Available online at www.sciencedirect.com
SCIENCE DIRECT®
Global and Planetary Change xx (2004) xxx–xxx
GLOBAL AND PLANETARY CHANGE
www.elsevier.com/locate/gloplacha

Extreme climatic events and their evolution under changing climatic conditions

Martin Beniston[a,*], David B. Stephenson[b]

[a]Department of Geosciences, University of Fribourg, Perolles, Fribourg CH-1700, Switzerland
[b]Department of Meteorology, University of Reading, United Kingdom

Received 3 September 2003; accepted 28 June 2004

Abstract

This short introductory paper illustrates some key issues concerning extremes by focusing on daily temperature extremes defined using quantiles and threshold exceedances. The examples include both a low and a high elevation site in the Swiss Alps where long records of homogenous daily data are readily available. The analysis of extremes highlights several features, some of them taken from the 2003 heat wave that affected Europe, in particular significant changes in the trends of quantiles in the course of the 20th century, differences in the altitudinal behavior of maximum or minimum temperatures, and close links between means and the extreme quantiles of daily temperatures.

Keywords: Climate; Climatic change; Extreme events; Statistical analyses

1. Introduction

Public awareness of extreme climatic events has risen sharply in recent years, in part because of instant media attention that serves to emphasize the catastrophic nature of floods, droughts, storms, and heat waves or cold spells. There is also a general perception that the number of extreme events has increased worldwide in the past few years, based on records on natural hazards as compiled by the insurance sector (Fig. 1, from Munich Re, 2002).

However, closer interpretation of these statistics shows that most of the increase in damage costs resulting from extreme climatic events is related to higher population densities in risk-prone areas than in past decades and a corresponding rise in insured infrastructure, rather than to an increase in the number of events themselves (Swiss Re, 2003).

Insurance statistics also highlight the fact that, with the exception of earthquakes, climate-related hazards take the heaviest toll on human life and exert high damage costs. In the second half of the

* Corresponding author. Tel.: +41 26 300 97 46.
E-mail address: martin.Beniston@unite.ch (M. Beniston).

0921-8181/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.gloplacha.2004.06.001

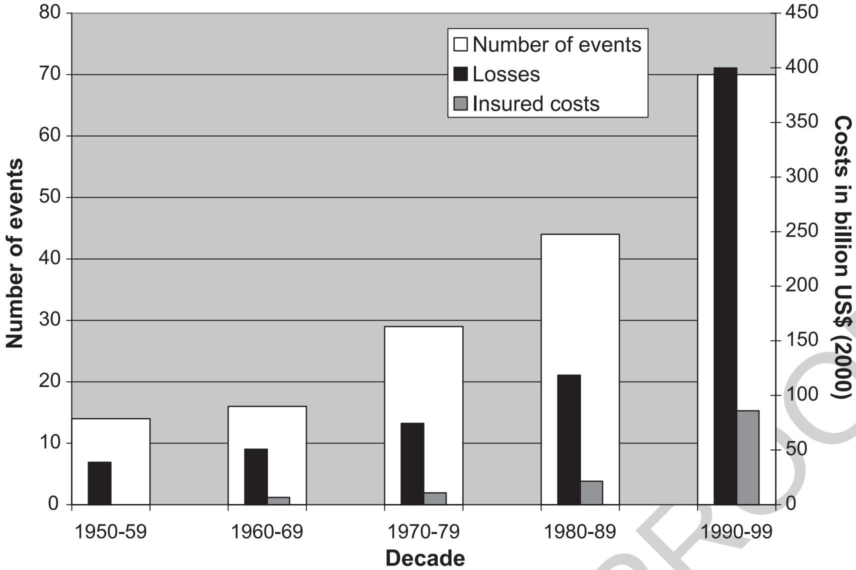

Fig. 1. Number of worldwide extreme climate-related events (including heat waves, cold spells, windstorms, extreme precipitation, and drought) and associated damage costs (from Munich Re, 2002).

