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Discussions

Forest fire danger rating in complex topography – results from a case study in the Bavarian Alps in autumn 2011

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Abstract

Forest fire danger rating based on sparse meteorological stations is known to be potentially misleading when assigned to larger areas with a complex topography. This case study examines outputs of several fire danger rating systems based on data from two meteorological stations in different elevations during a major drought period.

This drought was caused by a persistent high pressure system, inducing a pronounced temperature inversion with cool, humid conditions in the lower and warmer, dryer conditions in the upper layer. Thus, a massive drying of fuels, leading to a high fire danger level and multiple fire occurrences at higher elevations were contrasted by moderate fire danger in the valleys. The relative accuracy of fire danger rating indices was studied based on a comparison with the actual fire danger as determined from expert observations, fire occurrences and fuel moisture measurements.

The results revealed that, during temperature inversion, differences in daily cycles of meteorological parameters influence fire danger and that these are not resolved by standard meteorological stations and fire danger indices. Additional stations in higher locations or high-resolution meteorological models in combination with fire danger indices that accept hourly input data may allow reasonable fire danger calculations under these circumstances.

1 Introduction

1.1 Forest fire danger rating fundamentals and purposes

Forest fires are an important natural hazard influencing public safety, ecology and management as well as productivity of forests in many countries around the world. In order to facilitate fire danger assessment on a given day and location, fire danger rating systems have been developed which integrate meteorological variables (and potentially additional factors) to produce numeric indices of fire potential (Chandler et al.,

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1983; Davis, 1959; Pyne et al., 1996). These can be used as a management tool, e.g. for preparedness planning, public information and warnings, mutual assistance and scheduling of prescribed fires (Baumgartner et al., 1967; Camia et al., 2006; Pyne et al., 1996).

1.2 Effects of mountain meteorological phenomena on forest fires and fire danger rating

The diverse effects of mountain meteorological phenomena on forest fire danger and behaviour have been described by several authors (e.g. Butler et al., 1998; Gorski and Farnsworth, 2000; Holden and Jolly, 2011; Millán et al., 1998; Miller and Schlegel, 2006; Ryan, 1969). A comprehensive overview can be found in Sharples (2009). Key phenomena include changes of temperature and relative humidity associated with exposition and elevation leading to a distinctive spatial distribution of fuel types, effects on snow-melt and fuel moisture patterns, as well as diurnal mountain wind systems (e.g. thermally-caused along-slope, along-valley, cross-valley and mountain-plain wind systems, all affecting fire behaviour and especially the direction of fire spread). More complex features comprise temperature inversions (conditions more favorable to wildfires at higher than at lower elevations), thermodynamic Foehn winds (warm and dry katabatic lee slope winds causing high fire danger and intensive fire behaviour), dynamic channeling (a combination of upper winds and complex topography potentially leading to unexpected extreme fire behaviour and spotting), low-level jets (narrow currents of fast moving air influencing fire behaviour), and deflections and perturbations of airflows by mountainous terrain (mountain wind waves (e.g. gravity waves) linked to induced instability, strong gusty winds potentially leading to blow-ups; and thunderstorms with lightning as an ignition source) (Sharples, 2009).

Holden and Jolly (2011) modeled topographic influences on fuel moisture and fire danger from a network of temperature and relative humidity sensors, digital elevation models and one meteorological station. Their results show a high heterogeneity of fuel moisture and fire danger in the study area. In addition to aspect, cold air drainage and subsequent temperature inversion were found to be a major cause of this heterogeneity.

1.3 The general situation in the Bavarian Alps

Forest fire danger along the northern rim of the European Alps and in particular in southern Germany is usually quite moderate due to the temperate climate of the prevailing westerlies with relatively frequent year-round precipitation. Both large scale (orographically enhanced) and convective precipitation are the most important reasons for this (cf. Fig. 1); the summer maximum of precipitation is caused by convection which markedly decreases the forest fire danger when temperatures are highest. However, there are occasional dry spells during which fire danger can rise significantly. A considerable fire hazard can result when such periods occur in spring, when the dead ground fuels (grass) remaining from the previous year dry most rapidly.

