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Climate risks and their impact on agriculture and forests in Switzerland

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Abstract There is growing evidence that, as a result of global climate change, some of the most severe weather events could become more frequent in Europe over the next 50 to 100 years. The paper aims to (i) describe observed trends and scenarios for summer heat waves, windstorms and heavy precipitation, based on results from simulations with global circulation models, regional climate models, and other downscaling procedures, and (ii) discuss potential impacts on agricultural systems and forests in Switzerland. Trends and scenarios project more frequent heavy precipitation during winter corresponding, for example, to a three-fold increase in the exceedance of today's 15-year extreme values by the end of the 21st century. This increases the risk of large-scale flooding and loss of topsoil due to erosion. In contrast, constraints in agricultural practice due to waterlogged soils may become less in a warmer climate. In summer, the most remarkable trend is a decrease in the frequency of wet days, and shorter return times of heat waves and droughts. This increases the risk of losses of crop yield and forage quality. In forests, the more frequent occurrence of dry years may accelerate the replacement of sensitive tree species and reduce carbon stocks, and the projected slight increase in the frequency of extreme storms by the end of the century could increase the

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risk of windthrow. Some possible measures to maintain goods and services of agricultural and forest ecosystems are mentioned, but it is suggested that more frequent extremes may have more severe consequences than progressive changes in means. In order to effectively decrease the risk for social and economic impacts, long-term adaptive strategies in agriculture and silviculture, investments for prevention, and new insurance concepts seem necessary.

Keywords Agriculture · Climate change · Extreme events · Forests · Society · Switzerland

1 Introduction

1.1 Scope and aim

Climate risks arise from complex interactions between climate, environment, social and economic systems, and they represent combinations of the likelihood of climate events and their consequences for society and the environment. Society can be affected either directly or indirectly. Recent examples of direct effects in Europe were the flood damage caused by extreme rainfall in spring 1999 (Christensen and Christensen 2002), or the excess death particularly in France during the heat wave in 2003 (Valleron and Boumendil 2004). The present article deals with potential indirect effects, which may occur via impacts on the provision of goods and services to society by agricultural systems and forests. Historical events recorded in Switzerland show that heavy precipitation and droughts were most important for agricultural crop and forage production (Pfister 1999). Typically, impacts of isolated events on croplands, i.e. yield loss, were of short-term nature and could largely be alleviated by financial compensations. In the case of forests, winter storms are considered key climate risks, particularly in prealpine and alpine areas. Effects of climate extremes on forests can have both short-term and long-term implications for standing biomass, tree health and species composition (Dale et al. 2001; Bush et al. 2004), and similar principles apply to semi-natural grasslands (Grime et al. 1994). A climate extreme can thus be considered an ecological disturbance in semi-natural terrestrial ecosystems, and they are implicated as mechanistic drivers of species diversity, nutrient cycling or carbon (C) stocks (Parmesan 2000). Consequently, the frequency of climate extremes is important with respect to the development and succession of ecosystems.

The types of extreme climatic events considered in this article have significant damage potentials at the local and at the regional scales under today's climate. But their importance could increase over time, because extreme weather events may become more frequent as part of global climate change (e.g., IPCC 2001). The link between climatic extremes and climatic change is elusive because a few isolated events are difficult to relate in a statistically meaningful way to changes in mean climatic conditions (e.g., Frei and Schaer 2001; Beniston and Stephenson 2004).

The focus of this article is on climatological and ecological aspects. The aim is first to review information from the Swiss research program NCCR 'Climate' (Swiss National Center of Competence in Research 'Climate') and from other sources concerning temporal and spatial trends and scenarios for extremes in precipitation, temperature and wind, and secondly to relate their current and projected occurrence to possible implications for agricultural land and forests in Switzerland.

1.2 Climatic extremes and their simulation

There are different possibilities to define 'extreme events'. In a statistical sense, a climate extreme can be characterized by (1) the frequency of occurrence of anomalous weather (IPCC

2001), and an ‘extreme’ refers to the tail ends of a probability density function, for instance an event that occurs below the 10% or above the 90% quantile, or (2) the intensity of an event, which is described through the exceedance of a quantity measured per unit of time and/or area beyond some threshold. Alternatively, climate extremes can be characterized based on their socio-economic and/or ecological relevance, which implies the definition of specific thresholds beyond which serious impacts may occur in the systems concerned (Meehl et al. 2000). Regardless of the definition used, the characteristics of what is called an ‘extreme weather event’ may vary from place to place.

The assessment of extreme events and their implications is difficult because of issues of scale. Several studies documented those impacts of climate changes that are of greater magnitude when fine-scale scenarios are used compared to coarse-scale scenarios (e.g., Carbone et al. 2003; Doherty et al. 2003). Many of the processes determining the development and evolution of extremes (especially heavy precipitation and wind storms) are on spatial scales finer than what can be explicitly resolved by current general circulation models (GCMs) with their grid spacing of 150–400 km. The simplified representation of these processes in the GCM’s parameterizations raises concerns about the reliability of GCM scenarios on extreme events (e.g. Giorgi et al. 2001; Huntingford et al. 2003). Moreover, depending on the scope of the assessment, there can be a mismatch of spatial scales between what can be provided by a GCM and what is needed for impact modelling. This mismatch is particularly relevant when output and input variables refer to different surface types or different topographic environments (e.g., upstream vs. downstream slopes). Statistical and numerical modelling methods have been proposed to downscale GCM outputs to regional scales (Mearns et al. 2004; Wilby et al. 2004). The numerical approach by Regional Climate Models (RCMs) aims at a more explicit simulation of the relevant physical processes of extreme events and a better representation of the topographic and physiographic detail. Thus, RCMs with a resolution of 50 km are promising tools for the development of scenarios for extreme events at the subcontinental scale, and for application in impact modeling at smaller scales (e.g., Christensen et al. 2002). RCMs have been found to reproduce patterns in the climatology of extremes, which could not be expected from the use of GCMs alone (e.g. Huntingford et al. 2003; Frei et al. 2003; Kleinn et al. 2005). As an example, Figure 1 depicts a regional climatology of heavy precipitation in autumn for the European Alps. Here, simulations for present climate with a 50 km RCM (CHRM, Vidale et al. 2003) with boundary conditions from a GCM control experiment (HadAM3H, Pope et al. 2000) are compared with observations (Frei and

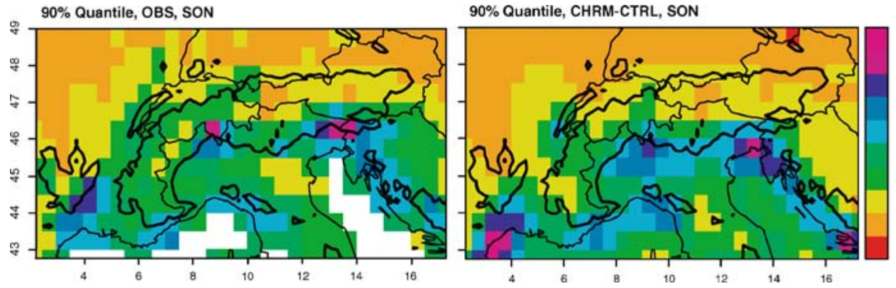

Fig. 1 Climatology of heavy precipitation in the Alpine region, as simulated by a control run with CHRM (right), and observations (left). The regional climate model CHRM (Vidale et al. 2003) was forced with HadAM3H (Jones et al. 2001) for control conditions (1961–1990). Observations are from high-resolution rain gauges upscaled to the climate model resolution (Frei and Schär 1998; Frei et al. 2003). The parameter shown is the 90% quantile of daily precipitation totals (in mm) for September to November

Schär 1998). Clearly, there are errors in magnitude and exact location of the pattern, but the visual correspondence is remarkable, given the complex distribution associated with details in topography and land-sea distribution.

Damage from windstorms may be fostered by strong sustained winds, but a large part of the small-scale impacts is due to gusts, and damage to infrastructures varies approximately exponentially with the speed of wind gusts (Dorland et al. 1999). Thus, data on finer spatial scales of a few kilometers is required. Statistical analysis of extremes in wind speed based on observed data can provide useful information on the return period for a given area (see Palutikof et al. 1999, for a review of methods); however, the relationship to the potential estimated damage can be established only for areas close to the observation station since spatial interpolation of the winds yields unreliable results. One alternative is given by the use of numerical models such as the Canadian RCM (Caya and Laprise 1999), and the application of multiple self-nesting with a RCM to obtain a fine resolution. The so-called 'medium' resolution RCMs (resolution ~50 km) cannot be used directly as such to infer the change in wind speed at the very fine scales. As a second step, numerical downscaling of re-analysis data using RCMs with a wind gust parameterization is necessary to reproduce the strong winds in a number of documented storms (e.g., Goyette et al. 2001, 2003). Simulated hourly means may then be compared with observations if grid spacing is on the order of 1–2 km. In addition, hourly maximum wind speed may be compared if a gust parameterization is implemented in the model. As an example, Figure 2 shows the maximum wind speed field simulated for February 27, 1990, on a 2 km horizontal grid over Switzerland using multiple self-nesting methodologies after downscaling the NCEP-NCAR re-analysis data (Kalnay et al. 1996). Maximum winds exceeding 40 m s^{-1} correspond well to observed forest damage areas.

1.3 Linking climate scenarios to ecosystem models

Results from climate models can either be used for numerical downscaling making use of nested RCMs (e.g., Goyette et al. 2003), or in combination with local weather data through statistical downscaling to the temporal and spatial resolution of a few kilometers (e.g., Wilby

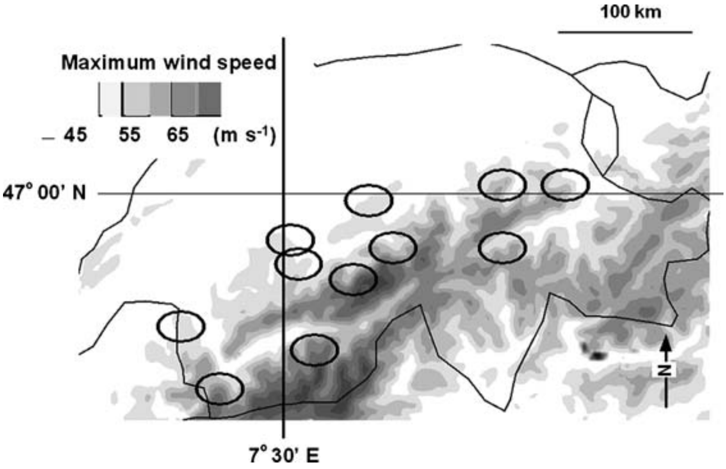

Fig. 2 Relationship between wind speed and storm damage to Swiss forests. Maximum wind speed simulated by the 2 km Canadian RCM during the 'Vivian' storm on February 27, 1990. Grey tones indicated in inset intervals of 5 m s^{-1}. Circles indicate main forest damage areas according to Schüepp et al. (1994)

et al. 1998; Gyalistras and Fischlin 1999). Downscaled monthly scenarios can be converted to daily and hourly scenarios by stochastic weather generation (e.g., Gyalistras et al. 1994, 1997; Zhang et al. 2004). These can then be used to force ecosystem models at a high spatial (e.g., 1×1 km) and temporal resolution (e.g., 1 h) (Riedo et al. 1999; Gyalistras and Fischlin 1999). Thus, with the current representation of meso-scale details across complex topographies, the spatial and/or temporal resolution more closely matches the requirements of many ecosystem impact assessments at the scales of interest to decision makers and practitioners, for instance at catchment or landscape scales.