20th century, there have been 71 "billion-dollar events" resulting from earthquakes, but more than 170 events related to climatic extremes, in particular windstorms (tropical cyclones and mid-latitude winter storms), floods, droughts and heat waves. The earthquake events took over 670,000 lives and generated overall economic losses of US$345 billion and insured costs of US$27 billion; in comparison, the climate-related events resulted in over 725,000 victims, economic costs of US$700 billion and insured costs of US$125 billion (Munich Re, 2002). There is thus an obvious incentive for the research community as well as the public and private sectors to focus on research related to extreme climatic events and the possible shifts in frequency and intensity of storms, floods, and heat waves following climatic change that is projected by IPCC (2001) to take place in the course of the 21st century as the climate system responds to increases in atmospheric greenhouse gases.

There is no single definition of what constitutes an extreme event. Extremes can be quantified inter alia on the basis of:

- how rare they are, which involves notions of frequency of occurrence;
- how intense they are, which involves notions of threshold exceedance;
- the impacts they exert on environmental or economic sectors, in terms of costs or damage, for example.

However, none of these definitions on their own is entirely satisfactory. For example, in its Third Assessment Report, the Intergovernmental Panel on Climate Change (IPCC, 2001) has based its definition on the frequency of occurrence of the event, i.e., an event that is as rare as the 10% or 90% quantile of a particular distribution of an atmospheric variable such as temperature, wind velocity or precipitation. The constraints of this definition are readily identifiable when interpreting temperature statistics, for example. The upper 10% of the temperature probability density function (PDF) in Athens will be very different from the same quantile in Helsinki because of salient differences in baseline climates. In terms of the impacts of the upper extremes of the temperature PDF on human health for example, the heat stress on the organism will be greater in Greece than in Finland, despite the fact that in terms of the rareness of the event, the IPCC definition is fulfilled at both locations. When analyzing the impacts that climatic events can generate, the definition of an extreme can become even more tenuous, because many damaging natural hazards can occur in the absence of an intense or rare climatic event that actually triggers the hazard. One example is the degradation of mountain permafrost, whereby a rise of atmospheric temperatures beyond a certain threshold that would not in itself constitute a temperature extreme (in the sense of the IPCC definition), can melt the permafrost to a sufficient degree for a significant reduction of the cohesion of mountain substrata to occur, thus enhancing the potential for rock and mud slides. In this respect, one is confronted with highly nonlinear processes and interactions that preclude a simple or single definition of extreme climatic events.

Understanding the mechanisms underlying various forms of climatic extremes is of interest to enable an assessment of the manner in which they may evolve in the future, under changing climatic conditions. There has been much speculation that the frequency and/or the intensity of extremes may increase in a warmer climate, because of the added thermal energy that is potentially available to trigger intense systems in a warmer atmosphere. However, attempting to relate rare or intense events to changes in mean climatic conditions is by no means trivial; causal relationships between isolated events and long-term trends are difficult to establish in any statistically meaningful manner, as was shown for example by Frei and Schär (2001).

This paper constitutes an introduction to the Special Issue devoted to the nature of extreme events, their possible evolution in a warming global climate, and the impacts that climatic extremes are capable of generating on environmental and socioeconomic sectors.

2. Observed temperature extremes in the Alpine region

Fig. 2 shows time series of the 10%, 25%, 50%, 75%, and 90% quantiles calculated for winter (DJF) daily minimum temperatures and summer (JJA) daily maximum temperatures measured at two stations in Switzerland. The 50% quantile is the median (central location) of the 90 daily values in the season and the difference between the 75% and 25% quantiles gives a good measure of intraseasonal variability (the so-called scale factor that measures the spread of the range). The 90% quantile for a season is the value that is exceeded by only 9 days (i.e., 10%) in the 90-day season. In addition to the contrasts between the hot and cold seasons, there is a contrast in altitude between the two stations: Saentis is at 2500 m whereas Basel is only at 367 m above sea level. A large amount of interannual variability in the quantiles can be seen in Fig. 2, especially in the more extreme 10% and 90% quantiles. Much common variation exists in the quantiles indicating that interannual variations in the mean contribute substantially to interannual variations in the probability distribution of daily values.

