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Linking extreme climate events and economic impacts: Examples from the Swiss Alps

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Abstract

This paper focuses upon topics related to current and possible future extreme weather events in order to highlight the links between climatic change and its economic impacts. Most of the examples given here are drawn from observations in Switzerland and the Alpine region that have a wealth of climatic, environmental and socio-economic data. These enable detailed studies to be undertaken on trends in mean and extreme climates and their impacts. Model simulations for a "greenhouse climate" suggest that risks associated with various forms of extreme events that affect the Alps may increase in the future, which could lead to high damage costs. In addition to the direct impacts of extremes, it is also necessary to take into account the increasing economic value of infrastructure located in zones potentially at risk. The final part of the paper addresses some of the issues that are related to fully integrated modeling approaches that are aimed at assessing the costs of damage in the wake of an extreme event.

Keywords: Climatic change; Extremes; Modeling

1. Introduction

As climate continues to warm during the course of the 21st century, it is expected that many forms of extreme events may also increase, because the thermal energy that drives many of these processes will be enhanced. Public awareness to extreme weather hazards has risen sharply in recent years, in part because of the instant media attention that serves to emphasize the catastrophic nature of floods, droughts, storms and heat waves. The economic costs of extreme events have increased in the past few decades, essentially because there has been a substantial rise in the number of inhabitants and penetration of infrastructure in risk-prone areas (e.g., Munich Re, 2005; Swiss Re, 2005). Insurance statistics highlight the fact that, with the exception of earthquakes, extreme climate events are those that take the heaviest toll on human life and exert some of the highest damage costs related to natural hazards. Table 1 shows that, in the second half of the 20th century, there were 71 "billion-dollar events" resulting from earthquakes, but more than 170 such events related to climatic extremes, in particular wind storms (tropical cyclones and mid-latitude winter storms), floods, droughts and heat-waves (Swiss Re, 2003). 2005 alone experienced one of the busiest hurricane seasons on record, with hurricane Katrina devastating the city of New Orleans with damages costs approaching an estimated USD 200 billion.

In Switzerland, extreme events have also placed a heavy burden on people and infrastructure in the relatively densely populated Alpine regions. The floods that affected many parts of the central and northern Swiss Alps in August 2005 are estimated to be the costliest weather-related hazards to date, according to press releases and unpublished information from the insurance industry.

There is thus an obvious incentive for the research community as well as the public and private sectors to focus on extreme climatic events and the possible shifts in their frequency and intensity as climate changes in the course of the 21st century. Attempting to relate shifts in extremes in a changing climate requires an understanding

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Table 1
Number of "billion-dollar events", total and insured costs for major types of hazards, in the second half of the 20th century, based on Munich Re (2005) statistics

Sector	Number of events	Loss of life (thousands)	Total costs (USD 1995)	Insured costs (USD 1995)
Earthquakes	71 (29%)	672 (48%)	345 (33%)	27 (13%)
Storms	95 (39%)	602 (43%)	324 (31%)	106 (39%)
Floods	63 (26%)	112 (8%)	282 (27%)	70 (33%)
Drought	15 (6%)	14 (1%)	94 (9%)	12 (6%)
Total climate	173 (71%)	728 (52%)	700 (67%)	188 (87%)

Figures in brackets give the proportion of the total for each column in %. "Total climate" table gives the sum and percentages of the climate-related hazards (storms, floods and droughts).

of the physical mechanisms that underlie these events, which in turn allow improvements in our ability to quantify the costs associated with climate-related hazards. Strategies for adapting to changes in mean and extreme climates can then be developed if there is a greater confidence in the understanding of these mechanisms. Among these strategies, energy policies that aim at reductions in greenhouse-gas emissions are an obvious candidate, although as will be seen in this paper, even low-emission scenarios in the future do not necessarily alleviate the "global warming" problem. In other words, there is already a commitment to a rather large and rapid amount of change, where even stringent reductions in fossil-fuel energy use may be insufficient to significantly curtail climatic warming. Thorough cost–benefit analyses are thus required to assess whether there is a threshold of warming beyond which the costs of extremes outweigh those of a significant and sustained switch in energy sources.

