INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **30**: 347–358 (2010)
DOI: 10.1002/joc.1895

Wind speed measurements and forest damage in Canton Zurich (Central Europe) from 1891 to winter 2007

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ABSTRACT: The most severe damage to forests in central Europe occurs during winter storms that are caused by Northern Hemispheric mid-latitude cyclones. These winter storms have caused several catastrophic windthrows during the past four decades. Amounts of forest storm damage are believed to be a function of both the size of the forest and the storm intensity. To test this hypothesis, the Zurich region (city and canton) was chosen because long-term climate observation data is available for the region. The relationships between forest attributes, wind speed and forest damage were explored by comparing data on forests and wind speed from 107 winters with forest damage. Storm damage was defined as the proportion of damaged forests with respect to the growing stock. The variables: daily wind run (91 years), daily maximum hourly average wind speed (107 years) and peak gust wind speed (74 years) were homogenized with respect to high wind speed and related to levels of forest damage.

High maximum wind speed at the end of the 19th century and at the beginning of the 20th century was followed by low maximum wind speed in the 1940s, 1960s and 1970s. Since then, maximum values have increased. Gusts (extremes of the maximum wind speed) increased from the beginning of the recordings in 1933 and peaked in the early 1990s.

Forest damage due to winter storms is best correlated with peak wind speed. Gusts exceeding 40 m/s and resulting in catastrophic windthrow have increased in recent winters. Copyright © 2009 Royal Meteorological Society

KEY WORDS long-term continuous measurement; long-duration instrumental series; daily and hourly average wind speed; peak gust wind speed; homogenization; winter storms; windthrow; forest damage

Received 4 September 2007; Revised 14 November 2008; Accepted 22 November 2008

1. Introduction

The most frequent and most severe damage to forests in Central Europe is caused by storms. West-wind storms, which occur especially frequently during winter months, affect forests directly by causing windthrow and windbreakage, or indirectly by providing conditions for post-storm damage, particularly bark beetle (*Ips typographus*) outbreaks (Meier *et al.*, 2006). For Switzerland, a long-term increase in winter storm damage to forests has been observed (Schmidtke and Scherrer, 1997; Schelhaas *et al.*, 2002; Erb, 2004). However, recent studies have failed to find a significant correlation between wind speed and inventoried windthrow damage in Switzerland, e.g. for the Lothar storm in 1999 (Mayer *et al.*, 2005; Schütz *et al.*, 2006). Varios factors have been suggested to cause wind damage to forests in Switzerland, e.g. soil moisture content, soil depth, soil/bedrock acidity, soil skeleton, proportion of Norway spruce and silver fir in the stands, stand mixture with respect to species composition and age structure, stand height and decay proportion (e.g. Coaz, 1880; Bosshard, 1967; Bazzigher and Schmid, 1969; Rottmann, 1986; König, 1995; Kuhn, 1995; Dobbertin, 2005; Indermühle *et al.*, 2005). However, the main influencing factors identified in the different studies tend to vary widely, possibly because they focus on different variables (Dobbertin, 2002; Hollenstein, 2002). In none of these investigations, however, has the factor wind yet been quantitatively included or incorporated in storm hazard models relevant to the Swiss landscape, where forests tend to be unevenly aged and to vary in composition, with some close-to-nature and others highly modified.

Most of the disturbance-induced damage to forests in Central Europe is caused by winterstorms, i.e.

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due to high gust wind speed and duration (Otto, 2000; Mayer and Schindler, 2002; Hubrig, 2004; WSL and BUWAL; 2001). Detailed long-term information about wind extremes, such as the peak gust or maximum average wind speed, is generally lacking. In Europe, only a few studies have reported systematic changes in storminess on the basis of station observations (Smits *et al.*, 2005). Precise, long-term records of forest storm damage, i.e. data that may correspond with wind extremes, are also rare (Schelhaas *et al.*, 2003).

1.1. Coincidental long-term wind and forest data in the region of Zurich

Wind speed has usually been measured as the current or average wind speed, starting with Hook's pendular-anemometer in 1667 (Hann, 1901). In contrast to measurements of precipitation or temperature, the observation of near surface wind is much more difficult (Hann, 1869; Schüepp, 1973). A major obstacle for consistent measurements is the great spatial variability of both wind direction and as wind speed (Woelfle, 1950). In addition, it is difficult to compare long-term wind datasets from different stations because of technical differences between the anemometers and their components, as well as changes during maintenance (Schüepp, 1950; Trenberth *et al.*, 2007). Finally, sound wind measurements (e.g. using the cups of the anemometer or Prandtl's pitot tube) require locations that are free from other aerodynamic influences (Maurer *et al.*, 1909). Utilizable gadgets for continuous wind measurement and recording have been available since the mid-19th century, e.g. Robinson anemometers. Such anemometers have been used for 135 years in the city of Zurich (Switzerland, Central Europe), in the center of Canton Zurich. During the whole period of instrumental wind measurement, the Zurich climate station was only moved twice: once 172 m and then 996 m away from the earlier position. In both cases the slope and exposition remained unchanged. We consider it exceptional to have such long-term and comparable wind measurements. Hence it is worth comparing them with analogue data series for both forest dimensions and damage to forests by winter storms. Schiesser *et al.* (1997) considered the Zurich wind observations representative of the wind pattern in the whole of Northern Switzerland.

Records of storm damage to forests in Canton Zurich were published in annual reports from the mid-19th century to 1979 in a nearly continuous series with high temporal and spatial resolution. Changes in forest area are well documented in both cantonal and federal reports, and changes in growing stock are listed in federal reports.

