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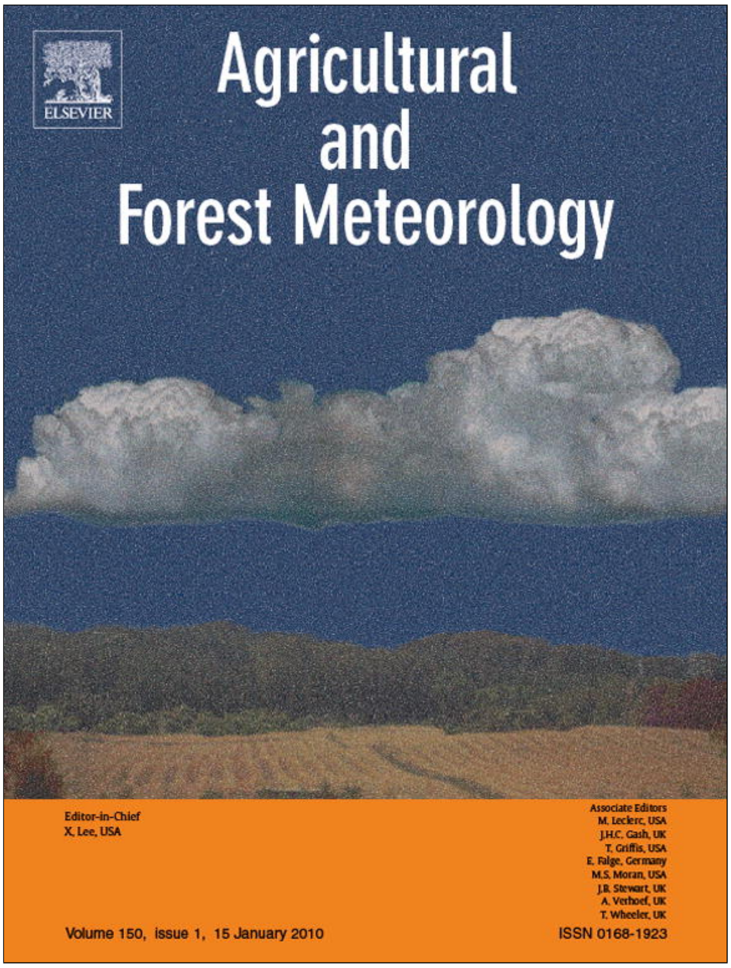

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Increasing storm damage to forests in Switzerland from 1858 to 2007

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ABSTRACT

The most severe damage to forests in Central Europe occurs during winter storms caused by Northern Hemispheric mid-latitude cyclones. Storm events in the winter semesters of the past 150 years were investigated to quantify changes and evaluate whether damage rates, forest properties and climate had changed. Records of damage extent (wind throw/snap/breakage), forest area and growing stock in Switzerland were comparatively analysed. Storm damage (m^3) was 17 times greater during the period 1958–2007 than during the period 1908–1957 and 22 times greater than in the period 1858–1907. Forest area in Switzerland has increased by 63% and growing stock by 292% over the past 150 years. The significant recent increase in storm damage could only partially be explained by increased growing stock. Weather reports prior to storms indicated that severe storm damage occurred almost always when soils were unfrozen (96%) and wet (96%). During the observation period mean winter temperature has increased by nearly 2 °C and winter precipitation has increased by nearly 50% in the study region. In the Zurich region, daily maximum gust wind speed and storm damage were compared. Maximum gust wind speed above 35 m s^{-1} was associated with extensive storm damage. Catastrophic storm damage and maximum gust wind speed measured during storms have increased during recent decades. In conclusion, increasing growing stock, warm winter temperature and high precipitation, and even more markedly, increasing maximum gust wind speed have all contributed to the recent increase in windstorm damage to forests.

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1. Introduction

Winter storms cause severe damage to Swiss forests (Schmidtke and Scherrer, 1997; Schelhaas et al., 2002). All winter storms originate from extra-tropical cyclonal processes (Schiesser et al., 1997a,b) during the winter half year from October to March and reach maximum wind speed south of their centres, especially in cold front situations (WSL and BUWAL, 2001). However, severe winter storms causing catastrophic forest damage have been rare in Switzerland (Lamb, 1991). During the last two centuries only six such events were classified catastrophic (Pfister, 1999; WSL and BUWAL, 2001).