In addition to the interannual variability, long-term upward trends are also apparent in all the series shown in Fig. 2. The “fingerprint” of the long positive phase of the North Atlantic Oscillation (NAO), whose influence on climate on both sides of the Atlantic is dominant in winter (Wanner et al., 2001), can be discerned in the winter Tmin time-series from the late 1970s onwards. Beniston and Jungo (2002) have shown that the reduction of the coldest extremes in the latter part of the record is well correlated with the behavior of the NAO. About 41% of the variance of $Tmin_{10}$ is explained by the behavior of the NAO, 31% of $Tmin_{50}$, and 23% of $Tmin_{90}$. The behavior of the NAO thus seems to be more closely linked to changes in the coldest extremes than of those of the warmest extremes of Tmin (Antoniadou et al., 2001). The behavior of the maximum temperatures, their extremes, and their trends, is substantially different from that of the minima as discussed in the preceding paragraphs. The asymmetric behavior of Tmin and Tmax trends have been reported in other studies at the hemispheric scales (e.g., Karl et al., 1993) and regional scales (e.g., Jungo and Beniston, 2001).

As a simple way of quantifying these trends, we have estimated the long-term (century-scale) linear trend in each of the quantiles and the slope of these trends is summarized in Table 1. All the trends are positive and range between 0.5 and 2.2 °C per century for the period spanning 1901–2000. Fig. 2 suggests that some of these trends may have accelerated in recent years (e.g., the trends in minimum winter temperatures). The trends at the colder high altitude

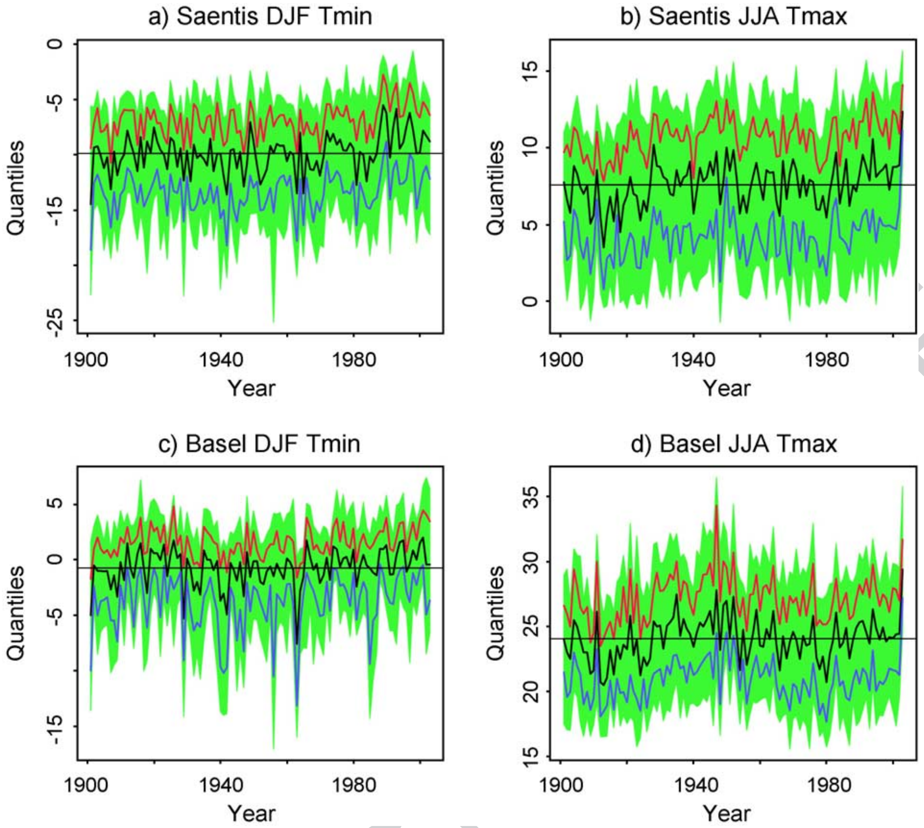

Fig. 2. Time series of the 25% (blue), 50% (black), and 75% (red) quantiles for various daily temperature series. The green shading extends from the lower 10% to the upper 90% quantile. All quantiles are in units of °C. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

