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 aims of this paper are: (i) to describe observed trends and scenarios for summer heat waves, windstorms and heavy precipitation, based on resulting from simulations with global circulation models, regional climate models, and other downscaling procedures; (ii) to discuss potential impacts on agricultural systems and forests in Switzerland. Linking global change scenarios to extremes in the Alpine region provides improved, quantitative scenarios of future regional changes. Although small-scale patterns differ among models, regional climate-features are reasonably well captured. 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 of loss of topsoil due to erosion. In contrast, the risk for constraints in agricultural practice due to waterlogged soils may 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. This increases the risk of loss of yield and farmers' income, and of forage quality due to drought, as observed in 2003. In forests, the frequent occurrence of dry years accelerates the replacement of sensitive tree species, and reduces carbon stocks. Historically, storm damage was the major disturbance in forest, and the projected slight increase in the frequency of extreme storms by the end of the century increases the risk of windthrow. Data from storm 'Lothar' in 1999 revealed that the magnitude of windthrow is patchy and depends on exposure, stand composition and tree age, and soil characteristics. Large-scale windthrow can cause short-term reductions in market prices for timber, and long-term shifts in biodiversity, carbon stocks, or protection of slopes. Possible measures to maintain goods and services of agricultural and forest ecosystems are discussed, but is concluded that more frequent extremes are likely to have more severe consequences than progressive changes in means because effects of individual events could overlap with recovery from previous events. To effectively decrease the risk for social and economic impacts will require long-term adaptive strategies in agriculture and silviculture, investments into preventive measures, and new insurance concepts.

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 via impacts on the provision of goods and services to society by agricultural systems and forests (Figure 1). 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 focus here is on indirect impacts. Historical patterns recorded in Switzerland show that effects of heavy precipitation and drought on agricultural crop and forage production were most important (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 pre-alpine 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). Climate extremes can thus be considered as ecological disturbances 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 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). However, ecosystems and society will adapt to new climatic conditions, including the introduction of more effective measures to prevent effects of climate risks, or adaptation of ecosystems due to naturally occurring or man-made species replacement. Thus, increasing climate risks may be offset by decreasing ecological risks, provided that the adaptive capacity is sufficiently large.

The focus of this article is on climatological and ecological aspects, while socio-economic considerations and the issue of adaptation are out of scope. The aim is first to review information from the Swiss research program NCCR 'Climate' (i.e. Swiss National Center of Competence in Research 'Climate') and other sources regarding 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, and to discuss possible adjustments in ecosystem management.

1.2. CLIMATIC EXTREMES AND THEIR SIMULATION

There are different ways to define an 'extreme event'. 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. Events such as heavy precipitation or windstorms are often associated with atmospheric processes spanning a wide range of spatial scales, e.g. from a couple of meters to a few hundred kilometers, whereas general circulation models (GCM) are operated at a grid-spacing of 150-400 km; hence, extreme events obtain, at best, an approximate representation. Regional Climate Models (RCM) are needed to resolve the topographic and physiographic details combined with the relevant physical processes needed for the representation of such extreme events. Thus, RCMs are promising tools for the development of scenarios for extreme events at the sub-continental 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 2 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 Schär, 1998). Clearly, there are errors in magnitude and exact location of the pattern, but the 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 very fine spatial scales is required, and estimating the storm risk depends on the capability of reproducing local impacts of well-documented events. 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 operate at resolutions around 50 km, and cannot be used as such to infer the change in wind speed at the very fine scales. But numerical downscaling of re-analysis data using RCMs with a wind gust parameterization is able to reproduce the strong winds in a number of documented storms (e.g., Goyette et al., 2001; Goyette et al., 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 reasonably compared if a gust parameterization is implemented in the model. As an example, Figure 3 shows the maximum wind speed field simulated for February 27, 1990, on a 2-km horizontal grid mesh over Switzerland using multiple self-nesting methodologies after downscaling the NCEP-NCAR reanalysis 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 needed for impact assessments (e.g., Wilby et al. 1998; Gyalistras and Fischlin, 1999). If necessary, monthly scenarios can be converted to daily and hourly scenarios by stochastic weather generation (e.g., Gyalistras et al., 1994; Gyalistras et al., 1997; Zhang et al., 2004), and be used to force ecosystem models at a high spatial (e.g., 1x1 km) and temporal resolution (e.g., 1 hr) (Riedo et al., 1999; Gyalistras and Fischlin, 1999). Thus, with the improvement of RCMs in representing meso-scale details across complex topographies, the spatial and/or temporal resolution more closely matches the requirements of 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). In the northern and western parts of Switzerland these changes manifest 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 4 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. 2005) 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 HadAM3H 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 5 shows the relative change in precipitation statistics, and it reveals distinct regional and seasonal patterns of change. In winter, both rain-day frequency and intensity (Figs. 5a,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 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. 2005 for details) was undertaken for the HadRM3H integration and is displayed in Figure 6. 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 (Fig. 6a). 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 (Fig. 6b), 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 for 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 (Fig. 6f) and the 5-year return period rainfall (Fig. 6b). Yet the changes for extremes are at the border of statistical significance. Especially for summer, the magnitude of the change varies considerably between RCMs, but there is a coherent pattern with a more pronounced increase for extreme than for average events (Frei et al. 2005)

The results from the selected model integrations are very similar in terms of their seasonal distribution and their large-scale geographic pattern to results found in other RCM experiments (e.g., Durman et al., 2001; Christensen and Christensen, 2003; Räisänen et al., 2004; Frei et al., 2005). However, the magnitude of change and the smaller-scale pattern vary considerably between RCMs. Hence, although a general increase of winter-time heavy precipitation 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 even vary in the sign between different models (Räisänen et al., 2004; Frei et al., 2005).

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 it came at the end of a 40-year period during which summers were markedly cooler than the warm summers of the mid-20th century. Figure 7 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 (i.e., 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 8 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 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 high-light 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. Higher temperature stimulates evapotranspiration (see accompanying paper by Calanca et al., this volume); therefore, the trend in temperature, combined with the downward trend in summer precipitation, will significantly increase the frequency of drought.