The severity and extent of storm damage in forests are a function of three types of factors (Hubrig, 2004; Schmoeckel and Kottmeier, 2008):

- the damage potential, i.e., the amount of growing stock exposed to strong winds;
- the susceptibility to wind, depending, for example, on tree species or stand height;
- the extent and severity of the causing event, i.e., storm extent, wind speed, and gusts.

The damage potential and its development over time are important for studies analysing long-term trends in storm damage in forests (Schelhaas et al., 2002; WSL and BUWAL, 2001). In Europe, forest growing stock has increased over the last five decades (Nabuurs et al., 2003) and so has its damage potential (Schelhaas et al., 2002).

Susceptibility of forests to storms has been intensively studied (Hubrig, 2004; Schmoeckel and Kottmeier, 2008). Earlier studies of winter storm damage to Swiss forests focused almost exclusively on their susceptibility to particular cyclonal storm event series (e.g., 21, 23 and 28 February 1967; Vivian and Wiebke 1990; Kurt, Lothar and Martin 1999) or to single storm events (Landolt, 1861; Coaz, 1880; Bosshard, 1967; Bazzigher and Schmid, 1969; Holenstein, 1994; Schmidtke and Scherrer, 1997; WSL and BUWAL, 2001; Indermühle et al., 2005; Schütz et al., 2006). Forest damage has been separately analysed for the storms Vivian in 1990 (Kuhn, 1995) and Lothar in 1999 (Mayer et al., 2005). In the two studies,

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various factors such as stand height, conifer proportion, altitude, slope and soil pH were found to correlate with the extent of damage. Dobbertin (2002) compared the damage in both events, Vivian (5 million m^3) and Lothar (14 million m^3), and found similarities in damage probabilities, e.g., for stand height, development stage, percentage of conifers, soil-water logging and soil depth. However, cross-validation using data from the two storms to predict damage failed. In a few studies a relation between weather conditions and soil stability was detected. High soil moisture content caused by high precipitation and temperatures above 0 °C can weaken soil stability, and in contrast, freezing can increase soil stability (Bosshard, 1967; Combe, 1998).

Finally, the extent of storm damage to forests depends on the wind in space and time, in particular on the dynamic wind field and its interaction with dimensions of trees or stand structures (Lundström et al., 2008; Schindler, 2008), in particular gap size (Panferov and Sogachev, 2008), topography (e.g., Rottmann, 1986; Schmoeckel and Kottmeier, 2008), crown shape (Sellier et al., 2008; Moore and Maguire, 2005), dumping effects (Spatz et al., 2007; Moore and Maguire, 2008), wind gust frequency (Lee, 2000), and their dynamic interactions (Rudnicki et al., 2001).

However, for correlative studies of long-term trends in wind damage and on large-scale storm events, information on most of the damage-causing factors mentioned above is not readily available.

In our study, we analyse severe winter storm damage since the late 1850s in Swiss forests on the basis of few but available variables concerning damage potential, susceptibility to wind and wind severity. For damage potential we used data on forest area and growing stock per hectare. Further we used the meteorological conditions prior to the storm, i.e., precipitation and below or above zero temperature that affect soil stability and indirectly the susceptibility of trees against uprooting. For wind variables we selected the daily maximum hourly wind gust from the Swiss meteorological station Zurich, which had been shown as a good proxy for storm severity in a prior study (Usbeck et al., 2009).

Severe winter storm damage is defined here as forest damage in timber volumes in three or more cantons exceeding 70,000 m^3. This limit was chosen to obtain storms with large-scale impact and sufficiently reliable damage estimates. Reliable data on forest growing stock, damage and meteorological data with sufficiently fine-resolution are available for the last 150 years. In order to detect general causes of winter storm damage, we correlated available winter storm damage data of severe winter storm damage events with the explanatory variables on forest area, growing stock, temperature, precipitation and wind speed.

We addressed the following questions:

1. Has severe winter storm damage increased during the last 150 years and, if so, is this increase related to increasing damage potential?
2. Which weather conditions prior to severe winter storms correlate best with the extent of storm damage, and have these weather conditions changed during the past 150 years?
3. How important is maximum gust wind speed in respect to forest damage and what is its general role in explaining winter storm damages?

