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Recent climate change: Long-term trends in meteorological forest fire danger in the Alps

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ABSTRACT

Climate change is one of the key issues in current scientific research. In this paper we investigate the impacts of rising temperatures and changing precipitation patterns on meteorological forest fire danger in the Alps. Our analysis is based on daily meteorological observations from 25 long-term stations in six Alpine countries. The selected stations are distributed more or less uniformly over the whole Alpine area and represent the different climate regions in this complex terrain. Stations with similar climatological conditions were grouped into regions. These were: Western Alps, Northern Alps, inner Alpine area and Southern Alps. The meteorological forest fire danger in the time period 1951–2010 was assessed on the basis of different forest fire danger indices (FWI, Nesterov, Baumgartner, etc.) calculated on a daily basis. A statistical percentile analysis revealed different impacts of recent climate change in the four regions. A significant increase in forest fire danger occurred at the stations in the Western Alps and even more strongly in the Southern Alps. Here, the yearly averaged fire danger increased during the past six decades. Additionally, in recent years the number of days with elevated forest fire danger (indices above a predefined threshold) has also increased. A comparatively weak increase was observed in the Northern Alps and no clear signal was evident at the stations in the inner Alpine valleys. In order to analyze extreme events (highest index value per year and region) extreme values statistics was applied. It was shown that the return period of extraordinarily high index values has decreased significantly over the past decades, especially in the Western and Southern Alps.

For three pilot areas (Valais in the Western Alps, Bavaria in the Northern Alpine region and Ticino in the Southern Alps) a comparison with observed historical fire data is shown. In Valais, a region in the Western Alps with a generally low fire hazard, a weak trend toward more forest fires and more area burned could be found. The correlation between calculated indices and observed fires was quite low in this region. In Bavaria (Northern Alps) this correlation was higher, but while the trend of forest fires in Bavaria was decreasing in terms of number and burned area, the meteorological fire danger in contrast increased. Reasons for this contrasting trend may be related to altered anthropogenic factors such as less military activities, technical progress, and higher awareness. The correlation between indices and forest fires south of the Alps (Ticino) was considerably lower because here most forest fires occurred in winter when the meteorological fire danger is usually lower than in summer. In this region a positive trend in meteorological fire danger over recent decades was also counterbalanced by decreasing anthropogenic ignitions.

1. Introduction

Since the beginning of the 20th century temperatures have increased globally. In 2007, the Intergovernmental Panel on Climate Change (IPCC, 2007) reported an observed increase in global mean temperature of about 0.7 °C over the last 100 years. Numerous general circulation models (GCMs) predict an amplification of this trend up to 0.8–3.5 °C by 2100 AD, depending on the emission scenario (IPCC, 2007). But this warming has and will not happen uniformly; it varies considerably between different regions. A much stronger warming due to feedback mechanisms (e.g. melting of ice caps, glaciers, vegetation changes, etc.) will be particularly experienced at higher latitudes and in mountainous regions such as the European Alps (Ruosteenoja et al., 2007). The increase of temperature and also changes in precipitation patterns has been attributed as a response to human activities. Impacts of global warming on our planet are diverse and range from changes in the hydrological cycle (melting of glaciers, altered precipitation, etc.), vegetation

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shifts (toward higher latitudes and altitudes), to a change in socio-economic factors (demography, consumerism, etc.). Beside these well known issues a changing climate also has profound and possibly unexpected impacts on global wildland fire activity.

In recent years, several studies have been carried out to assess changes in fire risk and forest fire activity around the world. In particular, scientists from countries strongly affected by huge forest fires causing extensive damage (US, Canada, Australia, and Russia) have put much effort into investigating changes in fire regimes due to an altering climate (Westerling et al., 2011). Advances in fire danger assessment have been facilitated by the use of historical datasets and a better understanding of regional and global climate variability and fire regime responses (Veblen et al., 2003). But much work is still to be done because fire activity is a complex topic, influenced not only by climate/weather but also by a number of factors including human interactions (activities likely to start fires, fire suppression and management, etc.). The general global trend is an increase in the area burned and number of fires, but with much variation between different areas (Flannigan et al., 2009; Liu et al., 2010).

However, most research studies assess temporal trends in potential meteorological fire risk by calculating different forest fire danger indices from historical meteorological observations or outputs of numerical climate models. The number of such fire indices is large and nearly every country affected by forest fires has developed its own system of fire risk assessment. The Canadian Forest Fire Danger Rating System (CFFDRS, (Van Wagner, 1987)), the Russian Nesterov index (Nesterov, 1949) or the US National Fire Danger Rating System (NFDRS; Bradshaw et al., 1983) are only three famous examples of fire danger evaluation methods. Some of these methods rely partially on a theoretical background but, due to complex interactions between the factors affecting forest fires, most of them are based on empirical approaches. A well known empirical method to create such an index is to combine long-term meteorological data with historical fire records (e.g. Baumgartner et al., 1967). Results of analyses regarding historical fire data have sometimes to be considered with care because trends in the number of forest fires and burned area depend not only on the meteorological conditions but also on changes in fire detection and fire management practices (Wotton et al., 2003).

Fox-Hughes (2008), for example, established a fire danger climatology for Tasmania by calculating different forest fire danger indices for a number of locations over an extended period. Significant features of this climatology included an apparent trend of increased severity in spring and differences in diurnal behavior between elevated and lower locations. A similar study revealed for Canada an increase in the average annual area of burned forest from around 1 million ha in the early 1970s to more than 2.5 million ha in the late 1990s (Skinner et al., 2002). Also in China a significant increase of potential fire danger in the past 50 years was detected by applying the Canadian Fire Weather index in the Yunnan Province (Zhao et al., 2009).

The regions mostly prone to forest fires in Europe are concentrated around the Mediterranean Sea from the Iberian Peninsula to France, Italy and Greece. Wildland fires in these regions have been on the rise since the early 1980s. Moriondo et al. (2006) observed both an increase in the length of the fire season and an increase of extreme events. In addition to changes in farming and land-use, this trend can mainly be attributed to an increase in droughts and higher temperatures.

The Alps are not a place commonly associated with forest fires, but the Southern Alpine slopes and the dry valleys in the Central Alps are particularly affected by forest fires almost every year. A look at the fire statistics of the whole Alpine region in the past decade reveals that on average about 1300 fires occurred per year, burning around 7000 ha. More than 80% of the burned area is restricted to the Southern Alps in France and Italy. Beside a great spatial variability, forest fires in the complex topography of the Alps show also a distinct temporal variability. Most of the fires north of the Alps occur between April and September, while south of the Alps the main fire season can be defined between December and April (Reinhard et al., 2005). Last but not least, there is a pronounced anthropogenic intervention to the Alpine fire regime.

However, despite extensive scientific investigation of the Alpine climate, very little is known about the impacts of climatic changes on forest fires. The few existing studies mainly focus on the Southern Alpine region (Switzerland, Italy). Reinhard et al. (2005) analyzed trends in drought variables for more than 30 years in southern Switzerland. Their results showed an increasing trend in all climatic variables favorable to droughts and forest fires (longer episodes without precipitation, more sunshine duration and a decrease in relative humidity). Zumbrunnen et al. (2009) investigated the relationship between the fire regime and local climatic variability in the 20th century in a dry inner Alpine area in Switzerland. They established that the marked temperature increase did not profoundly change the fire regime because of fire policy and fire management measures (e.g. prohibition of agricultural burning). This was also confirmed by Pezzatti et al. (in press), who discussed the change points in fire regimes in the past century occurring in the Cantons of Ticino and Valais, according to socio-economic, land use and climatic factors. Other Swiss studies (Conedera et al., 2006; Reineking et al., 2010) suggested that an increase in severity and frequency of prolonged summer drought periods due to a changing climate may also result in significantly more lightning induced fires. Beside the above-mentioned publications there have been no other studies so far dealing with fire danger trends at the whole Alpine scale. Thus, in this paper we study long-term trends in meteorological fire danger caused by climate change in the Alps based on several different fire danger indices. The term meteorological fire danger refers to a potential fire danger, which is based only on meteorological parameters without distinction whether a fire occurred or not. Changing anthropogenic factors (human behavior, technical progress, ...) are also not considered in this context. Since climate change affects different regions in the Alps in different ways, the purpose of the present paper is to identify regional differences. Conclusions are made by analysing 60-year trends at 25 climate stations along the Alpine rim. The content of our paper is as follows: after a description of the region of interest and the meteorological database we briefly describe climate change related temperature and precipitation trends in the Alps. We then focus on several statistical analyses of different forest fire danger indices and stations also with respect to extreme events. A comparison with observed forest fire statistics (burned area, number of fires) in three pilot regions is also included. The paper concludes with a summary of the main findings and an outlook on forthcoming research.

2. Material and methods

2.1. Climate observation data

The area under investigation (see Fig. 1) is situated in Central Europe and comprises the whole Alpine area and its surrounding flatlands (442,000 km^2). The countries within this area are France, Switzerland, Liechtenstein, Germany, Italy, Austria and Slovenia.