Because of the satisfactory data situation with respect to long-term records of both wind and forest parameters, we chose these series to test the assumption that direct forest damage caused by wind storms is a function of both wind speed and forest dimensions. The data analyses allow the effects of both wind force and forest dimensions to be estimated. These findings are particularly relevant today as it is assumed that the ongoing climate warming results in greater wind forces.

The following questions are addressed in this paper:

1. Have winter storm events in Zurich increased in number, in peak gust wind speed and in maximum average wind speed since the mid-19th century?
2. Do the observed wind data from Zurich's climate station correlate with cantonal and regional forest damage records?

2. Data and Analyses

2.1. Wind data

All wind measurements at the Zurich climate station are recorded in meters per second (m/s) or kilometers per hour (km/h). Automatic self-recording and permanent wind measurement using several instruments commenced on the roof of the Semper Observatory, Zurich (47°22′42″/+8°33′2″, position of the cup-cross), in summer 1872 (Billwiller, 1873) (Figure 1).

This reference and a few photos showing a Robinson anemometer with large cups and other equipment are the only details we have about the first period of Zurich's automatic wind measurement 1872–1890. In 1891 the Zurich climate station was moved 172 m south-eastward (47°22′38″/+8°33′9″), and a Beckley-system from R. Munro, London (Billwiller, 1893), was installed at the top of a meteorological tower ('Anemometerturm') on the roof of the first physics building of the Swiss Federal Institute of Technology, Zurich, (ETH Zurich). At this location, wind attributes from 1 January 1891 to

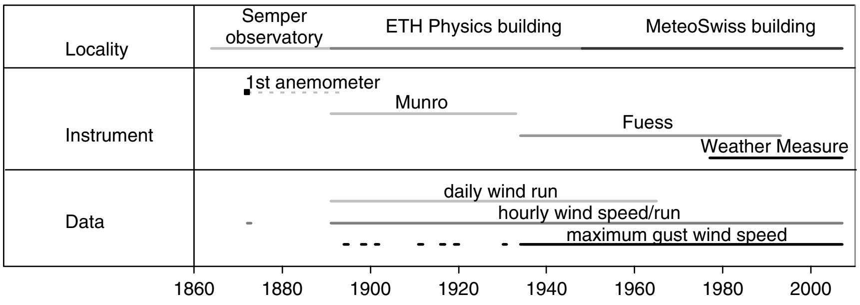

Figure 1. History of wind measurement at the Zurich climate station in terms of locality, instruments used and data collected.

16 November 1933 were automatically recorded using the same gauge. All recorded hourly averages of wind direction and wind speed (U_{HAW}) as well as daily wind run (U_{DRW}) were published (SMA, 1893–1934). During 43-year period, only nine values for daily peak gust wind speed (U_{PGW}) were mentioned, always in the context of storm events, in the publications. No other records, such as original data sheets, were found.

In 1933, the old Munro-anemometer was replaced by another cup-anemometer, a Fuess 82a 'Universal' from Fuess, Berlin-Spandau. The gust wind speed was observed with a pitot tube. Records were published as hourly averages of wind direction and wind speed for the period between 29 November 1933 and 1 January 1937 (SMA, 1934–1938). Hand-written compilations from 1936 (same values as in SMA, (1934–1938)) until 1981 are stored in the archives of MeteoSchweiz in Zurich. In 1949, the whole Zurich climate station was moved 966 m eastward to its current position. The Fuess anemometer was positioned again on top of a tower on the main building of MeteoSchweiz. The elevation of the anemometer cups (581.5 m a.s.l.) was raised by 71.2 m (Uttinger and Schüepp, 1951). The anemometer was moved 996 m (47°22′42″/+8°33′56″).

At the end of 1980, the Fuess 82a was rejected as the official wind gauge of the Zurich climate station, but was kept in use until September 1993 and eventually removed from the tower in 2002. During the last recording years, less complete data on hourly average wind speed, wind direction and gust wind speed were recorded. The complete, but demounted wind gauge was inspected by one of the authors in 2006. On photos dating back to the 1970s and 1980s, up to six different anemometers are visible on the tower, but data and further information are available from only one of these anemometers.

In 1976, two new measure devices were installed for the new automatic climate station net (ANETZ): Weather Measure W 103 (average wind speed and gust wind speed) and Weather Measure W104 (wind direction). These instruments became the official wind observation instruments in 1981. Since then, average wind speed values and peak gust wind speed values have been recorded at 10-min intervals. Earlier, unofficial and non-revised data were made available at MeteoSchweiz on special request.

Other hourly average wind speed data in Switzerland's lowlands were recorded at the Bern climate station from 1864 to 1890 (SMA, 1865–1892) and from 1891 to 1978 (unpublished; stored in the archive of the Astronomical Institute of the University Bern). For a short period (1891–1893), the measurements in Bern were compared with those in Zurich (unpublished synopsis; Schweizerisches Bundesarchiv, Bern). Because we considered the series from the Zurich climate station to be the most representative (Noetzlin, 1941; Uttinger, 1968; Schiesser *et al.*, 1997), no other wind data were used. Additional metadata were derived from an unpublished station history of the Zurich climate station, from original data sheets, and from different editions of the 'Lehrbuch der Meteorologie' (Hann, 1901; Hann, 1906; Hann and Süring, 1926; Hann and Süring, 1951).