2. Materials and methods

We used both historical and recent forest and meteorological data, mainly from federal and cantonal publications and databases of the past 150 years covering an area of roughly 35,000 km^2 with highly structured landscape. The first large inventory of forested areas in Switzerland started in 1858. Detailed information on winter storm damage to forests in subregions (cantons) has also been available since the late 1850s. A meteorological network of measuring stations was installed in 1863. Reliable maximum gust wind speed has been recorded since 1891.

The amount of damage (m^3) from severe winter storms since 1858 was compared with various explanatory variables. Daily maximum gust wind speed (U_{DMG}) was correlated to nearby recorded forest damage. Daily average temperature (T_{DA}) and daily total precipitation (P_{DS}) served as explanatory variables to explain soil status at the time of the damaging events.

2.1. Severe winter storm damage and damage potential

Total forest area was detected by using data from various federal statistics with first references for the year 1862 and available continuously without any large gaps from 1877 onwards (Landolt, 1862; Schweizerischer Bundesrat, 1878; EOFI, 1878–1994; ESA, 1907–1974, 1975–1977; BFS, 1978–1994; BUWAL, 1995–2007). Priority was given to the statistics of the federal forest service. Irregularities in the data refer to the time before the first National Forest Inventory (NFI 1; EAFV, 1988). In all cases we used original data, as the deviations, e.g., shifts in methods, were relatively small. Missing data were linearly interpolated. We fitted a 9-year moving average for the total forest area.

Forest growing stock has only recently been assessed for the whole of Switzerland (Mantel, 1990). Kurz et al. (1998) presented a model of national average growing stock per unit area for the period 1800–2050. We adopted this estimation for the time period 1860–1951 and interpolated linearly between the different forest inventories for the time after 1952. Growing stock was extrapolated for the years 2006 and 2007 by adapting the equation of the interpolation between NFI 2 and NFI 3 (Brassel and Brändli, 1999; LFI/WSL, 2007).

Data for the occurrence, extent and frequency of winter storms derived mainly from official records, i.e., federal or cantonal. We distinguished three 50-year time periods: 1858–1907, 1908–1957 and 1958–2007. To achieve a finer resolution and to better detect trends, severe winter storm damage was sub-divided into five damage classes exceeding 70,000 m^3 (1–5): 70,000–177,500 m^3, 177,501–285,000 m^3, 285,001–392,500 m^3, 392,501–500,000 m^3 and >500,000 m^3. The amount of winter storm damage to forests was adjusted proportionally to the total forest area and growing stock at the time of storm event Lothar (December 1999) by employing the following equation (1):

$$ad_w = a\,fd_w t\,fA_{2000} t\,fA_w{}^{-1} gs_{2000} gs_w{}^{-1} \quad (1)$$

with ad_w is the adjusted amount of damage in winter w [m^3]; $a\,fd_w$ is the estimated amount of damage in winter w [m^3]; tfA_{2000} is the total forest area in winter 1999/2000 [ha]; $t\,fA_w$ is the total forest area in the winter w of the winter storm [ha]; gs_{2000} is the growing stock in winter 1999/2000 [$m^3\,ha^{-1}$]; gs_w is the growing stock in the winter w of the winter storm [$m^3\,ha^{-1}$].

In the equation the winter semester with the largest storm damage, i.e., 1999/2000 from Lothar, served as reference (standardisation) for the other data.

We computed means for estimated and adjusted winter storm damage for the three 50-year periods. The probability that the amount of winter storm damage recorded in the last 50-year period had occurred randomly was tested by using resampling techniques (Manly, 1997). Using the 150 years of winter storm damage data as the basic population of severe winter storms, 10,000 samples of 50 randomly selected years were generated without replacement. This procedure is identical to randomly selecting different permutations of 50 years and thus differs from bootstrapping, which is done with replacement (see discussion in Manly, 1997). We then calculated the proportion of samples with

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higher estimated and adjusted severe winter storm damage sums that were reported into the most recent 50-year period. This procedure was repeated 10 times and proportions were expressed in means, minima and maxima.

