a longer season) and rain at low elevations (thus reducing the potential for snow accumulation).

Glacier mass balance, on the other hand, has responded very sensitively and negatively to warming since the termination of the "Little Ice Age" in Europe in the mid-nineteenth century. The principal explanation is related to the fact that most Alpine glaciers have a surface temperature close to the freezing point, so that any minor increase in temperature in the mountains can have a major and negative impact on the glaciers. Haeberli (1995) estimates that 40% of the surface area of glaciers in the Alps and over 50% of their volume have disappeared as a result of climatic change.

POSSIBLE CLIMATIC CHANGE AND IMPACTS IN THE ALPS IN THE 21st CENTURY

The complexity and mutual inter-dependency of mountain environmental and socio-economic systems pose significant problems for climate impacts studies (*e.g.*, Beniston, 1998), essentially because the current spatial resolution of General Circulation Climate Models (GCM) still remains too crude to adequately represent the topographic detail of most mountain regions. Most impacts research requires information with fine spatial definition, where the regional detail of topography and land-cover are important determinants in the response of natural and managed systems to change. Since the mid-1990s, the scaling problem related to complex topography has been addressed through regional modeling techniques, pioneered by Giorgi and Mearns (1999), and through statistical-dynamical downscaling techniques.

So-called "nested" approaches to regional climate simulations, whereby large-scale data or GCM outputs are used as boundary and initial conditions for regional climate model (RCM) simulations, have been applied to scenario computations for climatic change in the 21st century (Giorgi and Mearns, 1999). The technique is applied to specific periods in time ("time windows") for which high-resolution simulations are undertaken over a given geographical area. The nested modeling approach represents a trade-off between decadal- or century-scale, high resolution simulations that are too computationally expensive to attempt, and relying only on coarse resolution results provided by long-term GCM integrations. Although the method has a number of drawbacks, in particular the fact that the nesting is "one-way" (*i.e.*, the climatic forcing occurs only from the larger to the finer scales and not vice-versa), RCMs have shown their capacity in generally improving the regional detail of climate processes. This is an advantage in areas of complex topography, in particular where orographically-enhanced precipitation often represents a significant fraction of annual or seasonal rainfall.

Over time, the increase in spatial resolution of RCMs has allowed an improvement in the understanding of regional climate processes and the assessment of the future evolution of regional weather patterns influenced by a changing global climate. Since the mid-1990s, RCM spatial resolution has continually increased, partially as a response to the needs of the impacts community. Currently, detailed simulations with 5 km or even 1 km grids are used to investigate the details of precipitation in relation to surface runoff, infiltration, and evaporation (*e.g.*, Arnell, 1999), extreme events such as precipitation (Frei *et al.*, 1998), and damaging wind storms (Goyette *et al.*, 2001). This is an interesting development for impacts studies, because extreme climatological events tend to have a greater impact on natural and socio-economic systems than changes in the mean climate.

When applied to climate change scenarios, global and regional models are powerful tools that allow an insight into the possible climate futures in response to various levels of greenhouse gas emissions and concentrations (IPCC, 2001). According to the scenario, the response of climate ranges from an increase in global mean temperatures of 1.5°C to 5.8°C. These scenarios (IPCC, 2001) are based on the emissions of greenhouse-gases in the atmosphere that will depend on pathways of economic and population growth, hypotheses related to technological advances, the rapidity with which the energy sector may reduce its dependency on fossil fuels, and other socio-economic projections related to deforestation and land-use changes.