2 Extreme events in Switzerland and their evolution in a changing climate

2.1 Heavy precipitation

Europe has experienced pronounced changes in precipitation during the 20th century. Analyses of instrumental data revealed an increase in mean wintertime precipitation from central Europe to Scandinavia (e.g., Schönwiese et al. 1994; Hanssen-Bauer and Forland 2000; Osborn et al. 2000). For the Mediterranean region a tendency towards decreasing annual means is noted, yet with strong regional variations (e.g., Esteban-Parra et al. 1998; Buffoni et al. 1999; Xoplaki et al. 2000), and for the whole basin, a general downward trend of 2.2 mm month^{-1} decade^{-1} in wet season (October–March) precipitation occurred since the 1960s (Xoplaki et al. 2004). In Switzerland, in the northern and western parts the changes consist in a 20–30% increase of mean winter precipitation, while no significant changes were noted for the other parts of the country (Schmidli et al. 2002). There is evidence from a number of European data analyses that the wintertime changes are associated with an increase in intensity and frequency of rainfall (Klein Tank and Können 2003; Haylock and Goodess 2004). These shifts are also evident in many statistics of Swiss precipitation measurements (Schmidli and Frei 2005). For example, Figure 3 illustrates the observed increase in the occurrence of intense precipitation events in northern Switzerland. It is not possible to make clear statements about systematic changes in extremes due to statistical limitations associated with these very rare events (Frei and Schär 2001). Nevertheless, observational analyses suggest, for the 20th century, a trend towards more vigorous precipitation events in winter over central and northern Europe, including Switzerland.

Knowledge of possible future changes in heavy precipitation events on a regional scale is derived primarily from RCMs. Representative for the results of a range of recent model integrations (e.g., Räisänen et al. 2004; Frei et al. 2006) we present here results from two RCMs: CHRM is the climate version of the former weather forecasting model of the German and Swiss weather services and is operated at ETH Zurich (Vidale et al. 2003), and HadRM3H is the model of the UK Met Office Hadley Centre (Jones et al. 2001; Noguer et al. 1998). Results are from model integrations over the entire European continent, with a resolution of ~50 km. The boundary conditions were taken from HadCM3 and the IPCC SRES emission scenario A2 (Nakicenovic et al. 2000), where atmospheric CO_2 concentration reaches twice the value of year 2000 in about 2090. Results for the CHRM are from a 30-year integration for present (1961–1990) and future (2071–2100) conditions, while those for HadRM3H are from three independent members of a GCM ensemble in each of the two periods. Figure 4 shows the relative change in precipitation statistics. It reveals distinct regional and seasonal patterns of change. In winter, both rain-day frequency and intensity (Figure 4a,c) exhibit an increase north of about 45°N, while the rain-day frequency (but not intensity) decreases to the south. This is consistent with an increase of mean winter precipitation by 10–30% over

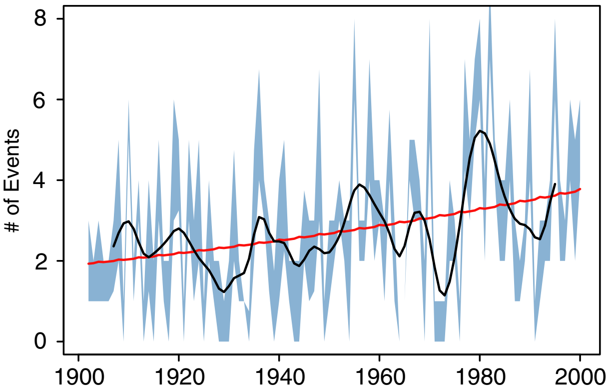

Fig. 3 Evolution of the number of heavy precipitation events per winter in northern Switzerland (days, when the daily total exceeds the climatological 90% quantile). Blue shaded: inter-quartile range from 35 stations; bold black line: smoothed time series (smoothing window is 11 years); red line: long-term trend estimated from the pooled data using logistic regression. The trend corresponds to an increase by 75% over the 20th century and is statistically significant at the 5% level (Schmidli and Frei 2005). (Courtesy of J. Schmidli, ETH Zurich)

most of central and northern Europe, and a decrease over the Mediterranean (not shown). These changes are reflected in changes for intense and heavy precipitation. For example, the 90% quantile, i.e. the typical rainfall with a recurrence of 20–30 days, increases by about 20% over northern Europe in winter.

An analysis for extreme events based on the method of extreme value statistics (see Frei et al. 2006 for details) was undertaken for the HadRM3H integration and is displayed in Figure 5. For winter, the HadRM3H model reveals an increase in the 5-year maximum 5-day precipitation event by 10–30% over large areas of central and northern Europe, including Switzerland (Figure 5a). This change corresponds roughly to a three-fold increase in frequency, i.e. the 15-year event of today's climate would become a 5-year event.

In summer, the most remarkable change is a strong decrease in the frequency of wet days (Figure 5b), for instance to about half in the Mediterranean, which goes along with a 20–50% decrease of mean summer precipitation (not shown). There is no similar tendency of drying in rainfall intensity. For example, a central part of Europe including Switzerland, which undergoes significant drying in the mean, shows a slight increase in the 90% quantile (Figure 4f) and the 5-year return period of extreme rainfall (Figure 5b). Yet the changes for extremes are at the border of statistical significance.

The results from the selected model integrations are very similar to results found in other RCM experiments (e.g., Durman et al. 2001; Christensen and Christensen 2003; Räisänen et al. 2004; Frei et al. 2006) in terms of their seasonal distribution and their larger-scale geographic pattern. However, the magnitude of change and the smaller-scale pattern vary considerably between RCMs. Hence, although a general increase of heavy precipitation during wintertime is noted in the simulations for the territory of Switzerland, there remains considerable uncertainty about the magnitude of this increase, even under a prescribed emission scenario. Moreover, little can be said today about regional differences within the country. Particularly uncertain are current scenarios of heavy precipitation for the summer season, where results for Central Europe vary even in the sign between different models (Räisänen et al. 2004; Frei et al. 2006). However, it is interesting to see the similarity among many models: the frequency of extreme precipitation events decreases modestly, or even increases,

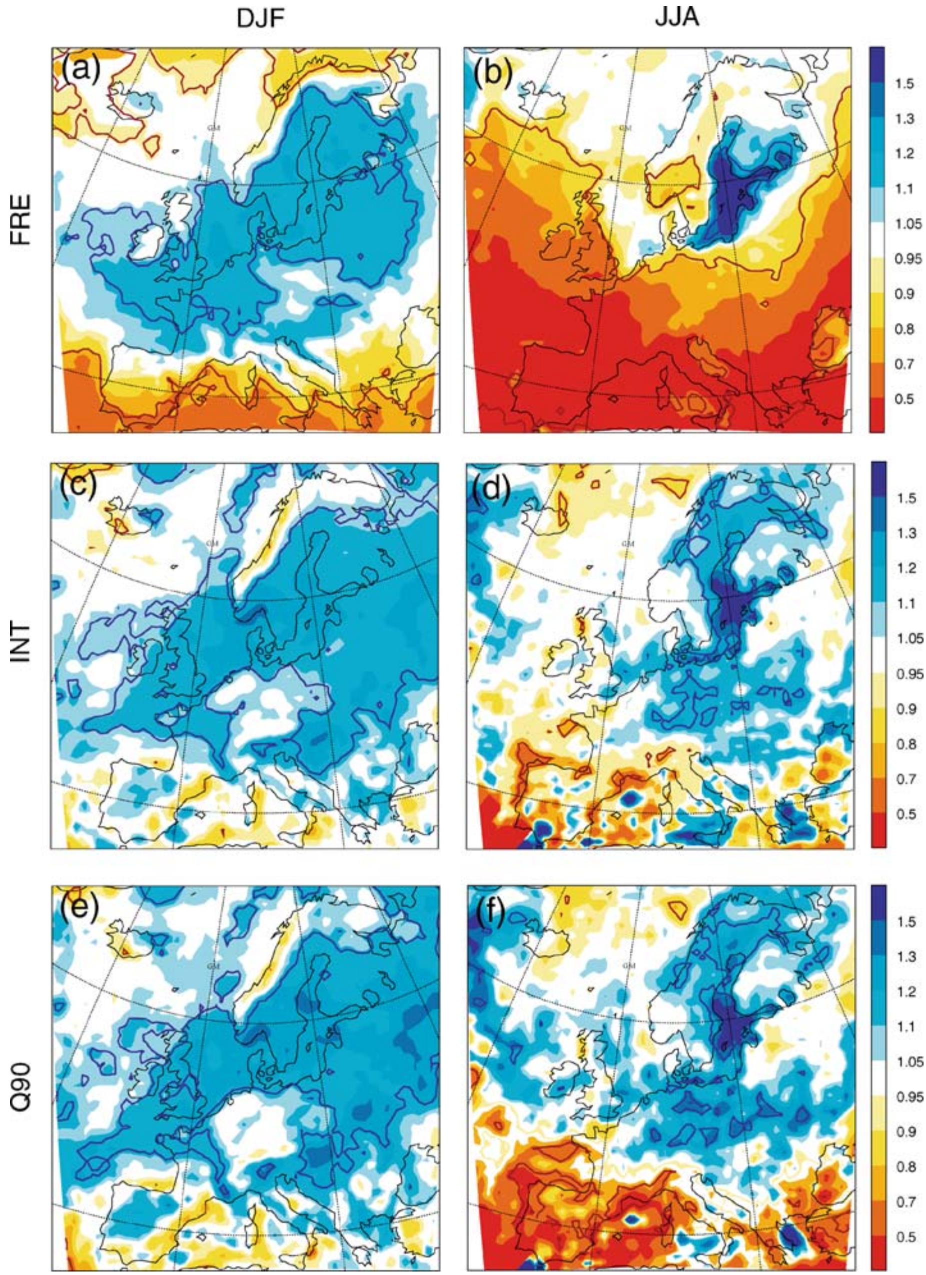

Fig. 4 Change in selected statistics of daily precipitation between 1961–1990 and 2071–2100. Scenario from the regional climate model CHRM with boundary forcing from HadAM3H and the SRES A2 emission scenario. The panels depict the ratio between future and present climate for wet-day frequency (a, b), wet-day intensity (c, d) and 90% quantile of daily precipitation (e, f), for winter (DJF, a, c, e) and summer (JJA, b, d, f). Blue colors for increase and yellow/red colors for decrease. Thick contour lines delineate areas where the change is statistically significant at the 5% level, according to a non-parametric resampling test (Courtesy of S. Fukutome, ETH Zurich)