2.2. Weather preceding storms and winter climate

Meteorological variables were exclusively derived from the data of the Swiss Federal Office of Meteorology and Climatology MeteoSwiss (MeteoSchweiz, 1865–2006), using both the present database via software Climap and published records of MeteoSwiss. The national meteorological network was established in 1863 (Mousson, 1864) and has since produced standardised measurements.

For the 1864–2007 period, 12 homogenised data series of T_{DA}, T_{MA}, P_{DS} and P_{MS} are available. Wind data were generally recorded three times a day as Beaufort-values until 1980 and afterwards as 10-min average and maximum gust wind speed. Before 1981, only few lowland stations of the meteorological network were equipped with anemometers. Out of these, the Zurich climate station, i.e., the climate station of the headquarters of the national meteorological service since 1864, has been producing reliable and homogenisable wind data from 1891 onwards (Maurer et al., 1909; Uttinger and Schüepp, 1951; Schüepp, 1973; Uttinger, 1968; Usbeck et al., 2009) that have also served for other winter storm studies in Switzerland (Schiesser et al., 1997a,b).

We selected meteorological stations located in different forest zones in Switzerland, distinguishing between the locations that were damaged at least once (damage regions), and those with no damage in the period studied (non-damage regions). Eight meteorological data series originated from stations located in the winter storm damage zone of Switzerland.

Winter climate was computed using homogenised T_{MA} and P_{MS} data for December (D), January (J) and February (F). We smoothed the winter season mean temperature according to Pfister (1984) and the following equation (2) for the winter N_{+2}:

$$N_{+2'} = (N + 2N_{+1} + 4N_{+2} + 2N_{+3} + N_{+4})10^{-1} \quad (2)$$

Linear trends for both temperature- and precipitation-smoothed winter means were calculated and used for providing graphical and readily identifiable short- and long-term trends.

To detect weather conditions preceding winter storms, temperature and precipitation information was derived either from data (T_{DA} and P_{DS}) or by quantification of verbal weather report information. We considered all winter storm days with reported forest damage or U_{DMG} of at least 30 m s^{-1} as focus days. Further, weather reports up to 10 days in advance of the storm event day were evaluated with respect to daily long-term means and whether soil states could be assumed to be frozen/unfrozen and wet/not-wet in the Swiss lowlands. Published daily weather reprints (aftercasts) served as data for this qualitative survey. Weather aftercasts cover large areas and are kept in archives. Spatially fine-resolution homogenised temperature and precipitation data were not yet at hand for all regions below the timberline. Nevertheless, we consider the qualitative information from aftercasts reliable and detailed enough to derive semi-quantitative data for the soil condition in the study region. For example, we categorised the term 'freezing day in the lowlands' in a prestorm period as 'frozen soil' for the Swiss lowlands on the day of a strong U_{DMG} event. Similarly, 'widespread rainfall in the Pre-Alps' was simplified and classified as 'wet soil' for the Pre-Alps. If several dry days preceded a winter storm day and precipitation started after the winter storm event itself, the storm event day was declared 'soil not-wet'. If the days before the storm events were described as freezing days, and the day when storms occurred was actually mild, the storm event day was still judged 'soil frozen'. Finally, we counted the differently classified storm event days and considered both the ratios between the numbers of storm event days with 'frozen soil' and 'unfrozen soil' (temperature caused soil condition) and the ratio between 'wet soil' and 'not-wet soil' (precipitation caused soil condition).

2.3. Case study: daily maximum gust wind speed and forest damage

In a case study region, we analysed the temporal trend of gust wind speed and its correlation with reported nearby forest damage during winter storms. Between 1891 and 1980, gust wind speed was measured at only a few stations in Switzerland. There is no homogenised series on wind speed for the whole observation period (MeteoSchweiz, 1865–2006) in the MeteoSwiss database nor was gust wind speed measured continuously using similarly standardised methods during this period. We therefore used the data from the Zurich MeteoSwiss station, which covers a long-time series in the midst of the damage zone. Measurements started in January 1891 and have continued after a short-distance move in close proximity to the old locality (Usbeck et al., 2009). Missing data were completed by values published in the local newspaper Neue Zürcher Zeitung (NZZ, 1891–1933).