Within the European Union project PRUDENCE (Christensen *et al.*, 2002), a suite of regional climate models have been applied to the investigation of climatic change over Europe for the last 30 years of the 21st century, enabling changes in a number of key climate variables to be assessed. A suite of regional models operating at a 50-km resolution have simulated two thirty-year periods, *i.e.*, "current climate" or the "control simulation" for the period 1961–1990, and the future "greenhouse-gas climate" for the period 2071–2100. Regional climate model simulations suggest that alpine climate in the latter part of the 21st century will be characterized by warmer and more humid winter conditions, and much warmer and drier conditions in the summer. Winter minimum temperature increases at the lower elevations of Switzerland, for example, such as Basel, Geneva, or Zurich, are projected to be in the range of 4°C, while summer temperatures will exceed 5.5–6°C compared to current values based on the 1961–1990 climatological mean record. Fig. 4 illustrates the range of summer temperatures at Basel, Switzerland, compared to 1961–1990 climate, that are projected to occur, both on the average (lower curve), and in the upper 10% extreme of maximum temperatures (*i.e.*, those associated with heat waves). Superimposed on this figure are the respective levels recorded in Basel during the 2003 heat wave that severely affected many parts of western and central Europe from June–August, 2003. The results indicate that the 2003 event may well be a precursor to the type of summers that are likely to occur with increasing frequency in a warmer climate by 2100 (for example, Schär *et al.*, 2004, suggest that 50% of future summers will resemble the 2003 event in Europe).

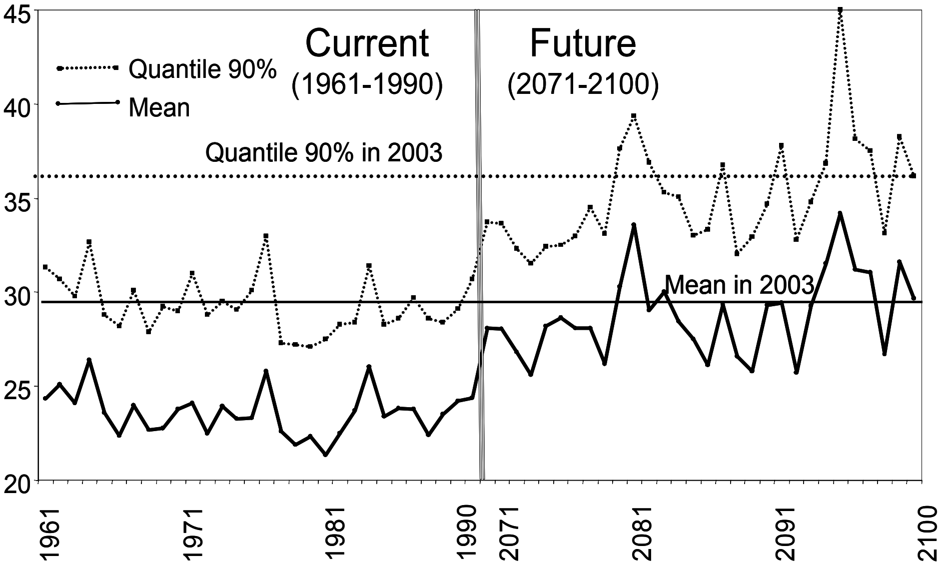

Fig. 4 – Average maximum summer temperatures in Basel, Switzerland, for the 1961–1990 reference period (left) and the 2071–2100 future simulated period (right). Solid line refers to mean summer temperatures, dashed line refers to the upper 10% extreme temperatures associated with heat waves. For comparison purposes, the horizontal lines identify the mean and upper 10% extreme maximum temperatures that were recorded at this location during the 2003 heat wave in Europe.

Precipitation change in the Swiss Alps exhibits a more heterogeneous behavior than temperature, with one model realization suggesting that winter precipitation could increase by about 25% in Alpine source areas, while summer precipitation is projected to decrease by about the same amount (Fig. 5), with relatively little significant change in the other seasons on the average. According to Christensen and Christensen (2003), reductions in *average* summer precipitation may be simultaneously accompanied by a sharp increase in short but potentially-devastating heavy precipitation events in many parts of Europe, including the Alps; first indications based on model results indeed show that while annual average precipitation is almost unchanged between current and future climates, drought events could increase by over 30% and heavy precipitation events (50 mm/day or more, that have the potential to lead to floods and slope instabilities in the mountains) may increase by as much as 25%. The sharp reduction in mean precipitation in summer explains the much stronger warming that occurs in the Alps and other parts of Europe than in winter. Cloudiness is reduced in the summer months, and therefore more incoming solar energy is available to warm the surface; in addition, soil moisture diminishes, thereby exerting a positive feedback effect on the lower atmosphere. Slightly enhanced winter precipitation, on the other hand, implies a small increase in snow accumulation but at higher altitudes than today, but more rainfall at or below 1,500–2,000 m above sea level (Beniston *et al.*, 2003). It is not expected that the increase in winter accumulate compensate to any large extent the direct influence of more elevated temperatures on glacier mass balance, however. Glaciers are likely to lose between 50% and 90% of their remaining mass, according to the extent of warming, by the end of the 21st century.