2. Some examples of heat waves, extreme precipitation and wind storms during the 20th century in Switzerland

The climate of the Alpine region is characterized by a high degree of complexity, due to the interactions between the mountains and the general circulation of the atmosphere, which result in features such as gravity wave breaking, blocking highs and föhn winds. A further cause of complexity inherent to the Alps arises from the competing influences of a number of different climate regimes in the region, namely Mediterranean, Continental, Atlantic, Polar and, on occasion, Saharan. Alpine climates have undergone significant change over the past 100–150 years; temperatures have risen by up to 2 °C in many parts of Switzerland between 1901 and 2000 (e.g., Jungo and Beniston, 2001), which is well above the global-average 20th century warming of about 0.6 °C reported by Jones and Moberg (2003). Climatic change in this region is a complex mix of short- to long-term forcings, related to the intensity and persistence of weather patterns such as the wintertime Scandinavian and Russian highs pressure zones, the influence of the North Atlantic Oscillation (e.g., Beniston and Jungo, 2002), and enhanced radiative forcing due to anthropogenic greenhouse gases (IPCC, 2001). Casty et al. (2005) show that in particular during the wintertime, the North Atlantic Oscillation correlated positively with Alpine temperatures and negatively with precipitation. These correlations have not been consistent throughout the 20th century, however, suggesting that controls other than the North Atlantic Oscillation can also influence Alpine climates.

Fig. 1 shows the evolution of temperature anomalies (i.e., departures of annual mean temperatures from the 1961–1990 reference baseline) during the course of the 20th century averaged for four Swiss climatological sites and plotted using digital data provided by the Swiss weather service, MeteoSwiss (Bantle, 1989). The four sites include two low-elevation stations (Basel, 317 m a.s.l.; Zurich, 569 m; Davos, 1595 m; and Saentis, 2500 m). Although synchronous with global-mean temperature change (dotted line, based on Jones and Moberg, 2003), the figure shows that warming in the Alpine region is even stronger than globally. Since local and regional factors are important in shaping climate at a particular location, global mean temperatures are not necessarily representative of regional or even continental scale trends. The Saentis data shown here indeed highlight the variability of climate that is strongly smoothed out in the global data, due to contrasting trends at various spatial scales around the globe.

The Alps experience both extremes of precipitation, i.e., heavy precipitation (including hail) and drought, according to the nature and persistence of the associated circulation patterns. Strong rainfall events commonly lead to flooding and geomorphologic hazards such as landslides, rock falls and debris flows within regions of complex topography. Other forms of extremes that are encountered in the Alps include strong winter wind storms and heat waves. Extremes of heat arise from large-scale blocking patterns such as the European heat wave in 2003 (e.g., Schär et al., 2004), and from regional processes such as föhn winds and those leading to winter warm spells, as will be discussed later. When extreme climate events occur in the vicinity of populated regions, the impacts in human and economic terms can be enormous.

Fig. 2 shows the behavior of summer precipitation events, in the form of August precipitation totals recorded each year at Altdorf, a location in the central–northern Swiss Alps that is often subject to heavy precipitation events (Beniston, 2006). August is a prime month for strong convective downpours, especially when moist air converges into regions that have experienced strong warming during the summer months; in addition, explosive convection is exacerbated by forced uplift of air by the topography. Fig. 2 shows that while record precipitation was registered during the devastating flood event of August 2005 in parts of the northern Swiss Alps, there are other periods in the 20th century where intense events have also