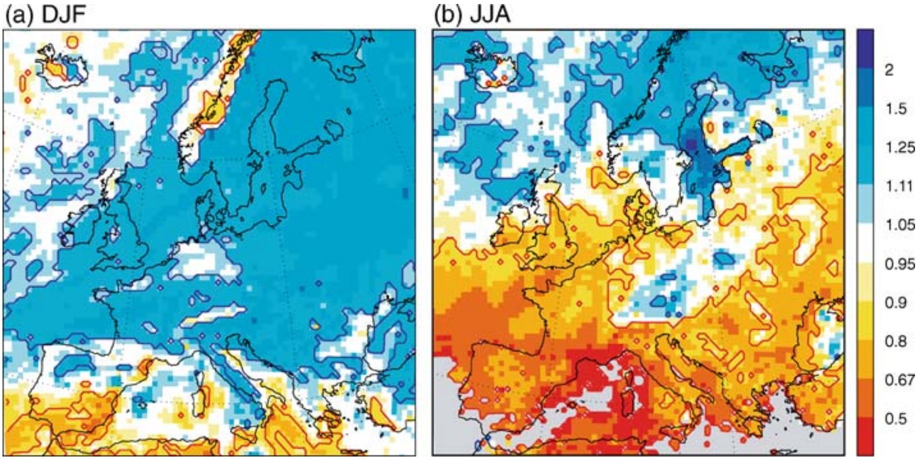

Fig. 5 Change in the 5-year extreme of 1-day precipitation totals in winter (a) and summer (b). The change is expressed as a ratio between future (2071–2100) and present (1961–1990) climate. Blue for increase, red for decrease. The blue and red contours delineate the two-sided 5% significance

despite a decrease in the frequency of average events (Christensen and Christensen 2003; Pal et al. 2004; Frei et al. 2006).

2.2 Heat waves and droughts

The record heat wave that affected many parts of Europe during the course of the summer of 2003 has been seen as typical of summers that may commonly occur in Switzerland towards the end of the 21st century (e.g., Beniston 2004a; Schär et al. 2004). The 2003 event stands out as a 'climatic surprise', in the sense that the departure from the mean 1961–1990 temperature is far greater than any recorded anomalies since the beginning of the 20th century". Figure 6 illustrates the course of annual values of summer maximum temperatures (i.e., daily maximum temperatures averaged for June, July, and August) at Basel, Switzerland, which puts 2003 into a long-term perspective.

Differences between current (1961–1990) and future (2071–2100) climates based on the IPCC A2 emission scenario and simulated by the HIRHAM4 model (Christensen et al. 1998), for example, suggest that warmer conditions will invade most of Europe, with summers in the Iberian Peninsula and southwestern France warming by 5–6 °C on average. Model-based statistics show increases in the 90%-quantile of maximum temperature that are greater than the rise in mean summer daily maxima, suggesting a change in the variance of the temperature distribution; this results in higher temperature extremes and a greater heat-wave frequency. To illustrate this point, Figure 7 shows the shift in summer maxima between the 1961–90 reference period and 2071–2100 for the RCM grid-point closest to the city of Basel. A shift by 6 °C in both mean and 90%-quantile is observed between the two 30-year periods, with a greater inter-annual variability in the scenario simulations. Mean and 90% quantile for the 2003 event are superimposed to highlight the fact that the recent heat wave in Europe closely mimicked summers that are expected to occur in Switzerland towards the end of the 21st century with the SRES A2 scenario. Because higher temperatures stimulate evapotranspiration (see accompanying paper by Calanca et al. 2006) the trend in temperature, combined with the downward trend in summer precipitation, will significantly increase the risk of droughts.

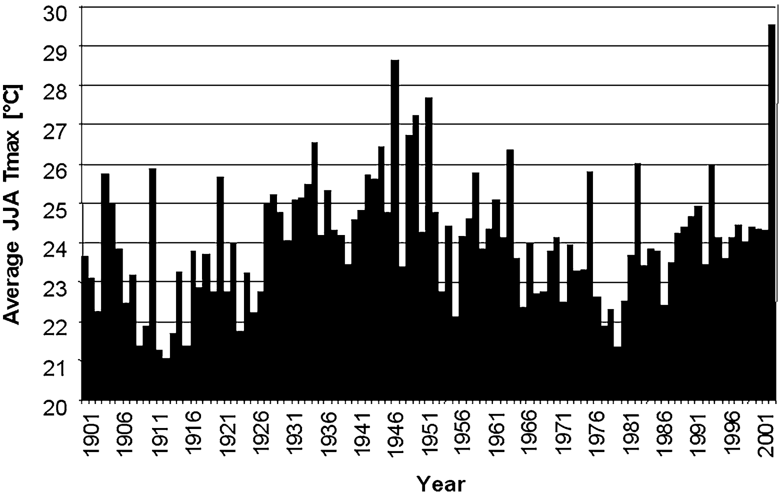

Fig. 6 Development of summer (JJA) daily maximum temperatures recorded at Basel, Switzerland, from 1901–2003

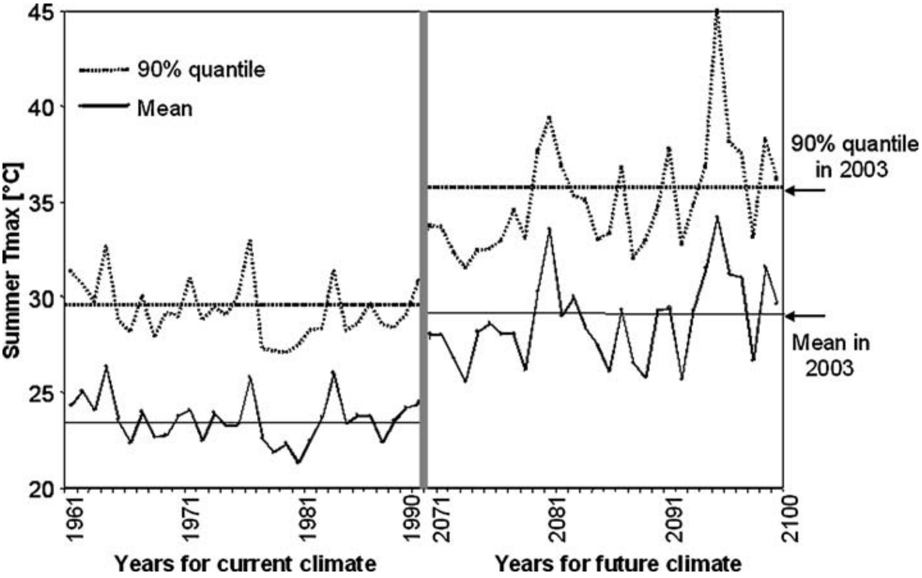

Fig. 7 Changes in mean and 90% quantile of summer (JJA) maximum temperatures in Basel, Switzerland, between current (1961–1990) and future (2071–2100) climates. Dashed and dotted lines show 30-yr means for each period. The arrow shows the temperature in 2003

2.3 Wind storms

Storms in the North Atlantic are capable of generating strong winds and gusts that have the potential to cause significant impacts (e.g., Beniston 2004b). During the last 25 years, a number of storms caused extensive damage in Western Europe including the Burns' Day storm in the UK on January 25, 1990 (McCallum and Norris 1990), the 'Vivian' storm in

Switzerland on February 27, 1990 (Schüepp et al. 1994), and the ‘Lothar’ storm that struck France and Switzerland on December 25–26, 1999 (Wernli et al. 2002). On the basis of a large documentary data set for the last 500 years, Pfister (1999) concluded that extremely violent storms such as Vivian (1990) occurred once in every century. Accordingly, the occurrence of ‘Lothar’ within the same decade of the 1990s was somewhat surprising. These storms are generated by cyclones whose climatology has been examined by a number of studies based on observations (e.g., Hanson et al. 2004; Alexandersson et al. 2000; McCabe et al. 2001; WASA Group 1998; Schmith et al. 1998; Heino et al. 1999), and also through simulations with GCMs for the current climate (e.g., Lambert et al. 2002), as well as for a future climate (e.g., Stephenson and Held 1993; Hall et al. 1994; Knippertz et al. 2000). The results suggest that during 1979–2000 there has been a general increase in weak cyclones and strong storms in the northern North Atlantic; however, the WASA Group (1998) concluded that the storminess has not increased in recent years beyond the bounds of natural variability. But for the period 1959–97, McCabe et al. (2001) have shown that there has been a significant decrease in the frequency of mid-latitude and high-latitude cyclones, and that storm intensity has increased in both the high and mid-latitudes. Similarly, modeling studies have shown that in a warmer climate cyclone activity undergoes a shift towards the north and west over Europe and the north-eastern Atlantic, which is accompanied by several weak cyclones and an increase in deep cyclones (Carnell and Senior 1998; Knippertz et al. 2000); an increase in mean wind speeds and in wind speed extremes have also been diagnosed. A consensus among many studies is the possibility that gale frequency will increase in the future in Northern Europe, independent of the emission scenario (Parry 2000; IPCC 2001). Extreme value analysis using the Canadian GCM outputs suggested increased wind speed extremes over Europe with warming, which is related to the negative pressure anomaly over northern parts of Europe (Zwiers and Kharin 1998). Generally, similar conclusions about the changes in the flow fields can be drawn from the equilibrium (e.g., $2\times CO_2$) and from time-dependent greenhouse-gas-induced climate change simulations. The models selected to analyze the precipitation and temperature changes based on the SRES A2 emission scenario have also been used to draw some general conclusions regarding changes in wind speed (Christensen et al. 2002). Results show an overall positive change in the mean wind speed fields over Western Europe. Leckebusch and Ulbrich (2004) found that global model simulations (HadCM3) with present GHG forcing reproduced realistic patterns of the storm track density. Changes occur in particular with respect to the SRES A2 scenario for extreme cyclone systems where track density tends to increase. Moreover, analyses of the responses of RCMs driven by a series of GCMs have shown that the changes in the mean wind field patterns are also in accordance with results of their driving models. Similar numerical approaches may allow projections of damage for future climates. Based on the output produced with HIRHAM4, analysis of changes in wind direction between the 1961–1990 and 2071–2100 indicates that north-westerly flows from December through February increase on average by up to 7% with a corresponding decrease of south-westerly flows over Switzerland (Christensen et al. 2002). This would suggest a slight increase in the occurrence of ‘extreme’ windstorms similar to ‘Vivian’ and ‘Lothar’.