For a mountainous region, the Alps are characterized by an extremely high weather station density (Schwarb, 2000). Currently more than 6000 stations are operating, although most of them are only recording precipitation. The statistical analyses of forest fire danger are based on 25 long-term operational weather stations distributed across the Alps (Fig. 1) with long time series of all standard

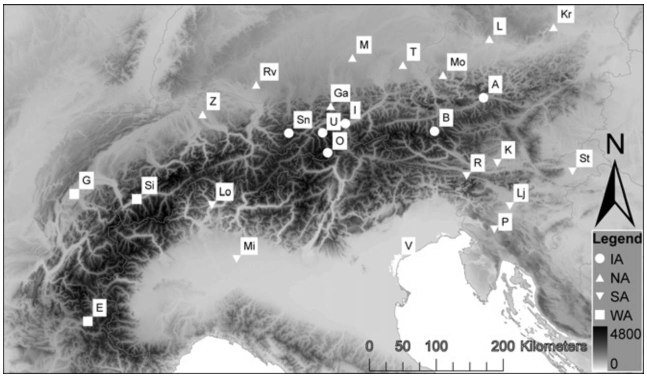

Fig. 1. Location of the 25 climate stations selected for the investigation. The station names, abbreviations and altitudes from West to East are: Geneva (G; 420 m); Embrun (E; 871 m); Sion (Si; 482 m); Zürich (Z; 556 m); Locarno (Lo; 383 m); Milano (Mi; 120 m); Ravensburg (Rv; 462 m); St. Anton (Sn; 1298 m); Umhausen (U; 1041 m); Obergurgl (O; 1938 m); Garmisch-Partenkirchen (Ga; 704 m); Innsbruck (I; 577 m); Munich (M; 535 m); Trostberg (T; 486 m); Venice (V; 25 m); Bad Gastein (B; 1100 m); Mondsee (Mo; 488 m); Ratece (R; 864 m); Aigen (A; 640 m); Linz (L; 260 m); Postojna (P; 533 m); Klagenfurt (K; 447 m); Ljubljana (Lj; 299 m); Krems (Kr; 207 m); and Starse (St; 240 m). The different symbols indicate the respective regions: Western Alps (WA; rectangles); Northern Alps (NA; upward facing triangles); inner Alpine area (IA; circles); and Southern Alps (SA; downward facing triangles).

meteorological parameters necessary for fire danger index calculation.

The data comprise the time period 1951–2010 and are provided by the DWD (Deutscher Wetterdienst, Germany, 4 stations), ZAMG (Zentralanstalt für Meteorologie und Geodynamik, Austria, 10 stations), MeteoFrance (France, 1 station), MeteoSwiss (Switzerland, 4 stations), Environmental Agency of the Republic of Slovenia (Slovenia, 4 stations), Aeronautical Service Agency Italy (Italy, 1 station) and the Venice Institution of Science (Italy, 1 station). Most of the selected stations recorded continuous data series and only a few stations had data gaps (e.g. Milano, Venice) or were installed after 1951 (Aigen, Mondsee, Obergurgl, Sion, Starse, Umhausen, and St. Anton).

The dataset consists of daily values of air temperature, precipitation, wind speed, relative humidity and snow cover. Due to the different national sources of the data, observations were not carried out at the exact same time of day. For example, evening readings differ between 19 CET (=UTC + 1 h) in Austria and 21 CET in Slovenia. However, for our climatological purposes it was not necessary to adjust for these time differences since we are not directly comparing index values of different stations, but only temporal trends. All stations are situated in plains or on valley floors, nevertheless the altitudes range from 25 m above sea level at the Adriatic Sea (Venice, V) to 1938 m in the Austrian Alps (Obergurgl, O).

For a better visualization of the results, we decided to assign the 25 stations into groups. Since all the stations used are part of the HISTALP project of the Austrian weather service (ZAMG, www.zamg.ac.at/histalp) we decided to use their regionalization method. The classification was based on a principal component analysis applied between all station records on an annual basis. Further details can be found in Auer et al. (2007). Due to the lack of long term observations in Italy, we decided to merge the two HISTALP regions south of the Alps (Southwest, Southeast) to one region South. Hence, the four regions under consideration were specified as: Western Alps (WA, 3 stations), Northern Alps (NA, 8 stations), inner Alpine area (IA, 6 stations) and Southern Alps (SA, 8 stations; see Fig. 1).

Typical climate conditions in these regions and the impacts of recent climate change will be discussed in Section 3.1 (Figs. 2 and 3). Regional means were calculated by a simple averaging of the individual station values. Temporal trends were assessed by applying a linear regression of the regional means on year over the whole time period (1951–2010).

2.2. Forest fire danger indices

The most important determinants of forest fire danger are climate and weather (Whitlock et al., 2003). Accordingly, strong emphasis has been put on the prediction of fire ignition and behavior using climate and weather variables. A common technique for forest fire risk assessment is the calculation of daily meteorologically based forest fire danger indices. In the present study we focus on seven well known and widely used indices (Table 1): the two German indices Baumgartner (Baumgartner et al., 1967) and M-68 (Käse, 1969), two indices (FWI – fire weather index, FFMC – fine fuel moisture content) of the Canadian Forest Fire Danger Rating System (CFFDRS, (Van Wagner, 1987)), the Russian Nesterov index (Nesterov, 1949), the Swedish Angstrom index (Chandler et al., 1983) and the McArthur index primarily used in Australia (Noble et al., 1980). All of these indices are calculated on a daily basis, but the recording time of the meteorological input data is not identical (see Table 1), depending on the practice of the national weather services. For a detailed description of the respective methods, see original publications.

The indices differ also in many other respects: their complexity ranges from the relatively simple Angstrom index for which only noon temperature and relative humidity is needed, to the very complicated M-68 index, where information about precipitation, wind speed, snow cover and phenology is also taken into account. Some of the indices (e.g. FWI, McArthur) do not only include relationships between weather conditions and fire activity but also between weather and soil moisture. Moreover, the Canadian system with its sub-indices also predicts distinct elements of fire activity, such as fire ignition, spread, and intensity.

Very simple indices designed to assess fire ignition probability considering only day-to-day weather conditions (Angstrom) can also be distinguished from cumulative indices that consider meteorological conditions or fuels over longer periods (Baumgartner, M-68, Nesterov).

Most fire indices are based on empirical models and are therefore adequate only for the specific type of climate or vegetation where they were developed. Transferring fire indices from one region to another one can be critical in some situations and has to be undertaken with caution. This has been shown in some comparative studies (e.g. Viegas et al., 1999; Weibel, 2009) where different indices were applied in different regions in Europe. However, in our analysis we do not intend to identify the best suited index for the different Alpine regions. Rather, all seven indices were calculated for all regions and used only to derive relative temporal trends (slopes of regression lines) of meteorological forest fire danger. By using this large number of potential indices and their temporal trends, we do not face the problem of comparing several different locally adapted indices.

2.3. Statistical analysis

After the index calculation the dataset comprised daily indices for all 25 stations and for the whole 60-year period. To handle this high amount of information we decided to perform a percentile analysis on an annual basis. Hence, various percentiles (50th, 75th, 90th, 95th, and 99th) of the statistical index distributions were computed for each station and year. As an example: the 95th percentile of the FWI in Ljubljana (SA region) had values of 15.7 in 1951 and 20.4 in 2010. Since the fire seasons are quite variable within the Alps (April–October in regions NA, IA; December–May

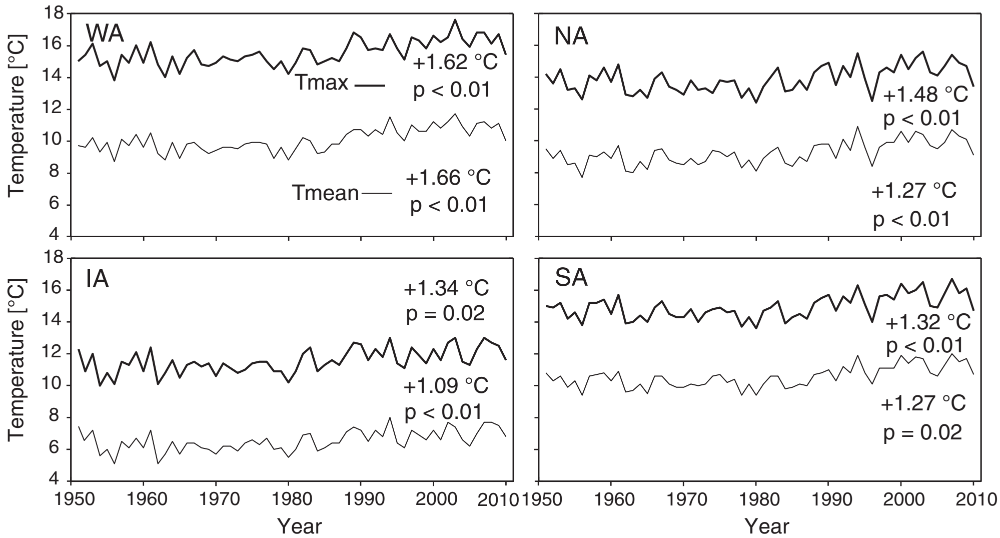

Fig. 2. Annual mean temperatures (thin lines) and annual average daily maximum temperatures (bold lines) in the four study areas Western Alps (WA), Northern Alps (NA), inner Alpine area (IA) and Southern Alps (SA). Numbers indicate the temperature change from 1951 to 2010 based on a linear regression for T_{max} (upper number) and T_{mean} (lower number), respectively. The *p*-values as a measure of significance are also given.