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. In agreement, modeling studies have shown that in a warmer climate cyclone activity undergoes a shift towards the north and west over Europe and the NE Atlantic, which is accompanied by several weak cyclones and an increase of deep cyclones (Carnell and Senior, 1998; Knippertz et al., 2000); an increase of mean wind speeds and of wind speed extremes have also been diagnosed. A consensus among many studies has stated that it is possible though 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., 2xCO_2) and in the time-dependent greenhouse-gas-induced climate change simulations. The models selected to analyze the precipitation and temperature changes following simulations 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 tend to increase, and a tendency towards more extreme winds caused by deeper cyclones has been identified for several regions in

Western Europe. Moreover, analyses of the responses of RCMs driven by a series of GCM have shown that the changes in the mean wind field patterns are also in accordance with wind 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 heavy precipitation events in the Alpine region (see 2.1) may significantly increase the risk of suffering losses through 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 Mio Swiss Francs (value in 2000), or more than 50 victims (Pfister, 2004). From a study of more than a 1000 heavy precipitation events occurring in Switzerland between 1971-1996 (Röthlisberger, 1998) the estimate burden amounted to costs of material losses of 120 million Euro (about 183 million Swiss Francs) per year, and a total of 112 fatalities. 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 concerned public infrastructure such as river embankments, streets, bridges and railways. But heavy precipitation can also have important nonmonetary 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 leads to excess supply of soil water (i.e. 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, in particular in the pre-alpine Thur river basin (1700 km^2) with currently 55% of the surface being used for agriculture. This catchment has been 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 9), 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 drainage (Jasper et al., 2005). 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 2.2), i.e. with higher maximum temperatures, and thus more relevant for agricultural production. Besides direct effects of heat on plants, high temperatures stimulate potential evapotranspiration (Calanca et al., this volume), 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, 1992; Pfister, 1999). Drought in 1947 had the most devastating effect on Swiss agriculture because of its length, i.e. it lasted from July to October, and the large geographical extent. Wheat yields in NW 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 to Switzerland was limited because of the concurrent crop losses in neighboring Europe (Schorer, 1992). More recently, during the 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 Mio 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 may not have lasting economic consequences, in contrast to more frequent events.

To estimate future risks due to low SWC, Jasper et al. (2004) using an ensemble of climate scenarios downscaled from GCM outputs estimated that for both northern and southern Switzerland an increase in average annual ET by 9-23% in 2071-2100, relative to 1981-2000, with largest effects during the summer months (Calanca et al., this volume). Combined with the projected reduction in summer precipitation (Schmidli and Freu, 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, pers. communication).

Effects of more frequent droughts concern not only croplands, but also permanent grasslands, which in Switzerland cover around 75% of the agricultural land and sustain 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, i.e. similar to the conditions in 2003, the 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 if compared to the present value of grassland production. However, 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 drought may drive grassland vegetation changes with local colonization and extinction, as suggested earlier by Grime et al. (1994). Hence, increased frequency of drought is likely to have important economic effects in productive grassland systems, and more 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 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 windblows of over 20 million m^3; the damage sustained in 1990 and 1999 was 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 Swiss timber harvest (e.g. Dobbertin et al., 2002). Wind velocities near Geneva, on top of the Jura Mountains, exceeded 200 km h^{-1}, and in other areas of Switzerland winds were measured at 240 km h^{-1}. The total amount of damage to forests 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 spread, the abundance of windthrown timber affected the European market: roundwood markets were temporarily in chaos after the ‘Lothar’ event, with sharply falling in prices (UN/ECE Timber Committee, 2000). Similar to the 1990 storm’s effects on wood products markets, the fluctuations in supply and price were absorbed during primary processing and there were little distinguishable effects in sawnwood, panels and pulp production, prices or sales. 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 and 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), and as it dries, the windblown wood presents ideal conditions for massive fires and insect outbreaks, thus threatening forests not affected by the storms themselves. Moreover, more frequent disturbance by windthrow can 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) extended by a disturbance sub-model (Mäder, 1999) was forced with several levels of mean 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 10 demonstrate that even a small increase in storm frequency can lead to significant impacts of considerably economic relevance in the short-term, similar to the ones caused by the storm 'Lothar', and long-term changes, notably a reduction in carbon (C) stock. Diversity might actually gain (not shown), as long as the frequency of the disturbance remains at the moderate levels projected above by the storm scenarios. 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 much shorter 40-year period with the forest scenario model MASSIMO and the soil carbon model YASSO showing that a storm frequency increase of 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, specific properties of the stand, and on site conditions (*cf.* Mayer, 1989; BUWAL, 2005). Based on 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 and spruce suggested that uprooting after 'Lothar' was inversely related to soil base saturation, and 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 carbon 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 climate system (e.g., Fischlin, 1997). 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). Mean stomatal conductance and rates of maximum net photosynthesis decreased considerably in mid-August across all species, however, daily peak values of sap flow remained surprisingly constant in *Q. petraea* over the whole period, and it decreased to only about half of the early summer maxima in *Fagus sylvatica* L. and *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 than a single event and would give *Q. petraea* a competitive advantage.

In the long run, a change in the frequency of hot any dry years will likely affect tree species composition and diversity in Swiss forests, as projected by model simulations (Keller et al., 2002). Simulations of forest responses to physically consistent downscaled transient climate change (Gyalistras and Fischlin, 1999) using a new version of the ForClim model (Théato C. and Fischlin, A., personal communication) demonstrated significant changes in species dominance over time in a mixed deciduous forest on the Swiss Plateau currently dominated by European beech (Figure 11). The used climate change scenarios implied that by ~2080 every second summer would be as warm or warmer than that of 2003 (Schär et al., 2004). Not surprisingly, the forest established under the new climate is typical of xeric conditions with dominance of more drought-tolerant species such as *Q. robur* L. and *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, which project effects far into the future, 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 can usually be observed only during subsequent year(s). For instance, crown conditions inventories in Bavaria revealed increased needle and leaf loss across all species in 2004 as a result of the 2003 summer (LWF, 2004); beech (*F. sylvatica* L.) and oak (*Q. spec.*) were most strongly affected, while deep-rooting species such as silver fir (*Abies alba* MILL.) were les affected. Both broad-leaved and coniferous species reacted with sprouting in 2004 to the conditions of the previous year. 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 (*F. sylvatica*), fir (*A. spec.*), *Fraxinus excelsior* L., and oak (*Q. spec.*), but only weak correlations were found for the coniferous species *Picea abies* L. and no relations were found for *A. alba* and *P. sylvestris*. However, in the largest inner-alpine valley of Switzerland (Valais), defoliation and mortality in the sensitive tree species Scots pine (*P. sylvestris*) 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 esthetic 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 about 3.1% of to 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 act as large-scale carbon sink. Finally, a recent study estimated the economic value of Swiss forests for recreational uses alone to 10.5 billion Swiss Francs per year (≈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 ecosystem goods and services in a manner. Effects of past isolated extreme events on Swiss agriculture and forests are well documented. But the analysis presented here shows that there is growing and stronger evidence for an increasing likelihood of climatic extremes. Consequently, 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 meso-scale climate situation 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. This is of particular relevance in regions with a complex terrain such as that of the European Alps. For instance, large-scale continental storms can generate strong winds and gusts, which are most damaging only at very small scales of few km^2 down to few hectares. Thus, physically consistent downscaling is an important and challenging tasks, but highly relevant to assess future climate risks at the relevant scales for societal responses. The work summarized here documents the advancement in these skills, and the progress made in linking extremes to global change scenarios using numerical downscaling. 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 are becoming 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 of 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 on 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, by intercropping, or by 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). But, the results for Switzerland suggest that related risks are reduced to some extend 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 moist 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 a more frequent situations like in 2003, as projected by RCM runs for Switzerland (Schär et al., 2003), would weigh heavily on agriculture, and on many other strategic economic sectors, and increasing return times of drought could rapidly 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 costly 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 will 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 would alter many services. Environmental stresses such as drought are supposed to be a primary, predisposing mechanism of forest decline, making trees more vulnerable to damage agents such as fungal disease or defoliating and wood-boring insects (*cf.* Zierl, 2004). In combination, a concurrent increase in storm frequency and dry spells could accelerate the species changes taking place as a result of the slowly increasing mean temperature. Thus, within the phase of greatest changes, sustainable management of forests at the typical time horizon of decades would become a particular, yet crucial challenge, and it may require costly 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 entire stands or even of entire forest districts. To cope with increased risks of windthrow, sustainable management of the species composition of forest stands, proper thinning, and maintenance of optimal soil physical and chemical properties will be essential (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 the 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 it 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 policy 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) , and 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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Figure legends

Figure 1: Overview of the relationships between climate, ecosystems and society.