Overall, these conditions lead to an average of 36 forest fires per year, affecting an area of 19.8 ha (reference period 2005–2011) in the whole State of Bavaria (total area 70 552 km^2, of which 35 % is forested). Most of these (few and small) fires occur in the lowlands with, on average, only two fires per year (8.8 ha burnt area per year) taking place in the Alpine area itself.

However, vulnerability to forest fires is much higher in the Alpine area than in the plains, because the steepness of the terrain, as well as the relative openness of forests near the timber line, cause much faster drying of fuels, more severe fire behaviour and more difficult fire-fighting operations (also reflected in the larger average burnt area per fire). Additionally, most Alpine forests have important protective functions (e.g. against avalanches, rock fall and debris flows) and a loss or disturbance of those forests is especially worrying. Last but not least, forest restoration in this terrain is definitely more difficult and expensive than in other areas.

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1.4 Autumn 2011 weather conditions

In autumn 2011, a meteorological situation occurred which resulted in a massive fire danger at the northern rim of the European Alps at a time when the first snows would normally have been expected. During this time, hardly any precipitation occurred due to persistent high pressure systems over Central Europe for more than one month. Mean precipitation recorded for the whole of Germany (approx. 3 mm) indicates that November 2011 was the driest month since the start of systematic meteorological observations in 1881 (DWD, 2011a). At many meteorological stations, no precipitation at all was registered. In contrast to the lowlands, where this drought event was accompanied mostly by foggy and cold weather, clear skies and high temperatures prevailed at higher elevations (DWD, 2011a; Zimmermann and Raspe, 2012; Raspe et al., 2012). This was due to strong subsidence in the high pressure systems causing very stable conditions with a distinctive temperature inversion during the nights and early mornings.

The fire danger was further increased by dry-warm katabatic Foehn winds from the south of the Alps on several days. In addition, some annual live fuels had already died off in a previous cold period and thus responded much faster to the drought event.

These meteorological conditions led to a massive drying of fuels: moisture contents $< 15\,\%$ dry-weight-basis in surface fuels (dead grass and forest litter) were measured by the authors during the dry period. Under this prevailing high fire danger, several fires occurred in higher elevation Alpine forests in Germany and Austria; one of these (the Sylvenstein reservoir fire) caused great concern as it burned for several days, was extremely difficult to put out, and with 15 ha accounted for almost half (47 %) of the annual area burnt in the State of Bavaria (Germany) in 2011.

Although this severe fire danger situation (by local standards) was very unusual, it shows features of mountain meteorology (temperature inversion, Foehn winds) which occur regularly in most areas with complex topography around the world. We examined the behaviour of six selected fire danger indices (Angstrom, McArthur's FFDI, FFMC,

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DMC as well as hourly versions of McArthur's FFDI and FFMC) during this period, focusing on the differences between the actual and calculated fire danger in the valleys and at higher elevations and their implications for fire danger rating and management.

2 Methods

2.1 Study site

In order to calculate fire danger indices for different elevations, a location within the Northern Alps was selected where two meteorological stations with a marked difference in elevation exist in close proximity. Garmisch-Partenkirchen, Germany is located in a wide basin surrounded by the Ammer Mountains (elevations up to 2340 m a.s.l.) to the northwest, the Ester Mountains (elevations up to 2086 m a.s.l.) to the east and the Wetterstein Mountains (including the Zugspitze, at 2962 m a.s.l. the highest mountain in Germany) to the south. The flat basin is used mostly for human settlements, infrastructure and agriculture, whereas the lower mountain slopes are covered by forests (approx. 800–1600 m a.s.l., depending on slope, exposition and human use). These forests are usually mixed forests dominated by Norway spruce (*Picea abies* (L.) Karst.), European silver fir (*Abies alba* Mill.), European beech (*Fagus sylvatica* L.) and Sycamore (*Acer pseudoplatanus* L.), although pure stands, especially of Norway spruce, can also occur. On south-facing slopes, a significant amount of Scots pine (*Pinus sylvestris* L.) stands can be found. Higher elevations are covered by grass, dwarf trees and shrubs, mainly Mugo pine (*Pinus mugo* T.), or bare rock.

2.2 Meteorological measurements

The meteorological station "Garmisch-Partenkirchen" is located on the valley floor (719 m a.s.l., 47.48° N 11.06° E). It is run by the German Meteorological Service (Deutscher Wetterdienst, DWD), and supplies hourly values of temperature and relative humidity as well as hourly means of wind speed and hourly precipitation sums.