station (Saentis) are larger than those at the low altitude station (Basel). The trends in quantiles for Saentis are similar for both winter minimum temperatures and summer maximum temperatures. The trends at Saentis are larger for the warmer quantiles (e.g., 90% quantile) suggesting an asymmetric trend in the probability distribution that could be linked to processes characteristic of high elevation sites that are well removed from urban effects, winter inversion layers, and above the moist low-level layers, as pointed out by Beniston and Rebetez (1996) and Giorgi et al. (1997). The trends at Basel are smaller than those at the high altitude station and are largest in the cold winter season. It should be noted that all these trends in local values are greater than the well-known 0.5 °C/century trend noted for global mean warming.

To investigate how much of the variation and trends in quantiles is due to the mean, we have centered the quantiles by subtracting out the median for each season (Fig. 3). This approach of relating the changes in the distribution to changes in median and spread has been developed much further recently by Ferro et al. (submitted for publication). The time series in Fig. 3 exhibit much less variation and trends than the uncentered series shown in Fig. 2. Therefore, much of the interannual variation and trends in

Table 1
Linear trends (°C/century) of the quantiles shown in Fig. 2 over the period 1901–2000

Station and variable	Quantiles				
	10%	25%	50%	75%	90%
Saentis Tmin DJF	1.2	1.5	1.8	1.8	2.2
Saentis Tmax JJA	1.1	1.4	1.7	1.7	2.2
Basel Tmin DJF	1.5	1.5	1.2	1.2	1.3
Basel Tmax JJA	0.5	0.7	1.2	1.1	0.8