Figure 2: Climatology of heavy precipitation in the Alpine region, as simulated by a control experiment 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.

Figure 3: 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).

Figure 4: 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.)

Figure 5: 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).

Figure 6: 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.

Figure 7: Development of summer (JJA) daily maximum temperatures recorded at Basel, Switzerland, from 1901-2003.

Figure 8: 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.

Figure 9: 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., 2004). 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., 2004). Inset: Projected changes in mean monthly precipitation (P).

Figure 10: 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 the forest model ForClim for selected Swiss sites (Bern - Swiss Plateau, Bever - Subalpine Upper Engadine, Sion - Rhône Valley).

Figure 11: 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 (Théato, C. and Fischlin, A. personal communication) for the mesic site Taenikon on the Swiss Plateau. The initial start-up phase begins in year 800 under baseline 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).

Fig. 1

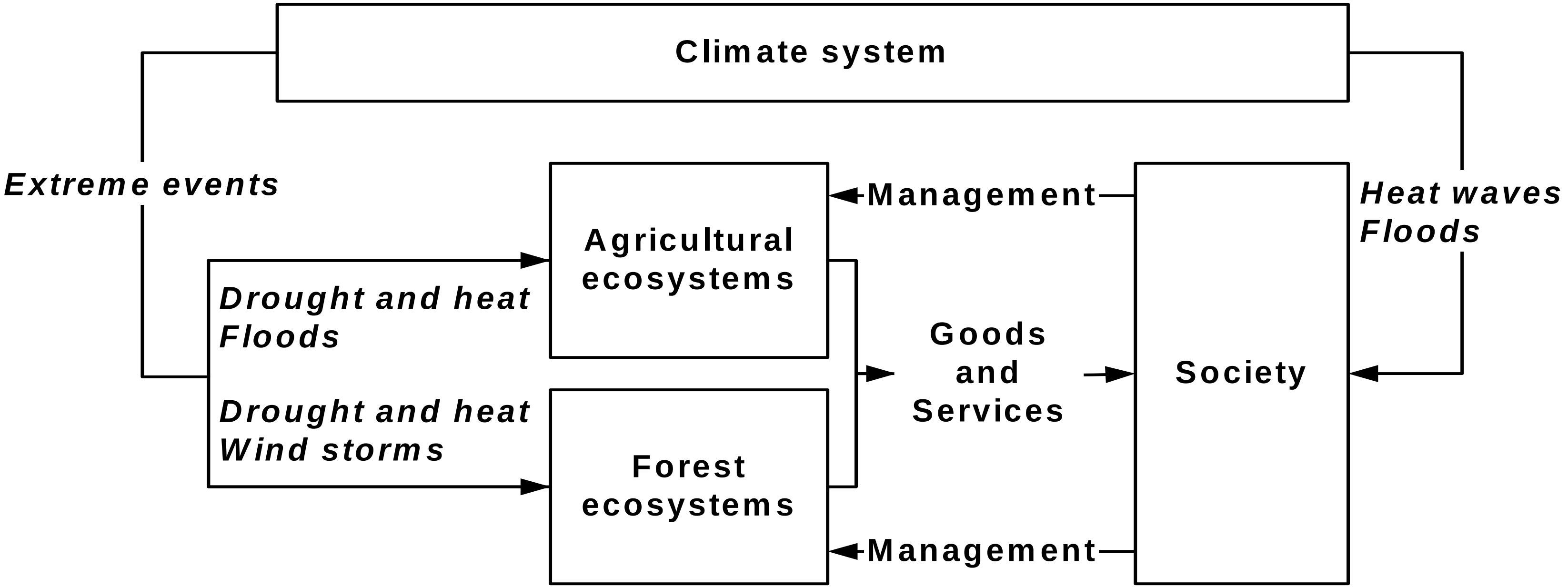
Climate system
Extreme events
Agricultural ecosystems
Management
Heat waves
Floods
Drought and heat
Floods
Goods and Services
Society
Drought and heat
Wind storms
Forest ecosystems
Management

Fig. 2

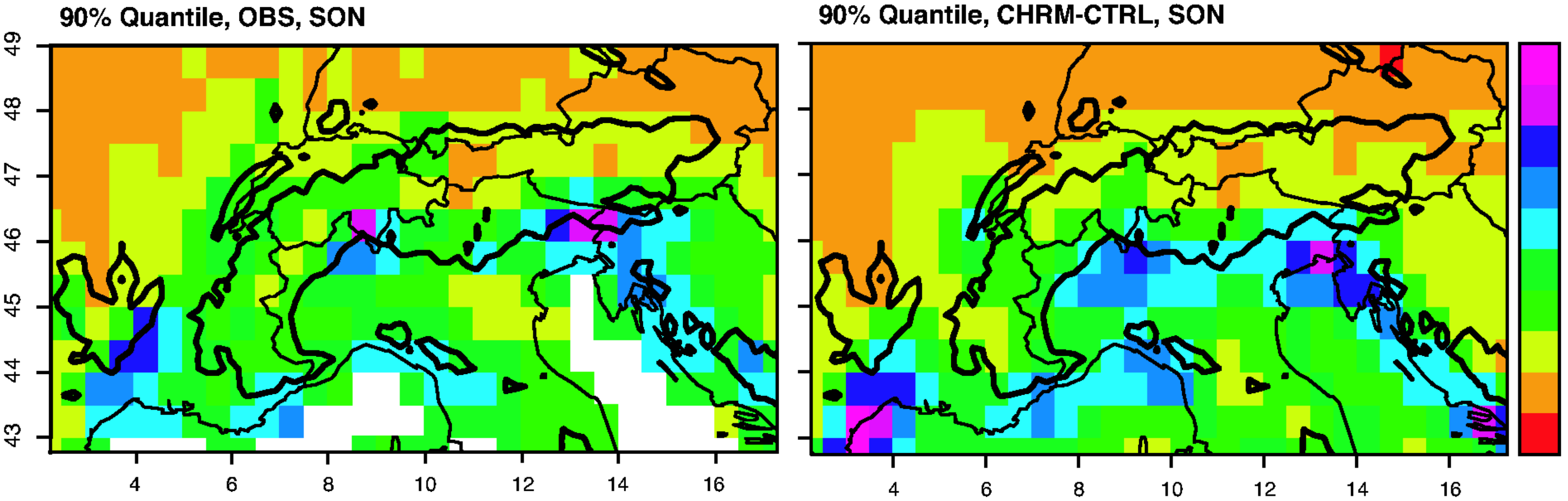
90% Quantile, OBS, SON
90% Quantile, CHRM-CTRL, SON
49
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Fig. 3