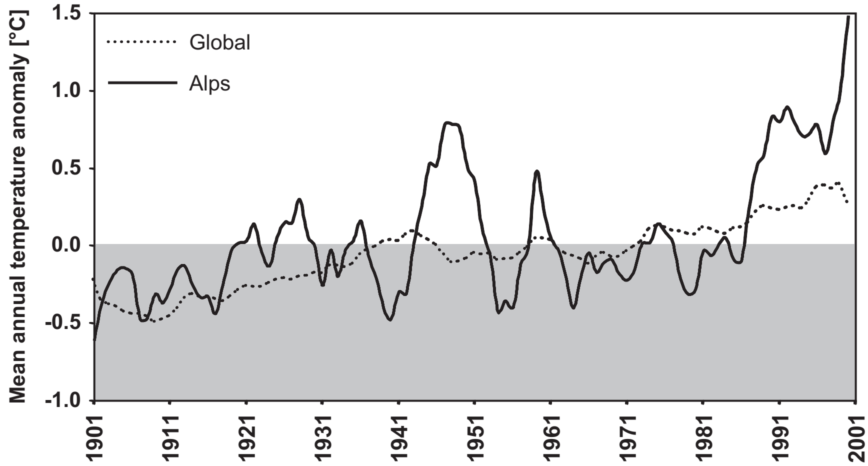

Fig. 1. Evolution of mean annual temperature anomalies (based on the 1961–1990 reference mean) averaged for four representative Swiss climatological stations, and comparison with the annual change in mean global temperature, 1901–2005.

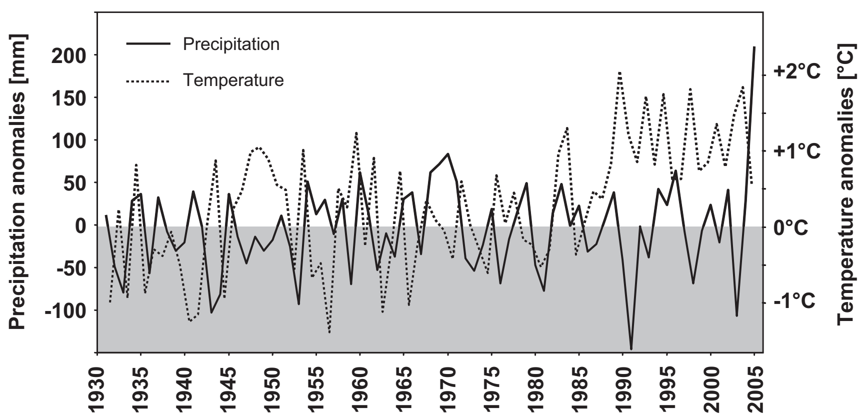

Fig. 2. August daily precipitation and temperature anomalies measured each year from 1930 to 2005 at Altdorf, a site located in a part of the Alpine region that is vulnerable to heavy rain and flood events.

occurred, such as in the late 1960s, for example. Superimposed on the precipitation data are the August temperature anomalies that serve to show that there is no discernible trend that links rainfall trends to changing temperature patterns, even though the latter, warmer part of the record shows a possible increase in variability.

This does not mean that precipitation trends are inexistent, however. Schmidli and Frei (2005) and Frei et al. (2006) find significant increases in high precipitation levels particularly in winter in northern and western Switzerland and throughout much of the Alpine zone in autumn, but no discernible trends in summer.

Similarly, heat waves exhibit no trends with respect to the evolution of average summer temperatures during the 20th century, as seen in Fig. 3. Here, summer maximum temperature anomalies are plotted from 1901 to 2005 for a low-level site (Basel; 317 m a.s.l.) and the Saentis site already discussed. Both time series are remarkably similar and highlight the fact that apart from a clustering of very warm summers in the middle of the 20th century, there have subsequently been isolated heat waves such as in 1976, 1983 or 1994, prior to the record-breaking 2003 heat wave that affected much of western and central Europe (Beniston and Diaz, 2004). The 2003 event, estimated to have been the warmest in almost 5 centuries (Luterbacher et al., 2004), resulted in severe impacts for the environment (sharply curtailed discharge in many rivers originating in the Alps; rapid mass wasting of mountain glaciers; unusually high amounts of slope instability events) and on socio-economic systems (huge losses for the agricultural sector estimated by the Swiss Agricultural Union at over €300 million), and numerous heat-related health problems and mortality (e.g., Schär and Jendritzky, 2004; WHO, 2003).