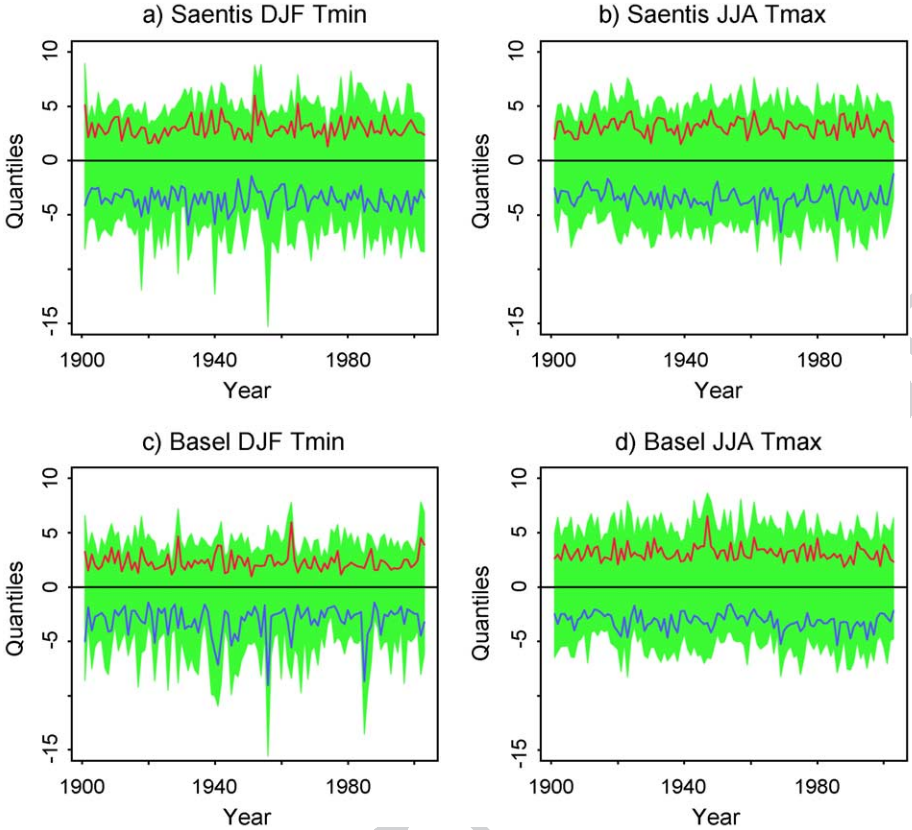

Fig. 3. Time series of the centered 10%, 25%, 50%, 75%, and 90% quantiles for various daily temperature series (in units of °C). The quantiles have all been centered by subtracting the 50% quantile (the median) for each season.

quantiles is related to the variation and trends in the median. However, there are some very prominent outliers in the cold quantiles of the winter series (e.g., Fig. 3c) that are not due to changes in the median, which seems to be the case for the particularly cold winters of 1956 and 1985 in Basel. From Fig. 3, there are no apparent strong trends in the scale (width) of the distributions of daily temperatures.

Another approach to interpreting the extremes of temperature, as a complement to the analysis of quantiles, is through threshold analysis, whereby the frequency of occurrence of events that are either below or above a given temperature can yield information on the changing tendencies of heat waves or cold spells in the alpine domain. While this approach may have a more immediate significance than the use of quantiles, in the sense that it is perhaps easier to perceive events on the basis of threshold exceedance, there are conceptual limits to the use of fixed thresholds. For example, the threshold above which a heat wave may occur can be arbitrarily set at 30 °C, which is typically a level that is exceeded at low elevations in Switzerland a few days each year. At higher elevations, above 1000 m or higher, the likelihood of encountering temperatures above 30 °C is negligible under current climate. Setting a lower threshold for higher elevations disrupts to a large extent the perception of what a heat wave actually is; at Saentis or other mountain sites, temperatures that exceed 15 °C may have significance for the functioning of high-alpine ecosystems, but can hardly be considered to be a heat wave. The temperature threshold for cold spells poses similar problems for different altitudes, because what might be a normal winter temperature at 3000 m above sea level becomes a rigorous cold spell in the lowlands. With these caveats in mind, the following paragraphs will briefly touch upon “hot days” on the basis of the exceedance of the 30 °C threshold in Basel. This is not an arbitrarily chosen limit but is very close to the 90% quantile for summer temperatures at that particular location.

Furthermore, the Saentis site is also analyzed in order to have stations representative of temperatures at low and high elevations. Basel and Saentis have been chosen to determine whether the behavior of summer Tmax at these locations is similar or decoupled because of the influence of altitude. The mean and extremes of daily summer maximum temperatures have been analyzed to assess whether significant changes have emerged over the past century, and whether there exists a relationship between summer Tmax and the upper extreme values defined by the 90% quantile as suggested by IPCC (2001). The behavior of the 90% quantile of Tmax at both Basel and Säntis is a measure of changes over time in the upper extreme of the probability density function (PDF) of temperature. It exhibits a close resemblance to the summer Tmax records, thereby suggesting a link between changes in means and shifts in the extremes of the distribution.