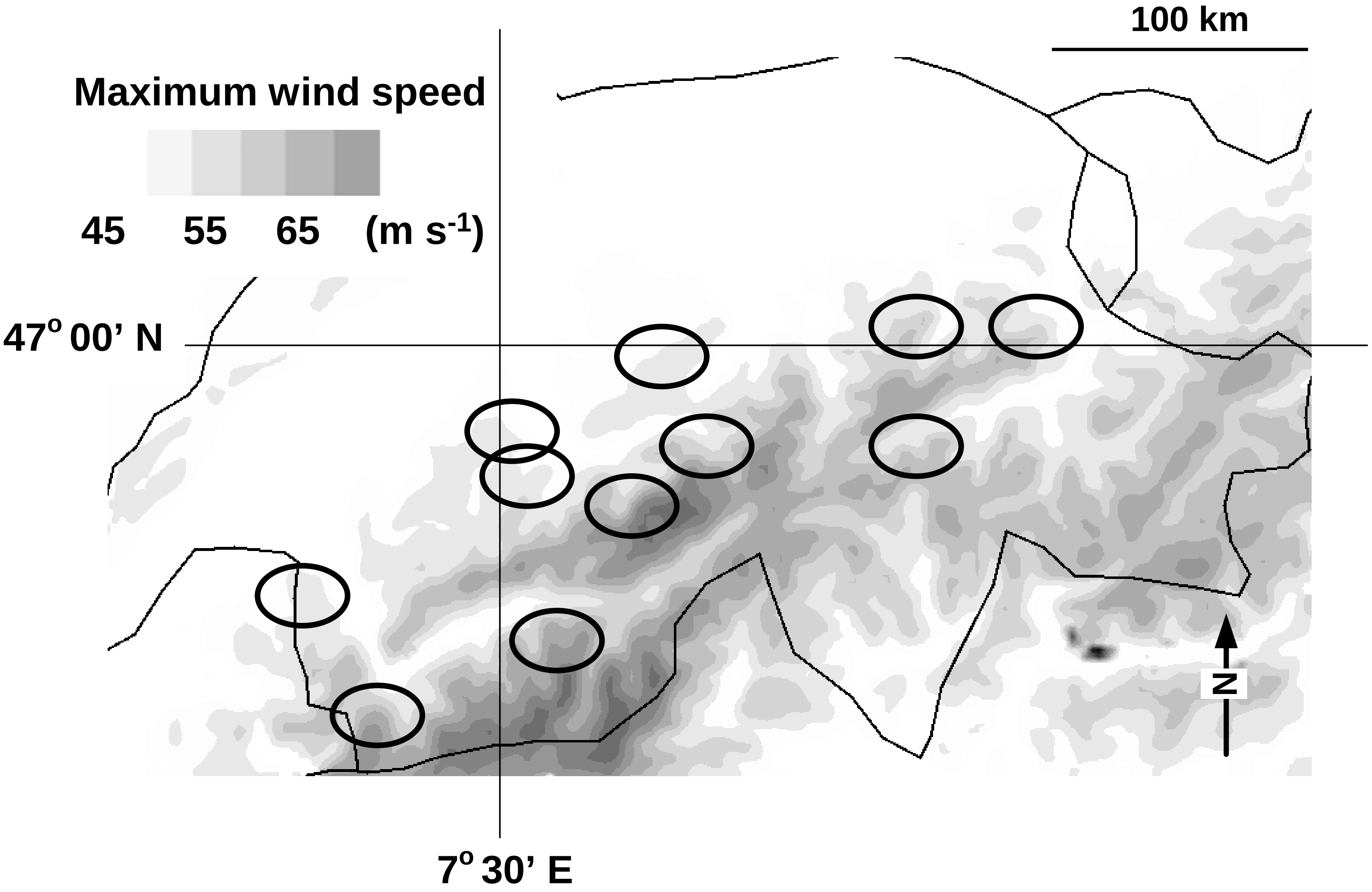


Fig. 4

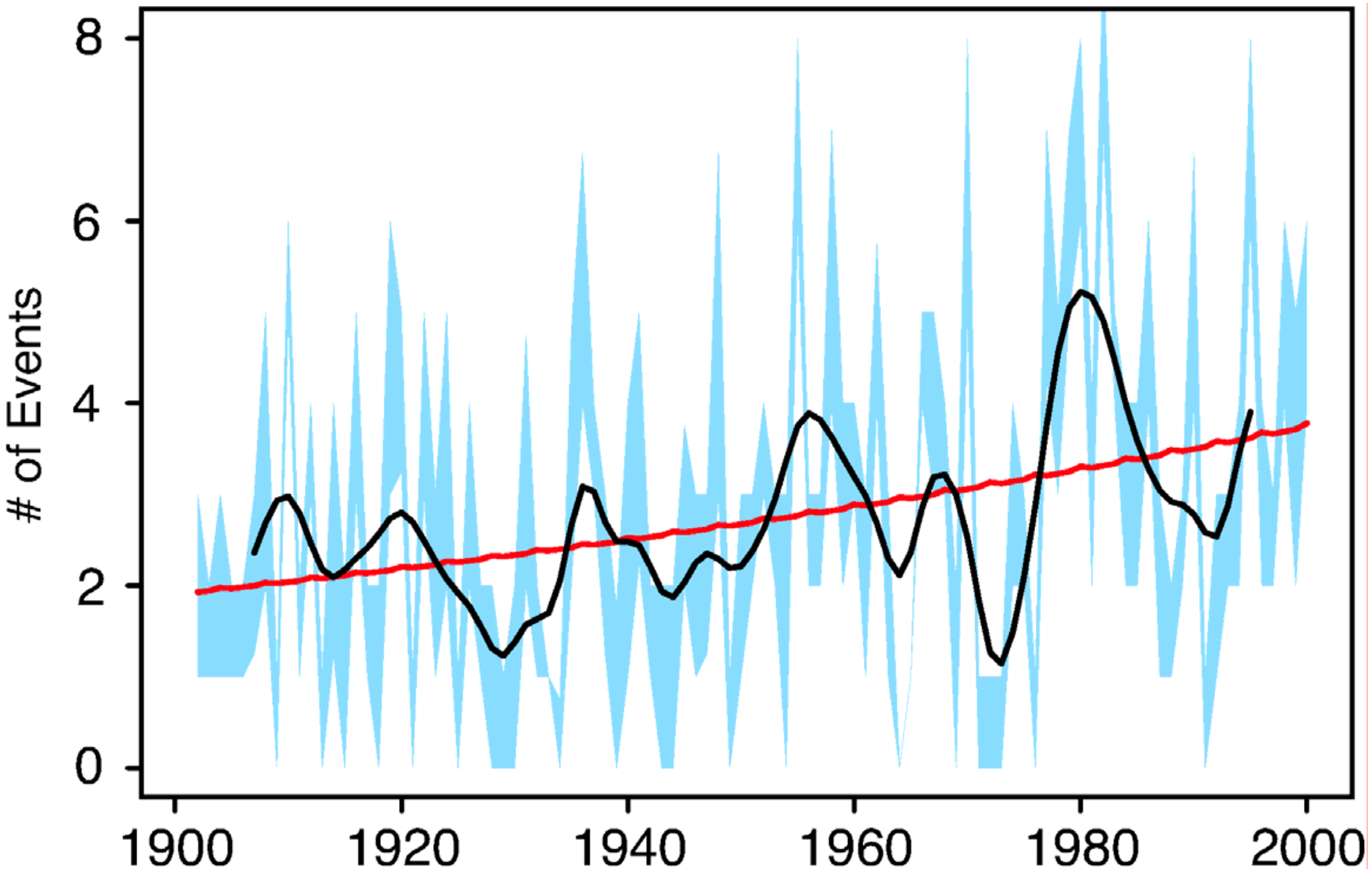


Fig. 5

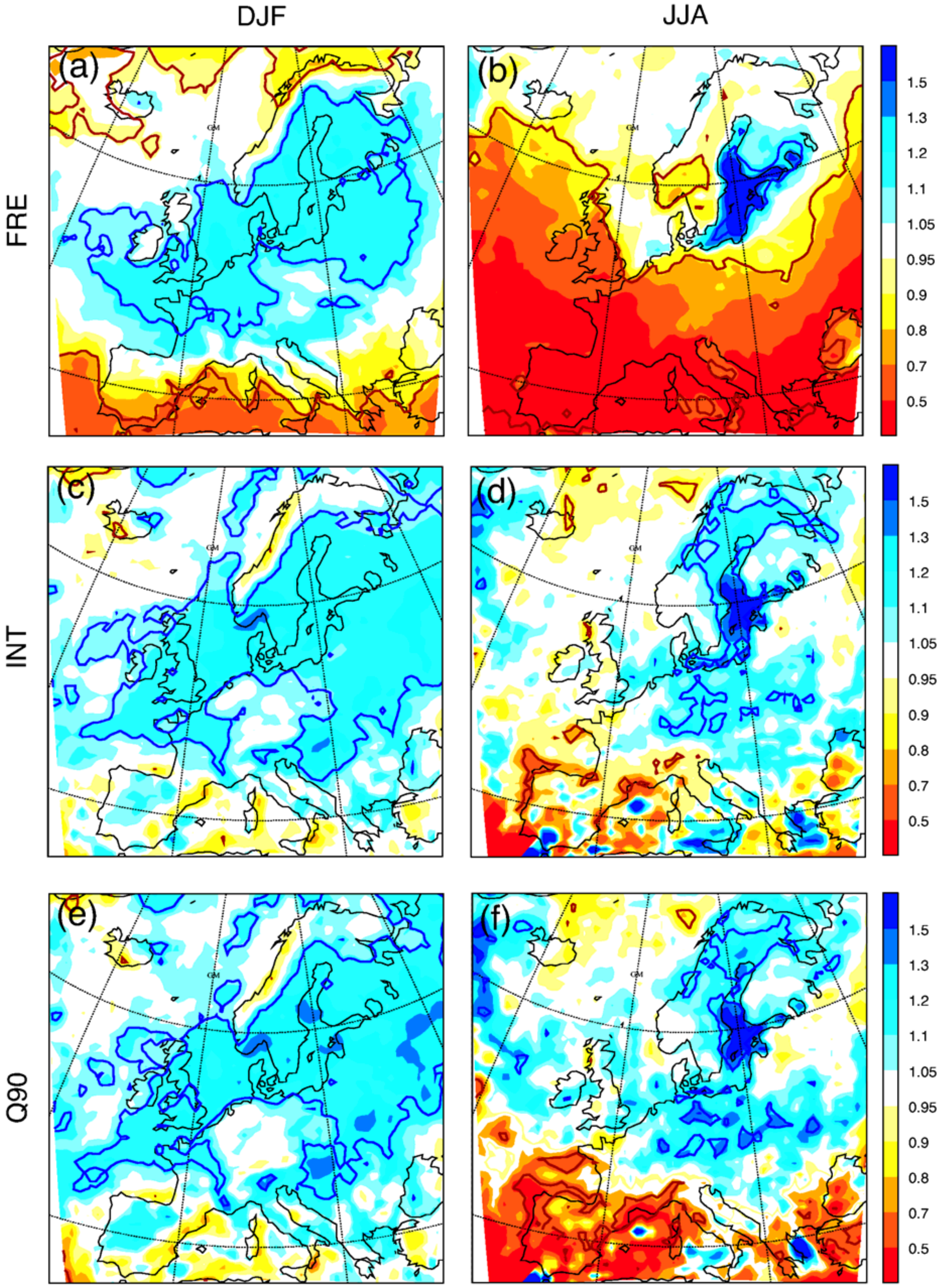