2.2. Forest damage data

2.2.1. Damage amounts and metadata

Information about the severity of damage, which is usually scaled in cubic meters (m^3) were derived from the official sources available, i.e. from cantonal and federal records or similar. Official annual reports for Canton Zurich started in 1831 and included comments about forests. The first information about forest hazards was recorded in 1835 for cantonal, communal and corporational forests. Since 1899, the reports have also covered private forests. However, until 1930, forest damage was largely reported as qualitative information only. After the exceptional level of forest damage in 1930, small levels of damage were not recorded until the 1970s. Since 1980, information about storm damage has not been given in the cantonal annual reports apart from about the catastrophic events Vivian (1990) and Lothar (1999). For years without numbers, storm damage data for Canton Zurich was derived either from non-cantonal publications or, most recently, directly from the cantonal Forest Services. In addition, we used metadata concerning regional localizations of storm damage from annual cantonal reports, especially in cases where the amount of damage was small.

2.2.2. Forest area data

Total forest area was extracted from the published annual cantonal reports. For missing periods, the forest area data given in the federal statistics were adopted. Descriptions of Swiss forests with cantonal references date back to the years 1858 to 1860 (Landolt, 1862). This inventory was followed by the 'Etat Forstbeamte' (EOFI, 1878–1994) and the Statistical Yearbook of Switzerland (SFSO, 1891–2007). These started with an inventory in 1877, with annual reports from 1891 to 1949 without larger gaps and again from 1986 to the present. The Swiss Forest Statistics (BAFU, 1908–2006) started in 1908 with the 1877 data, continuing with the data from 1950 and from 1955 annually to the present (from 1986 on it was combined with the Statistical Yearbook of Switzerland).

2.2.3. Growing stock data

The data on growing stock are rather inadequate, but as most parts of Canton Zurich are located in the Swiss Plateau, the Swiss Plateau data given in Weber (1867), EIFJF (1954) and Ott (1972) were adopted. Growing stock data were combined with information about Canton Zurich and Swiss Plateau values in EAFV (1988) and in Brassel and Brändli (1999).

2.3. Analyses

2.3.1. Selection of the observation area

West-wind winter storms over the European continent are caused by cyclonal processes (e.g. Schiesser *et al.*, 1997; Chang *et al.*, 2002; Bengtsson *et al.*, 2006). Such events usually affect large areas along the storm track and last for longer periods than thunderstorms (usually several hours, and more rarely one full day). Therefore we assumed: (1) there was a high probability that each point in a region affected by a westerly winter storm would be hit by at least one of the strong gusts and would also be exposed to a high average wind speed during the event, so long as the wind unhindered at the location of measurement, i.e. there were no shelter effects. Because the terrain relief around the west-exposed climate station of Zurich in the Swiss Plateau is moderately structured, weather flow can pass unhindered; (2) the observation area for storm damage encompasses a compact local perimeter, especially compared to the main west storm direction. The climate station is roughly in the center of Canton Zurich, which extends 50 km from NNW to SSE and 40 km from WSW to NEN (surface 1729 km^2, 28% forested). To meet the main objective of comparing reliable data sets, it was necessary to create both homogenized wind series and homogenized forest damage data.

2.3.2. *Homogenization of wind data*

Usually homogenizations of meteorological long-term data series require data from simultaneous observations (e.g. Auer *et al.*, 2001; Begert *et al.*, 2005; Thomas *et al.*, 2005; Della-Marta and Wanner, 2006; Gimmi *et al.*, 2007). For both the average and maximum wind data, only the wind series of the Zurich climate station were satisfactory. Other series, such as the Dübendorf airport series, which started in 1949 about 6 km away from the Zurich series, were not considered because they covered shorter periods and measured different wind characteristics (Uttinger, 1968).

We excluded low to medium wind speed from the homogenization because we were focusing on the connection between wind speed and storm damage. In a stepwise procedure, the reliability of the data was improved by: (1) proving raw data using metadata, (2) detecting inhomogeneities such as shifts, (3) removing them with adjustments concerning high values. For the latter step, the inhomogeneities were either recalculated or combined with simultaneous measurement periods.

The following data from the Munro and Fuess anemometers were digitized: (1) U_{DRW} (km/d), (2) U_{HAW} (km/h) for the winter half year, 1 October to 31 March, additionally 1930 to 1936 for all seasons, and (3) U_{PGW} (m/s) of at least 30 m/s for the winter half years (Figure 1). U_{PGW} exceeding 20 m/s during the uncorrected period until 4 March 1934 were assessed, as well as U_{PGW} during the winter seasons from 1980 to 1986 that exceeded 30 m/s. In addition, 3-hourly average wind speed data (converted to hourly values) from January to March and from October to December 1879 and the hourly average wind speed data from January to March and October to December 1890 from the Bern climate station were digitized.

Scatterplots of all series from the Zurich climate station were checked by eye for major breaks in the series. Any relevant metadata information available was analyzed to find potential explanations of the inhomogeneities.

The periods between break points were adjusted either by the ratio method (a) or by the comparison-and-substitution method (b). The ratio method (a) was used with a single dataset when adjustment information from metadata was available. Data from each period were modeled simply according to the proportion of the appropriate original parameters found in the literature. The original Equation (1) of Hann and Süring (1926):

$$v = c + f_K \times n \tag{1}$$

where v = wind speed, c = minimum wind speed for the anemometer-cup move, f_K = factor according to the Kew-model = 2.2, and n = distance from the anemometer-cup center was therefore modified for our purpose to

$$v_h = c + v \times f_K/f_R \tag{2}$$

where v_h = homogenized wind speed, and f_R = factor according to Robinson = 3.00

The constant c in Equation (2) was set to 0 because some specific anemometer instrumental data specific to the anemometer were missing for the Zurich Munro-anemometer. The resulting uncertainty about c in Equation (1) is assumed to be negligible if the focus is on high wind speed only. We used these equations because no appropriate corrections were found for the wind series 1864–1893 of the Bern climate station. However, the data series 1891–1893 from Bern and Zurich are in the same range. The factor f_R of the Bern climate station anemometer was set to the original Robinson standard of 3.00 (Wild, 1866).