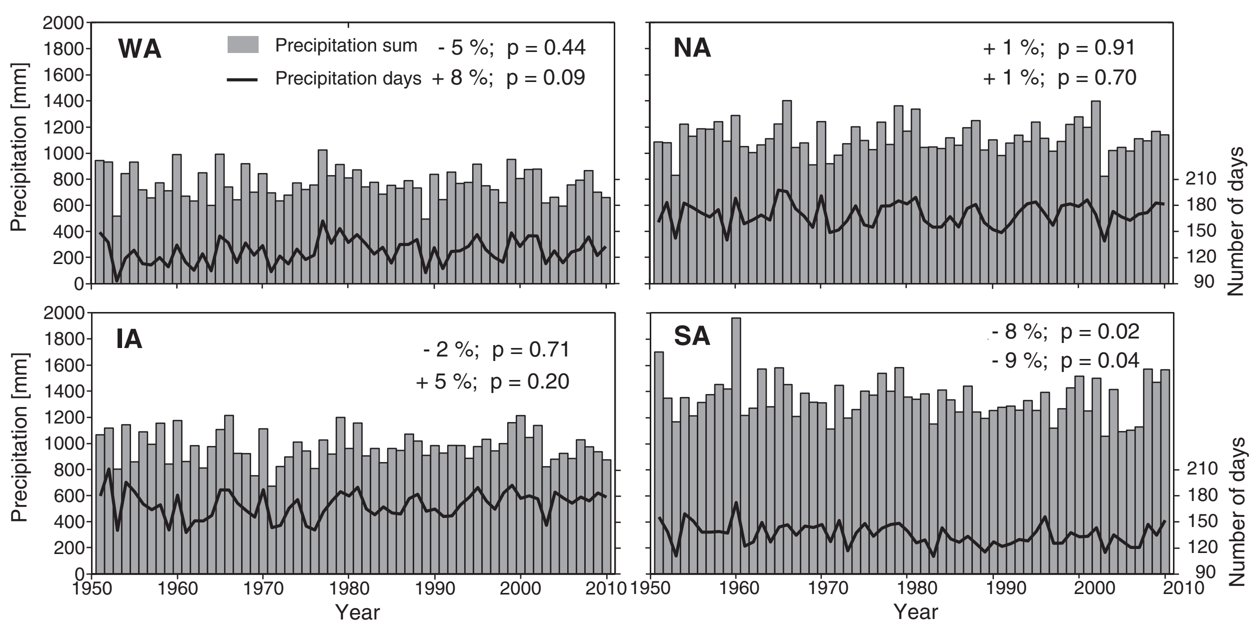

Fig. 3. Annual precipitation sums (gray bars) and number of days with precipitation (bold lines) in the four study areas: Western Alps (WA), Northern Alps (NA), inner Alpine area (IA) and Southern Alps (SA). Numbers indicate the changes of precipitation sums (upper numbers) and precipitation days (lower numbers), respectively, in 1951–2010 based on linear regressions. Additionally also the *p*-values as a measure of significance are given.

Table 1
Description of the fire danger indices used, including name, region or vegetation that the index was originally developed for, meteorological input parameters and observation time. The abbreviations for the meteorological parameters are: *T* (temperature, °C), *H* (relative humidity, %), *P* (precipitation, mm), *U* (wind speed, m/s or km/h), *S* (snow depth, cm). The last column indicates whether the index is accumulated over a time period.

Index name	Region/vegetation	Input data	Time	Cumulative
Baumgartne	Germany	T, H, P, U	Daily, at 2 pm	Yes
M-68	Germany/Pine forests	T, H, P, U, S, Phenology	Daily, at 1 pm	Yes
FWI	Canada/Pine forests	T, H, P, U, S	Daily, at 12 pm	Yes
FFMC	Canada/Pine forests	T, H, P, U, S	Daily, at 12 pm	Yes
Nesterov	Russia	T, H, P, S	Daily, at 1 pm	Yes
Angstrom	Sweden	T, H	Daily, at 1 pm	No
McArthur	Australia/Eucalyptus forests	T, H, P, U	Daily, at 3 pm	Yes

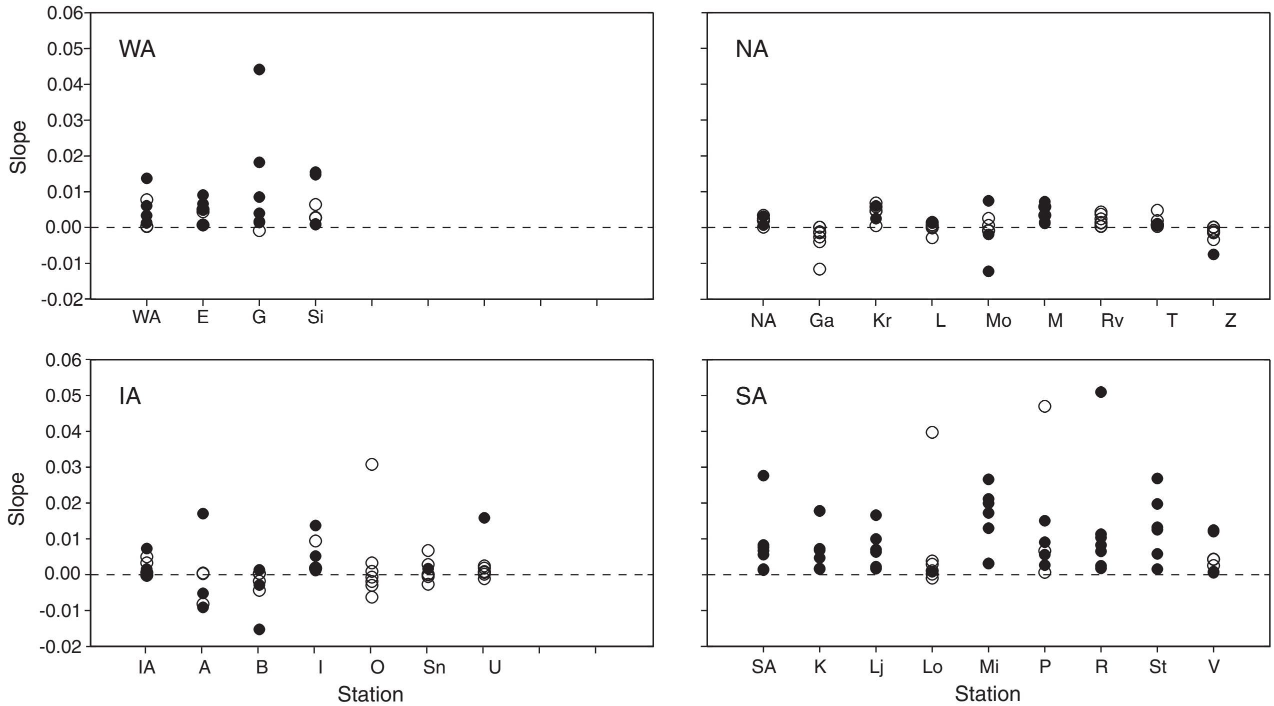

Fig. 4. Trends of the 50th percentile of different indices (each index is one circle) for stations within regions (see Fig. 1 for abbreviations). The leftmost column of circles in each panel refers to the regional mean. The values on the *y*-axis are normalized slopes. The four panels represent the four regions Western Alps (WA), Northern Alps (NA), inner Alpine area (IA) and Southern Alps (SA). Filled circles indicate statistically significant trends and empty circles non-significant trends respectively.

in regions SA, WA) the index percentiles were calculated over all days in the year. Thus, we avoided problems linked to a potentially different length of fire season (e.g. defined by fire occurrence or growing season) in the individual regions and the regions became more comparable. In the following we focus only on the 50th and 95th percentile. The median (50th percentile) represents a yearly averaged meteorological forest fire danger, the 95th percentile represents days with an exceptional high forest fire danger.