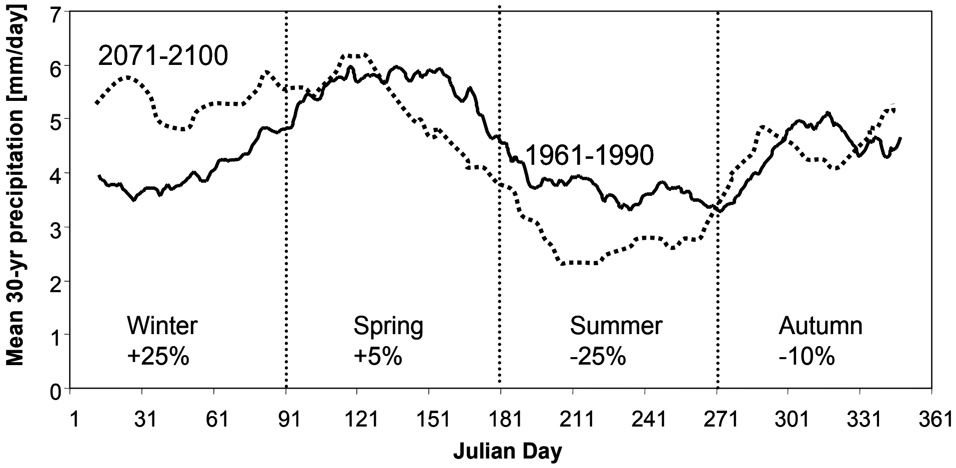

Fig. 5 – Changes in precipitation in the Alps, averaged over the 1961–1990 reference period (solid line) and the 2071–2100 future simulated period (dotted line). Figures refer to the shifts in precipitation amounts by season, in %.

Impacts of climatic change on physical systems will affect water, snow and ice, and shifts in extremes will lead to changes in the frequency and intensity of natural hazards. Water availability in some regions may decline because of a reduction in precipitation amounts, and also because of the reduced snow-pack and snow season in many mountain regions. Changes in snow amount will lead to significant changes in the timing and amount of runoff in various hydrological basins averaged over the 1961–1990 and 2071–2100 periods, as seen in Fig. 6 for a typical Alpine catchments such as the Rhine or the Rhône (Graham *et al.*, 2005). This Figure clearly highlights the strong shift in seasonality in the distribution of water throughout the year, with a potential risk of enhance flooding in late winter compared to today, and enhanced drought (with riverbeds running dry) in the late summer and early autumn. Such regimes as projected by regional climate model simulations are reminiscent of current conditions in the Mediterranean mountain regions. Water supply to more populated areas outside the mountains themselves will be influenced by shifts in precipitation regimes (both rain and snow) in the source regions of many of Europe’s rivers.