We applied the comparison-and-substitution method (b) if parallel measurements from two different instruments were available. The parallel measurement periods were then divided into sub-periods according to metadata breakpoints derived from the station's history. The two U_{PGW} measurements in each sub-period were tested by Wilcoxon signed rank tests. For both measurements for each sub-period, linear regression was applied. Any inhomogeneities detected were left unchanged if no clear breakpoints were detectable or if there was no information to explain them.

2.3.3. *Amount of damage*

How much of a forest is damaged after strong wind depends on various forest attributes such as its area and growing stock. To quantify damage probabilities, forest attributes need to be adjusted. Given the simple fact that forest damage occurs only where forests are present, both the proportion of forest in a study area as well as the amount of standing wood influences the damage potential of storms. The extent of damage in forests after windthrow is usually measured or estimated in absolute numbers, normally in m^3 of timber. Both published and unpublished values were derived from official, reliable statistics.

Data on the land and forest area in Canton Zurich were taken from various sources. The cantonal annual reports on forests provided information about forest areas. Obvious breakpoints were checked for causes (administrative, e.g. classificatory or real, extreme events). Only those changes in the forest area were considered that were the result of real events. Time series were fitted by a linear regression.

Values for the growing stock were fitted by the quadratic term of a polynomial regression. The relevant data for Canton Zurich were based on Weber (1867), EIFJF (1954), Ott (1972), EAFV (1988) and Brassel and Brändli (1999). We chose the percentage of damage to the growing stock as an appropriate measure for long-term damage values calculated as: amount of damage/growing stock.

2.3.4. *Comparison of wind and damage*

The damage series were compared to the different series of daily wind speed measurements. Distributions of wind speed during damage days were compared separately for the three periods 1891–1931, 1932–1979 and 1980–2007. Comparisons distinguished days with damage occurrences close to the wind observation site from damage days with respect to the distant vicinity. A period of low U_{PGW} measurements, 1947–1957, was excluded from the comparisons because the measurements of gust wind speed were inexplicably low (Uttinger, 1968).

Wind data for the damage days were ranked with respect to damage threshold periods. Ranks were used for semi-percentile distributions and trends were defined for different temporal wind speed resolutions. The levels of the damage thresholds were based on finer data resolution. We correlated the wind force of the three wind variables U_{DRW}, U_{HAW}, and U_{PGW}, with the extent of damage to the forests using damage data for forest areas either close to (surrounding forest region) the anemometer or further away (all other forest regions). To simplify computation of wind force, we used the mean drag coefficient of $C_d = 1.11$ of a static round-shaped plate, and $C_d = 1.10$ of a static square-shaped plate.

3. Results

3.1. Homogenization of the wind data

Two inhomogeneous periods were homogenized at the Zurich climate station in comparison to recent measurements. For the period from 1891 to 5 March 1934, the average wind speed was homogenized using the extreme values of U_{HAW} (Figure 2) and the following U_{DRW}. Daily averages of about 50 km/h completely disappeared (data given in supplement 2a and 2b) and the extremes of recorded storm days moved into the range of today's storm days (Figure 3; data give in supplements 3a to 3d). In the 1981–1984 period, missing extreme U_{PGW} values were replaced by homogeneous values from parallel measurements from the same site (Figure 4). No U_{PGW} above 30 m/s was recorded from the time when Fuess was replaced by Weather Measure 1981 as the official anemometer up until when the Weather Measure W 103 equipment was replaced by a technically different Weather Measure W 103 in 1984. A significant difference in U_{PGW} between the records of the Fuess and Weather Measure gauges was found in 1981 (359 values; Wilcoxon signed rank test, $p < 0.0001$). When the same test was applied to 180 smaller values as well as to values equal or smaller than 7 m/s (Fuess), no significant difference resulted ($p = 0.41$ and $p = 0.27$). Comparisons of the 180 higher values and values greater than 25 m/s (Fuess) revealed significant differences ($p < 0.0001$). High U_{PGW} measured by the Fuess gauge resulted in generally higher values than those measured by Weather Measure. Hence the Weather Measure was replaced, both gauges have recorded high U_{PGW} in the same range.

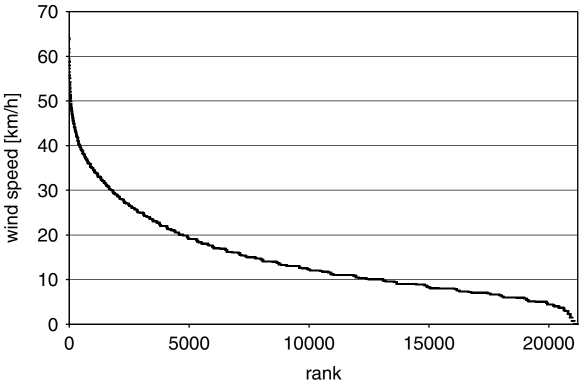

Figure 2. Ranked values of the high-tail homogenized daily maximum hourly average wind speed in winter from 1 January 1891 to 31 March 2007 at the Zurich climate station.

From 1895 to 2004, windiness in the Swiss Plateau, i.e. especially strong average wind speed, changed in both frequency and strength (Figure 3). Between 1915 and 1970, both the strength and frequency of U_{HAW} was low and varied considerably in different 5-year periods. Since the early 1970s, high wind speed has increased continuously. Observed extremes of U_{PGW} have increased since the mid-1930s, the time when data first became available for the reference station (Figure 4). U_{PGW} is more variable than average wind speed. In the period from 1947 and 1957 peak gust wind speed measurements were inexplicably low, and few high gusts were measured. During this period, however, only one medium forest damage event occurred.