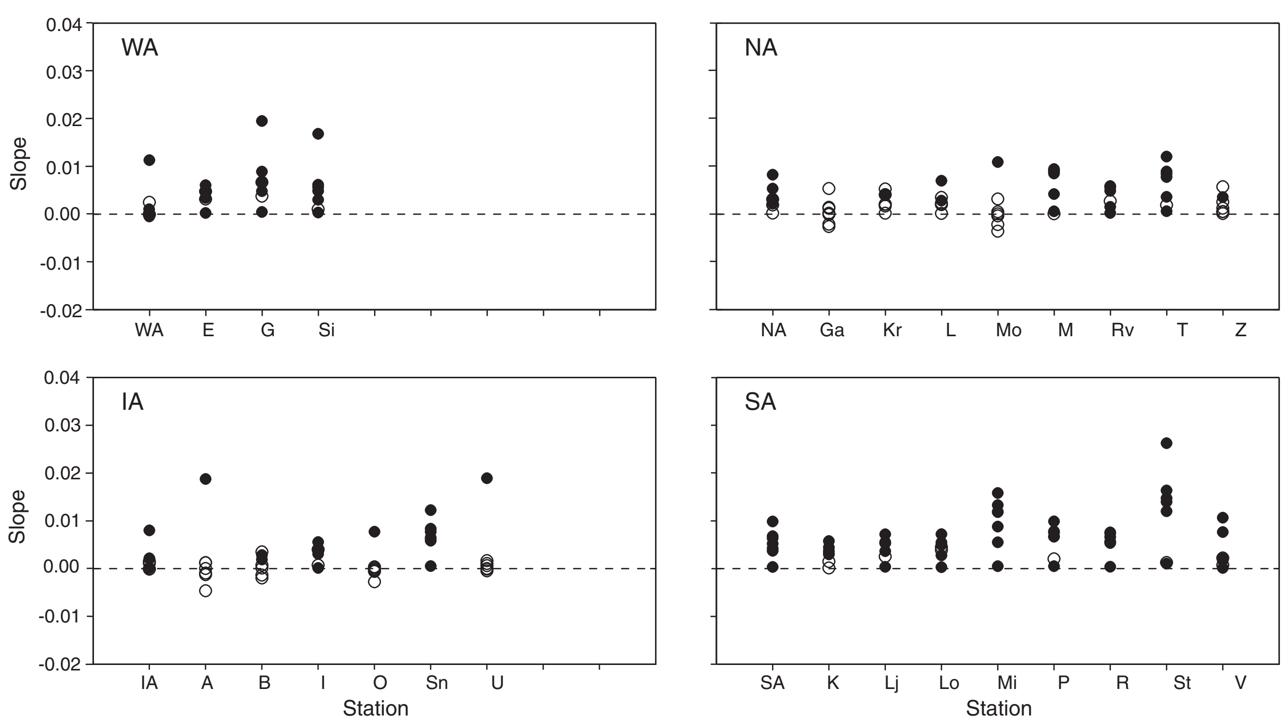

Fig. 5. Trends of the 95th percentile of different indices (each index one circle) at stations within regions (see Fig. 1 for abbreviations). The leftmost column of circles in each panel refers to the regional mean. The values on the *y*-axis are normalized slopes. The four panels represent the four regions Western Alps (WA), Northern Alps (NA), inner Alpine area (IA) and Southern Alps (SA). Filled circles indicate statistically significant trends and empty circles non significant trends, respectively.

The analysis is based on regional averages calculated as a simple arithmetic mean of the index values of the respective stations in each region. Figs. 4 and 5, containing the individual station values in addition to the regional average (first data points in each panel), demonstrate that regionalization is justifiable. Additionally, a calculation of the temporal autocorrelation of residuals was done as a basis for the significance tests. Since there was no significant autocorrelation in the time series of annual forest fire indices, we calculated temporal trends as linear regressions of the annual percentiles. The *p*-values of the regressions were used as indicators of the strength of the trends, according to a threshold value of 0.05. Furthermore, the residuals for all indices were more or less normally distributed which justifies the use of this classical approach. However, the very different dimensions of the indices were problematic. For instance: the Nesterov index in Ljubljana varied between 0 and 12,000, whereas the FWI only had values between 0 and 146 Hence we normalized the index values by a division by the average percentile value over the whole time period before calculating the slopes of the regression lines. Additionally, the sign of the slopes of some indices (Baumgartner and Angstrom) had to be changed to ensure that a positive slope implies an increase of meteorological forest fire danger.

A positive shift of an index can be induced either by higher absolute index values or by an increase of days with elevated index values. To pick out whether the number of days with meteorologically high fire danger has changed during the past six decades the 95th percentile of the whole time period was calculated for each index and was used as our threshold for such events. Hence, we counted the number of days exceeding this threshold for each year and for each index. We then averaged over the seven different indices and did a linear regression over the past 60 years.

Furthermore, we also looked at changes in the occurrence of extreme index values (highest index value per year in each region) over the past 60 years. Since traditional statistical approaches are not always adequate for analyzing extreme events, we applied the extreme values statistics to our fire danger database (e.g. Moritz, 1997; Beverly and Martell, 2005). Here the occurrence rate of extreme values is described by the tail of a probability distribution, which can be approximated by using the generalized extreme value distribution GEV (Embrechts et al., 1997; Coles, 2001). A standard approach in extreme value statistics describes the probability distribution of the most extreme values within a block of consecutive data points (block maxima method). Hence, we created for each index a time series of the highest annual index value (block length of one year) in all four regions. To convey information about the likelihood of rare events we used the concept of return levels and return periods. The return level is defined as the minimum standardized anomaly that is expected to be exceeded in a pre-specified number of years. Alternatively, the return period is the number of years one should expect to wait for exceedance of a particular return level. The two inverse indices Baumgartner and Angstrom have been transformed to ensure that a high return level implies a high fire danger. To assess temporal trends in extreme values we split the 60-year periods into two sub-periods of equal length (1951–1980, 1981–2010). The generalized extreme value models were fitted with the R package ismev (Stephenson, 2010), the plots were created with the extRemes toolkit (Gilleland et al., 2010; Stephenson and Gilleland, 2006).

In the statistical comparison between calculated meteorological fire danger and observed forest fires in Section 3.3 we applied a multiple linear regression. Hence, the trend in number of fires is calculated as a function of time (year) and the meteorological fire danger. Thus, we can better distinguish between anthropogenic and meteorological effects in the observed forest fire trends.

3. Results and discussion

3.1. Climate data

Before discussing trends in forest fire danger we start by assessing how long-term temperature and precipitation trends in the respective regions have developed under recent climate change.

3.1.1. Temperature

Trends of annual mean temperatures (thin lines) and annual average daily maximum temperatures in the time period 1951–2010 are displayed in Fig. 2 for each of the four regions described in Section 2.1. The four regions were characterized by different temperature regimes, with annual mean temperature ranging from 6.6 °C (for the climate normal period 1971–2000) in the inner Alpine region (IA) to 10.5 °C in the Southern Alps (SA). The strong differences can partly be attributed to the high altitudes of the stations in the inner Alpine area. Comparing the individual stations, the spread in annual mean temperature was between 3.0 °C in Obergurgl at 1938 m (IA region) and 16.1 °C in Venice on the Adriatic Sea (SA region).

Annual mean daily maximum temperatures (bold lines) were highest in the Western Alps (WA, 15.5 °C) and lowest in the inner Alpine region (IA, 11.6 °C). However, from Fig. 2 it is clear that the signal of climate change was quite similar in the different regions: The strongest temperature increase occurred from the end of the 1970s/beginning of the 1980s onwards and can be mainly attributed to forcing by greenhouse gases (IPCC, 2007). Mean annual temperature increase in the 60 years under consideration was between 1.1 °C in the IA region and 1.7 °C in the WA region. These trends were all statistically significant ($p < 0.02$). Surprisingly, the inner Alpine area exhibited a comparatively low temperature increase, because higher mountain areas are usually expected to be more strongly influenced by climate change than the surrounding flatlands (IPCC, 2007). At this point it has to be mentioned that the stations were not tested regarding homogenization. Hence, some stations in or near cities (Geneva, Zürich, Munich; Reinhard et al., 2005) were possibly more affected by urbanization and consequent temperature increases than meteorological stations in small Alpine valleys (e.g. Obergurgl in the IA region).

Because maximum temperatures are essential in assessing forest fire danger we also included average daily maximum temperatures in Fig. 2. These were also subject to a very pronounced increase (all $p < 0.02$) over the past six decades, but the differences between regions were not as large (between 1.3 °C and 1.6 °C) as for the mean temperatures. This confirms the theory of inhomogeneous station series, because urbanization primarily influences night temperatures and has a relatively low effect on maximum temperatures. Nonetheless, the strongest warming for this parameter also occurred from the late 1970s onwards.

3.1.2. Precipitation

Fig. 3 shows the precipitation climatology for the four regions in the Alps. As with the temperature analysis in Fig. 2, precipitation characteristics varied markedly between the regions. The mean regional annual precipitation sum differed between 768 mm (averaged over 1971–2010) in the driest region (WA) and 1324 mm in the Southern Alps. The station with the highest annual accumulated precipitation was Locarno (1800 mm) on the southern slopes of the Swiss Alps, and the lowest was Sion (580 mm) located in a deep valley in the Western Alps. Generally, stations in deep valleys of the main Alpine crest (Umhausen, Obergurgl, etc.) were characterized by low precipitation sums due to strong rain-shadowing effects of the high surrounding mountains. In contrast, stations south of the Alps exhibited extraordinarily high precipitation sums due to effective orographic precipitation enhancement in connection with southerly flows (e.g. trough (low pressure system) over Western Europe). The seasonal precipitation distribution differed between the Alpine regions. While the greatest precipitation north of the Alps usually occurred in summer (convection), autumn and winter were the seasons with highest precipitation amounts south of the Alps. The long-term trends of precipitation sums in Fig. 3 were not as clear as for the temperature analysis. The upper numbers in this figure show the relative change of annual precipitation sums based on a linear regression over the past 60 years. No clear precipitation trend was evident for the regions, except for the Southern Alps (SA). Here a slight decrease of about 8% in annual precipitation ($p = 0.02$) was observed which corresponded to a reduction of about 100 mm in absolute quantity. These findings are consistent with other studies (Rebetez, 1999; Schmidli and Frei, 2005) where the overall Alpine precipitation did not exhibit a significant trend, except in the Southern Alps.