3 Implications of climate extremes for agriculture

3.1 Heavy precipitation

More frequent heavy precipitation events in the Alpine region (see Section 2.1) may significantly increase the risk of damage from flooding, erosion, debris flow or land slides. In

Switzerland, floods in the past were most severe in autumn 1868 and in late August 1987, as defined by material losses equivalent to >300 Million Swiss Francs (value in 2000), or more than 50 victims (Pfister 2004). It is noteworthy that the major part of these losses was attributable to a few particularly severe events, such as those of 1987 and 1993 (see also Frei et al. 2001; OcCC 2003). According to the structure of today's economy, most of the financial losses associated with these events concerned public infrastructure such as river embankments, streets, bridges and railways. But heavy precipitation can also have important non-monetary adverse effects on agriculture, for instance, through the loss of fertile topsoil by erosion (Williams et al. 2001). Soil erosion is particularly sensitive to the intensity of individual precipitation events (Pruski and Nearing 2002); hence, the projected increase in the frequency and intensity of rainfall could significantly increase the risk of erosion from croplands in sloped terrain, unless preventive measures were taken. Moreover, heavy precipitation can cause soil waterlogging, which can cause crop damage through anoxic soil conditions, increased incidence of plant diseases, or impaired workability (Rosenzweig et al. 2002). As given in FAT (1996), soil water content (SWC) above field capacity (FC) impedes or delays fieldwork due to restricted operation of machinery, which can be costly for the farmers. Waterlogging of soils becomes most critical during periods with frequent or sustained intense rainfall, as for instance during May 1999 when heavy precipitation coincided with snowmelt (Grebner and Roesch 1999) resulting in large-scale flooding and in excessive SWC in Switzerland. The pre-alpine Thur river basin (1700 km^2) with currently 55% of the surface being used for agriculture was selected for analyzing the implications for SWC of shifts in the seasonality of precipitation. Simulations with a distributed hydrological model (WASIM-ETH; Schulla 1997) revealed a decrease in area-mean SWC for an ensemble of climate projections for the next 100 years, with largest changes towards the end of the growing season, but also in early spring (Jasper et al. 2004). From the mean seasonal pattern of SWC for the period 2081–2100 (Figure 8), it can be estimated that from March to May the number of days with SWC exceeding FC varies from 51 days (CSIRO [B2] scenario) down to 0 (HadCM3 [A2] scenario). For sites with slopes larger than 3 °, SWC is always smaller than the FC threshold because of subsurface flows (Jasper et al. 2006). Thus, on average the occurrence of waterlogged soils during March, April and May could decline with climate warming due to the change in the partitioning of solid to liquid precipitation (Kleinn 2002), earlier and reduced springtime snowmelt, and increased potential evapotranspiration. Even one single extreme rainfall would not significantly increase the number of critical days because of sufficiently rapid soil drying under the warmer conditions (data not shown).

3.2 Heat waves and drought

Historically, heat waves have not been a major issue with respect to effects on crops and grasslands, but they may become more frequent and intense (see Section 2.2), with higher maximum temperatures, and thus become more relevant for agricultural production. Besides direct effects of heat on plants, high temperatures stimulate potential evapotranspiration (Calanca et al. 2006), which contributes to more rapid soil water depletion (Jasper et al. 2004).

Unlike heat, agricultural drought resulting from a lack of precipitation has been an important issue in the past. Using a stochastic soil moisture model, Calanca (2004) found that in 20 out of the past 100 years SWC during the growing season in northern Switzerland was close to the permanent wilting point, suggesting potential crop losses due to drought. Number and timing of these years closely matched historic records of yield losses (Schorer

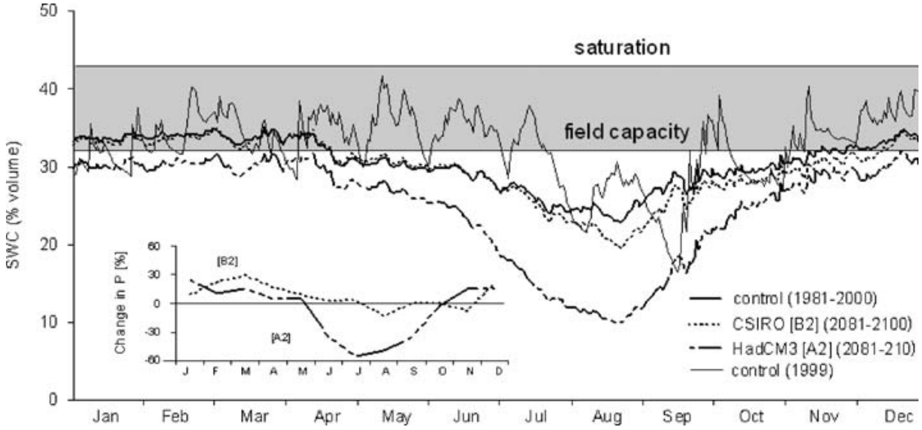

Fig. 8 Seasonal pattern of mean daily volumetric soil water content (SWC) for farmland on loamy soils and gentle slopes (<3 °) in the Swiss Thur basin simulated with the runoff and water balance model WaSiM-ETH (e.g., Schulla 1997; Jasper et al. 2006). Data are results of the control run (1981–2000) and the 2081–2100 projections obtained by using two different climate scenarios (HadCM3 (A2) and CSIRO (B2) (see Jasper et al. 2006). Inset: Projected changes in mean monthly precipitation (P)

1992; Pfister 1999). Drought in 1947 had the most devastating effect on Swiss agriculture because of its long duration (July to October) and its large geographical extent. Wheat yields in northwestern and central Europe dropped by 25–35% relative to the long-term average, and fodder became scarce and expensive throughout the continent (FAO data, cited in Schorer 1992). In contrast to the droughts in 1952 and 1953, import of forage into Switzerland was limited because of the concurrent crop losses in neighboring European countries (Schorer 1992). More recently, in 2003 yields of various crops and fodder cereals decreased by an average of 20% relative to the mean for 1991–99 (Keller and Fuhrer 2004). Low forage production during the second half of the season resulted in a shortage of fodder, which was compensated by increased imports at a reduced tax. Overall, the extreme weather in 2003 lowered the national net revenue of farmers from plant production by 11.1%, equivalent to about 500 Million Swiss Francs, while the fluctuations in supply had no effect on final prices of agricultural goods (Swiss Federal Office for Agriculture 2003). Hence, an isolated extreme event may not have lasting economic consequences.

To estimate future risks due to low SWC, Jasper et al. (2004) estimated for both northern and southern Switzerland an increase in average annual ET by 9–23% by 2071–2100, relative to 1981–2000, with largest changes during the summer months (see also Calanca et al. 2006). Combined with the projected reduction in summer precipitation (Schmidli and Frei 2005), this trend increases the likelihood of episodic drought. This is supported by preliminary estimates of the probability of the occurrence of agricultural drought on the Swiss Central Plateau from currently about 10–15% to over 50% towards the end of the century (Calanca 2006).

Effects of more frequent drought concern not only croplands, but also permanent grasslands, which in Switzerland cover around 75% of the agricultural land and sustain domestic meat and dairy production. The value associated with animal production was estimated at 5.2 billion Swiss Francs, or 68% of the total value of agricultural production (Swiss Farmers' Union 2001). Using a simple grassland model, Calanca and Fuhrer (2005) showed that grassland productivity could benefit in the future from moderately increased temperatures, higher radiation, and elevated CO_2. But if changes in the thermal and hydrological conditions were more pronounced and similar to the conditions in 2003, grassland production could become strongly water-limited. The authors estimated that the costs for setting up fixed irrigation systems for the entire grassland area of Switzerland would amount to 0.3 billion Swiss Francs annually, which is substantial but still a reasonable amount when compared to the present value of grassland production. Alternatively, fodder imports would be necessary from regions with more favorable conditions.

Effects of drought include not only decreased productivity, but also declining quality resulting from the formation of gaps in the sward, which can be colonized by weeds (cf. Lüscher et al. 2005); in turn, this has negative implications for animal nutrition. While in managed systems this effect can be addressed by farmers' interventions such as re-seeding, in semi-natural grasslands with little or no influence of management natural re-colonization following perturbation by drought is considered a primary driver of vegetation dynamics. A study by Stampfli and Zeiter (2004) in southern Switzerland (Ticino) confirmed that more frequent droughts might drive grassland vegetation changes with local colonization and extinction, as suggested earlier by Grime et al. (1994). Hence, increased frequency of drought has important economic effects in productive grassland systems and ecologically relevant effects in semi-natural systems.

4 Implications of climate extremes for forests

4.1 Wind storms

Storm is considered the most important natural disturbance agent in European forests. It is responsible for one third of total unplanned fellings (Brassel and Brändli 1999). Since 1868 European forests were impacted at least 16 times by the effects of several severe storms (Schelhaas et al. 2003), and 10 times since the early 1950s with windthrow of over 20 million m^3; damages in 1990 and 1999 were by far the worst of all these years (UN/ECE Timber Committee 2000). Apparently, windthrow damage in Europe has increased in the past century; yet, loss of timber was typically smaller than annual timber harvests (Schelhaas et al. 2003). An exception was storm 'Lothar' in 1999, which was among the four most extreme events since 1500 (Pfister 1999) and threw 12.7×10^6 m^3 in Switzerland, which is equivalent to 2.8 times the average annual timber harvest (e.g. Dobbertin et al. 2002). Wind velocities on top of the Jura Mountains near Geneva exceeded 200 $\mathrm{km\,h^{-1}}$, and in other areas of Switzerland winds were measured at 240 $\mathrm{km\,h^{-1}}$. The total amount of damage was estimated at more than 750 million Swiss Francs, plus another 38 million due to damages to individual trees and fruit trees (WSL/BUWAL 1999). Because of the large spatial extent, the abundance of windthrown timber affected the European market: roundwood markets were temporarily in chaos after the 'Lothar' event, with sharply falling prices (UN/ECE Timber Committee 2000). Similar to the effects of storms in 1990 on markets for wood products, fluctuations in supply and price were absorbed during primary processing and there were little distinguishable effects in prices or sales for sawn wood, panels and pulp. Greater market calamity was mitigated through sector solidarity.