3.2. Damage normalization

The forest area of Canton Zurich has remained quite constant at about 48,000 ha during the last 115 years. During World War II there was a light decrease of several hundred hectares. All other larger deviations over the past century have been the result of changes in the definition

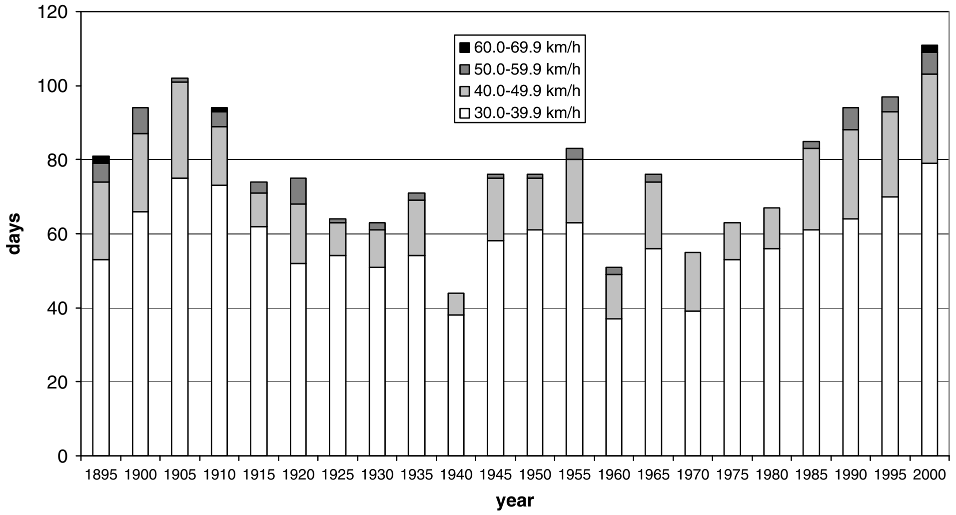

Figure 3. Number of days with high maximum hourly average wind speed in winter (October-March) from 1895 to 2004 at the Zurich climate station at 5-year intervals.

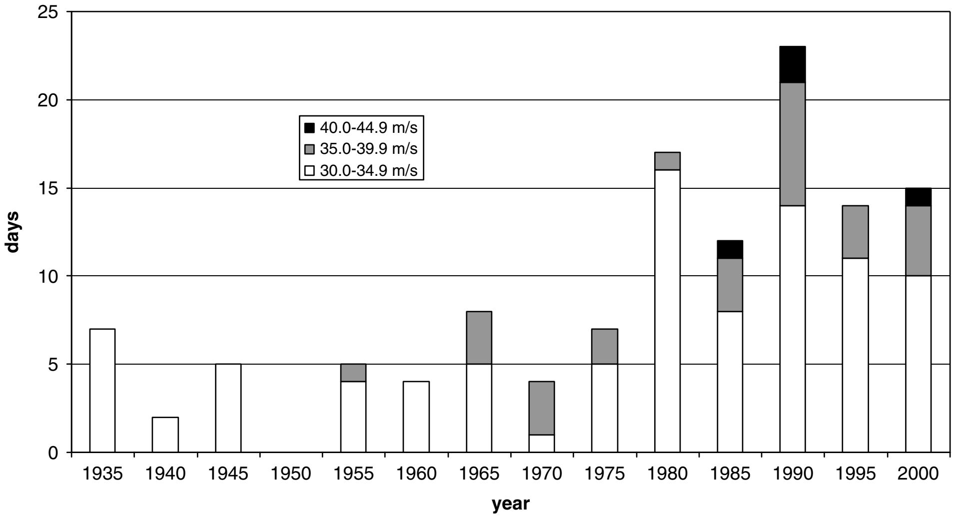

Figure 4. Number of days with high maximum gust wind speed in winter (October-March) from 1935 to 2004 at the Zurich climate station at 5-year intervals.

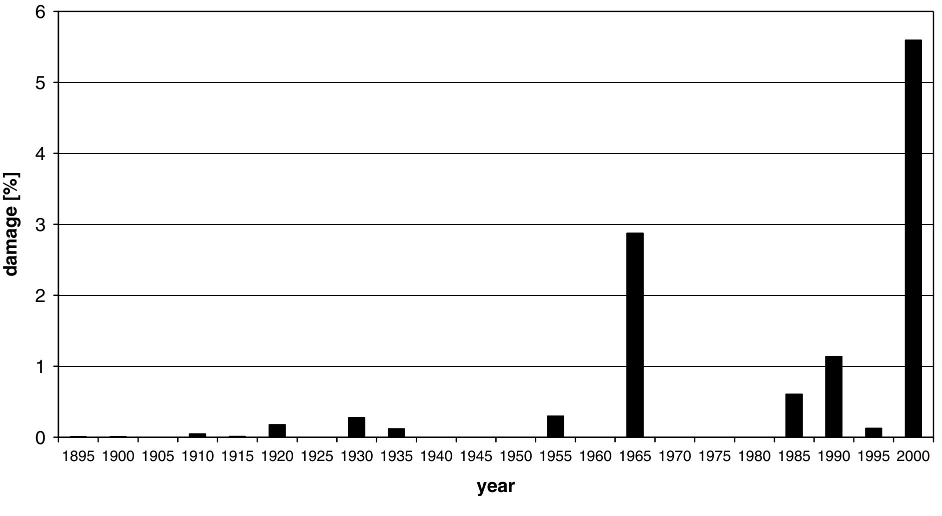

Figure 5. Winter storm damaged part of the growing stock from 1895 to 2004 in Canton Zurich at 5-year intervals.

of forest. For our purposes, we assumed a constant total forest area.