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A second meteorological station "Felsenkanzel" (1260 m a.s.l., 47.51° N 11.07° E, 2.4 km horizontal distance from Garmisch-Partenkirchen station) is operated by the Technische Universität München. This station is located on a steep south-facing slope near the upper end of the altitudinal forest range and measures selected standard meteorological parameters (temperature, relative humidity, precipitation, and others) at 10 min intervals. The location of both stations as well as the local topography and areas covered by forest and human settlements are shown in Fig. 2.

In addition, atmospheric sounding data were obtained from the nearby radiosonde station at Innsbruck airport (47.26° N 11.35° E, approx. 30 km from Garmisch-Partenkirchen) to illustrate the vertical stratification of the atmosphere.

2.3 Data processing and fire danger index calculation

All available data for both stations were obtained for 2011. The 10 min data of Felsenkanzel were subsequently converted to hourly values and missing parameters (wind speed) were filled by respective data from Garmisch-Partenkirchen, since it was the closest meteorological station available. Some data gaps still remained, but these were short enough not to have any noticeable influence on index calculations.

A wide range of fire danger indices were calculated representing fire danger rating systems from several continents (North America, Europe, and Australia), and comprising very simple to rather complex formulations. Here, we only provide some brief information about these indices. Both fast- and slow-reacting indices are all based on standard meteorological observations only (since snow parameters and phenology, which are required for some specific indices, were not measured at Felsenkanzel). In order to identify even small variations in the index behaviour, all analyses are based on the direct index outputs, without any classification into a danger scale.

The Angstrom index is a simple Swedish fire danger index based on daily values of temperature and relative humidity taken at 13:00 LST (Chandler et al., 1983; Langholz and Schmidtmayer, 1993). Angstrom index values are high in times of low fire danger and low in times of high fire danger.

McArthur's Forest Fire Danger Index (FFDI, Mark 5, Noble et al., 1980) is used in Australia to rate fire danger. It is calculated from daily values of temperature, relative humidity, wind speed, and the Keetch–Byram Drought Index (Keetch and Byram, 1968). Calculations at higher temporal resolution were performed following the procedure described in Boer et al. (2008).

Both the Fine Fuel Moisture Code (FFMC) and the Duff Moisture Code (DMC) are components of the Canadian Forest Fire Danger Rating System (CFFDRS) and have been described in Van Wagner (1987) and Van Wagner and Pickett (1985). They are bookkeeping systems meant to track the moisture content of pre-defined fuels based on 12:00 LST meteorological observations. Whereas the fast-responding FFMC covers forest litter and other dead fine fuels and takes into account temperature, relative humidity, precipitation and wind speed, the DMC represents a 5 $\mathrm{kg\,m^{-2}}$ decomposing organic layer, not requiring wind speed inputs (Van Wagner, 1987). Starting values for 1 January were defined as 85 for FFMC and 6 for DMC (Van Wagner and Pickett, 1985).

Hourly values of FFMC can generally be calculated using the methods of Lawson et al. (1996) and Van Wagner (1977). There has been some discussion regarding the relative performance of those methods (Anderson, 2009; Beck and Armitage, 2001), however we preferred Van Wagner's (1977) method since it calculates hourly FFMC directly from hourly inputs.

2.4 Data analysis

The meteorological data and the fire danger indices described above were plotted for several time periods. Qualitative comparisons between the particular index progressions were made from visual inspections of these plots.

Independent fire danger assessments were available in the form of expert observations and fire occurrence data. Gravimetric measurements of dead fine fuel (forest litter, dead grass) moisture content were made by the authors on 8 November in the vicinity of the meteorological stations and again on 23 November 2011 (three days after the Sylvenstein reservoir fire mentioned above), also including a steep slope close to the

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fire location. Although they support the statements made in this paper, unfortunately all of these additional observations and measurements were sparse and are therefore not adequate for further statistical analysis.

All calculations and plotting were performed with R, version 2.15.0, its package RadioSonde, version 1.3, and ArcMAP, version 9.3.