In addition to the amount of precipitation, the temporal distribution of rainfall events is also considered to be crucial for assessing meteorological forest fire danger. Hence, the trends of days per year with gaugeable precipitation (>0.1 mm) are indicated by the bold lines in Fig. 3. Precipitation was most frequent in the NA and IA regions (average 170 days/year). In contrast, an average of 130 days/year was recorded in the Western Alps and Southern Alps. Nevertheless most precipitation fell in the SA region. Thus, this region was characterized by extremely heavy precipitation events (predominantly in autumn and early winter) and prolonged dry spells in summer. As for precipitation sums, only the SA region revealed a statistically significant trend ($p = 0.04$) with a decrease over the past 60 years by about 9% or 12 days/year in absolute numbers. The linear regression for the WA region (upper left panel in Fig. 3) indicates an increase of precipitation days of about 8%, but this trend was not significant ($p = 0.09$).

3.2. Forest fire danger trends

3.2.1. Mean forest fire danger

The statistical analysis of the 50th percentile for the three stations in the WA region (upper left panel in Fig. 4) revealed an increase in the mean annual forest fire danger during the last 60 years from 0 to 0.02 in normalized numbers. Only at Geneva (G) did one index (Baumgartner) increase considerably more (0.042). For a better understanding of these normalized slopes the following example is given: a slope of 0.01 for the median of the Nesterov index in Geneva means an increase of the index during the past six decades from 112 to 184, thus by about 1% per year.

The variation between the trends in indices in the WA region was quite small and nearly all indices showed a positive trend. The proportion of significant trends was very high (5 or 6 out of 7), only in Sion some trends in indices were not significant.

The situation in the Northern Alps (NA) was different. Even though the differences between the indices were quite small regarding the regional mean, the variation within the eight stations was quite high. Additionally, the signs of the slopes were also different. At Garmisch (Ga) and Zürich (Z) the 50th percentile of 6 out of 7 indices decreased during the study period, but most of these trends were not pronounced ($p > 0.05$). For all other stations the majority of the indices exhibited a slight increase of the mean annual fire danger, but the slopes were lower than in the WA region. In addition, the proportion of significant trends was less than in the WA region, except for Munich where all indices had clearly increased. To summarize, the mean fire danger trend in the NA region was not consistent between stations, but overall a slight increase (<0.01) was observed during the past 60 years.

The situation in the IA region was similar, but even more stations had a negative trend. In particular, at Aigen (A) and Bad Gastein (B) in Austria, most indices decreased. Trends at the high elevated station of Obergurgl (O, 1938 m) were not clear, with pronounced differences between indices. The stations in the vicinity of Obergurgl (St. Anton (Sn), Umhausen (U)) confirm this ambiguous signal. For the IA regional mean it is obvious that the mean annual fire danger in the central Alps has not substantially changed during the 60 years under consideration.

The clearest pattern is given for the region south of the Alps (SA) where the mean fire danger at nearly all stations strongly increased. At Milano (Mi) and Starse (St) increases were very high with normalized values up to 0.03. Moreover, the proportion of significant trends was the highest of all four regions. Only Locarno (Lo) did not show many pronounced index trends.

An examination of meteorological data in the Southern Alps reveals that the fire-relevant parameters precipitation and especially humidity have decreased in a non ambiguous way at all stations. Hence, the regional mean in the Southern Alps indicates positive slopes for all seven indices, with a maximum value of 0.03 for the German Baumgartner index. This is equivalent to a relative enhancement of this index of more than 80% over 60 years.

Comparing the slopes of the different indices, the two German indices Baumgartner and M-68 generally revealed the highest positive values in all four regions. This can primarily be explained by a pronounced temperature dependency of these two indices. Since temperature is the parameter that has changed most distinctively in recent decades, the slopes of these two indices are especially high. The indices with the smallest slopes were generally the Australian McArthur and Swedish Angstrom index, which both strongly depend on humidity and precipitation, respectively.

3.2.2. Days with high forest fire danger

The number of days with exceptionally high meteorological fire danger was assessed by the 95th percentile, hence the top five % of daily index values during a year. The trends for the three stations in the Western Alps and the WA regional mean are displayed in the upper left panel in Fig. 5. Note that the scale of the *y*-axis is different from Fig. 4. All stations in this region showed positive trends with slopes up to 0.02, which is comparable to the mean trends in Fig. 4.

The spread within WA stations was quite small and the Baumgartner index again had the strongest increase. The regional mean (WA) confirms the slight increase in high fire danger events during the past 60 years in the Western Alps. A rise in the 95th percentile of an index can be caused in two different ways. Either it is possible that the number of days with high forest fire danger has increased or higher absolute index values could have led to an increase of the percentile values. Possible changes in the number of days with elevated fire danger will be the topic of the analysis in Section 3.2.3.

The pattern in the NA region was quite similar. The 95th percentiles at most of the NA stations had increased significantly with slopes between 0 and 0.02. For example, in Munich (M, slope of 0.01) the 95th percentile of the FWI increased from 6.0 in the 1950s to 8.9 in the 2000s which corresponds to an increase of almost 50%. However, the regional mean for the Northern Alps shows a positive slope with values that are definitely higher than in Fig. 4. This implies that high fire danger events in this region have increased more during recent decades than the mean annual fire danger did.

The IA regional mean of the 95th percentile in the inner Alpine area also slightly increased for most indices. The greatest rise was observed for the M-68 index with a normalized value of 0.01. There are distinct differences between stations in this region. As for the mean fire danger in Fig. 4, the trends at Aigen (A) and Bad Gastein (B) were not consistent, and the proportion of significant trends was quite low. In contrast, the high fire danger events at Innsbruck (I) and St. Anton (Sn) have strongly increased with slopes of more than 0.01. The situation at the high-altitude station Obergurgl (O) is ambiguous.

The region with the strongest increase was again the region south of the Alps (lower right panel in Fig. 5). The SA regional mean of the slopes was generally high for all indices, taking values between 0.005 and 0.01 which relate to 60-year increases of between 40% and 70% in relative numbers. Only the McArthur index changed less, but trends for all seven indices were statistically significant. A comparison of the SA regional mean values of the 95th percentile with those of the median in Fig. 4 reveals that the slopes are more or less of the same magnitude. The eight individual stations within this region show a quite consistent pattern. In particular, at the easternmost station Starse (St) the 95th percentile changed very markedly, with a maximum value of 0.03 for the M-68 index.

In summary of the 95th percentile, all four regions revealed a pronounced increase of the meteorological fire danger with the highest slope rates in the Southern Alps. Comparing these indices, the German indices Baumgartner and M-68 showed the greatest changes and the Australian McArthur index the smallest which can be attributed to the different characteristics of the indices. The range of the slopes (<0.02) is comparable with those of the 50th percentile in Fig. 4, but the proportion of significant trends for the 95th percentile is slightly higher than for the median. Moreover, there are only a few stations with a negative slope in Fig. 5, which implies that the trend toward more and stronger fire danger events is quite general across the whole Alpine area.

3.2.3. Frequency analysis

To assess temporal changes in the frequency of extreme fire danger days we used two different approaches. Firstly, we calculated the annual number of days above a certain threshold (the 95th percentile for the whole 60-year period) for the regional means (Fig. 6). Secondly, we applied extreme values statistics to calculate return periods of extreme index values in each region (Fig. 7).

The upper left panel in Fig. 6 shows that in the WA region 3 years with an exceptionally high number of days with elevated meteorological fire danger have occurred (1953, 1962 and 2003). The maximum number was reached in 1953 and 2003, when around 60 days exceeded the overall 95th percentile in this region. All three years were very dry with extreme hot summers and scarce precipitation events. In some years (e.g. 1977, 1978) the indices barely reached the threshold on any day.

The 1960s and 1970s were generally characterized by low forest fire danger in the Western Alps. The linear regression line for this region produces a positive slope of 0.08 days/year, which equates to an increase of 5.1 days during the whole period. However, this trend shows a low statistical significance with a p-value of 0.34.

The situation in the Northern Alps (NA) is a little different. The years with the highest number of extreme fire danger days occurred in 1976, in the early 1990s (1990, 1992) and in the extraordinarily hot summer of 2003. In these years between 40 and 50 days exceeded the 95th percentile threshold, thus the peaks are distinctively lower than in the WA region. In general, the fire danger in this region was quite low compared to the other regions. The value of the 95th percentile of the FWI, for example, was 8.3 in the NA region; distinctly lower than in the WA region (13.9). This is mainly due to the high precipitation sums and the very frequent precipitation events north of the Alps. The variance between years is also very high. After the extreme year 2003 with more than 40 days exceeding the threshold, the weather in the following year 2004 was not very favorable to forest fires and hence only 7 days exceeded the threshold. The linear regression for this region showed that the number of extreme fire danger days has increased from an average of 13 days per year in the 1950s to 23 days per year in the 2000s, which corresponds to an increase of 76%. Even though the variance between years is quite high, the long-term trend is statistically significant ($p = 0.03$).

The trends in the 95th percentile for the regions WA and NA are similar (see Fig. 5), but the number of days with high fire danger in region NA increased twice as much as in the WA region (Fig. 6). This implies that extreme index values have changed more in region WA, while in the NA region the number of fire danger days has considerably increased.

The results in Fig. 5 have shown that the IA region is characterized by a relatively weak climate change signal in the meteorological fire danger and by a high variance between stations. This is confirmed by the analysis summarized in Fig. 6. The slope of the regression line is the lowest of all four regions. At some stations (e.g. Obergurgl, Umhausen) a negative trend was even observed. The absolute maximum occurred in 1976 (45 days), which was characterized by an extreme dry spring in the inner Alpine valleys.