This is illustrated in Fig. 4, where a very significant linear relationship between means and extremes exists at the 99.9% level for both the low and the high elevation sites. The higher order statistics (variance, skewness and kurtosis) are essentially de-correlated from the average statistics, implying a symmetric shift in the probability density function of summer Tmax; i.e., as the average summer Tmax changes, the upper and lower bounds of the Tmax PDF undergo a similar

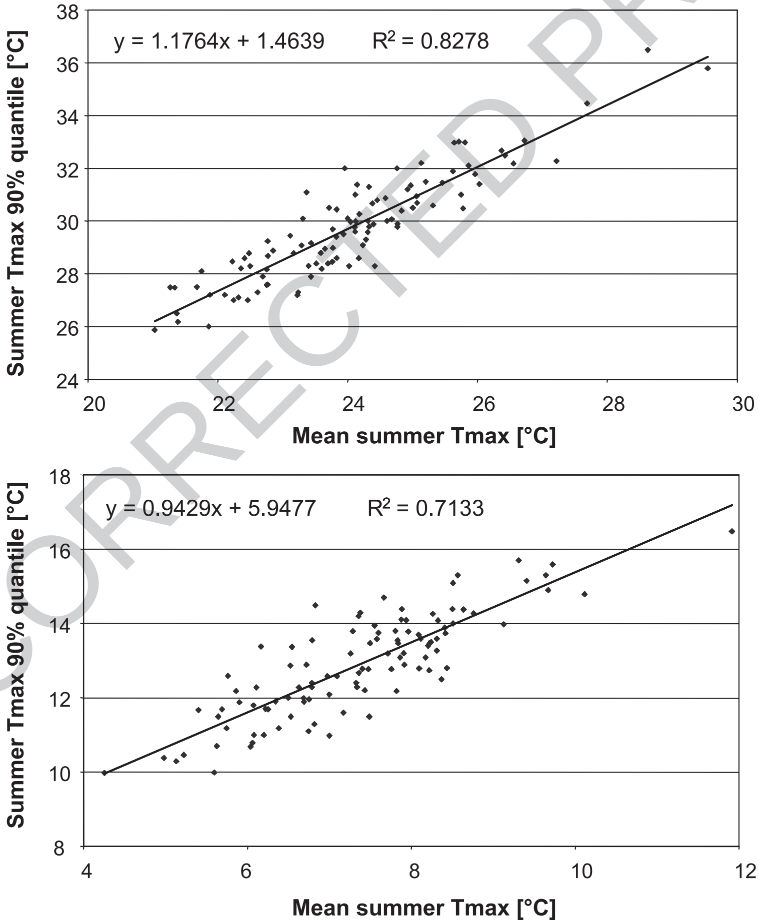

Fig. 4. Relationship between mean summer maximum temperatures and the 90% quantile of summer maxima at Basel (upper) and Säntis (lower).

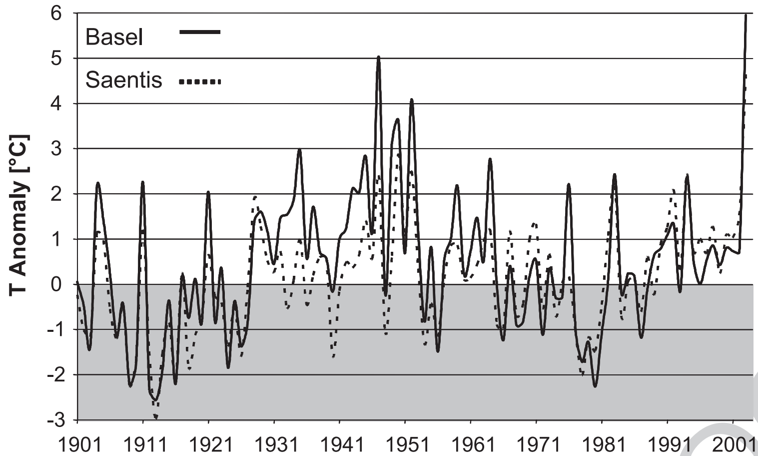

Fig. 5. Anomalies of mean summer maximum temperatures at Basel and Säntis computed as departures from the 1961–1990 mean.

amount of change (i.e., the mean changes but the shape of the distribution does not). This is not necessarily the case elsewhere, as has been pointed out by Katz and Brown (1992; also D. B. Stephenson, University of Reading, UK; personal communication; 2003).