While summer heat waves are obviously characterized by large departures of maximum temperatures from their mean values, these anomalies remain small in comparison to those that are increasingly observed at high elevations. Beniston (2005) has shown that daily maximum temperature anomalies during some winters can exceed 15 °C (compared with anomalies less than 10 °C during summer heat waves) at sites such as Saentis, Grand-Saint-Bernard

(2479 m) and Jungfraujoch (3572 m). Exceedances beyond 10 °C have become quite common in the last 2–3 decades and appear to be governed primarily by the behavior of the North Atlantic Oscillation. These warm winter spells can be considered to be, in a statistical sense, strong "heat waves" that occur during the coldest period of the year. When they occur, their impacts are not the same as those triggered by summer heat waves, where there are discernible effects on health, natural ecosystems, agriculture, water supply and energy demand (e.g., Schär and Jendritzky, 2004). However, warm winter spells and their associated large positive temperature anomalies can exert significant impacts, particularly if the temperatures associated with a warm winter spell exceed the freezing point for any length of time (Beniston, 2005). Temperatures persistently above 0 °C will result in early snow-melt and a shorter seasonal snow cover, early water runoff into river basins, an early start of the vegetation cycle, reduced income for alpine ski resorts and changes in hydro-power supply because of seasonal shifts in the filling of dams (Beniston, 2004a).

It is currently impossible to establish direct relationships between severe wind storms and warming trends, at least in the Alpine region, because of the rare nature of these events. Strong storms are generated either over the Atlantic or are associated with föhn-type flows over the Alps, and as such have very little to do with local climatic conditions in the Alpine domain. Fig. 4 shows the 90% quantile of wintertime wind velocities at Saentis, and highlights the fact that there is no discernible link between winter storms and warmer temperatures. Indeed, the end of the record suggests an abatement of wind velocities after a rather active period during the 1980s, even though mean temperatures have risen rapidly in the last 30 years.

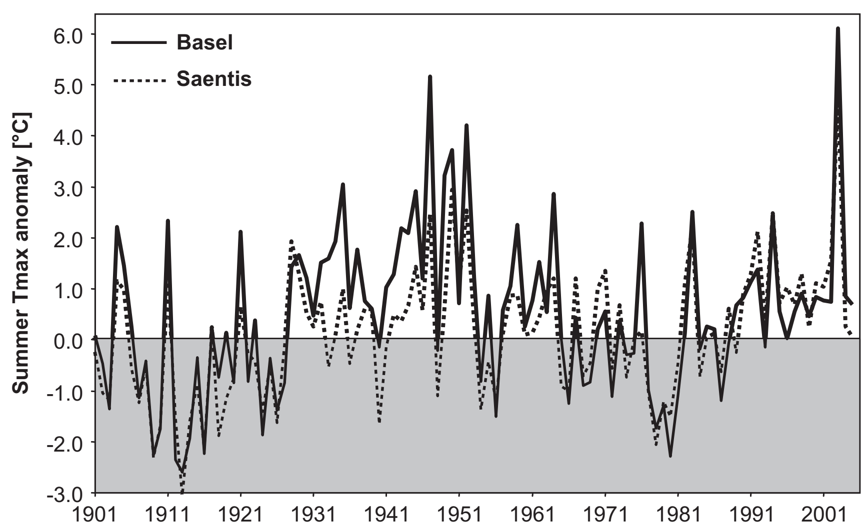

Fig. 3. Summertime maximum temperature anomalies at low (Basel, 367 m) and high (Saentis, 2500 m) elevation sites in Switzerland from 1901 to 2005.