Besides the loss of timber, windthrow can also have positive ecological effects (Schönenberger 2001), but where damage levels exceed harvesting or salvage harvesting costs are high, e.g. in mountainous terrain, adverse effects of wind storms outweigh any positive ones resulting from wood utilization (Widmer et al. 2004). As it dries, the wind-blown wood presents ideal conditions for massive fires and insect outbreaks, thus threatening

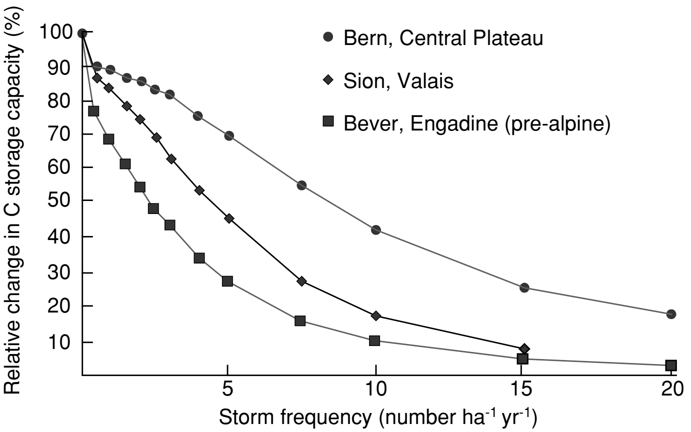

Fig. 9 Change in average carbon storage capacity (t C ha^{-1}) of young to middle-aged stands in relation to increasing frequency of storms (number of storm events ha^{-1} yr^{-1}) simulated by FORCLIM 2.6–4.0 for selected Swiss sites (Bern - Swiss Plateau, Bever - Subalpine Upper Engadine, Sion – Rhône Valley)

forests not affected by the storms themselves. More frequent disturbance by windthrow can also have long-term consequences. To quantitatively assess effects of changed storm frequency on species composition and C stocks, the FORCLIM model (Fischlin et al. 1995; Bugmann 1996) was used to simulate impacts on forest structure and maximum C-stocks. The most recent FORCLIM version 2.6–4.0 features (i) a refined response to climatic drivers, notably their variability, supporting the simulation of transient forest responses in a physically and ecologically consistent manner (based on work by Gyalistras 1997; Gyalistras and Fischlin 1999), (ii) an improved carbon cycle submodel simulating litter and soil carbon derived from Perruchoud et al. (1999), and (iii) a submodel simulating disturbances (fire, storms, avalanches, rockfall, landslides, and insect damage), derived from Mäder (1999). FORCLIM 2.6–4.0 was forced with several levels of storm frequencies, assuming an exponentially distributed storm severity up to those of ‘Vivian’ and ‘Lothar’. The frequency in terms of events per year and surface area was gradually increased from 0 up to a maximum of 20 times the historical base line estimate (Schmidtke 1997; Schelhaas et al. 2003; Jungo et al. 2002). The results shown in Figure 9 demonstrate that even a small increase in storm frequency can lead to significant impacts of considerable economic relevance in the short-term, similar to the ones caused by the storm ‘Lothar’, and a long-term reduction in C stock. Diversity might increase, as long as the frequency of disturbance remains at the moderate levels projected by the storm scenarios (not shown). At the sub-alpine site Bever in the Upper Engadine an increase by only 7% appears to be sufficient to significantly reduce forest C stocks over a 1000-year simulation period. This is in contrast to results obtained for a 40-year period with the forest scenario model MASSIMO and the soil C model YASSO showing that an increase in storm frequency by 30% has only a small impact on the national C budget of forests (Thürig et al. 2005). The discrepancy between the two studies suggests that longer time periods need to be considered to detect the effects of changes in storm frequency and possibly other disturbances on forests.

Storm damage to forests depends not only on storm frequency and intensity, but also on the topography of the site, the specific properties of the stand, and the site conditions (cf. Mayer 1989; BUWAL 2005). Based on the experience gained from the storms ‘Vivian’ and ‘Lothar’, monocultures of coniferous species are more sensitive than those of deciduous species (BUWAL 2005), and stands with a high fraction of coniferous trees and high average breast height-diameter seem to be most vulnerable (Dobbertin et al. 2002). Thus, from an economic point of view, windstorms are of particular importance because older trees with a higher value are preferentially affected, as opposed to the probability of damage from drought or snow, which is high for young stands and gradually decreases with age (Kuboyama and Oka 2000). The data for damage by ‘Lothar’ underline the importance of stand composition in determining storm risks, which can be addressed by silvicultural measures (BUWAL 2005). Finally, the chemical environment influences the risk of windthrow (BUWAL 2005). Data for beech (*Fagus sylvatica* L.) and spruce (*Picea abies* L.) suggested that uprooting after ‘Lothar’ was inversely related to soil base saturation. In beech stands, the latter was positively related to nitrogen concentrations in foliage, thus indicating that the sensitivity of trees to storm could be highest at sites with acid soils and receiving high atmospheric nitrogen inputs (Braun et al. 2003).

4.2 Heat waves and droughts

The immediate response of trees to dry spells such as the one in 2003 can be documented by site-specific physiological measurements. A survey of net ecosystem C fluxes revealed that the extreme conditions pushed many forest ecosystems from being a net C sink to being a net C source (Ciais et al. 2005). Thus, heat waves can affect the regional terrestrial C balance and, through an increase in net CO_2 emission, cause a biological feedback to the climate system (e.g., Fischlin 1997). However, data from a 100-year-old mixed deciduous forest near Basel suggested that several tree species investigated, particularly oak (*Quercus petraea* (Matt.) Liebl.), did not experience severe water stress at this site in 2003 (Leuzinger et al. 2005). Although mean stomatal conductance and rates of maximum net photosynthesis decreased considerably in mid-August across all species, daily peak values of sap flow remained surprisingly constant in oak over the whole period, and it decreased to only about half of the early summer maxima in beech and European hornbeam (*Carpinus betulus* L). Elevated CO_2 had only a minor effect on the water status of the trees. Compared to the previous year, leaf longevity was greater in 2003, but the seasonal increase in stem basal area reached only about 75%. Consequently, more frequent exceptionally dry summers could have a more serious impact at this site than a single event and would give oak trees a competitive advantage.

In the long run, a change in the frequency of hot any dry years could affect tree species composition and diversity in Swiss forests (Keller et al. 2002). Simulations using FORCLIM 2.6–4.0 demonstrated significant changes in species dominance over time in a mixed deciduous forest on the Swiss Plateau currently dominated by European beech (Figure 10). The climate change scenarios in this application implied that by ~2080 every second summer would be as warm or warmer than in 2003 (Schär et al. 2004). Not surprisingly, the forest established under the new climate is typical of xeric conditions with the dominance of more drought-tolerant species such as oak (*Q. robur* L.) and chestnut (*Castanea sativa* MILL.). This change in species dominance was more pronounced than found earlier in simulations with scenarios characterized by less frequent extremes (Fischlin and Gyalistras 1997; Lischke et al. 1998), thus suggesting that more frequent extremes accelerates species replacement. The scenario also caused a transitory loss of C towards the end of this century, which was only fully compensated for by the end of the 23rd century.

These simulation results are corroborated by recent experimental and observational evidence. Drought stress is thought to be a frequent cause for tree defoliation, but effects of dry years on forests are lagged. Consequences of an occasional extremely warm and dry year

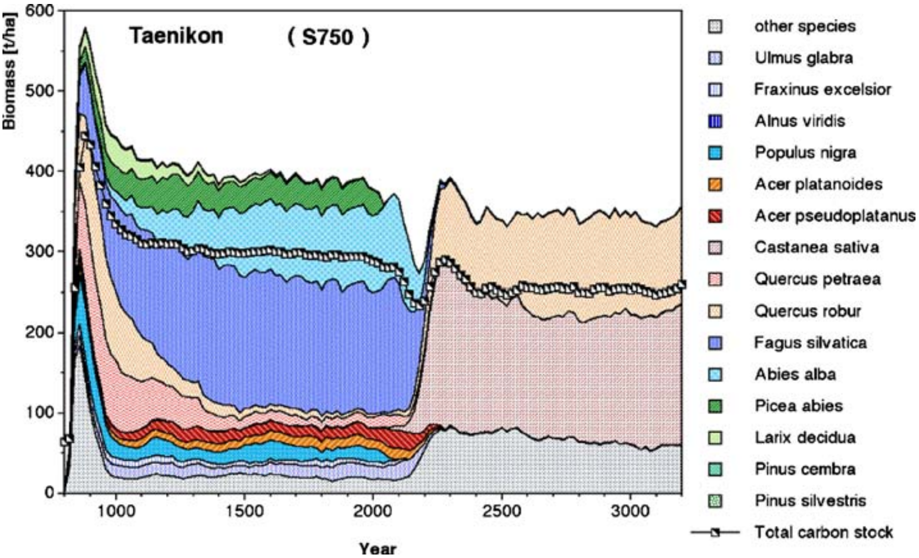

Fig. 10 Long-term changes in tree species composition (t biomass ha^{-1}) of a deciduous forest dominated by European beech in response to climate change. Transient simulations with ForClim 2.6–4.0 for the mesic site Taenikon on the Swiss Plateau. The initial start-up phase begins in year 800 under base-line climate (Gyalistras 2003). Superimposed is a climate change sensitivity derived by statistical downscaling from a HADCM3 (SRES A2) run for the means. Estimates of changes in the variances of temperature and precipitation for present (1970–2000) and future (2070–2100) were derived from Schär et al. (2004). The S750 stabilization scenario (Houghton et al. 1995) was used to compute the actual transient climate change scenario by the method of Gyalistras and Fischlin (1999).

can usually be observed only during the subsequent year(s). For instance, crown condition inventories in Bavaria revealed increased needle and leaf loss across all species in 2004 as a result of the 2003 summer (LWF 2004); beech and oak (*Q. spp.*) were most strongly affected, while deep-rooting species such as silver fir (*Abies alba* Mill.) were less affected. Both broadleaved and coniferous species reacted to the conditions of the previous year with sprouting in 2004. A statistical analysis of temporal relations across Swiss forests by Zierl (2004) revealed significant impacts of drought on crown conditions for all deciduous tree species under consideration, i.e. beech, fir, European ash (*Fraxinus excelsior* L.), and oak, but only weak correlations were found for spruce and no relations were found for fir and Scots pine (*Pinus sylvestris* L.). In the largest inner-alpine valley of Switzerland (Valais), defoliation and mortality in Scots pine observed in each year during 1996–2002 was related to the precipitation deficit and hot conditions of the previous year (Rebetez and Dobbertin 2004). These authors suggested that an increase in the frequency of warm years could be critical for ecosystems with Scots pine as the dominant species. Warm and dry years may also favor insect calamities of economic relevance (e.g., bark beetle infestations; Wermelinger and Seifert 1999) in areas with increased amounts of dead or damaged wood. Finally, lack of precipitation together with high temperatures alters the disturbance regime by forest fires. Today, forest fires are already a serious threat in southern Switzerland, and for this region Reinhard et al. (2005) reported an increasing trend over the past 32 years in most climatic variables favoring forest fires; with increasing drought frequency, this problem may spread to regions north of the Alps.