Fig. 6

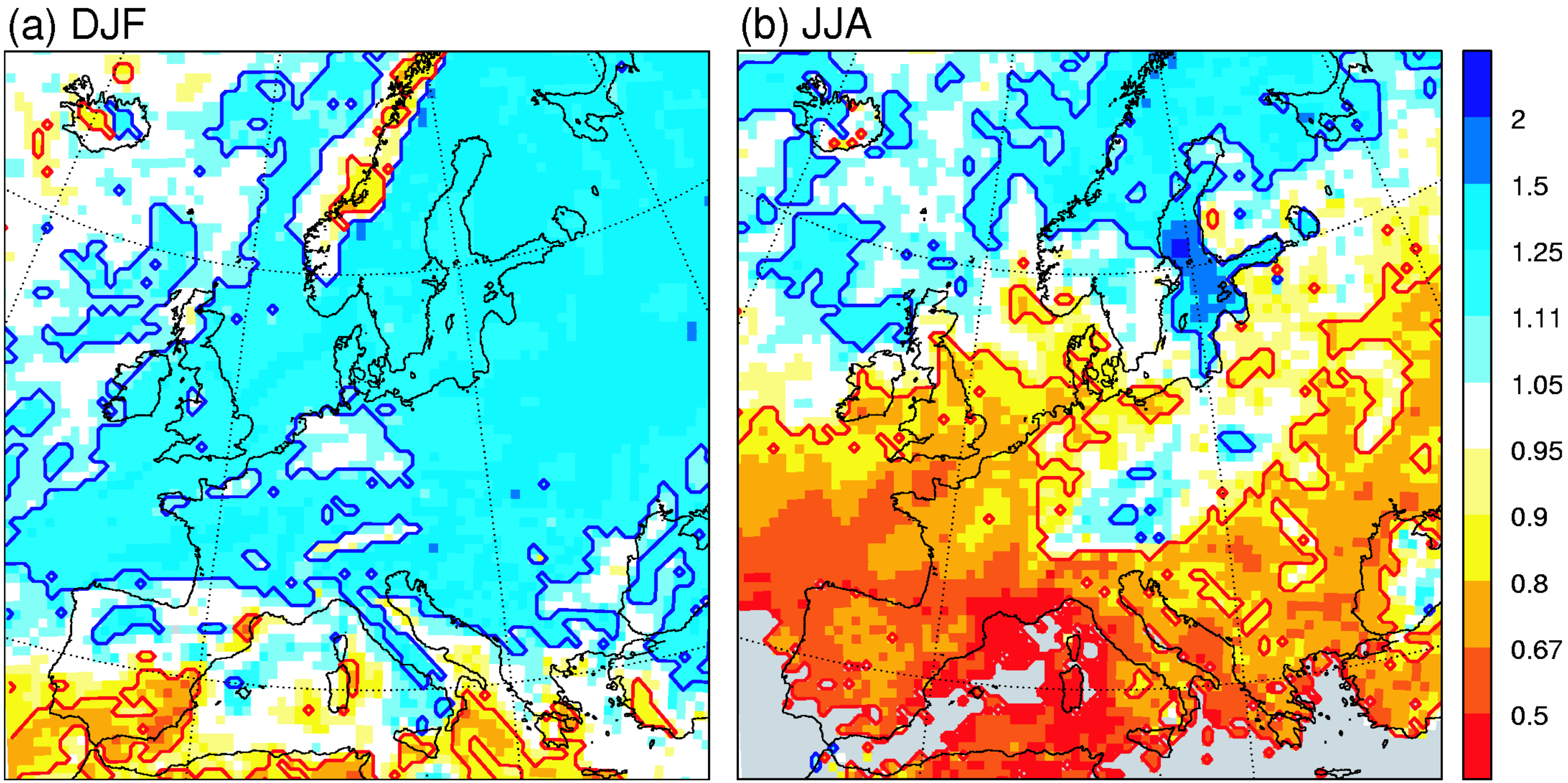


Fig. 7

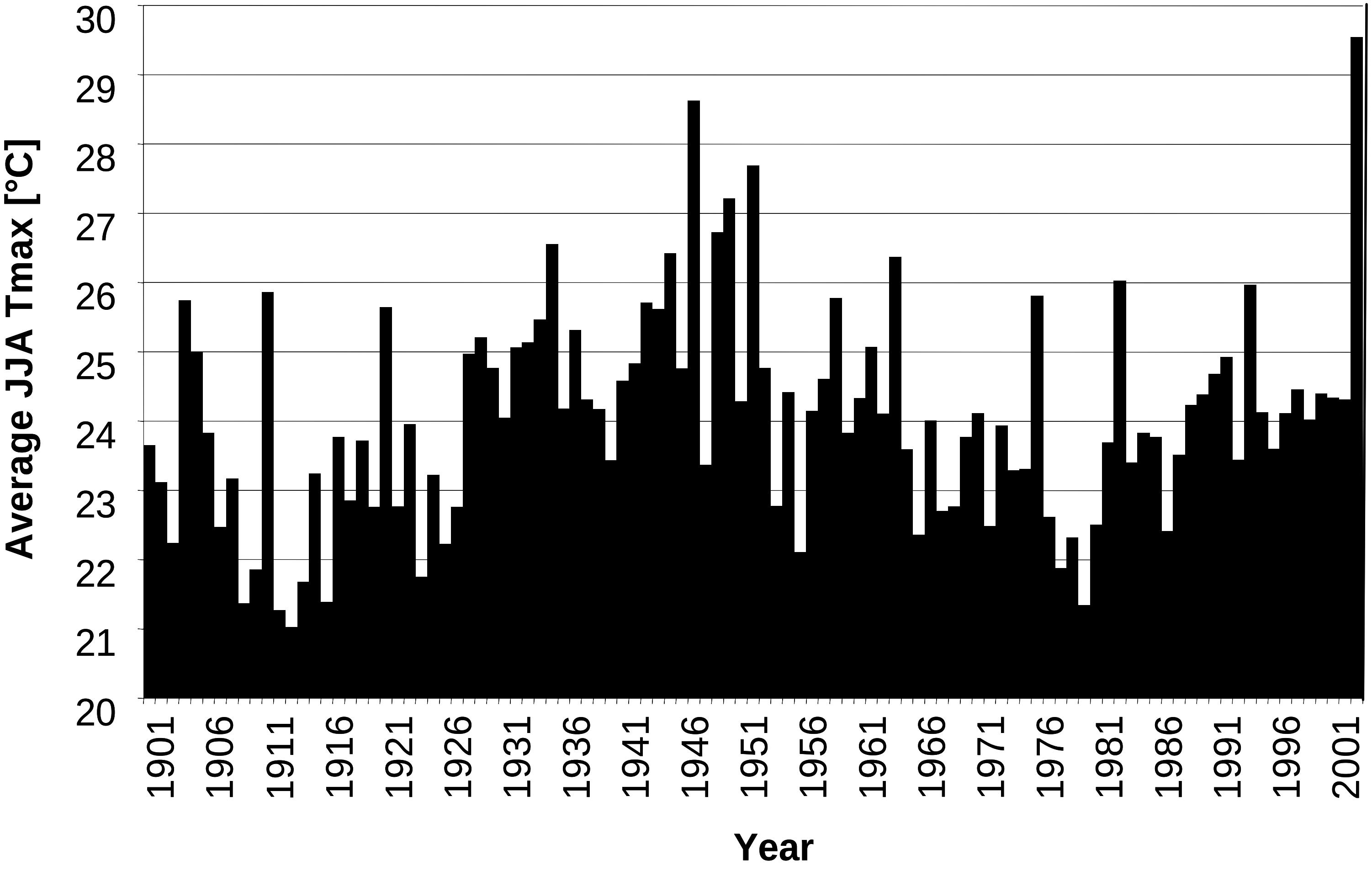

Average JJA Tmax [°C]
30
29
28
27
26
25
24
23
22
21
20
1901
1906
1911
1916
1921
1926
1931
1936
1941
1946
1951
1956
1961
1966
1971
1976
1981
1986
1991
1996
2001
Year