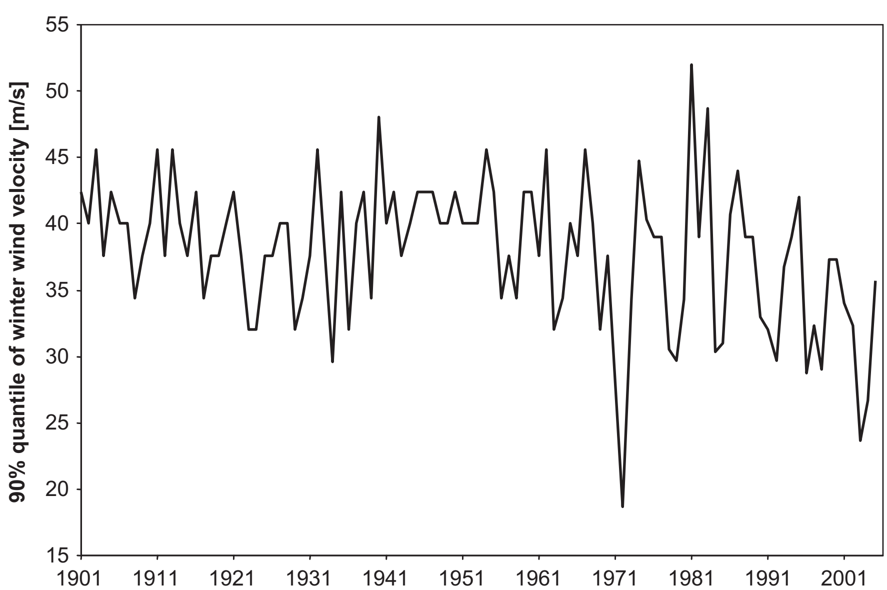

Fig. 4. Annual average peak wind velocities measured at Saentis for the period 1901–2005.

Loss of life and economic damage resulting from strong wind storms, which generally occur during the winter in western Europe and the Alpine area, can be significant (e.g., Ulbrich et al., 2000). The December 1999 *Lothar* storm resulted in uprooted or damaged trees equivalent to up to six times the annual felling rate in certain Swiss cantons (BUWAL, 2000), and damage to infrastructure that exceeded €1 billion in Switzerland alone and over €20 billion in the countries affected by the winter storm from France to central Europe, according to Swiss Re (2003). Current 20-year return periods of wind velocities associated with winter storms are in the range 30–75 m/s, according to the altitude and the latitude of the site (Goyette et al., 2003).

3. Climatic extremes by the end of the 21st century

A crucial question when assessing climatic change forced by increased levels of greenhouse gases in the atmosphere is related to the manner in which extremes of climate as discussed in the former section may change in intensity and/or frequency (e.g., OCCC, 2005). Although additional heat in the atmosphere may be a necessary condition, it is by no means a sufficient condition for generating extreme events. The future behavior of a non-linear system such as climate needs to be studied through 3-D numerical modeling techniques. Climate models must be capable of simulating the response of climate to various levels of greenhouse-gas emissions for both average climatic conditions and extremes (Beniston et al., 2007), at the global to regional scales. In the following, reference is made to the IPCC SRES A2 high emissions scenario (one of a range of high greenhouse-gas emission futures developed by Nakićenović et al. (2000)) and the lower B2 scenario. Greenhouse-gas emission rates based on the A2 scenario lead to atmospheric CO_2 levels of 800 ppmv and a global temperature rise of more than 4 °C by 2100; for the B2 scenario, the corresponding figures are 500 ppmv and 2.5 °C, respectively.

At the regional scale, regional climate model (RCM) simulations at high spatial and temporal resolution have been undertaken for Europe by a network of research groups working within the EU "PRUDENCE" project (Christensen et al., 2002). Results from the model experiments based on the IPCC A-2 Scenario (Christensen and Christensen, 2007) suggest that much of Europe may experience a rise in annual temperatures of about 4 °C by 2100 compared with the 1961–1990 reference climate, with stronger warming around the Mediterranean and the Iberian Peninsula than further north. Christensen and Christensen (2003) have shown that in the course of the 21st century, precipitation in southern, central and western Europe may undergo a general reduction in *average* precipitation and an increase in *extreme* rainfall events. This apparent paradox is related to the fact that, in a much warmer climate, thermal instabilities generated by a warm surface will trigger explosive convection whenever sufficient moisture converges into a given region.

Fig. 5 illustrates the evolution of summer maximum daily temperatures and the 90% quantile in Basel, for the period 1961–1990 (left-hand quadrant) and for the A2 and B2 scenarios discussed above (right-hand frame). Following the IPCC (2001), the 90% quantile is considered here to represent the threshold of extreme temperatures. For the observed climate, it is seen that mean summer maximum temperature is about 23 °C for the 30-year time series, and the 90% quantile values are close to 30 °C. Simulations with the HIRHAM RCM (Christensen et al., 1998) for the two future scenarios suggest, on the other hand, that mean summer maximum temperatures and their upper extremes shift by 5 °C (B2 scenario) to 7 °C (A2 scenario). In other words, at this location, the level of future summer temperatures is likely to be as high as the threshold for present-day heat waves. The upper quantiles of maximum temperature are completely out of the range of the current