3 Results

3.1 Meteorological conditions during the study period

Detailed meteorological conditions at both stations during the period of interest are plotted in Fig. 3. No precipitation was recorded at either station in the period from 27 October 2011 to 3 December 2011. During this period, temperatures ranged between −6.6 °C and 19.5 °C and relative humidity between 19 and 100 % (extreme values from both stations). However, distinct differences were observed between the two stations. On the valley floor, Garmisch-Partenkirchen experienced more pronounced daily cycles of temperature and humidity, and the mean daily minimum temperature in the period was well below freezing (−1.5 °C). Daily maximum relative humidity was frequently close to 100 % (cf. Fig. 3). In contrast the Felsenkanzel station at 1260 m a.s.l. measured less extreme daily cycles with a mean daily minimum temperature of 4.9 °C and a mean daily maximum humidity of 67.2 %.

This meteorological situation can be considered as a typical example of a stable boundary layer with nightly temperature inversion in complex terrain as it frequently occurs in most mountainous areas. Its relevance for forest fire danger will be considered later in this paper (Sects. 3.2 and 3.3). Southerly Foehn winds had only minimal effects in this area and period, since a large amount of cold air was present in the valley and the high, west–east oriented Wetterstein Mountain range acted as a barrier for these southerly winds.

An atmospheric sounding taken at Innsbruck during this period is shown in Fig. 4. From this Skew-T Log-P diagram, information about vertical profiles of temperature, dew point, and wind speed and direction through the atmosphere can be obtained. The temperature inversion near the ground is clearly visible at a height of up to 1600 m (840 hPa). Close to the ground, temperature and dew point were identical as the air was saturated and fog occurred. With increasing altitude, the temperature-dew point spread increased until reaching a maximum of 41 °C at 4550 m (580 hPa). In this layer, very dry air was present due to strong synoptical subsidence in the high pressure system. While at lower elevations almost no wind was measured, south–westerly to southerly winds of 21–39 knots could be found at higher elevations (above 4550 m/580 hPa).

3.2 Annual progression of selected fire danger indices

The annual progression of four of the selected forest fire danger indices for 2011 is shown in Fig. 5. In addition to the autumn event, a major drought period occurred in spring (end of April–beginning of May 2011) and another minor one in summer (end of August 2011).

Low values of the Angstrom index represent high fire danger and high values low fire danger, as opposed to all other indices shown here. Because of this, the Angstrom index values are plotted inversely in Fig. 5. Due to the high day-to-day variation in this non-cumulative index, the high danger periods described above do not show up very clearly in the index raw values of this graph. However, a local decrease of the Angstrom values during these periods and a rise of the index afterwards are detectable.

The Australian McArthur Forest Fire Danger Index also tends to react quickly, especially when dry conditions are combined with high wind speeds, and reveals the first and second dry periods rather clearly. While the summer event accounts for the maximum McArthur value, only a very moderate rise in the index could be observed in November. The overall values of McArthur's FFDI, however, are very low when compared to those occurring in its place of origin (Dowdy et al., 2009).

The CFFDRS's Fine Fuel Moisture Code (FFMC) is yet another fast reacting index, which gets close to its maximum value (100) after a few days without precipitation. During all danger periods, high or even near-maximum values of the FFMC could be observed. As the end of the scale was (almost) reached, there was no clear differentiation of the relative severity of the respective danger periods.

The Duff Moisture Code (DMC), however, responds more slowly to drought and shows the three events rather clearly. Because of its slower response, it suggests that in autumn the danger level was rising until the end of the drought event. The maximum danger values were obtained for the spring event (maximum value of 46), closely followed by the autumn (maximum value of 38) and summer drought (maximum value of 35) and another short September drought event (maximum value of 26).

When comparing the indices calculated for the two different climate stations (black and gray lines in Fig. 5), it could be noted that fire danger at Felsenkanzel was almost always equal or even lower than Garmisch-Partenkirchen. This is true even for large parts of the autumn drought period, when the actual fire danger, as described above, was supposedly much more severe at higher (e.g. Felsenkanzel) than at lower (e.g. Garmisch-Partenkirchen) elevations.