The growing stock increased from 9 000 000 m^3 to 23 500 000 m^3 over the whole period from 1891 to 2006. By regressing the data of 1862, 1952, 1969, 1984 and 1994 with a quadratic term ($R^2 = 0.9995$), the growing stock increased from about 200 m^3/ha in 1890 to an extrapolated 490 m^3/ha in 2006. With respect to maximum events, the normalized forest damage rose from 0.11% of the growing stock on 6 December 1895 to 5.42% on 26 December 1999 (Figure 5). This represents an exponential increase.

3.3. Comparison of wind and damage

Correlations of winter storm damage with wind forces in Canton Zurich depend on the wind and damage variables used. These differ in time and space. Rank correlation coefficients of damage and daily wind run were generally weak. In contrast, correlating records of damage with U_{PGW} clearly pointed to strong gusts influencing damage occurrence. The highest rank correlation coefficients between wind force and damage for stronger events were found in recent years, 1980–2007 (Table I).

The relationship between wind intensity and damage event days were analysed by means of 0.5 percentiles (Table II). It shows that damage event days generally corresponded to the highest quantiles of the wind speed variables, and that they corresponded better to peak gust wind speed measured daily or hourly than to average wind speed. The most severe damage corresponded to the highest quantiles of wind speed variables. Correlations were generally better for damage occurring close to the climate station (station) than for damage that occurred further away (canton). The closer the damage occurrence was to the climate station site, the higher were the interquantile segments of the wind values of the corresponding damage event (Table II).

4. Discussion

4.1. Wind as an explanatory variable

Inland surface wind measurements have rarely been studied, probably because the instrumentation used to record the data, the methodology or the exposure of the instruments are often inconsistent over time (Trenberth *et al.*, 2007). Most of the literature on wind data homogenization is ocean-limited (Isemer and Hasse, 1991; Gebhardt and Hense, 2001; Smits *et al.*, 2005; Thomas *et al.*, 2005; Weisse *et al.*, 2005). Homogenizations of weather variables other than wind are much more frequent, e.g. temperature (e.g. Vincent, 1998; Allen and DeGaetano, 2000; Jones, 2001), precipitation (e.g, Hanssen-Bauer and Forland, 1994; Klein Tank and Könnnen, 2003; Raible *et al.*, 2006) and air pressure (e.g. Pozo-Vázquez *et al.*, 2000; Slonosky *et al.*, 2000; Auer *et al.*, 2001; Gebhardt and Hense, 2001; Jones, 2001; Luterbacher *et al.*, 2001; Raible *et al.*, 2005). The main reason for this fact is that wind, or more precisely, strong wind is not only difficult to measure but also challenging to handle statistically (Hann, 1869; Köppen, 1874; Schüepp, 1950; Schüepp, 1973). This applies especially to mountainous regions, such as the Alps and areas to the north of the Alps, where there are macro- and meso-scale effects on wind due to the topography, (Mousson, 1864; DWD, 1996).

The cup anemometers used today (Robinson cup anemometers) have remained nearly unmodified for more than 150 years. In contrast, the design of the recording units, i.e. anemographs, has been greatly developed and varies considerably (Wild, 1866; Krebs, 1879; Hann, 1901; Noetzlin, 1941; Schüepp, 1950; Guyard, 2000). To achieve a higher comparability of measurements, the recording unit should be closely connected to the sensor unit (but seeWild, 1866). In addition, both the transmission units and the service management can influence the precision of the gauge (Schüepp, 1950; Heinrich Bührer, 2006, *personal communication*). At the Zurich station, similar cup anemometers have always been used. The gauges have been changed only four times in 135 years, and the anemometer position have been shifted slightly only twice. This long-term measurement consistency makes it possible to homogenize the Zurich wind series regarding strong wind events in accordance with reliable standards and principles (Auer *et al.*, 2001).

In an early publication, Maurer *et al.* (1909) explicitly excluded the data of the wind observations for Zurich until 1891 because of the very inappropriate earlier installation directly behind the observatory tower. Data series for the years 1872 to 1890 were therefore ignored in analyses at the time (Hann, 1901). An adequate installation of a sensor unit, however, outweighs the homogeneity of an inadequately measured data series (Auer *et al.*, 2001).

In several studies of storm damage in Central Europe, wind-related approaches have been applied to study the

Table I. Rank correlation coefficients between wind force and windstorm damage in Canton Zurich with respect to daily wind distributions in winter (October–March) from 1 January 1891 to 31 March 2007: number of measurements (n) in brackets, significant values underlined ($p < 0.05$).

Correlation matrix	1891–2007		1891–1931		1932–1979		1980–2007	
Region	Canton	Station	Canton	Station	Canton	Station	Canton	Station
Average wind force $^{-d}$	−0.22 (18)	−. 20 (16)	−0.17 (8)	0.00 (7)	0.50 (3)	−(2)	−0.04 (7)	−0.04 (7)
Average wind force $^{h/d}$	0.03 (21)	0.11 (18)	−0.07 (8)	0.09 (7)	−0.06 (6)	0.40 (4)	0.43 (7)	0.50 (7)
Maximum wind force $^{-d}$	$0.\underline{62}$ (13)	$0.\underline{67}$ (11)	−(0)	−(0)	0.71 (6)	0.80 (4)	$0.\underline{93}$ (7)	$0.\underline{93}$ (7)

Table II. Semi-percentile statistic of the qualitatively and quantitatively recorded windstorm damage events of Zurich with respect to daily wind speed distributions in winter (October–March) from 1 January 1891 to 31 March 2007.