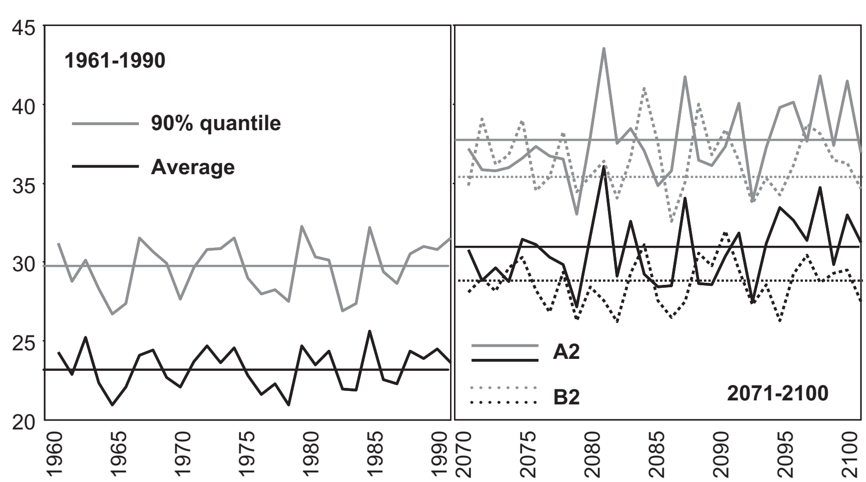

Fig. 5. Thirty-year evolution of summer mean maximum temperatures and their 90% quantile at Basel for the 1961–1990 reference climate, and their behavior in the period 2071–2100 for the IPCC SRES A2 and B2 greenhouse-gas emission scenarios, as simulated by the HIRHAM regional climate model.

climate, with the exception of the 2003 heat wave (Beniston, 2004b; Schär et al., 2004). It is also noteworthy that the difference between the low and high emissions scenarios are not widely different, perhaps 1–2 °C at the most. However, the temperatures associated with the A2 scenario are so high that the negative implications for energy use, water supply and human health would warrant implementing energy policies and technology changes aiming for the smallest possible level of climatic change.

The response of precipitation to warmer climatic conditions is more subtle than the change in temperatures, according to the scenario considered. Numerical models of the climate system have greater difficulty in simulating precipitation than temperature, because of the complex microphysics involved and the role that sub-grid-scale features of topography or land-use impose on the location and intensity of rainfall. However, recent studies with RCMs applied to Europe show that they generally capture the broad features of observed precipitation and their seasonal shifts, even in the complex Alpine domain (e.g., Beniston, 2006). When applied to the A2 and B2 scenario climates for the period 2071–2100, most RCMs agree on the sign of seasonal precipitation change compared with 1961–1990, i.e., increases in winter and spring, and reductions in summer and autumn. Fig. 6 illustrates the seasonal shift in precipitation totals for the HIRHAM model only, in one part of the Alps that is prone to strong rainfall and flooding. This is the region of the northern Alps and Alpine forelands stretching from Bern and Fribourg in the west to St. Gallen in the east, which was affected by the August 2005 catastrophic floods. While the annual precipitation amounts remain remarkably similar between current and future climates (around 1600 mm), the distribution throughout the year is markedly different. The principal cause of the change in seasonal patterns is related to the strong summer warming and drying in the Mediterranean zone that is likely to spread north to the Alps and beyond, and the distinctly rainier rainfall season that a milder climate is expected to bring to the region in winter.