A strong maximum gust wind speed was defined as an U_{DMG} of 30 m s^{-1} and more. First, the number of winter days (October to March, ONDJFM) with strong maximum gust wind speed was counted from January 1891 to winter 2006–2007, and for periods January 1891–1929, 1930–1968, and 1969–2007. Second, the relative frequency of days with strong maximum gust wind speed was calculated by employing the ratio between the number of days with strong U_{DMG} of the period and the number of winters of the period. Then, the total maximum gust wind speed per period was selected to compare extreme values among each other and with damage levels. Both Pearson's correlation and Spearman's rank correlation coefficients were calculated between the fraction of the growing stock damaged and the maximum gust wind speed using logarithmically transformed data.

In the case study region winter storm damage was expressed as total damage amount in m^3 ha^{-1} and as relative value in percentage of the total growing stock. Because small forest damage was not always reported, in particular since the end of the 1960s, we added published information about non-forest damage to all events of at least 35 m s^{-1} U_{DMG}, e.g., damage to people, trees in urban regions, orchards, infrastructure, buildings, and vehicles (hit by wind thrown trees). Finally, we checked the scatter plot of all strong U_{DMG} events and winter storm damage reports with less strong U_{DMG} for any relationship between U_{DMG} and levels of $<0.05\%$, $<0.5\%$ and $\geq 0.5\%$ damage of the growing stock during the observed period for temporally and quantitatively distinctive features.

3. Results

3.1. Damage-causing severe winter storms

The total forest area in Switzerland has increased from 768,478 ha in 1860 to 1,250,000 ha in 2006, which corresponds to an overall increase of 63% (Fig. 1). In 2006, 30.3% of the total surface in Switzerland was covered by forest.

In 1860 and 2006 growing stock in Switzerland tripled (292%; Fig. 1). Since the Lothar storm event (1999), numbers have remained stable (Fig. 1).

Table 1 in total, 25 out of the 26 detected severe winter storms between 1858 and 2007 were quantitatively recorded. Only qualitative information is at hand for a severe winter storm in

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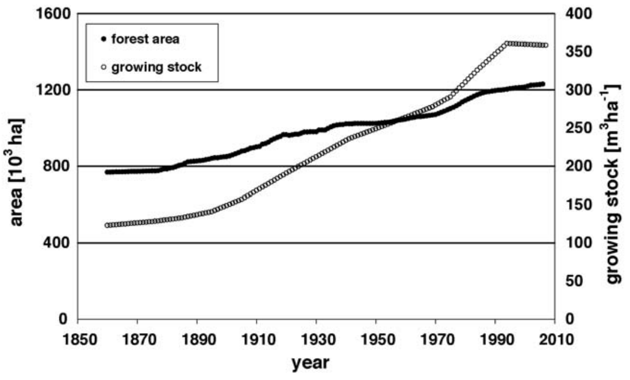

Fig. 1. Total forest area 1859–2006 and average growing stock per hectare 1860–2006 in Switzerland according to various data sources and interpolations (see text).

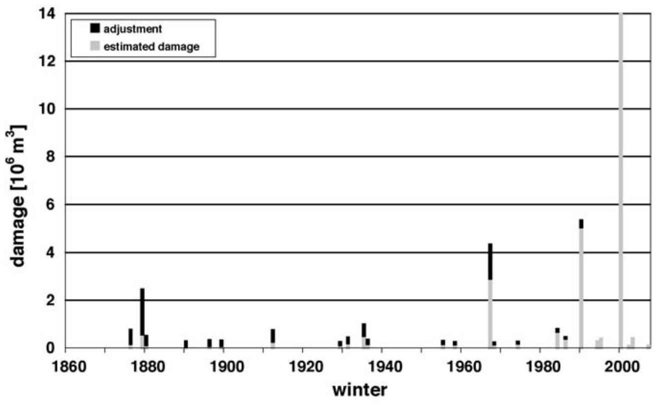

Fig. 2. Amount of severe winter storm damage in Swiss forests: estimated values in grey, adjustments indicated in black (difference).

Table 1
Severe winter storm damage >70,000 m^3 during the past 150 years.

	1858–1907	1908–1957	1958–2007
Total damage [$\times 10^3$ m^3]	1100	1433	24744
Number of events	6	6	13
Class 1: 70–177.5 $\times 10^3$ m^3	5	3	4
Class 2: 177.5–285 $\times 10^3$ m^3	0	2	2
Class 3: 285–392.5 $\times 10^3$ m^3	0	0	1
Class 4: 392.5–500 $\times 10^3$ m^3	0	0	2
Class 5: >500 $\times 10^3$ m^3	1	1	4

Table 2
Severe winter storm damage and climate in the damaged region during the past 150 years.