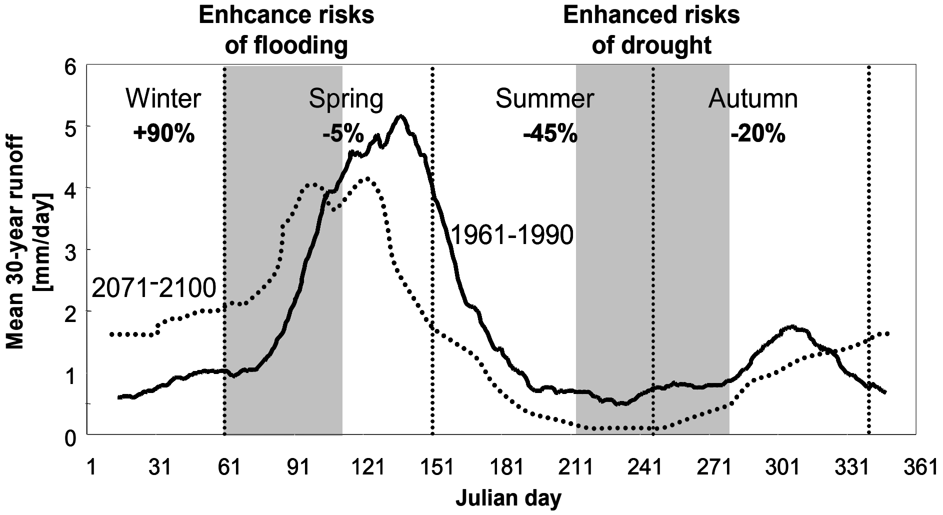

Fig. 6 – Changes in surface runoff in a typical Alpine catchment area, such as the Rhône or the Rhine, averaged over the 1961–1990 reference period (solid line) and the 2071–2100 future simulated period (dotted line). Figures refer to the shifts in runoff by season, in %.

A key variable that controls the various components of the hydrological cycle contributing to discharge in Alpine rivers is behavior of the winter snow-pack that determines the timing and amount of runoff that will feed into rivers during the snow-melt season. A two-dimensional representation in temperature-precipitation space first shown by Beniston *et al.* (2003; Fig. 7) shows that as a result of the expected winter minimum temperature warming of more than 4°C by the end of the 21st century, a reduction in snow duration by more than 100 days is likely to occur at the Säntis and at Arosa sites that have been represented in Fig. 7 (Beniston *et al.*, 2003). The increase in winter precipitation that intervenes during this period only slightly modulates the dominant effect of the +4°C warming. The "migration" of the Arosa and Säntis statistics can be considered to be highly significant, because the location of snow duration in the temperature-precipitation space by the 2070s is well outside the range of natural variability of current snow duration. This variability is defined by the ellipses that are centered on the average temperature-precipitation data for the two alpine sites (see Beniston *et al.*, 2003, for more details).

In a changed climate, meteorological extremes may also occur in regions that are today less prone to such events, and vice versa. Because of the amount of precipitation and relief, the added effect of intense rainfall in low to middle altitude regions is to produce some of the highest global rates of slope erosion. Climate change could alter the magnitude and/or frequency of a wide range of geomorphologic processes (Dehn *et al.*, 2000). Increases in extreme precipitation events, associated with snowmelt, could increase the frequency and severity of floods. Such extreme events would affect erosion, discharge and sedimentation rates, which damage hydro-power infrastructure; furthermore, sediments deposited in large quantities on agricultural lands, irrigation canals and streams would lead to reductions in agricultural production.