Supporting evidence for this exceptional pattern of fire danger in autumn 2011 is also found in expert-based assessments (e.g. in DWD, 2011a; Raspe et al., 2012; Zimmermann and Raspe, 2012 and information from local forest officers). It is further confirmed by multiple fire occurrences at these elevations in Germany and Austria and the fuel moisture measurements carried out by the authors. The latter ones showed distinctly lower values (and thus greater fire danger) at mid and higher elevations (gravimetric moisture content for dead grass and forest litter between 10 and 25 %) than near the valley bottom (litter moisture content > 40 %). Furthermore, the altitudinal variation in fire danger is nicely visualized in Fig. 6, showing rime-covered vegetation in a valley while firefighting activities were taking place near the ridge top.

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3.3 Diurnal meteorological conditions and their impact on fire danger and fire danger rating system calculations

In order to more closely investigate this striking fact, meteorological conditions and selected fire danger indices have been plotted for part of the autumn drought period (19–30 November 2011) in Fig. 7.

During this period it was quite obvious that the daily amplitudes of both temperature and relative humidity were generally much more pronounced in Garmisch-Partenkirchen (black lines) than at Felsenkanzel (gray lines). In fact, temperature was mostly very low and humidity generally very high at Garmisch-Partenkirchen, only for a short period after noon every day, the temperatures in the valley exceeded those measured at Felsenkanzel and the relative humidity was equal. The reason for this was the disintegration of the nocturnal temperature inversion by strong solar heating during the day in the prevailing high pressure systems. During the night the clear sky caused strong radiative cooling and a gathering of the coldest air in the valley floor (i.e. at Garmisch-Partenkirchen in our case). Hence, the meteorological differences between Garmisch-Partenkirchen and Felsenkanzel were more pronounced during the night. The strong daily cycle for Garmisch-Partenkirchen can be clearly observed at the beginning of the plotted period (19–22 November 2011), during which the previously mentioned Sylvenstein reservoir forest fire started (20 November 2011). Later on, with decreasing day length, the nocturnal temperature inversion and associated fog disintegrated less evenly, leading to less regular cycles of temperature and relative humidity (e.g. 24 November 2011).

Throughout the selected period, both the daily FFMC and McArthur's FFDI values (dashed lines in Fig. 7) were elevated or high and in contrast to reality, the fire danger at both stations was rated as almost identical in the beginning. From 23 November 2011 onwards, conditions were found to be more severe at Felsenkanzel than at Garmisch-Partenkirchen with McArthur's FFDI showing a distinctly faster reaction to changing environmental conditions.

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The hourly calculated fire danger indices (solid lines in Fig. 7) manage to capture the situation much better with both the hourly FFMCs and McArthur's FFDIs showing a marked difference between Garmisch-Partenkirchen and Felsenkanzel from 19 November 2011 onwards. Even a diurnal variation is apparent for Garmisch-Partenkirchen. Once more, a much more rapid reaction of McArthur's index to the meteorological input parameters is found.

4 Discussion

Daily fire danger rating systems seem to misjudge the altitudinal differences in fire danger when a temperature inversion is present, as observed in the selected example of the autumn 2011 situation (especially in the period 19–22 November 2011).

The reason for this lies in the missing sensitivity of most daily fire danger rating systems to the diurnal cycle of meteorological conditions. All daily fire danger indices considered in this study, as well as most known fire danger rating systems, are calculated from meteorological values between 12:00 and 14:00 LST. During this period, as can be gathered from Fig. 7 for our example, meteorological conditions in a valley and a mid-slope position may be almost identical because the temperature inversion (partially) disintegrates during the day due to solar heating (cf. also Fig. 8 in Holden and Jolly, 2011). Therefore the indices use similar input parameters for both locations/stations and are bound to rate fire danger at similar levels. In our example, they neither include the low temperatures and very high humidity at Garmisch-Partenkirchen (so that dew and even rime may occur and wet the fuels) at night, nor the almost constant higher temperatures and lower relative humidity (which are likely to cause substantial fuel drying) at Felsenkanzel. Therefore and because temperature inversions are a regular feature in most complex topographic areas, we state that not only can fire danger calculations from lowland stations be expected to be misleading (Sharples, 2009), but even such calculations based on higher elevation stations may provide spurious results if they are carried out only with standard daily fire danger indices.