The clearest and strongest trend was observed at stations in the Southern Alps (SA). In the first 30 years of our investigation the annual number of days was mostly below 20, only in some years (1961, 1962) reaching values around 30. After 1980 the frequency of fire danger days has distinctly increased with numbers above 20 in most years. The increase in high fire danger events is consistent with the pronounced temperature increase during the last 30 years (see Fig. 2). The absolute maximum in this region occurred in the extreme summer of 2003 when more than 60 days were classified as high fire danger days in our analysis. The slope of the regression line, which was statistically highly significant ($p < 0.01$), was 0.38 days/year which corresponds to an increase of 23 days over the last 60 years. This rise is impressive, because the most recent three years were quite wet and therefore not so favorable for high fire danger south of the Alps. In this analysis it should be noted that the 95th percentile threshold for the SA region was the highest of the four regions (e.g. 14.9 for the FWI).

The generalized extreme values return level plots for the different fire danger indices are displayed in Fig. 7. A comparison between the white (1951–1980) and the black (1981–2010) line reveals shifts in the extreme value distributions in the four regions under consideration. For example, the Baumgartner index of 40 in region WA had a return period of 70 in the time period 1951–1980 and a return period of 8 in the recent 30 years, which indicates that such an event has become much more frequent in this region. The return periods of the Baumgartner index have also decreased significantly in the SA region, while in the Northern Alps and in the inner Alpine region the two lines are very close. For the other indices the signal is quite similar, with decreasing return periods especially in the WA region and south of the Alps. Interestingly also in the IA region the annual extreme values of 5 out of 7 indices were higher in the recent 30 years than in the period 1951–1980, which represents a significantly higher proportion than for the slopes in the 95th percentile in Fig. 5. In the NA region the two lines are generally very close which confirms the weak trends of the percentile analysis. The shading in Fig. 7 shows the 95% confidence interval, but especially for high return periods it should not be over-interpreted because it represents the edges of the generalized extreme value distributions.

To summarize the results of this frequency analysis, the pronounced temperature increase over 60 years due to global warming has resulted in an enhancement of the occurrence of days with exceptionally high fire danger in all four regions, with the strongest trends in the Western and Southern Alps.

3.3. Comparison with fire data

The results presented so far have referred to a potential fire danger based on data from weather stations or calculated fire weather indices and do not necessarily correspond to actual forest fires. A specific analysis of the various indices against historical forest

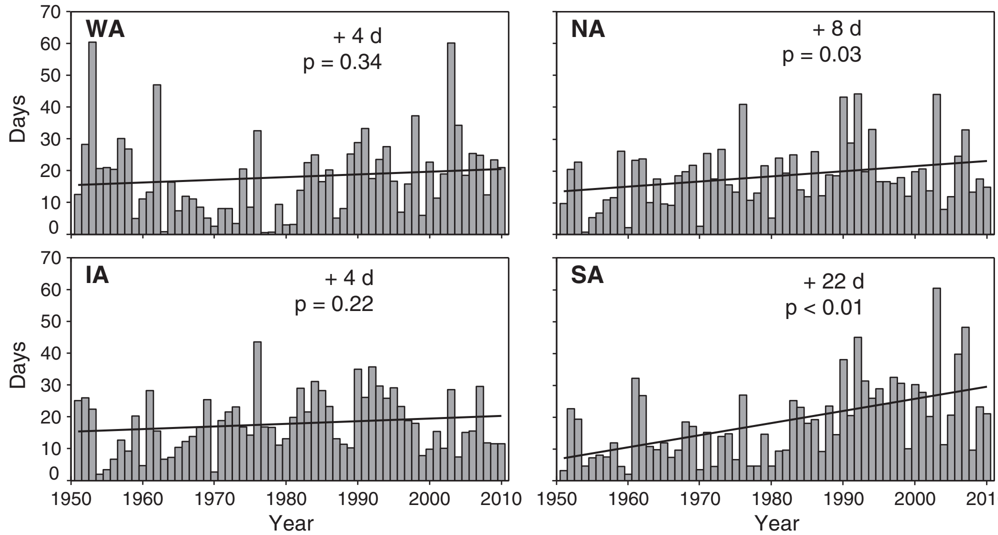

Fig. 6. Annual number of days that exceeded the 95th percentile of the whole 60-year period. The four panels represent the four regions Western Alps (WA), Northern Alps (NA), inner Alpine area (IA) and Southern Alps (SA). The thick lines illustrate the temporal trends based on linear regression. Numbers indicate the absolute change in the number of days from 1951 to 2010 based on a linear regression (upper numbers) and the respective statistical significance (lower numbers).

fires is beyond the scope of this paper (see e.g. Viegas et al., 1999), but to assess our achieved results we compare the index values with long-term datasets of observed fires. At this point it has to be mentioned that the acquisition of forest fire data in the Alps is encountered with difficulties because each country (sometimes even region) has its own reporting system with different regulations. Hence, we can make a comparison with observed fires only for some selected pilot areas. Our study areas in this context are the Swiss canton Valais which contains the station Sion in the WA region, Bavaria in southern Germany, a region that is located north of the Alps and that contains some of the stations in the NA region in Fig. 1 (Munich, Traunstein, Garmisch-Partenkirchen) and the Swiss canton Ticino, which is located south of the Alps and contains the station Locarno in the SA region. The forest fire data of Switzerland were collected by the cantonal forest services and centralized into a database by the Swiss Federal Institute for Forest, Snow and Landscape Research WSL (Pezzatti et al., 2010). In Bavaria the forest fire dataset was collected by the Bavarian State Ministry of Food, Agriculture and Forestry (Bayerisches Staatsministerium für Ernährung, Landwirtschaft und Forsten) and was published in annual reports. Unfortunately, we lack fire data from a pilot area in the inner Alpine region, because no long term records of forest fires are available in Austria (archived only since the 1990s, incomplete). But the forest fire data of the pilot area Valais can somehow also be considered as representative for the inner Alpine region, because this canton is quite large and its eastern part shows distinctive characteristics of an inner Alpine valley with low precipitation sums and comparatively high summer temperatures (Zumbrunnen et al., 2009).

Fig. 8 shows the annual sum of forest fires and the respective burned area in Valais, Bavaria and Ticino. The Swiss canton Valais is generally a region with very few forest fires. On average in the last 60 years 9 forest fires have occurred per year burning an area of about 30 ha. On the other hand, looking at the bars and the black line in Fig. 8 also shows that in some years (1979, 1981 and 2003) very big (for Alpine conditions) fires have occurred burning several hundred hectares. The absolute maximum occurred in 1981 when only 4 fires burned nearly 500 ha. The formation of such big fires can be explained by the usually low occurence of fires (moderate fire-fighting capacities), the coniferous vegetation types more prone to crown fires and the steep topography, which causes additional difficulties in fire-fighting (bad accessibility). The correlation between the number of forest fires and the area burned is generally quite low (0.21, $p = 0.10$).

In Bavaria, in the last 60 years on average 95 forest fires have occurred per year burning an area of about 60 ha. But the variation between years is very high with values ranging from less than 20 fires burning only 10 ha (2008) to more than 350 fires burning almost 220 ha (1976). The characteristics of the bars and the thick black line in Fig. 8 reveals a positive relationship between number of fires and burned area. The correlation coefficient between these two variables is 0.74 and the relationship is statistically highly significant with a p-value < 0.01. This implies that the average size of forest fires, which normally lies between 0.5 and 1.0 ha, has not changed very much over the 60 years under consideration. Only in years with very big (in a regional sense) forest fires did the average fire size exceed 2 ha (1955, 1961).

In Ticino, the average number of fires per year was 68 and the respective area burned 675 ha, thus more than 20 times larger than in Valais and about 10 times larger than in Bavaria. This is all the more remarkable considering that the forest area in Ticino (1300 km^2) is similar to that in Valais (1200 km^2) and much smaller than in Bavaria (25,000 km^2). This fact underlines that forest fires have been a considerably bigger problem south of the Alps. The average size of forest fires in Ticino is about 10 ha (same dimension as in Valais, 15 times that in Bavaria) but also here the variation between years is high. The absolute maximum occurred in 1973 when 180 fires burned more than 7200 ha of forest (truncated in the figure). The correlation coefficient between number of fires and area burned is 0.67 with a statistical significance $p < 0.01$.