5 Discussion and conclusions

Extreme events, i.e., extremely rare climatic events under current conditions, have potentially great impacts on ecological, economic and social systems, with a strong interdependence between them. In many regions of Europe, ecosystems play an important role in providing goods and services to the society; in Switzerland, agricultural production systems cover about 60% of domestic consumption, and the value of annual production is roughly 7 billion Swiss Francs. Together with forests, agroecosystems improve the livelihood and aesthetic value of rural landscapes. Forests cover about 28% of the land surface and provide 4.5 million m^3 of timber annually, and the forestry sector offers about 85,000 jobs, equivalent to 3.1% of the total workforce. In pre-alpine and alpine regions forests are of vital relevance by protecting settlements, roads and other infrastructures from avalanches and landslides. Moreover, forests have a high ecological conservation value, similar to semi-natural grasslands and wetlands, since they harbor about 50% of all species occurring in Switzerland, they play an important role in the cycling of water and nutrients at the watershed level, and they act as large-scale C sinks. Finally, a recent study estimated the economic value of Swiss forests for recreational uses alone at 10.5 billion Swiss Francs per year (about 2.4% of GDP, Ott and Baur 2005). Hence, negative effects of climate extremes on agriculture and forests are relevant, and increasing frequencies would create considerable strain on the society to maintain their goods and services. Effects of past isolated extreme events on Swiss agriculture and forests are well documented, but the analysis presented here shows that there is growing evidence for an increasing likelihood of climatic extremes. Effects of individual events could overlap with the recovery process from previous events, thus mutually augmenting the detrimental impacts upon the system concerned.

The assessment of climate risks depends on both the skills to simulate these events at various scales, and the understanding of the responses of the target system. One of the major advances made recently in projecting climate risks concerns the improvement in linking the larger-scale climate simulation to small-scale effects. Extreme events are often related to large-scale synoptic conditions, but the scales at which impacts occur can vary from local to regional. For instance, large-scale continental storms can generate strong winds and gusts, which are most damaging at very small scales of a few km^2 down to a few hectares. Thus, physically consistent downscaling is an important and challenging task, but it is highly relevant to assess future climate risks at the scales at which societal responses take place. This is of particular relevance in regions with a complex terrain such as that of the European Alps. The work summarized here documents the advancement in these skills, and the progress made in linking extremes to global change scenarios. Smaller-scale patterns still vary considerably between RCMs, but current RCM integrations provide quantitative scenarios of the regional future change, which are valuable for examining possible impact mechanisms, until more formal regional probabilistic scenarios become available.

The review shows that already during the 20th century, the likelihood for extremes has increased. Instrumental data reveal remarkable changes in precipitation characteristics in central Europe, which are difficult to explain by changes in the large-scale circulation alone (Widmann and Schär 1997; Hanssen-Bauer and Forland 2000; Schmith 2000). Clearly, the uncertainty attached to future scenarios of precipitation extremes remains large, and sufficiently long RCM simulations exist for only a small set of GCM boundary conditions, but there is considerable agreement for an increase in wintertime precipitation extremes, and physical arguments have been advanced to explain this tendency (e.g., Trenberth 1999). Episodes that inflict catastrophic flooding may increase with climate warming, in spite of less summertime precipitation (Christensen and Christensen 2002; Allen and Ingram 2002).

For agriculture, the projected increase in the frequency of heavy rainfall during winter and spring may cause a considerable loss of topsoil from croplands, particularly in areas with sloped terrain such as the pre-alpine and alpine regions of Switzerland, and in the presence of inappropriate cultivation practices, soil compaction, overgrazing, or construction (Grimm et al. 2002). This type of risk can be mitigated effectively by taking measures to cover and protect the soil surface, for instance by avoiding fallow periods, intercropping, or application of conservation tillage or no-till. Such measures can be implemented quickly and at low costs. In addition, larger amounts of winter precipitation could cause excess soil moisture during the early part of the growing season, which could delay fieldwork, as suggested by Rosenzweig et al. (2002); however, the results for Switzerland suggest that related risks are reduced to some extent by more rapid soil drying in the warmer climate. Hence, in this region and in other pre-alpine and alpine areas of Europe, the potential of agriculture may be sufficiently large to cope with the exposure of cropland to more frequent intense precipitation.

The more serious threat relates to the projected scarcity of soil water during the growing season (Jasper et al. 2004). Crops currently cultivated in Switzerland have been selected for cultivation in temperate, humid conditions. Thus, their sensitivity to precipitation deficits during the main growing season is high, as demonstrated by the yield losses in the most affected areas in 2003. Currently, in the absence of any insurance system for crop losses due to drought, measures taken by the Federal administration are necessary to alleviate economic losses of individual farmers. However, the consequences of more frequent situations like in 2003 would weigh heavily on agriculture. Increasing return times of droughts could exceed the financial capacities for government interventions. Consequently, adaptive measures would be necessary to avoid or to cope with drought risks, including altered crop and cultivar selection, improved nutrient and water management at the local and regional scale, or increased storage of fodder. However, such measures would require long-term planning and investments (e.g., irrigation equipment).

Main effects of climate extremes on pre-alpine and alpine forests include short-term loss of timber due to windstorms, and drought effects on tree vitality, as well as long-term effects on services such as biodiversity, C sequestration, soil and water conservation, and protection. Increasing storm frequency would have immediate economic implications for the forest owners and the lumber industry, as observed after ‘Lothar’ in 1999, but the effects on many forests may take place during century-long phases of drastic changes before new and more stable phases can be reached again. More frequent periods of droughts would affect forest health and succession, as already observed in the dry Valais, and long-term simulations show how species replacement could alter several services. Environmental stresses such as drought are supposed to be predisposing mechanisms of forest decline by making trees more vulnerable to damaging agents such as fungal disease insects (cf. Zierl 2004). A concurrent increase in storm frequency and dry spells could accelerate species replacement taking place in response to a gradual increase in mean temperature. Thus, suitable management of forests over the typical time horizon of decades could become a crucial challenge. It may require measures such as selective tree harvesting and repeated re-planting of sensitive seedlings, regardless of how well-adapted they might be as adults under the then altered climatic conditions, or reforestation of stands or even entire forest districts. To cope with increased risks of windthrow, management of the species composition of forest stands, proper thinning, and maintenance of optimal soil physical and chemical properties would also be essential measures (BUWAL 2005).

In conclusion, projections emerging from the improved understanding of the evolution of the global climate system and of the resulting regional aspects show that what lies ahead may well exceed past risks. There is now better evidence for an increasing likelihood of extreme precipitation and windstorms during winter, or heat waves during summer, with an improved spatial resolution of these projections for the Alpine region. More frequent extremes are likely to be at least as important, if not more important than a gradual change in climate, and this will affect both agricultural systems and forests in Switzerland. This poses great challenges for society, and the lessons learned for instance in 1999 (storm ‘Lothar’) or 2003 (heat wave) should be given appropriate scientific and political consideration, particularly in view of the long replacement times of infrastructure (∼30 yrs), land-use (∼decadal), or the long response times of forests growth (∼50–100 yrs), succession (several hundred yrs), or soil formation (many centuries). To ignore the change in climatic risks may turn out to be increasingly difficult, and adaptation to become more costly. To secure ecosystem goods and services within the limits set by biophysical, economic and societal constraints, shifts in agricultural and silvicultural practices, new insurance schemes, or investments in preventive measures will be necessary. However, some indirect consequences may remain for the socio-economic development, and for the esthetic value of the landscape in pre-alpine and alpine regions.

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References

Alexandersson H, Tuomenvirta H, Schmith T, Iden K (2000) Trends of storms in NW Europe derived from an updated pressure data set. Clim Res 14:71–73

Allen MR, Ingram WJ (2002) Constraints on future changes in climate and the hydrologic cycle. Nature 419:224–232

Beniston M (2004a) The 2003 heat wave in Europe. A shape of things to come? Geophys Res Lett 31:2022–2026

Beniston M (2004b) Climatic change and its impacts – an overview focusing on Switzerland. Advances in global change research, vol. 19. Kluwer Academic Publisher, Dordrecht, p 297

Beniston M, Stephenson DB (2004) Extreme climatic events and their evolution in a changing climatic conditions. Global Planet Change 44:1–9

Brassel P, Brändli UB (eds) (1999) Schweizerisches Landesforstinventar: Ergebnisse der Zweitaufnahme 1993–1995. Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft (WSL), Birmensdorf and Bundesamt für Umwelt, Wald und Landschaft, Bern, Verlag Haupt, Bern, Switzerland, p 442

Braun S, Schindler C, Volz R, Flückiger W (2003) Forest damages by the storm ‘Lothar’ in permanent observation plots in Switzerland: the significance of soil acidification and nitrogen deposition. Water Air Soil Pollut 142:327–340

Buffoni L, Maugeri M, Nanni T (1999) Precipitation in Italy from 1833 to 1996. Theor Appl Climatol 63:33–40

Bugmann HKM (1996) A simplified forest model to study species composition along climate gradients. Ecology 77:2055–2074

Bush, MB, Silman MR, Urrego DH (2004) 48,000 years of climate and forest change in a biodiversity hot spot. Science 303:827–829

BUWAL (2005) Lothar – Ursächliche Zusammenhänge und Risikoentwicklung. Umwelt-Materialien Nr. 184, Swiss Federal Office of Environment, Forest and Landscape, Bern, Switzerland, p 145

Calanca PL (2004) Interannual variability of summer mean soil moisture conditions in Switzerland during the 20th century: a look using a stochastic soil moisture model. Water Resour Res 40, doi: 10.1029/2004WR003254

Calanca PL (2006) Climate change and drought occurrence in the Alpine region: how severe are becoming extremes? Global Planetary Change, in press

Calanca PL, Fuhrer J (2005) Swiss agriculture in a changing climate: grassland production and its economic value. In: Haurie A, Viguier L (eds) The coupling of climate and economic dynamics – essays on integrated assessment, advances in global change research, vol. 22. Springer, Dordrecht, NL, pp 341–353

Calanca PL, Roesch A, Jasper K, Wild M (2006) Global warming and the summertime evapotranspiration regime of the Alpine region. Clim Change, (this issue) DOI 10.1007/s10584-006-9103-9

Carnell RE, Senior, CA (1998) Changes in mid-latitude variability due to increasing greenhouse gases and sulphate aerosols. Clim Dyn 14:369–383

Caya D, Laprise R (1999) A semi-implicit semi Lagrangian regional climate model: the Canadian RCM. Mon. Weather Rev 127:341–362

Christensen JH, Carter TR, Giorgi F (2002) PRUDENCE employs new methods to assess European climate change. EOS 83:147

Christensen JH, Christensen OB (2003) Severe summertime flooding in Europe. Nature 421:805–806

Christensen OB, Christensen JH, Machenhauer B, Botzet, M (1998) Very high-resolution regional climate simulations over Scandinavia – present climate. J Clim 11:3204–3229

Ciais Ph, Ciais Reichstein M, Viovy N, Granier A Ogée J, Allard V, Buchmann N, Aubinet M, Bernhofer Chr, Carrara A, Chevallier F, De Noblet D, Friend A, Friedlingstein P, Grünwald T, Heinesch B, Keronen P, Knohl A, Krinner G, Loustau D, Manca G, Matteucci G, Miglietta F, Ourcival JM, Pilegaard K, Rambal S, Seufert G, Soussana JF, Sanz MJ, Schulze ED Vesala T, Valentini R (2005) European-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437:529–533

Dale, VH, Joyce LA, McNulty S, Neilson RP, Ayres MP, Flannigan MD, Hanson PJ, Irland LC, Lugo AE, Peterson CJ, Simberloff D, Swanson FJ, Stocks BJ, Wotton BM (2001) Climate change and forest disturbances. Bioscience 51:723–734