The assessment based on the hourly calculated FFMC (Van Wagner, 1977) and McArthur's index (Boer et al., 2008) is quite different and shows a distinctly higher danger at Felsenkanzel and a diurnal variation of the danger level in Garmisch-Partenkirchen. Therefore this type of index seems much closer to the observed reality. However, the situation at Garmisch-Partenkirchen should probably be rated even less severe, since fuel wetting by dew/rime occurred and there is no such wetting function implemented in either of the systems.

Another fire danger rating system that might be able to correctly account for the phenomenon described here is the National Fire Danger Rating System (USA, Bradshaw et al., 1983), which uses maximum and minimum temperature and relative humidity in some of its components. Furthermore, there are physically-based fuel moisture models available (e.g. Wittich, 2005; Matthews et al., 2007), which can also operate with hourly or higher resolved meteorological data. A new fire danger index *Waldbrandgefahrenindex* (WBI; DWD, 2011b) is currently in development at the German Meteorological Service, which will also be able to provide this capability.

5 Conclusions

From the fuel measurements, expert observations and fire occurrences during our case study, we can confirm the findings of Holden and Jolly (2011) and Sharples (2009), who stated that temperature inversions may produce unusual and highly heterogeneous patterns of fire danger in mountainous areas.

Due to the availability of meteorological data from a mid-slope and a valley station, we managed to analyze how such a situation, which may occur at any given time in most complex topographic areas in the world, is resolved by fire danger rating indices. In order to capture the relevant atmospheric conditions, meteorological stations in the valleys and at higher elevations (where forests or other vegetation still occur) or high-resolution meteorological model data are necessary (note that contrary to most conventional weather stations, which are usually found in the valleys, the "RAWS" stations

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used for NFDRS calculations in the US are typically located at mid-elevation south-facing slopes, Cohen and Deeming, 1985; Holden and Jolly, 2011). Fire danger rating systems to be used in such areas and situations should be able to correctly account for variations in the daily cycle between the individual stations or grid points. Potential indices are components of the National Forest Fire Danger Rating System (Bradshaw et al., 1983), the hourly version of the McArthur Forest Fire Danger Index (Noble et al., 1980) and the hourly Fine Fuel Moisture Code (Van Wagner, 1977). Further investigation as to which of these (or other additional) indices are best suited for fire danger rating purposes under the conditions described in this paper are necessary, as our current assessment is limited to qualitative comparisons.

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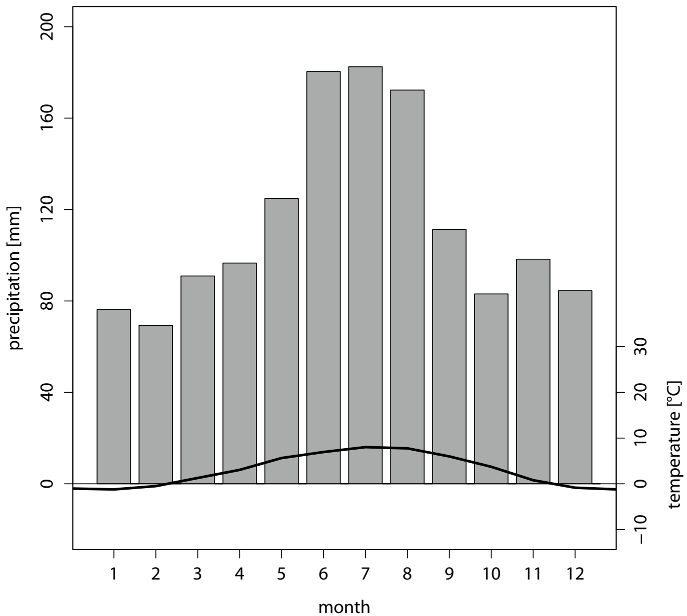

Fig. 1. Climograph for the meteorological station Garmisch-Partenkirchen (719 m a.s.l., 47.48° N 11.06° E), black line: mean monthly temperature, gray bars: mean monthly precipitation sum; reference period: 1971–2000.