Comparing the fire statistics of Valais with the frequency analysis for the WA region (Fig. 6) reveals a quite low correlation between observed fires and calculated meteorological fire danger. Many of the years with an extreme high number of forest fires (1956, 1957, 1962, 1990, 1996 or 2003) do not show an exceptional high number of days above our 95th percentile threshold. Only in the year 1962 and in the very hot summer 2003 a large number of high fire danger days resulted in many forest fires burning a large area. On the other hand, in some years with an exceptionally high meteorological fire danger (e.g. 1953, 1998) only very few fires occurred (7, 16). To assess the statistical relationship between meteorological fire danger and observed fires we calculated the Spearman's rank correlation. The correlation coefficients with meteorological

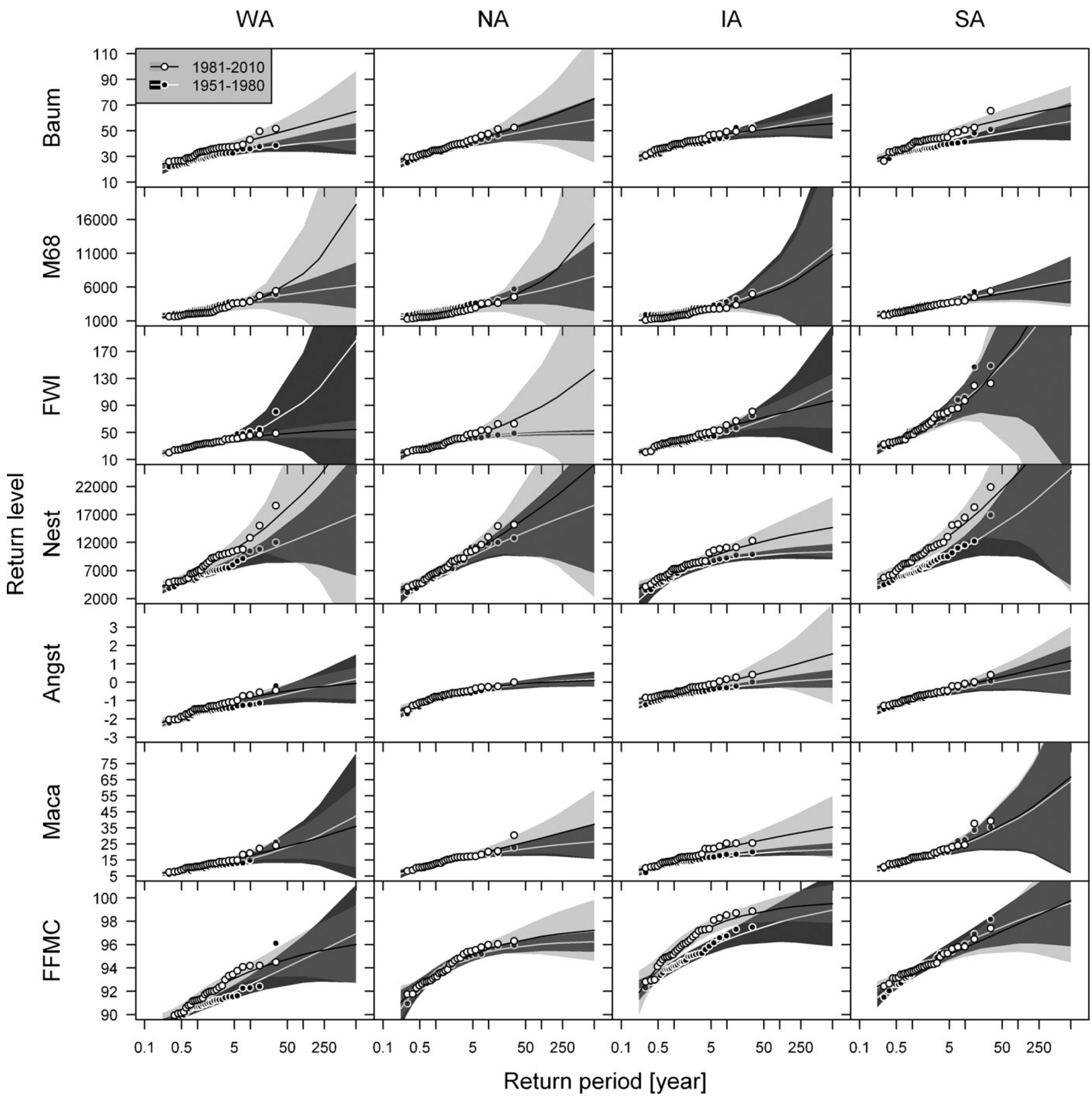

Fig. 7. Generalized extreme value return level plots for the different fire danger indices in the 4 regions under consideration. The white line with the black circles refers to the time period 1951–1980, the black line with the white circles to the period 1981–2010. Shading indicates the respective 95% confidence intervals.

fire danger in Valais are quite low with values of 0.41 for number of fires and 0.39 for the area burned with statistical significances of 0.002 and 0.003, respectively.

In the frequency analysis for the NA region (Fig. 6) the years 1976, 1990, 1992 and 2003 were characterized by an exceptionally large number of days (more than 40) above our 95th percentile threshold. These peaks can mostly also be found in the fire statistics in Fig. 8. The two years with the highest burned area in Bavaria were 1976 and 2003 with 220 and 210 ha, respectively. There were 350 fires in 1976 and 185 in 2003. The agreement between calculated fire danger and observed fires is also quite good for the 1990 peak in Fig. 7. In this year the number of fires (180) and the area burned (105 ha) were considerably higher than in the previous years. Only the local maximum in the calculated fire danger in 1992 cannot be found in the historical fire statistics.

The agreement with the forest fire danger indices in Bavaria is not so good in years with a low number of recorded fires. Most of the local minima in Fig. 8 (e.g. 1965, 1978, 1994 and 1995) are not apparent in Fig. 6. This can be explained by the nature of forest fire ignition. As the large majority of forest fires (>95%) in this study area are caused by human activities, the annual number of fires strongly depends on factors other than meteorological ones. Hence, the fact that in one year only a few fires have been observed does not imply that the fire danger was generally low during the whole fire season. It is also possible that the number of ignitions during the periods of high fire danger was very low due to public warnings, prohibitions,

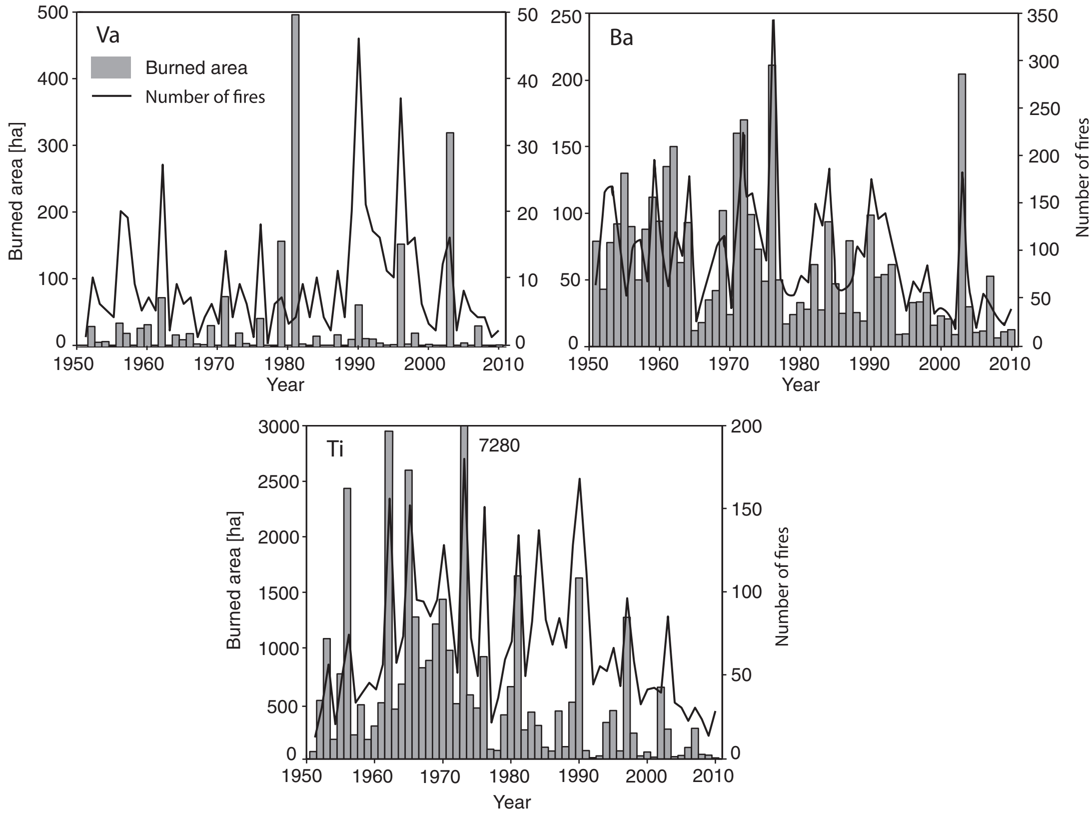

Fig. 8. Annual number of forest fires (black line) and respective sum of area burned (in ha, gray bars) for the time period 1951–2010 in Valais (Va) in the Western Alps, Bavaria (Ba) in the Northern Alps and Ticino (Ti) in the Southern Alps.

etc. In contrast, in years with an exceptionally high area burned by forest fires the meteorological conditions also have to be favorable because without high temperatures, strong winds, etc. it is not usually possible to create numerous big fires. Looking at the Spearman's rank correlation coefficients between meteorological fire danger and observed fires reveals quite low values with 0.41 for the number of fires and 0.18 for the area burned with statistical significances of 0.003 and 0.168, respectively. These low correlations underline the strong anthropogenic influences on forest fires in this pilot area.