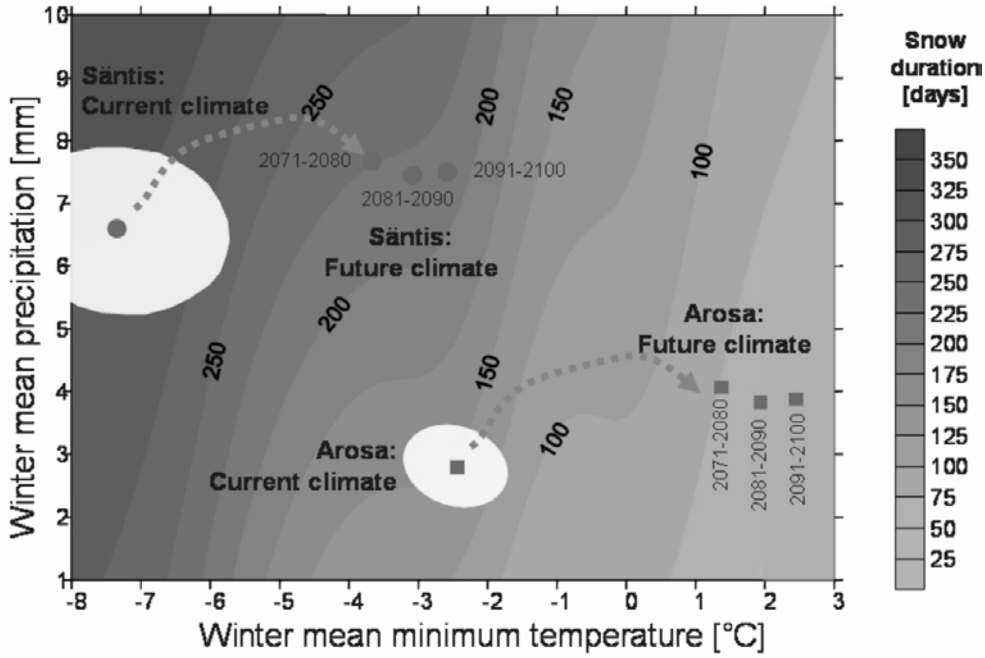

Fig. 7 – 2-D contour surfaces of snow-cover duration as a function of winter (DJF) minimum temperature and precipitation, based on data from more than 20 Swiss climatological sites. Superimposed on this figure is the temperature-precipitation-snow duration data for the Arosa and Säntis sites, for current climatic conditions, and for the three last decades of the 21st century. The ellipses show the 2σ range of DJF minimum temperature and precipitation, and corresponding spread of snow-cover duration for Arosa, and Säntis. The orientation of the ellipses is related to the covariance of temperature and precipitation. The figures on the isolines identify the length of the snow season.

Due to much longer growing season and higher temperatures, the European Alpine areas will in the 21st century face a considerable upward shift in the Alpine tree-lines of 300–400 m (Holten and Carey, 1992). Depending on the magnitude of temperature increase, the response time for the invasion of mountain birch into the current low Alpine zone, can be fairly short, and easily be observed within 2 to 3 +decades (Woodward *et al.*, 1995). The area reductions of the Alpine zones will probably be relatively smaller in the Alps, due to the higher and very often steeper mountains. Melting of permafrost and changes in hydrology at higher altitudinal levels will change the ecological conditions in steep mountain slopes, making them much more unstable, probably causing a higher frequency and maybe intensity of avalanches and landslides.

CONCLUSIONS

There is a large consensus as to the very real threat which abrupt global warming poses to a wide range of environmental, social and economic systems both globally and regionally such as in the Alps. The IPCC (2001) has been instrumental in providing state-of-the-art information on climatic change and its environmental and economic consequences, so that while science can continue to refine its predictions for the future, there is sufficient material to justify joint international action for reducing the risks related to climatic change and to define strategies for adapting to change as soon as possible, before such actions become much more costly in the future.

The United Nations Framework Convention on Climate Change (FCCC) has the explicit objective of protecting the climate system, through political, economic and legal measures destined to reduce the emissions of greenhouse gases in the atmosphere and ultimately to stabilize their concentrations. Indeed, in terms of ecological systems, Article 2 of the FCCC explicitely states that:

"*...The ultimate objective of the FCCC... is the stabilization of greenhouse gas concentrations at a level which would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a timeframe sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner...*„

In facing up to environmental change, it will be necessary to think in terms of decades and centuries, because the impacts of these profound changes may not become unambiguously apparent for several generations. Many of the policies and decisions related to pollution abatement, climatic change, deforestation or desertification would provide opportunities and challenges for the private and public sectors. A carefully selected portfolio of national and international responses aimed at mitigation, adaptation and improvement of knowledge can reduce the risks posed by environmental change to ecosystems, food security, water resources, human health and other natural and socio-economic systems.

REFERENCES

ARNELL, N. (1999), *The effect of climate change on hydrological regimes in Europe*. Global Environmental Change, **9**, 5–23.