Fig. 5 illustrates the anomalies of mean summer Tmax recorded each year from 1901–2003 at both sites, computed as departures from the 1961–1990 climatological average period (Jones and Moberg, 2003). Both series are essentially in phase, with perhaps the exception of the mid-century warm peak at the end of the 1940s that is more pronounced in Basel. The 2003 event stands out as a "climatic surprise", in the sense that it is the first time that average JJA Tmax in Basel has exceeded the 27 °C threshold since 1952, the 28 °C threshold since 1947, and the 29 °C for the first time in this century-long record (Beniston, 2004). The 2003 heat wave came at the end of a 40-year period during which summers were markedly cooler than the warm summers of the mid-20th century. Positive Tmax anomalies in Basel exceeded 6 °C (1 °C higher than the previous record of 1947), and 4.7 °C in Säntis (almost 2 °C more than the 1950 record for this location).

A closer analysis of the persistence of the event based on a count of daily exceedance of the 30 °C threshold at Basel reveals, however (Fig. 6), that 2003 exhibited fewer such days (41) than 1947 (49), for example. Furthermore, there were 12 consecutive

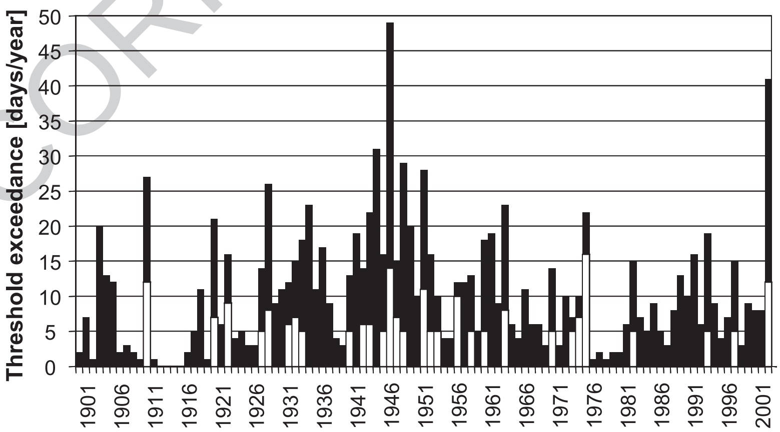

Fig. 6. Number of days during which temperatures exceed the 30 °C threshold in Basel (black) and number of consecutive days of threshold excess (white), from 1901 to 2003.

days in 2003 during which Tmax exceeded 30 °C as opposed to 1976 (16) or 1947 (14), as reported by Beniston (2004; see also this volume, paper by Beniston and Diaz). The 1940s stand out as a decade in which a clustering of summers with a threshold excess of 20 days or more is not uncommon, whereas such events tend to diminish in the 1970s and 1980s. According to the statistics considered, therefore, 2003 is not seen to have broken all records in terms of extremes: the sudden jump to high exceedance values following over a quarter century where summers never exceeded the 30 °C threshold for 20 days or more does, however, constitute a "climatic surprise". This is essentially because all the quantiles were anomalously high as opposed to just the upper quantiles as observed for previous heat waves, due to the longer persistence of the 2003 heat wave compared to past events.

3. Conclusions

While changes in the long-term mean state of climate will have numerous consequences on a range of environmental, social, and economic sectors, many significant impacts of climatic change are likely to come about from shifts in the intensity and frequency of extreme weather events. Indeed, insurance costs resulting from extreme weather events have been steadily rising since the 1970s, essentially in response to increases in population pressures in regions that are at risk, but also in part because of recent changes in the frequency and severity of certain forms of extremes.

This paper has given a brief overview of one particular form of weather extremes, namely heat waves as they have affected the alpine region in the course of the 20th century. The behavior of the upper extreme of temperature, beyond the 90% quantile as defined by IPCC (2001) and beyond a fixed threshold, has been analyzed for the Swiss site of Basel, a location where homogenized daily data is available in digital form since 1901. In addition, a second Swiss alpine site has been selected (Saentis, at 2500 m above sea level) in order to assess whether there is an altitudinal dependency of extremes.