Dobbertin M, Seifert H, Schwyzer A (2002) Standort und Bestandesaufbau waren mitentscheidend für das Ausmass der Sturmschäden. Wald und Holz 83:39–42

Dorland C, Tol RSJ, Palutikov JP (1999) Vulnerability of the Netherlands and Northwest Europe to storm damage under climate change. Clim Change 43:513–535

Durman CF, Gregory JM, Hassell DC, Jones RG, Murphy JM (2001) A comparison of extreme European daily precipitation simulated by a global and a regional climate model for present and future climates. Quat J Roy Meteorol Soc 127:1005–1015

Esteban-Parra MJ, Rodrigo FS, Castro-Diez Y (1998) Spatial and temporal patterns of precipitation in Spain for the period 1880–1992. Int J Climatol 18:1557–1574

FAT (1996) Wetterrisiko und verfügbare Feldarbeitstage in der Schweiz. FAT-Berichte 490: Swiss Federal Research Station for Agricultural Economy and Engineering, Tänikon, Switzerland, p 5

Fischlin A (1997) Biospheric feedbacks in the global climate system. J Environ Qual 26:2

Fischlin A, Bugmann H, Gyalistras D (1995) Sensitivity of a forest ecosystem model to climate parameterization schemes. Environ Pollut 87:267–282

Fischlin A, Gyalistras D (1997) Assessing impacts of climatic change on forests in the Alps. Global Ecol Biogeogr Lett 6:19–37

Frei C, Christensen JH, Déqué M, Jacob D, Jones RG, Vidale PL (2003) Daily precipitation statistics in regional climate models: evaluation and intercomparison for the European Alps. J Geophys Res 108(D3):4124, doi: 10.1029/2002JD002287

Frei C, Davies HC, Gurtz J, Schär C (2001) Climate dynamics and extreme precipitation and flood events in Central Europe. Integr Assessm 1:281–299

Frei C, Schär C (1998) A precipitation climatology of the Alps from high-resolution rain-gauge observations. Int J Climatol 18:873–900

Frei C, Schär C (2001) Detection probability of trends in rare events: theory and application to heavy precipitation in the Alpine region. J Clim 14:1568–1584

Frei C, Schöll R, Schmidli J, Fukutome S, Vidale PL (2006) Future change of precipitation extremes in Europe: an intercomparison of scenarios from regional climate models. J Geophys Res 111, D06105, doi: 10.1029/2005JD005965

Giorgi F, Hewitson B, et al. (2001) Regional climate information – evaluation and projections. In: Climate change 2001. The scientific basis. The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), pp 581–638

Goyette S, Beniston M, Caya D, Laprise JPR, Jungo P (2001) Numerical investigation of an extreme storm with the Canadian Regional Climate Model: the case study of windstorm 'VIVIAN', Switzerland, February 27, 1990. Clim Dyn 18:145–178

Goyette S, Brasseur O, Beniston M (2003) Application of a new wind gust parameterisation. Multi-scale case studies performed with the Canadian RCM. J Geophys Res 108:4374–4390

Grebner D, Roesch T (1999) Zusammenhänge und Beurteilung der Hochwasserperiode in der Schweiz vom 11. bis 15. Mai 1999. Wasser, Energie, Luft 5/6:127–132

Grime JP, Willis AJ, Hunt R, Dunnett NP (1994) Climate-vegetation relationships in the Bibury road verge experiments. In: Leigh RA, Johnston AE (eds) Long-term experiments in agricultural and ecological sciences. CAB International, Wallingford, UK, pp 271–285

Grimm M, Jones RJA, Montanarella L (2002) Soil erosion risk in Europe. Report EUR 19939 EN, Office for Official Publications of the European Communities. Luxemburg, p 40

Gyalistras D (1997) Projecting scenarios of climatic change and future weather for ecosystem models: derivation of methods and their application to forests in the Alps. PhD Dissertation ETH No. 12065, Swiss Federal Institute of Technology: Zürich, Switzerland, p 103

Gyalistras D (2003) Development and validation of a high-resolution monthly gridded temperature and precipitation data set for Switzerland (1951–2000). Clim Res 25:55–83

Gyalistras D, Fischlin A (1999) Towards a general method to construct regional climatic scenarios for model-based impacts assessments. Petermanns Geogr Mitt 143:251–264

Gyalistras D, Fischlin A, Riedo M (1997) Herleitung stündlicher Wetterszenarien unter zukünftigen Klimabedingungen. In: Fuhrer J (ed), Klimaänderung und Grünland, Vdf Hochschulverlag AG and der ETH Zurich, Zurich, pp 207–276

Gyalistras D, von Storch H, Fischlin A, Beniston M (1994) Linking GCM-simulated climatic changes to ecosystem models: case studies of statistical downscaling in the Alps. Clim Res 4:167–189

Hall NMJ, Hoskins BJP, Valdes J, Senior CA (1994) Storm tracks in a high-resolution GCM with doubled carbon dioxide. Quart J Roy Meteor Soc 120:1209–1230

Hanssen-Bauer I, Forland EJ (2000) Long-term trends in precipitation and temperature in the Norwegian Arctic: can they be explained by changes in atmospheric circulation patterns? Clim Res 10:143–153

Hanson CE, Palutikov JP, Davies TD (2004) Objective cyclone climatologies of the North Atlantic-a comparison between the ECMWF and NCEP reanalyses. Clim Dyn 22:757–769

Haylock MR, Goodess CM (2004) Interannual variability of extreme European winter rainfall and links with mean large-scale circulation. Int J Climatol 24:759–776

Heino R, Brázdil R, FØrland E, Tuomenvirta H, Alexandersson H, Beniston M, Held C, IM (1999) Large-scale dynamics and global warming. Bull Amer Meteor Soc 74:228–241

Houghton JT, Meira Filho LG, Bruce J, Lee H, Callander BA, Haites E, Harris N, Maskell K (eds) (1995) Climate change 1994: Radiative forcing of climate change and an evaluation of the IPCC IS92 emission scenarios. Reports of Working Groups I and III of the Intergovernmental Panel on Climate Change (IPCC), forming part of the IPPC Special Report to the first session of the Conference of the Parties to the UN Framework Convention on Climate Change. Cambridge University Press, Cambridge, p 339

Huntingford C, Jones RG, Prudhomme C, Lamb R, Gash HHC, Jones DA (2003) Regional climate-model predictions of extreme rainfall for a changing climate. Quart J Roy Meteorol Soc 129:1607–1621

IPCC (2001) In: Houghton JT, Ding DJ, Griggs DJ, Noguer M, van der Linden PJ, Xiasou D (eds), Climate change 2001. The scientific basis. Cambridge University Press, Cambridge and New York, p 944

Jasper K, Calanca PL, Gyalistras D, Fuhrer J (2004) Differential impacts of climate change on the hydrology of two alpine river basis. Clim Res 26:113–129

Jasper K, Calanca PL, Fuhrer J (2006) Changes in summertime soil water patterns in complex terrain due to climatic change. J Hydrology 327:550–563

Jones R, Murphy J Hassell D, Taylor R (2001) Ensemble mean changes in a simulation of the European climate of 2071–2100, using the new Hadley Centre regional climate modelling system HadAM3H/HadRM3H. Hadley Centre Report 2001, available from www.prudence.dmi.dk (accessed 10/06/2005)

Jungo P, Goyette S, Beniston M (2002) Daily wind gust speed probabilities over Switzerland according to three types of synoptic circulation. Int J Climatol 22:485–499

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Leetmaa A, Reynolds B, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Jenne Roy, Joseph Dennis (1996) The NCEP/NCAR 40-year reanalysis project. Bull Am Meteorol Soc 77:437–472

Keller F, Fuhrer J (2004) Landwirtschaft im Hitzesommer 2003. Swiss Agric Res 11:403–410

Keller F, Lischke H, Mathis T, Möhl A, Wick L, Ammann B, Kienast F (2002) Effects of climate, fire, and humans on forest dynamics: forest simulations compared to the paleological record. Ecol Model 152:109–127

Klein Tank AMG, Können GP (2003) Trends in indices of daily temperature and precipitation extremes in Europe, 1946–1999. J Clim 16:3665–3680

Kleinn J (2002) 'Climate change and runoff statistics in the Rhine basin: a process study with a coupled climate-runoff model', Doctor of Natural Sciences Thesis Dissertation No. 14663, Swiss Federal Institute of Technology, Zurich, p 114

Kleinn J, Frei C, Gurtz J, Lüthi D, Vidale PL, Schär C (2005) Hydrological simulations in the Rhine basin, driven by a regional climate model. J Geophys Res 110:D04102, doi: 10.1029/2004JD005143

Knippertz P, Ulbrich U, Speth P (2000) Changing cyclones and surface wind speeds over the North Atlantic and Europe in a transient GHG experiment. Clim Res 15:109–122

Kuboyama H, Oka H (2000) Climate risks and age-related damage probabilities – effects on the economically optimal rotation length for forest stand management in Japan. Silva Fenn 34:155–166

Lambert S, Sheng J, Boyle J (2002) Winter cyclone frequencies in thirteen models participating in the Atmospheric Model Intercomparison Project (AMIP 1). Clim Dyn 19:1–16

Leckebusch GC, Ulbrich U (2004) On the relationship between cyclones and extreme windstorm events over Europe under climate change. Global Planet Change 44:181–193

Leuzinger S, Zotz G, Asshoff R, Körner C (2005) Responses of deciduous forest trees to severe drought in Central Europe. Tree Physiol 25:641–650

Lischke H, Guisan A, Fischlin A, Williams J, Bugmann H (1998) Vegetation responses to climate change in the Alps: modeling studies. In: Cebon P, Dahinden U, Davies HC, Imboden DM, Jäger CC (eds), Views from the Alps: regional perspectives on climate change. MIT Press, Boston, Massachusetts, pp 309–350

Lüscher A, Fuhrer J, Newton PCD (2005) Global atmospheric change and its effect on managed grassland systems. In: McGolloway DC (ed), Grassland – a global resource. Wageningen Academic Publishers, pp 251–264

LWF (2004) Waldzustandsbericht 2004. Bayrisches Staatsministerium für Landwirtschaft und Forsten. http://www.lwf.bayern.de/ (accessed 10/06/2005)

Mäder J (1999) Effekte externer Störungen auf den Sukzessionslauf subalpiner Wälder: Modellierung und Analyse. Master of Environmental Sciences Thesis, Institute of Terrestrial Ecology, Swiss Federal Institute of Technology, Zurich, p 62

Mayer H (1989) Windthrow. Phil Trans R Soc Lond B 324:267–181

McCabe G J, Clark MP, Serreze M (2001) Trends in northern hemisphere surface cyclone frequency and intensity. J Clim 14:2763–2768

McCallum E, Norris WJT (1990) The storms of January and February 1990. Meteorol Mag 119:201–210