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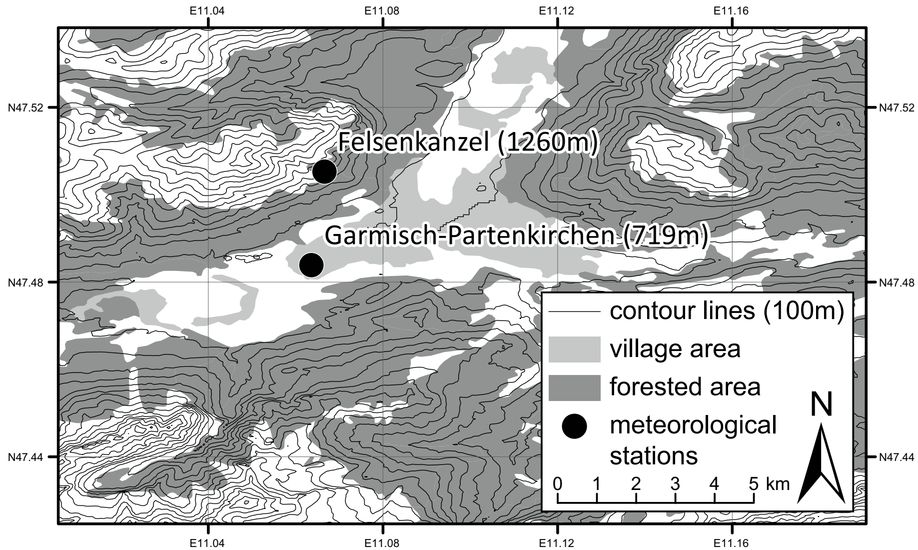

Fig. 2. Elevation, forested area, human settlements and locations of the meteorological stations in the study area.

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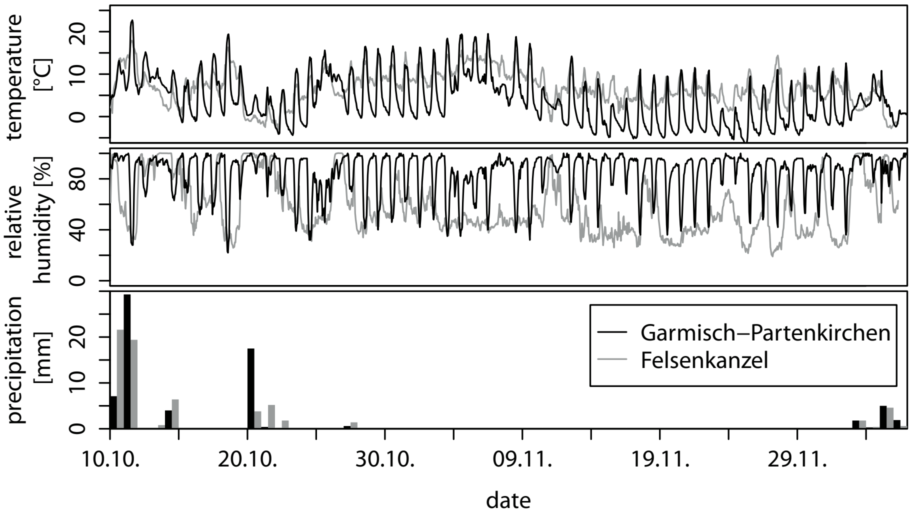

Fig. 3. Meteorological conditions (diurnal course of temperature, relative humidity and daily sum of precipitation) during the exceptional dry period in autumn 2011 at Garmisch-Partenkirchen (black lines/bars) and Felsenkanzel (gray lines/ bars) stations.