The severity of the impacts related to the persistence of elevated temperatures, coupled to the prolonged drought conditions, have been exemplified in the heat wave that affected much of Europe, including Switzerland, during the summer of 2003. The excess deaths recorded in France and Italy (WHO, 2003), the severe financial losses in the agricultural sector in numerous countries, and the strongly reduced discharge in many rivers are signals that should not be ignored by decision-makers. Beniston (2004) has shown that the 2003 heat wave may well be a "shape of things to come" when assessing future climatic change in Europe; heat waves of similar magnitude to the 2003 event in Europe are projected by regional climate models to become more common in the latter decades of the 21st century. In view of the trends discussed in this paper and the projections of change in a future, warmer climate, it would seem appropriate to plan strategies aimed at addressing the negative impacts of climatic change such as those that Europe has recently experienced.

References

Antoniadou, A., Besse, P., Fougeres, A.-L., Le Gall, C., Stephenson, D.B., 2001. L'Oscillation Atlantique Nord (NAO) et son influence sur le climat Européen. Rev. Stat. Appl. XLIX (3), 39–60.

Beniston, M., 2004. The 2003 heat wave in Europe: a shape of things to come? Geophys. Res. Lett. 31, L02022.

Beniston, M., Jungo, P., 2002. Shifts in the distributions of pressure, temperature and moisture in the alpine region in response to the behavior of the North Atlantic Oscillation. Theor. Appl. Climatol. 71, 29–42.

Beniston, M., Rebetez, M., 1996. Regional behavior of minimum temperatures in Switzerland for the period 1979–1993. Theor. Appl. Climatol. 53, 231–243.

Ferro, C.A.T.F, Hannachi, A., Stephenson, D.B., 2003. Attribution of changes in probability distributions and extremes to changes in location and scale. J. Clim. (submitted for publication).

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.

Giorgi, F., Hurrell, J., Marinucci, M., Beniston, M., 1997. Height dependency of the North Atlantic Oscillation Index. Observational and model studies. J. Clim. 10, 288–296.

IPCC, 2001. Climate Change. The IPCC Third Assessment Report. Volumes I (Science), II (Impacts and Adaptation) and III (Mitigation Strategies). Cambridge Univ. Press, Cambridge.

Jones, P.D., Moberg, A., 2003. Hemispheric and large-scale surface air temperature variations: an extensive revision and an update to 2001. J. Clim. 16, 206–223.

Jungo, P., Beniston, M., 2001. Changes in the anomalies of extreme temperature in the 20th century at Swiss climatological stations located at different latitudes and altitudes. Theor. Appl. Climatol. 69, 1–12.

Karl, T.R., Jones, P.D., Knight, R.W., Kukla, G., Plummer, N., Razuvayev, V., Gallo, K.P., Lindseay, J., Charlson, R.J., Peterson, T.C., 1993. Asymmetric trends of daily minimum and maximum temperature. Bull. Am. Meteorol. Soc. 74, 1007–1023.

Katz, R.W., Brown, B.G., 1992. Extreme events in a changing climate: variability is more important than averages. Clim. Change 21, 289–302.

Munich Re, 2002. Topics, An Annual Review of Natural Catastrophes. Munich Reinsurance Company Publications, Munich. 49 pp.

Swiss Re, 2003. Natural Catastrophes and Reinsurance. Swiss Reinsurance Company Publications, Zürich. 47 pp.

Wanner, H., Broennimann, S., Casty, C., Gyalistras, D., Luterbacher, J., Schmutz, C., Stephenson, D.B., Xoplaki, E., 2001. North Atlantic Oscillation—concepts and studies. Surv. Geophys. 22, 321–381.

WHO, 2003. The health impacts of 2003 summer heat-waves. Briefing note for the Delegations of the fifty-third session of the WHO (World Health Organization) Regional Committee for Europe. 12 pp.