As a result of the shifts in mean precipitation, the frequency of extreme events may also change in seasonality compared with current climate. Fig. 7 illustrates the seasonal change in the number of heavy precipitation events, represented by the 99% quantile of precipitation, in the northern part of the Swiss Alpine region. For the

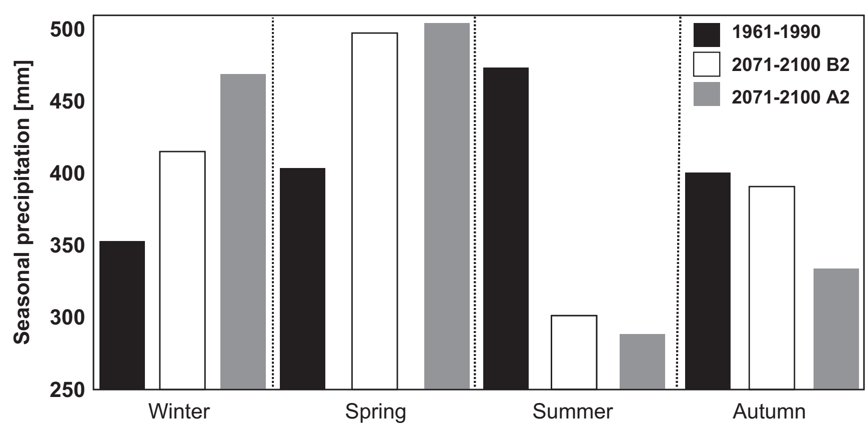

Fig. 6. Seasonal precipitation totals in the northern Swiss Alps and Alpine foreland area for the reference climate and the A2 and B2 scenario climates, as simulated by the HIRHAM regional climate model.

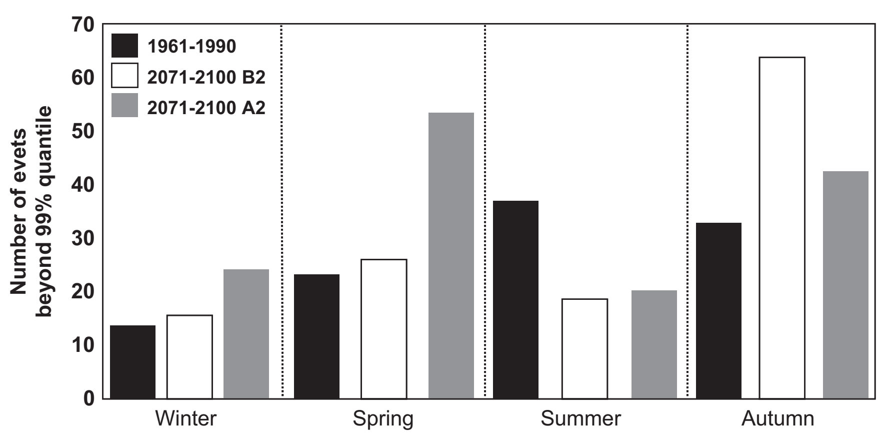

Fig. 7. As Fig. 6, except for extreme precipitation frequency.

scenario climates, the HIRHAM model (and other models, not shown here) projects the largest changes in spring and autumn, with large increases in intense precipitation. As expected, the A2 climate represents an amplification of the seasonal change over the B2 climate. Summer rainfall extremes are projected to decline and some models other than the HIRHAM RCM results shown in Fig. 7 suggest that autumn events may become more frequent than summer events. In the B2 scenario, annual events beyond the threshold of the 99% quantile increase by approximately 15% compared with the reference 1961–1990 climate; the rise is about 25% for the A2 scenario.

Heavy precipitation is a necessary but not always a sufficient condition for floods, landslides and other related damages. The response of hydrological systems to high precipitation levels is also a function of the prior history of rainfall, evaporation rates, the permeability of soils and, a factor unique to mountain regions, the buffering effect of the altitude at which snow falls during an event. As the freezing level rises, so does the potential for strong runoff since rainfall is captured over a greater surface area and thus more water may be channeled into river catchments (Stoffel et al., 2005). The same quantity of precipitation can thus lead to a very different hydrological response according to the level at which snow falls during an intense precipitation event. Without the buffering effect of snow, a heavy downpour can become a catastrophic event. Estimates for a warmer climate paradoxically point to the fact that flood events and other rainfall-triggered hazards may not necessarily increase, because snowfall levels in future springs and autumns are projected to remain below those of current summers. However, because summer precipitation events will also exist in the future even if they are less frequent than today, they may lead to an increased hazard potential because the snowline will then be located much higher than under current climatic conditions.