Mearns LO, Giorgi F, Whetton P, Pabon D, Hulme M, Lal M (2003) Guidelines for use of climate scenarios developed from Regional Climate Model experiments. Technical Report. The IPCC Data Distribution Centre, Norwich, UK, p 38

Meehl GA, Karl T, Easterling DR, Changnon S, Pielke R, Changnon D, Evans J, Groisman PY, Knutson TR, Kunkel KE, Mearns LO, Parmesan C, Pulwarty R, Root T, Sylves RT, Whetton P, Zwiers F (2000) An introduction to trends in extreme weather and climate events: observations, socioeconomic impacts, terrestrial ecological impacts, and model projections. Bull Am Soc Meteorol 81:413–416

Nakićenović N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grübler A, Jung TY, Kram T, La Rovere EL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Raihi K, Roehrl A, Rogner HH, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, van Rooijen S, Victor N, Dadi Z (2000) IPCC special report on emissions scenarios. Cambridge University Press, Cambridge and New York, p 599

Noguer M, Jones RG, Murphy JM (1998) Sources of systematic errors in the climatology of a regional climate model over Europe. Clim Dyn 14:691–712

OcCC (2003) Extremereignisse und Klimaänderung, Organe Consultatif sur lse Changements climatiques, Bern, Switzerland, p 88

Osborn TJ, Hulme M, Jones PD, TA Basnett (2000) Observed trends in the daily intensity of United Kingdom precipitation. Int J Climatol 20:347–364

Ott W, Baur M (2005) Der monetäre Erholungswert des Waldes, Umwelt-Materialien Nr. 193, Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern, Switzerland, p 68

Pal JS, Giorgi F, Bi X (2004) Consistency of recent European summer precipitation trends and extremes with future regional climate projections. Geophys Res Lett 31:L13202, doi: 10.1029/2004GL019836

Palutikof JP, Brabson BB, Lister DH, Adcock ST (1999) A review of methods to calculate extreme wind speeds. Meteor Appl 6:119–132

Parmesan C, Root TL, Willing MR (2000) Impacts of extreme weather and climate on terrestrial biota. Bull Am Soc Meteorol 81:443–449

Parry ML (ed) (2000) Assessment of potential effects and adaptation for climate change in Europe: the Europe ACACIA project. Jackson Environment Institute, University of East Anglia, Norwich, UK, p 320

Perruchoud D, Joos F, Fischlin A, Hajdas I, Bonani G (1999) Evaluating time scales of carbon turnover in temperate forest soils with radiocarbon data. Global Biogeochem Cycle 13:555–573

Pfister C (1999) Wetternachhersage. 500 Jahre Klimavariationen und Naturkatastrophen 1496–1995. Verlag Paul Haupt, Bern, p 304

Pfister C (2004) Von Goldau nach Gondo. Naturkatastrophen als identitätsstiftende Ereignisse in der Schweiz des 19. Jahrhunderts. In: Pfister C, Summermatter S (eds) Katastrophen und ihre Bewältigung. Perspektiven und Positionen. Paul Haupt, Bern, Switzerland, pp 53–78

Pope DV, Gallani M, Rowntree R, Stratton A (2000) The impact of new physical parameterizations in the Hadley Centre climate model: HadAM3. Clim Dyn 16:123–146

Pruski FF, Nearing MA (2002) Runoff and soil-loss responses to changes in precipitation: a computer simulation study. J Soil Water Conserv 57:7–16

Räisänen J, Hannson U, Ullerstig A, Döscher R, Graham LP, Jones C, Meier HEM, Samuelsson P, Willén U (2004) European climate in the late twenty-first century: regional simulations with two global models and two forcing scenarios. Clim Dyn 22:13–31

Rebetez M, Dobberin M (2004) Climate change may already threaten Scots pine stands in the Swiss Alps. Theor Appl Climatol 79:1–9

Reinhard M, Rebetez M, Schlaepfer R (2005) Recent climate change: rethinking drought in the context of forest fire research in Ticino, South of Switzerland. Theor Appl Climatol, DOI 10.1007/s00704–005-0123-6

Riedo M, Gyalistras D, Fischlin A, Fuhrer J (1999) Using an ecosystem model linked to GCM-derived local weather scenarios to analyze effects of climate change and elevated CO_2 on dry matter production and partitioning, and water use in temperate managed grasslands. Global Change Biol 5:213–223

Rosenzweig C, Tubiello FN, Goldberg R, Mills E, Bloomfield J (2002) Increased crop damage in the US from excess precipitation under climate change. Global Environ Change 12:197–202

Schär C, Vidale PL, 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

Schelhaas MJ, Nabuurs GJ, Schuck A (2003) Natural disturbances in the European forests in the 19th and 20th centuries. Global Change Biol 9:1620–1633

Schmidli J, Frei C (2005) Trends of heavy precipitation and wet and dry spells in Switzerland during the 20th century. Int J Climatol 25:753–771

Schmidli J, Schmutz C, Frei C, Wanner H, Schär C (2002) Mesoscale precipitation in the Alps during the 20th century. Int J Climatol 22:1049–1074

Schmidtke H, Scherrer HU (1997) Sturmschäden im Wald. vdf Hochschulverlag AG an der ETH Zürich, Zurich, p 38

Schmith T (2000) Global warming signature in observed winter precipitation in Northwestern Europe. Clim Res 17:263–274

Schmith T, Kaas E, Li T-S (1998) Northeast Atlantic winter storminess 1875–1995 re-analysed. Clim Dyn 14:529–536

Schönenberger W (2001) Trends in mountain forest management in Switzerland. Schweiz Z Forstwes 152:152–156

Schönwiese C-DJ, Rapp T Fuchs, M Denhard (1994) Observed climate trends in Europe 1891–1990. Meteorol Zeitschrift N.F.3:22–28

Schorer M (1992) Extreme Trockensommer in der Schweiz und ihre Folgen für Natur und Wirtschaft. Geographica Bernensia G 40, Institute of Geography, University of Bern, p 192

Schubert M, Perlwitz J, Blender R, Fraedrich K, Lunkeit F (1998) North Atlantic cyclones in CO_2-induced warm climate simulations: frequency, intensity, and tracks. Clim Dyn 14:827–837

Schüepp M, Schiesser HH, Huntrieser H, Scherrer HU, Schmidtke H (1994) The winterstorm 'VIVIAN' of 27 February 1990: about the meteorological development, wind forces and damage situation in the forests of Switzerland. Theor Appl Climatol 49:183–200

Schulla J (1997) Hydrologische Modellierung von Flussgebieten zur Abschätzung der Folgen von Klimaänderungen, Zürcher Geographische Schriften 69: Swiss Federal Institute of Technology (ETH), Zürich, p 187

Stampfli A, Zeiter M (2004) Plant regeneration directs changes in grassland composition after extreme drought: a 13-year study in southern Switzerland. J Ecol 92:568–576

Stephenson DB, Held IM (1993) GCM response of Northern winter stationary waves and storm tracks to increasing amounts of carbon dioxide. J Clim 6:1859–1870

Swiss Federal Office of Agriculture (2003) Agrarbericht 2003. Bern, Switzerland

Thürig E, Palosuo T, Bucher J, Kaufmann E (2005) The impact of windthrow on carbon sequestration in Switzerland: a model-based assessment. Forest Ecol Manage 210:337–350

Trenberth KE (1999) Conceptual framework for changes of extremes of the hydrological cycle with climate change. Clim Change 42:327–339

UN/ECE Timber Committee (2000) Forest Products Annual Market Review 1999–2000. Timber Bulletin, Vol. LIII, ECE/TIM/BULL/53/3, United Nations, Geneva, Switzerland, p 228

Valleron A-J, Boumendil A (2004) Epidemillionlogy and heat waves: analysis of the 2003 episode in France. Compt Rend Biol 327:1125–1141

Vidale PL, Lüthi D, Frei C, Seneviratne S, Schär C (2003) Predictability and uncertainty in a Regional Climate Model. J Geophys Res 108(D18):4586, doi: 10.1029/2002JD002810

WASA Group (1998) Changing waves and storms in the north-east Atlantic? Bull Am Meteorol Soc 79:741–760

Wermelinger B, Seifert M (1999) Temperature-dependent reproduction of the spruce bark beetle Ips typographus, and analysis of the potential population growth. Ecol Entomol 24:103–110

Wernli H, Dirren S, Liniger M A, Zillig M (2002) Dynamical aspects of the life cycle of the winter storm 'Lothar' (24–26 December 1999). Quart J Roy Meteor Soc 128:405–429

Widmer O, Said S, Miroir J, Duncan P, Gaillard JM, Klein F (2004) The effects of hurricane 'Lothar' on habitat use of roe deer. For Ecol Manage 195:237–242

Widmann M, Schär C (1997) A principal component and long-term trend analysis of daily precipitation in Switzerland. Int J Climatol 17:1333–1356

Wilby RL, Charles SP, Zorita E, Timbal B, Whetton P Mearns LO (2004) Guidelines for use of climate scenarios developed from statistical downscaling methods. Technical Report. The IPCC Data Distribution Centre, Norwich, UK, p 27

Wilby RL, Wigley TML, Conway D, Jones PD, Hewitson BC (1998) Statistical downscaling of general circulation model output: a comparison of methods. Water Resour Res 34:2995–3008

Williams AN, Nearing M, Habeck M, Southworth J, Pfeifer R, Doering OC, Lowenberg-Deboer J, Randolph JC, Mazzocc MA (2001) Global climate change: implications of extreme events for soil conservation strategies and crop production in the midwestern United States. In: Stott DE, Mohtar RH, Steinhardt GC (eds), Sustaining the global farm. Proceedings of the 10th international soil conservation organization meeting, Purdue University, West Lafayette, pp 509–515

WSL/BUWAL (1999) Lothar. Der Orkan (1999) Ereignisanalyse. Eidg. Forschungsanstalt WSL und Bundesamt für Umwelt, Wald und Landschaft BUWAL (Hrsg.), 2001, Birmensdorf, Bern, p 391

Xoplaki E, Gonzalez-Rouco JF, Luterbacher J Wanner H (2004) Wet season Mediterranean precipitation variability: influence of large-scale dynamics and trends. Clim Dyn 23:63–78

Xoplaki E, Luterbacher J, Burkard R, Patrikas I, Maheras P (2000) Connection between the large-scale 500 hPa geopotential height fields and precipitation over Greece during wintertime. Clim Res 14:129–146

Zhang X-C, Nearing MA, Garbrecht JD, Steiner JL (2004) Downscaling monthly forecasts to simulate impacts of climate change on soil erosion and wheat production. Soil Sci Soc Am J 68:1376–1385

Zwiers FW, Kharin VV (1998) Changes in the extremes of the climate simulated by CCC GCM2 under CO_2 doubling. J Clim 11:2200–2222

Zierl B (2004) A simulation study to analyse the relations between crown condition and drought in Switzerland. For Ecol Manage 188:25–38