Fig. 8

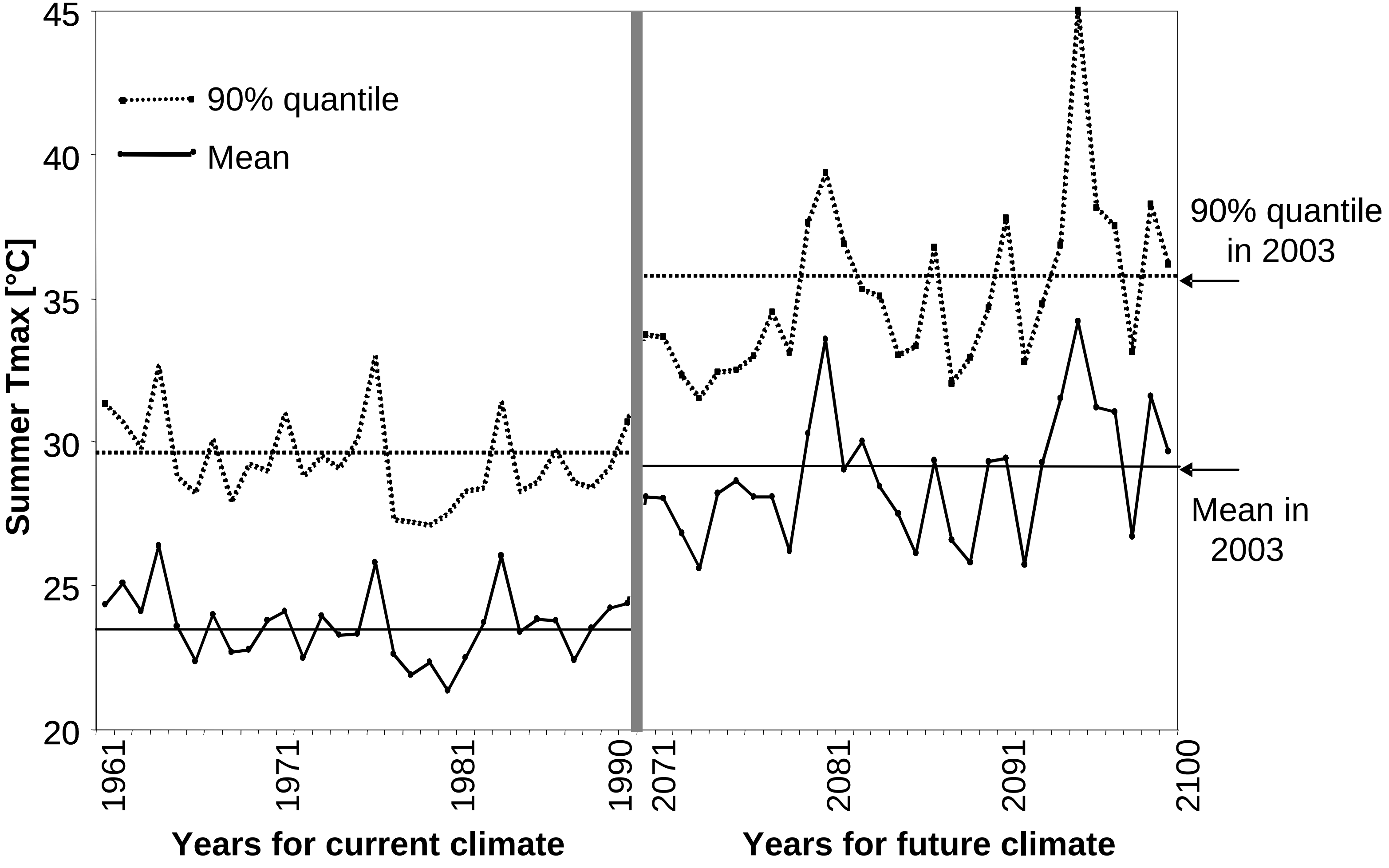

45
40
35
30
25
20
Summer Tmax [°C]
90% quantile
Mean
90% quantile in 2003
Mean in 2003
1961
1971
1981
1990
2071
2081
2091
2100
Years for current climate
Years for future climate

Fig. 9

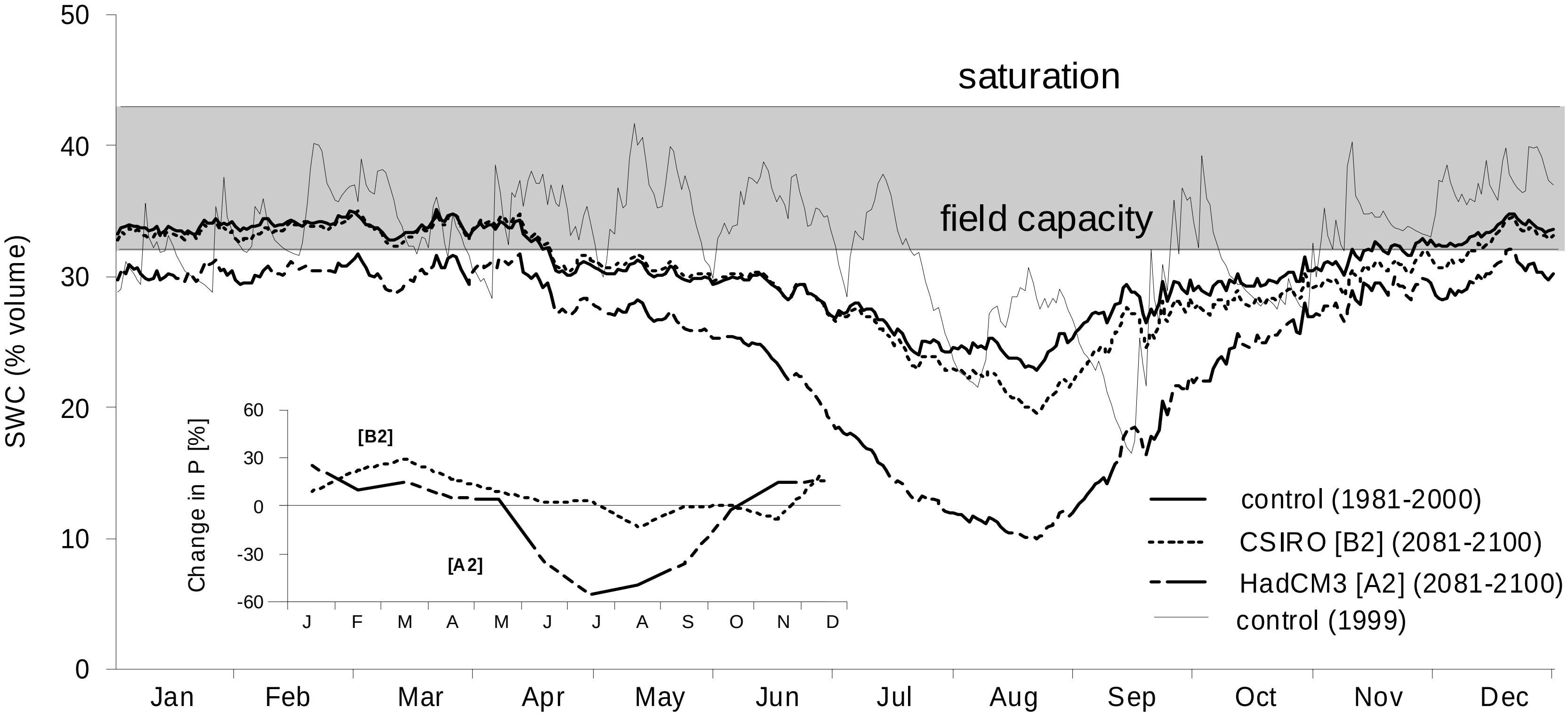

saturation
field capacity
SWC (% volume)
50
40
30
20
10
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
control (1981-2000)
CSIRO [B2] (2081-2100)
HadCM3 [A2] (2081-2100)
control (1999)
Change in P [%]
60
30
0
-30
-60
[B2]
[A2]
J
F
M
A
M
J
J
A
S
O
N
D