	1858–1907	1908–1957	1958–2007
Total, estimated damage [$\times 10^3$ m^3]	1100	1433	24,744
Total, adjusted damage [$\times 10^3$ m^3]	4577	2993	26,833
Number of events (estimated damage)	6	6	13
Mean winter temperature [°C]	−1.9[a]	−1.2	−0.3
Mean winter precipitation [mm]	172.8[a]	204.2	215.3

[a] 1864–1907.

1860 (Landolt, 1861). The amounts of estimated damage per 50-year period and the details on storm frequency are given in Table 2. The storm damage during the period 1958–2007 was estimated to be 17 times greater than during the period 1908–1957 and 22 times greater than during the period 1858–1907, and storm frequency was about twice as high compared to the period 1858–1907 or the period 1908–1957 to the period 1958–2007. The randomised sampling using 10 reruns from 10,000 samples of each 50 years resulted in an average proportion of 0.0016 of samples with higher total damage than had been measured in 1958–2007 (min: 0.0010, max: 0.0021). A likelihood test showed that differences between time periods with respect to damage amount are significant (one-sided test; p-value = 0.05).

For the 25 severe winter storms we found data at a cantonal level (in total for 90.4% of all cases). Little or no data were found for Canton Ticino, which usually is not affected by winter storm damage, and for Canton Geneva, where damage is not reported because of its small forest area. Most severe, i.e., catastrophic winter storms happened in 1879, 1935, 1967, 1983, 1990 and 1999. Corresponding amounts of damage are displayed as proportions of the total forest area and growing stock (Fig. 2).

The adjustment resulted in considerably higher values for severe winter storm damage in the first two periods (Table 3). Adjusted total damage in the last period was still estimated to be five to eight times higher than in the previous periods. In less than 2% of the 10,000 random samples of 50-year periods, the adjusted total damage was higher than during the period 1958–2007 (min: 0.0162, max: 0.0197). This means that it was 10 times more likely that the observed adjusted damage occurred by chance than without adjustment. However, even following adjustment the likelihood still remained low (<0.05).

3.2. Winter climate and prestorm weather

In the regions affected by severe winter storms, winters have become warmer, with a 2 °C rise during the last 140 years (Fig. 3). They have become wetter, with an increase in precipitation of

Table 3
Comparison of qualitative soil conditions in the Swiss lowlands during 215 winter storm events (according to weather reports) and the 26 recorded severe winter storms.

Period damage	Minimum damage reported	Events no %		Soil condition							
				Temperature-dependent				Moisture-dependent			
				Unfrozen		Frozen		Wet		Not-wet	
		No	%	No	%	No	%	No	%	No	%
1858–1907	$\times 10^1$ m^3	72	100	67	93	5	7	60	83	12	17
1908–1957	$\times 10^2$ m^3	45	100	44	98	1	2	40	89	5	11
1958–2007	$\times 10^3$ m^3	98	100	96	98	2	2	94	96	4	4
1858–2007 <70 $\times 10^3$ m^3		189	100	182	96	7	4	169	89	20	11
1858–2007 >70 $\times 10^3$ m^3		26	100	25	96	1	4	25	96	1	4

Line 1–3: 50-year sub-periods; line 4 and 5: non-severe and severe damage.

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nearly 50% (Fig. 4). Mean winter temperature above 0 °C were rare in the 19th century, but have become frequent since the mid-1970s.

'Frozen soil' prior to winter storm damage occurred in one out of 25 events. In 96% of all events considered, soils were unfrozen. Severe winter storm damage occurred in all but one event (96%) during 'wet soil' conditions (Table 3).

The ratios of both 'wet/not-wet' and 'unfrozen/frozen' soil conditions preceding a winter storm event have slightly increased with respect to the comparison of 50-year periods while the minimum damage recorded also increased (Table 3, row 1–3).

Before severe winter storm damage soil conditions were mostly wet and unfrozen in contrast to non-severe events where the respective ratios were smaller (Table 3, rows 4 and 5).