	U_{DRW}						U_{HAW}						U_{PGW}					
Period	1891–1931		1932–1965		1985–2007		1891–1931		1932–1980		1985–2007		1891–1931		1932–1979		1980–2007	
Values	7378		6176		4190		7378		8821		4190		9		158		4990	
Region	incl stn[a]	not stn[b]	incl stn	not stn	incl stn	not stn	incl stn	not stn	incl stn	not stn	incl stn	not stn	incl stn	not stn	incl stn	not stn	incl stn	not stn
200th iq-segment	6	0	2	1	3	0	9	0	6	4	5	0			7	1	8	0
199th iq-segment	1	1	0	0	2	0	1	1	2	0	3	0			1	0	0	0
198th iq-segment	1	1	1	0	1	0	0	0	0	0	0	0					0	0
197th iq-segment	2	0	0	0	1	0	0	0	0	0	0	0	no exact classification possible				0	0
196th iq-segment	0	0	1	0	0	0	0	0	0	0	0	0			0	2	0	0
191st–195th iq-segment	0	0	0	1	1	0	0	1	0	0	0	0			no exact classification possible		0	0
176th–190th iq-segment	0	1	0	1	0	0	0	0	0	0	0	0					0	0
151st–175th iq-segment	0	0	0	0	0	0	0	1	0	0	0	0					0	0
101st150th iq-segment	0	1	0	0	0	0	0	1	0	0	0	0					0	0
1st–100th iq-segment	0	0	0	0	0	0	0	0	0	0	0	0					0	0
1st–200th iq-segment	10	4	4	3	8	0[c]	10	4	8	4	8	0[c]	10	4	8	3	8	0[c]

[a] incl stn: area surrounding of the Zurich climate station affected by windstorm damage

[b] not stn: area surrounding of the Zurich climate station not affected by windstorm damage

[c] no spatially resolved data available

relationship between wind intensity and the extent of (forest) damage (e.g. König, 1995; Schiesser *et al.*, 1997; Schmidtke and Scherrer, 1997; Quine *et al.*, 1999; Otto, 2000; Hollenstein *et al.*, 2002; Mayer and Schindler, 2002; Hubrig, 2004; Wolf *et al.*, 2004; Mayer *et al.*, 2005). However, it has, until now, been more common to investigate other potential explanatory variables for the extent of damage such as tree age, tree height, slenderness (breast-height – diameter ratio), tree species/species classes, forest structure, number of stand layers, forestry management effects, soil depth, soil type, soil acidity, soil moisture content, slope and exposition. If wind is included in regression models, it is usually included as simulated data, in contrast to, e.g. forest inventory data (e.g. König, 1995; Mayer *et al.*, 2005).

Mayer *et al.* (2005) analysed $19,000\ \mathrm{km}^2$ of windthrown forests (after the storm Lothar) encompassing forests in France, southern Germany and Switzerland by logistic regression with simulated peak gust wind speed. They found peak gust wind speed was significant only for forest damage in France ($p < 0.001$). König (1995) reported a good correspondence between simulated and observed wind data from the nearby meteorological stations in a study area covering $160.2\ \mathrm{km}^2$ of damaged forest in southern Germany. In his cumulative logistic regression model, peak gust wind speed was significant ($p < 0.001$).

Other examples of forest storm damage models incorporating wind variables are ForestGALES (Gardiner *et al.*, 2000; Gardiner and Quine, 2000) and HWIND (Peltola *et al.*, 1999a, 1999b). Windthrow hazard ratings are described in Ruel *et al.* (1997) and Blennow and Sallnäs (2004). However, wind variables are often not considered in studies where windthrow can have various causes. This holds especially for regions with highly variable topography (Bosshard, 1967; Bazzigher and Schmid, 1969; Hollenstein, 2002; Hollenstein *et al.*, 2002; Braun *et al.*, 2003), and for studies where wind speed cannot be related to storm damage (Mayer and Schindler, 2002). In such cases, soil and topography parameters are usually cited as explanatory variables (König, 1995; Kuhn, 1995; Dobbertin, 2002; Hollenstein, 2002; Braun *et al.*, 2003; Mayer *et al.*, 2005).

4.2. Extent of forest damage as a dependent variable

Our results from wind observations at the Zurich station support findings about the main wind factors that cause forest damage. The occurrence of only moderate damage is related to lower wind speed. If wind speed is lower, other damage-influencing factors become more important (Schmidtke and Scherrer, 1997; Otto, 2000; Hollenstein, 2002; Nieuwenhuis and Fitzpatrick, 2002; Cucchi and Bert, 2003; Erb, 2004). Data related to only slight damage resulted in small correlation coefficients in less marked periods of inter-quantile distributions. These findings suggest that other factors besides wind force play an important role in influencing the damage impact of smaller storms. Such storms also tend to be spatially unevenly distributed. In models for greater extents of damage, variables for site conditions are clearly less significant (Schmidtke and Scherrer, 1997).

With wind variables, strong gusts seem to be (still) considerably more dangerous for forests than high mean wind speed (Woelfle, 1950; Vanomsen, 2006). Our results show that the correlation coefficients for wind and damage are most significant for storms where severe damage occurs. The same holds for the inter-quantile distributions. A close relationship between fine-scaled wind data including gusts and wind damage was also found. However, there is a marked lack of damage data in Switzerland for the second half of the 20th century (Pfister, 1998). This holds also for parts of the country such as Canton Zurich, especially with respect to the years after 1980.