BENISTON, M. (1998), *From Turbulence to Climate*. Springer Verlag, Heidelberg and New York, 298.

BENISTON, M. (2004), *Climatic change and impacts; an overview focusing on Switzerland*. Kluwer Academic Publishers, Dordrecht (NL) and Boston (USA), 286.

BENISTON, M., JUNGO, P. (2002), *Shifts in the distributions of pressure, temperature and moisture in the alpine region in response to the behavior of the North Atlantic Oscillation*. Theoretical and Applied Climatology, **71**, 29–42.

BENISTON, M., KELLER, F., KOFFI, B., GOYETTE, S. (2003), *Estimates of snow accumulation and volume in the Swiss Alps under changing climatic conditions*. Theoretical and Applied Climatology, **76**, 125–140.

CHRISTENSEN, J.H., CARTER, T.R., GIORGI, F. (2002), *PRUDENCE employs new methods to assess European climate change*. EOS (American Geophysical Union Newsletter), **83**, 13–14.

CHRISTENSEN, J.H., CHRISTENSEN, O.B. (2003), *Severe summer-time flooding in Europe*. Nature, **421**, 805–806.

DEHN, M., BÜRGER, G., BUMA, J., GASPARETTO, P. (2000), *Impacts of climate change on slope stability using expanded downscaling*. Engineering Geology, **55**, 193–204.

DIAZ, H.F., BRADLEY, R. S. (1997), *Temperature variations during the last century at high elevation sites*. Climatic Change, **36**, 253–279.

FREI, C., SCHÄR, C., LÜTHI, D., DAVIES, H.C. (1998), *Heavy precipitation processes in a warmer climate.* Geophysical Research Letters, **25**, 1431–1434.

GIORGI, F., MEARNS, L.O. (1999), *Regional climate modelling revisited*. Journal of Geophysical Research, **104**, 6335–6352.

GOYETTE, S., BENISTON, M., JUNGO, P., CAYA, D., LAPRISE, R. (2001), *Numerical investigation of an extreme storm with the Canadian Regional Climate Model: The case study of windstorm Vivian, Switzerland, February 27, 1990*. Climate Dynamics, **18**, 145–168.

GRAHAM, P. *et al.* (2005), *Changes in runoff regimes in Europe by the end of the 21st century*. Climatic Change (in preparation).

HAEBERLI, W. (1995), *Glacier fluctuations and climate change detection – operational elements of a worldwide monitoring strategy*. WMO Bulletin, **44**, *1*, 23–31.

HOLTEN, J.I., CAREY, P.D. (1992), *Responses of climate change on natural terrestrial ecosystems in Norway*. NINA Institute Research Report, **29**, 1–59.

HURRELL, J. (1995), *Decadal trends in the North Atlantic Oscillation regional temperatures and precipitation*. Science, **269**, 676–679.

IPCC, (2001), *Climate Change. The Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report*. Cambridge University Press, Cambridge and New York.

JONES, P.D., MOBERG, A. (2003), *Hemispheric and large-scale surface air temperature variations: an extensive revision and an update to 2000*. Journal of Climate, **16**, 206–223.

KELLER, F., KÖRNER, C. (2003), *The role of photoperiodism in alpine plant development. Arctic.* Antarctic and Alpine Research, **35**, 361–368.

MYNENI, R.B., KEELING, C.D., TUCKER, C.J., ASRAR, G. (1999), *Increased plant growth in the northern high latitudes from 1981 to 1991*. Nature, **386**, 698–702.

SCHÄR, C., VIDALE, P.L., LÜTHI, D., FREI, C., HÄBERLI, C., LINIGER, M., APPENZELLER, C. (2004), *The role of increasing temperature variability in European summer heat waves*. Nature, **427**, 332–336.

WOODWARD, F.I., SMITH,, T.M., EMANUEL, W.R. (1995), *A global primary productivity and phytogeography model*. Global Biogeochemical Cycles, **9**, 471–490.

Received: July 18, 2005
Accepted for publication: August 28, 2005