Fig. 10

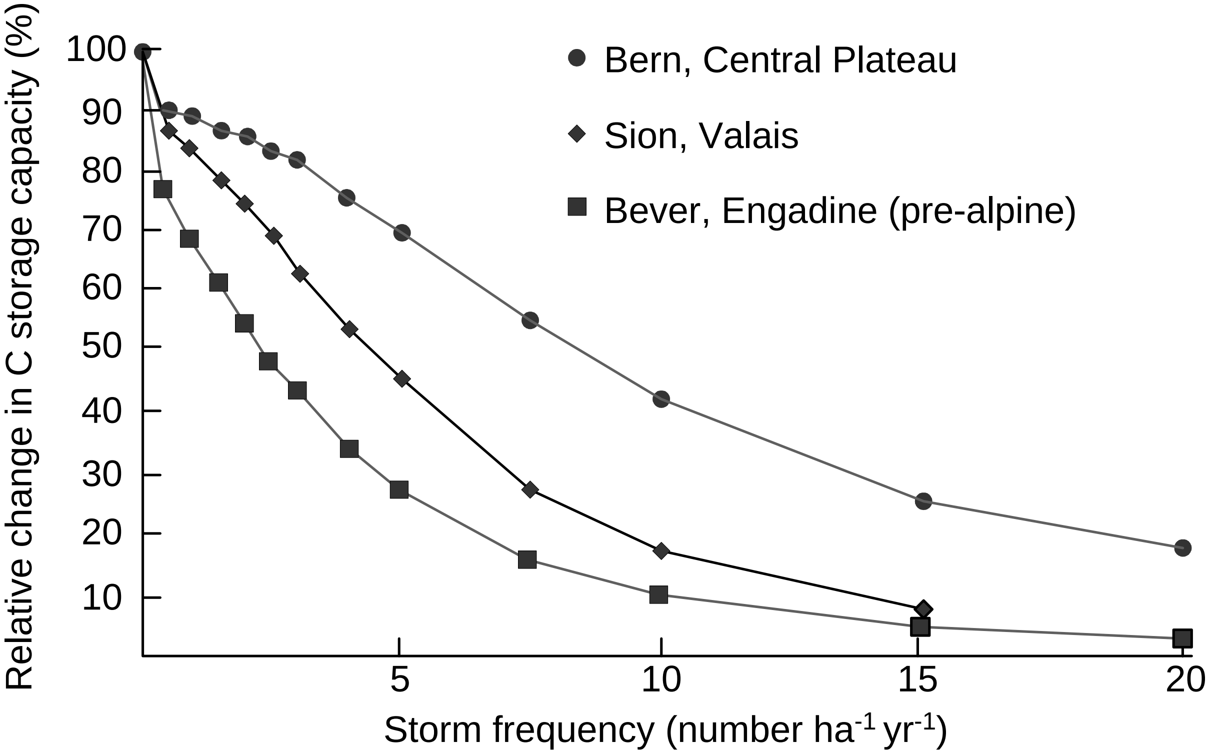
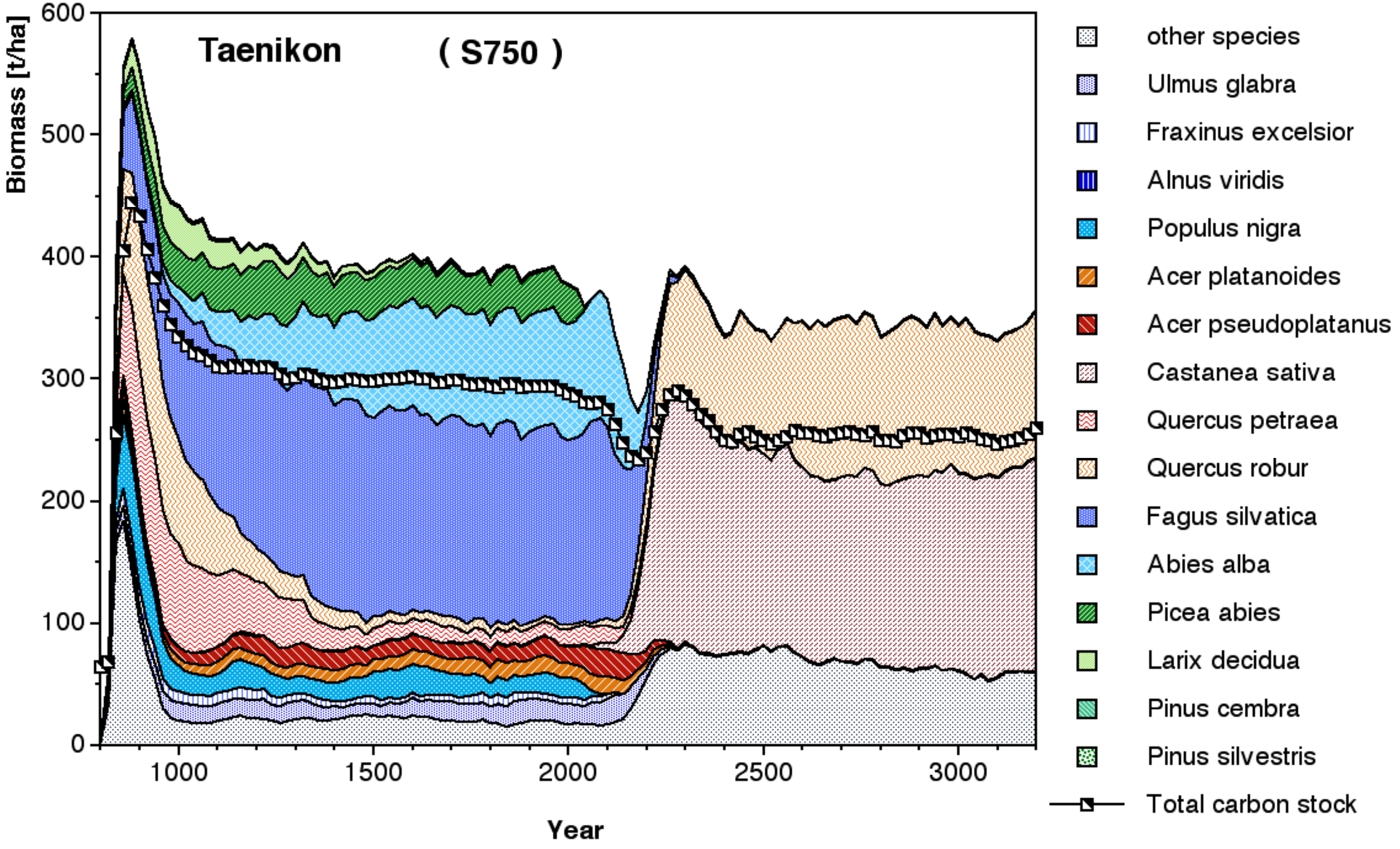

● Bern, Central Plateau
◆ Sion, Valais
■ Bever, Engadine (pre-alpine)
Relative change in C storage capacity (%)
100
90
80
70
60
50
40
30
20
10
5
10
15
20
Storm frequency (number ha-1 yr-1)

Fig. 11


Taenikon
(S750)
Biomass [t/ha]
600
500
400
300
200
100
0
1000
1500
2000
2500
3000
Year
other species
Ulmus glabra
Fraxinus excelsior
Alnus viridis
Populus nigra
Acer platanoides
Acer pseudoplatanus
Castanea sativa
Quercus petraea
Quercus robur
Fagus silvatica
Abies alba
Picea abies
Larix decidua
Pinus cembra
Pinus silvestris
Total carbon stock