The highest rank correlation coefficients between wind force and damage for stronger events were found in the last period of time observed, 1980–2007. These findings suggest that the impact of small storm events is very local, which means that anemometers, as they are positioned far apart, only rarely document strong gusts due to local storms.

Windthrow damage has not always been recorded precisely, and often only the total windthrow damage from several consecutive events was assessed (e.g. caused by cyclones in a series). Calendar days as time units are therefore inappropriate for comparing days with and without damage. Windstorms with strong gusts (30 m/s and more) often occur during the night, e.g. as in the storm Jürgen from 17 January 2007 to 18 January 2007, and the consecutive storm Kyrill from 18 January 2007 to 19 January 2007. It is also impossible to estimate the damage from a cyclone chain separated by single days. In summary, there is still much uncertainty about the correlation between wind and damage. For a better correlation, highly resolved damage data would be needed.

4.3. Implications for (future) forest management

New climate model runs project that more storm events in Switzerland in the future (Beniston *et al.*, 2007). The wind speed measurements in Zurich point in the same direction according to the extrapolations from past trends in maximum wind speed during winter storm events. As our findings show there has been a correlation between strong wind and forest damage in Canton Zurich, we can expect that future storm events will reach catastrophic dimensions when gusts of $45\ \mathrm{ms}^{-1}$ or more are reached (Schütz, 2005). In the last 74 years, two such events have taken place, Vivian in 1990 and Lothar in 1999, i.e. both within the last 18 years.

Uncertainty about the reoccurring period for severe storms remains and depends to some extent on the focus. For severe winter storms such as Vivian and Lothar, Pfister (1999) expects a 15-year cycle in the near future. However, the last storm with comparable severity dates back to 1739. Estimates of reoccurring periods vary between 12-year cycles (WSL and BUWAL, 2001) and 600-year cycles for widespread damage in the Swiss Plateau at the level of forest stands (Schütz, 2002). In more detail, a cycle of 120 years was proposed for Norway spruce and 300 years for beech in the Reusstal-Limmattal region of the Swiss Plateau (Schütz, 2005). The current ongoing climate change, however, may shorten these reoccurring periods. If the frequency of catastrophic gusts exceeds current rotation periods, forest management will need to adapt to strong wind by, e.g. shortening rotation periods.

Which solutions are adopted will depend on the local context and needs. In Switzerland, the spatial occurrence of storm damage is unevenly distributed. Little is known about the potential local and regional scale pattern of storm damage. Therefore, further investigations of risk potential should focus on higher spatial resolutions and on the interplay between exact measurements of wind gusts at storm levels, and of various forest dimensions and the extent of damage.

5. Conclusions

Only a few long-term inland wind measurement series have been produced so far, basically because they are difficult to create. Many of the wind series lack consistency because the observation site moved during the observation period. Parallel wind series in the same area usually have different characteristics, especially in topographically varied terrain. Homogenizations also often fail because metadata on gauge descriptions or detailed station histories are not available. In the Zurich case, the reliable wind measurements and the existence of extensive metadata have allowed a consistent homogenization.

We have learned from the homogenized U_{HAW} that average wind forces sometimes reached the same level during storms 100 years ago as they have during today's most severe storms. Because people's personal experiences date back to a period of little storminess in Central Europe, severe storms today are often described as exceptional extreme events. However, during this same time-span, storm damage to forests has increased relatively more than the growing stock volume. Today's storm events may be gustier and hence affect forest more severely. Extreme wind speed gusts have increased in Zurich as reliable data first became available in the 1930s, with peaks in the 1990s. On the other hand, growing stock has more than doubled during the last 100 years. Forests are more vulnerable to storms simply because they are more voluminous than earlier. Severe storms cannot be prevented, but if forest management adapts to take into account results of spatially fine risk estimates, it will increase the chances of optimizing yields and generally reducing damage.

Acknowledgements

This paper would not have been possible without the help of the following people from MeteoSwiss (Bundesamt für Meteorologie und Klimatologie MeteoSchweiz): Thomas Konzelmann, Stephan Bader, Gregor Stork, Deborah van Geijtenbeek, Gérard Decrouy and Frank Lumpert. The latter discovered the hourly wind-reading compilations from 1936 to 1981 that were previously believed lost (Schiesser *et al.*, 1997). We thank Christian Mätzler, Graziella Troxler and Andreas Verdun from the University of Bern for helping us to finding the original Bern wind series 1864-1978. Johannes Behrendt, Albert Kölbl and Wolfgang Fricke of the Deutscher Wetterdienst (DWD) drew on their experience in Germany in the discussion of the long-term wind time series and measurement equipment. We greatly appreciate the help of the librarians and archivists of the following libraries and archives: WSL, ETH (Bildarchiv, Alte Schriften, Depotbibliothek, Institut für Geschichte und Theorie der Architektur (gta), Grüne Bibliothek), Bauarchiv of the city of Zurich, Handschriftensammlung of the Zentralbibliothek Zürich, Staatsarchiv Zürich, Schweizerische Nationalbibliothek, Schweizerisches Bundesarchiv, Naturforschende Gesellschaft in Zürich (NFGZ) and the Swiss Academy of Sciences (sc|nat).

We thank Silvia Dingwall for English correction and an anonymous reviewer for the constructive comments.

This research was supported by PhD-fellowship no. 113425 from the Hans Böckler Stiftung (HBS; Germany), by the LOTHAR Programme of the Swiss Federal Office of the Environment (FOEN), and by the research programme Forest Dynamics (WSL).

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