Results from modeling studies of extreme winter storms, based on model studies of events such as the 1990 *Vivian* storm (Goyette et al., 2001) or the 1999 *Lothar* storm (Goyette et al., 2003), suggest an increase in the frequency of strong winds originating in the Atlantic at the expense of föhn-type storms related to southerly flow across the Alps. Based on the return periods of winter wind storms, there is a strong probability that the Alpine region will experience at least one event with similar intensity to the 1999 *Lothar* "storm of the century" by 2020 (Goyette et al., 2003). While this may not appear to be significant, it should be borne in mind that insured infrastructure is likely to increase over the next decades, thereby leading to a strong rise in damage costs.

4. Relating climate model results and economic damage costs

Linking RCMs and economic models in order to estimate damage costs following extreme events poses a range of conceptual and technical problems. There is no universal approach to couple economic and climate models whose concepts, structure and objectives are very different. It seems currently illusory to aim for a totally integrated model approach in which the estimates of damage costs could be obtained through one single modeling system. It is probably more appropriate to focus upon issues such as the type of data needed for the economic impacts assessment, a model's capability in delivering such data, and the spatial and temporal scales of the event under consideration.

Table 2 highlights the problems of scale that need to be addressed and helps explain why a unique method cannot be applied to *all* damage costs for *all* extreme events. There is also the added complexity of the compatibility of scales between those that an economic assessment requires and those that a climate model can realistically deliver. Even high-resolution climate models cannot provide information below scales of 5–10 km, while quantifying the impacts on infrastructure may require data at the very local scales of individual buildings. Gridded model data can be provided for a range of relevant variables, but many of the impacts

Table 2
Typical spatial and temporal scales of extreme climatic events, illustrating the difficulty of defining a unique strategy for using climate data in economic impacts assessments

Type of extreme	Typical spatial scale of event	Typical spatial scale of impact	Typical time scale of event	Typical time scale of impact
Winter wind storms	System: 1000 km Track: >1000 km	Individual buildings to large areas along storm track	1 day	A few seconds (response to gusts)
Heat waves, cold spells	100–>1,000,000 km^2	From persons to large areas	>3 days	Comparable to the duration of the event
Extreme precipitation	1–10,000 km^2	Individual buildings to large areas	Minutes to hours	A few minutes to a few hours
Floods	1–>10,000 km^2	Individual buildings to large areas	Minutes to months	A few minutes (flash floods) to several weeks after the event
Hail	1–10 km^2	Cars and buildings to large agricultural surfaces	Minutes	A few seconds (damage by hail)
Drought	100–>1,000,000 km^2	Comparable to the scale of the event	Several days to several months	A few days to several weeks after the event

themselves may be restricted to scales that may be orders of magnitude smaller than the resolution of the models. These problems thus need to be addressed through appropriate downscaling techniques that allow a coherent transfer of information from the grid-resolved scales to the sub-grid scales associated with the impacts themselves. Some of these downscaling techniques are discussed at length, for example, by von Storch and Navarra (1999) among others and are beyond the scope of this paper.

5. Concluding remarks

While changes in the long-term mean state of climate will have many important consequences on numerous environmental, social and economic sectors, the most significant impacts of climatic change are likely to arise from shifts in the intensity and frequency of extreme weather events. Indeed, insurance costs resulting from such extremes have been steadily rising since the 1970s (e.g., Munich Re, 2005), essentially in response to greater population pressures in regions that are at risk. Regions now reasonably safe from catastrophic wind storms, heat waves and floods could become more vulnerable in the future, resulting in much higher damage costs. There is thus a very real need to improve the conceptual and numerical basis for linking climate and economic models, even though the examples shown here emphasize the current difficulties in linking the two types of models. Such improvements should pave the way for a better assessment of the potential for damage that may befall a particular region, thereby enabling the formulation of appropriate response strategies.

The problem of climate change and its impacts is closely intertwined with that of energy use; the IPCC (2001) estimates that close to 75% of current global carbon emissions are directly or indirectly linked to the use of fossil fuels. Long-term energy policies that aim toward a reduction in fossil-fuel consumption may represent one way of addressing the complex issues of climatic change and its economic impacts. Common sense and the precautionary principle should motivate future decision making in the energy sector in order to limit the social and economic risks associated with the extreme weather that may well become part of tomorrow's world.

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