The correlation between observed fires and calculated fire indices in Ticino is generally low. Neither the extreme fire year 1973 nor the other local maxima in 1962, 1965 and 1990 can be found in the frequency analysis for region SA in Fig. 6. Hence, the rank correlation coefficients with meteorological fire danger are also very low with values of 0.12 for number of fires and −0.14 for the burned area. Neither of these relationships is statistically significant. Besides the above mentioned anthropogenic reasons, the seasonal distribution of forest fires also plays a decisive role in this context. South of the Alps forest fires mainly occur during the non vegetative season (winter season and in early spring, between December and April) when precipitation amounts are low and leaf unfolding has not yet started (Rebetez, 1999). Moreover during those months many regions south of the Alps are also characterized by several days with strong gusts of a katabatic (descending) dry wind from the north (foehn), which causes drops in the relative humidity to values as low as 20%. However, the majority of the index values in this period are generally lower than in summer due to the low temperatures. For instance, in a year with a dry winter and many forest fires (e.g. 1973) our frequency analysis did not reveal a local maximum because the 95th percentile threshold was barely reached in winter. Hence, we repeated the statistical analysis separately for vegetative and non vegetative periods. The rank correlation coefficients in the vegetative period were now significant (0.61 and 0.45) and the local maxima in the calculated meteorological fire danger (1976, 1990, 2003 and 2007) can also be found in the fire statistics. At this point it has to be mentioned that the percentage of naturally occurring forest fires (by lightning) in Ticino is very high during the summer season (up to more than 30%). In this region lightning-induced fires are originated by the thunderstorms developing also during dry summer months, and occur comparatively at higher elevations, on steeper slopes and mainly in coniferous vegetation types (Conedera et al., 2006).

Looking at temporal trends in Fig. 8 shows a slight increase in Valais for both, the number of fires and the area burned. A linear regression (not shown) reveals an increase in the number of fires from 8 in the 1950s to 10 (+25%) in the last decade and a respective increase from 22 ha to 39 ha (+70%) in the area burned, both trends being not statistically significant ($p > 0.05$), Hence, the positive trend in the meteorological fire danger in the WA region could also be found in the observed forest fire statistics. Pezzatti et al. (in press) suggest that the increase in forest fires in Valais may be due mainly to the land use change in the 1950s, when livestock grazing in forests and litter collection were progressively abandoned, and to an increment in forest area and the increase in number of days with high fire weather danger later in the 1980s.

The slope of the regression line (not shown) in Fig. 8 would clearly be negative for the region NA. During the past six decades the annual area burned by forest fires in Bavaria has decreased ($p = 0.03$) from around 95 ha in the 1950s to less than 25 ha in the last decade, which corresponds to a relative decrease of more than 75%. The annual number of forest fires also has a significantly negative trend. From 130 fires on average in the early 1950s the number has continuously decreased to less than 60 fires in the 2000s. These trends in the historical forest fire database in Bavaria are in sharp contrast to the positive slope of the meteorological fire danger. Reasons for these contrasting trends can again be found in the nature of forest fire ignition. The number of fires and especially the area burned by forest fires in Bavaria is strongly dependent on anthropogenic factors as well as meteorological conditions. An examination of ignition sources, which were also recorded in the fire database, revealed that in the first few decades after the Second World War a large proportion of fires were caused by the military. A reduction of military exercises, improved technical equipment and better preventive measures have led to a clear reduction in the number of forest fires ignited by military actions. Furthermore, the technical progress in public transport (a switch from steam to diesel and electric locomotives) is another reason for the decrease of forest fires in Bavaria. Human behavior has also clearly changed over the past decades. Fire clearance was a common silvicultural practice in Germany in the 1950s, 1960s and 1970s. Currently, this method is used rarely and only on a small scale. Public warnings and temporary prohibitions of e.g. barbecue, naked flames, etc. in periods with high fire danger have also resulted in a moderation of human activities. Last but not least, technical progress has improved the efficiency of the fire suppression system. New technologies (e.g. helicopters, fire trucks, etc.) and enhanced tools for extinguishing fires (more powerful fire engines, pumps, nozzles, etc.) are a few examples of faster and more efficient fire fighting practice. Furthermore, an increased population density and a higher mobility of people have also substantially improved forest fire detection over the past decades. All this has resulted in a decreasing number of forest fires and area burned, even though the meteorological fire danger has increased significantly over the past decades due to climate change

A multiple linear regression, where the number of fires is calculated as a function of time and meteorological fire danger, revealed a negative coefficient for the variable time (the above-mentioned anthropogenic reasons) and a positive coefficient for the meteorological variable in Bavaria. The *p*-values of both variables are <0.01 and the multiple correlation coefficient for this model is 0.71. This shows that there is a significant positive relationship between meteorological fire danger and observed fires in Bavaria, but this trend is counterbalanced by a decreasing trend of anthropogenic caused ignitions.

The temporal trend of observed forest fires in Ticino in the Southern Alps is not linear; with an increase in number of fires and burned area until the 1970s and a subsequent general decrease. The increase at the beginning of our data series has its origin in important socio-economic and land-use changes starting in the mid-1950s, with the abandonment of extensive agriculture and the related forest litter management (Pezzatti et al., in press). The decrease in the past three decades can be traced back mainly to the fire brigades reorganization, fire prevention measures in case of high fire danger and a legal act regarding the interdiction of burning garden debris in the open (Pezzatti et al., in press). Regarding only forest fires in the summer season, there has been a slightly positive trend over the past 40 years in Ticino (high percentage of natural ignition causes). The multiple linear regression (made only for the time period 1971–2010) revealed a negative correlation between number of fires and time and a positive relationship between number of fires and meteorological fire danger. Both correlations are significant and the multiple correlation coefficient for this model is 0.61. Hence, also in the region south of the Alps an increasing meteorological fire danger is associated with more forest fires.

4. Conclusions

The results of our study indicate that global warming due to forcing by greenhouse gases does not have a homogeneous impact on the Alpine climate. While temperatures during the past 60 years have increased area-wide, the signal of precipitation changes is much more complex and variable on a small scale. In addition to these two well investigated parameters (e.g. IPCC, 2007) global warming may also have an influence on many other meteorological parameters such as humidity, wind or sunshine. Since the risk of a forest being ignited (e.g. by human activities, lightning) is strongly dependent on a combination of different meteorological conditions (especially temperature, precipitation, wind and humidity) it is extremely difficult to assess climatological changes in forest fire danger. Furthermore, forest fire danger also depends on the composition of vegetation, litter, etc. which itself is altered by increasing temperatures. One approach to integrate many of these factors is to calculate statistical trends of forest fire danger indices. The diversity of such indices is very large and therefore we picked out only the most common ones (Baumgartner, M-68, FWI, FFMC, Angstrom, Nesterov, McArthur). For a direct comparison of the different indices we applied several conversions and adaptations.

As a first analysis we calculated an average mean annual fire danger from the 50th percentile of each index distribution. The slopes of the respective regression lines south and west of the Alps were clearly positive indicating an increase in the mean fire danger in these regions. The variation between stations in these regions was quite low and a high proportion of the trends were statistically significant. The situation north of the Alps and especially in the inner Alpine valleys was much more difficult to describe with a high proportion of statistically non significant signals.

To find out whether the high index values have changed we analyzed the 95th index percentiles. At nearly every station a trend toward higher index values was evident, with strongest slopes again for the region south of the Alps. Only some stations in the inner Alpine valleys and at the northern slopes of the Alps did not change significantly during the past 60 years. To distinguish whether the frequency of extreme forest fire danger events or the absolute index values had changed, we also did a frequency analysis. For this purpose we analyzed the annual number of days above a certain threshold (95th percentile of the whole period). Generally the number of days with high index values increased across the Alps, but the slopes in the inner Alpine area and interestingly also in the Western Alps were very low. This implies that at the stations in the Western Alps the frequency of dangerous days has changed only slightly but these days have become more extreme. The stations south of the Alps again experienced the strongest changes. This fact was underlined by the analysis of return levels of the highest annual index values, calculated by generalized extreme value distributions.

We compared our results to observed forest fires in three pilot areas (Valais, Bavaria, Ticino). In Valais (Western Alps) the correlation between meteorological forest fire danger and observed fires was generally quite low, but the positive trend in the fire danger indices could also be found in the forest fire statistics. In Bavaria (Northern Alps) this correlation was generally quite good, but in contrast to the meteorological forest fire danger, the observed fires and also the annual area burned have significantly decreased over the past 60 years. Since the majority of forest fires in this region are ignited by human activities (accidental or deliberate) we had to search for the reasons of these contrasting trends in social changes. Reduced military activity, replacement of steam power in public transport, changing silviculture and a better public awareness (fostered by forest fire danger warnings and prohibitions) have led to a distinct decrease of forest fires in southern Germany even though the meteorological conditions have become more favorable to forest fires.

The correlation between calculated indices and observed fires south of the Alps was considerably lower because here most of forest fires occurred in winter when the meteorological fire danger is usually low. A multiple linear regression revealed that in this region the positive trend in meteorological fire danger over the past decades was also counterbalanced by decreasing anthropogenic ignitions.

The results presented in this paper are based on data from meteorological observations and indicate that recent global warming has already influenced forest fire danger in the Alps. Most of the changes in forest fire danger occurred in the years after 1980 and related to a rapid increase of global temperatures. Outputs of various climate models predict an amplification of this trend in the coming decades and, if no rigorous rethinking occurs, this will continue into the far future. In a forthcoming study we intend to adapt our analysis to regional climate models to make long-term predictions of forest fire danger in the Alpine area. Such predictions are of general interest because adaptation strategies of the Alpine environment to changing climatic conditions have to be agreed soon in order to keep damage low.

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