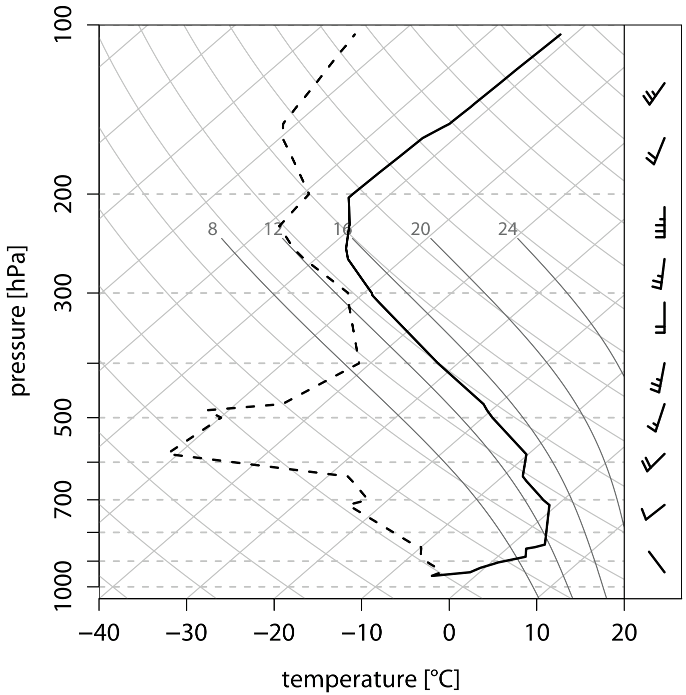

Fig. 4. Skew-T Log-P diagram of the atmospheric sounding taken at Innsbruck airport on 19 November 2011, 04:00 LST. Solid line: temperature, dashed line: dew point temperature, wind barbs and wind arrows: wind speed and direction, respectively.

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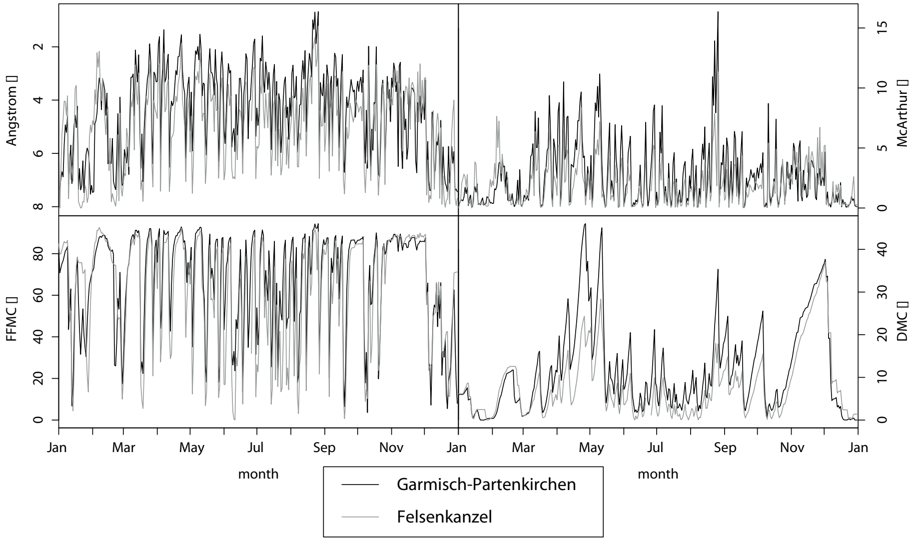

Fig. 5. Selected fire danger indices at Garmisch-Partenkirchen (black line) and Felsenkanzel (gray line) stations in 2011. Note that for the Angstrom index, the y-axis has been inverted since high values represent low fire danger and low values represent high fire danger, in contrast to all other indices.

Fig. 6. Mop-up operations are in progress after the Sylvenstein reservoir fire (near the ridge at the center of the image) on 23 November 2011, at noon, while rime covers the vegetation in the valley (foreground).

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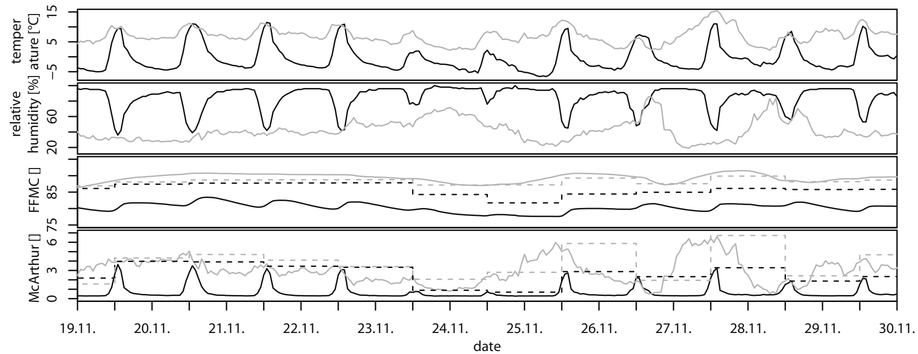

Fig. 7. Meteorological conditions and selected fire danger indices (solid lines: hourly values, dashed lines: daily values) at Garmisch-Partenkirchen (black lines) and Felsenkanzel (gray lines) stations.

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