3.3. Daily maximum gust wind speed and forest damage in Zurich

We found an average of 0.21 days per year with a U_{DMG} of at least 30 m s^{-1} for the first period January 1891–1929, 0.85 days per year for the second period 1930–1968, and 2.51 days per year for the third period 1969–2007. The extremes of U_{DMG} increased by roughly 12 m s^{-1} between the first and last period (Table 4).

In total, we analysed 22 data pairs to compare forest damage caused by winter storms in Canton Zurich and U_{DMG} at the Zurich MeteoSwiss station (Table 5). Pearson's and Spearman's rank correlation coefficients between U_{DMG} and damage were $r_p = 0.61$ and $r_s = 0.68$, respectively. While for the first period almost no correlation was found, for the second and third periods, both Pearson's and Spearman's rank correlation coefficients increased. They reached statistical significance in the third period (Table 5).

Storm damage was found to be significantly associated with maximum gust wind speed ($p = 0.0015$; Fig. 5). In addition, we found an increase in the maximum damaged part of the growing stock and a temporal increase in extremes of U_{DMG} in winter (Fig. 6 and Table 5). Highest U_{DMG} are usually also indicated by reports on forest damage or damage to other goods. All U_{DMG} events of at least 35 m s^{-1} were caused by winter storms (Fig. 6).

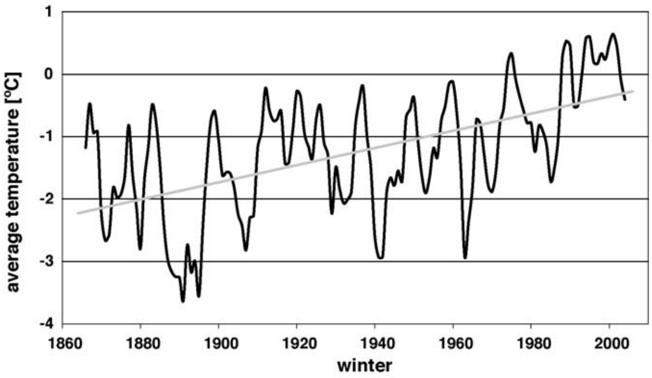

Fig. 3. Trend in average daily winter temperatures as weighted for the 5-year running means of the eight MeteoSwiss stations Basel, Bern, Chateau-d'Oex, Davos, Engelberg, Genève, Sion, and Zurich. Homogenised data for the periods December to January to February derived from MeteoSwiss.

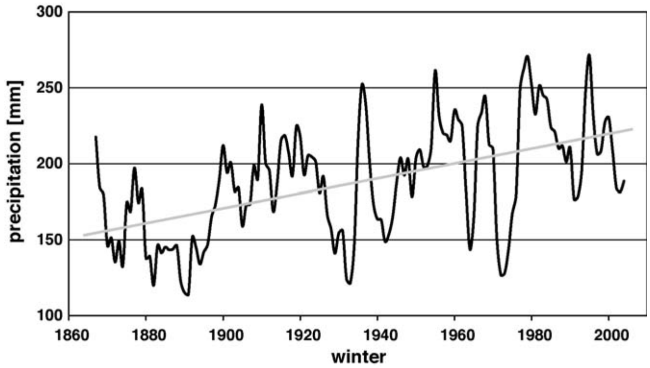

Fig. 4. Trend in winter precipitation as weighted for the 5-year running means of the eight stations Basel, Bern, Chateau-d'Oex, Davos, Engelberg, Genève, Sion, and Zurich. Homogenised data for the periods December to January to February derived from MeteoSwiss.

Table 4
Summary of strong daily maximum gust wind speed events (≥30 m s^{-1}) recorded at the Zurich climate station from 1 January 1891 to 31 March 2007.

	Total period	Period 1	Period 2	Period 3
	1891–2007	1891–1929	1930–1968	1969–2007
Number of winter half years (October to March)	116.5	38.5	39	39
Number of days with strong gust wind speed events	139	8	33	98
Average number of strong gust wind speed events per winter half year	1.20	0.21	0.85	2.51
Maximum gust event measured [m s^{-1}]	44.1	32.2	38.2	44.1

Table 5
Correspondence between maximum gust wind speed [m s^{-1}] at the Zurich climate station and forest damage [m^3 ha^{-1}] in Canton Zurich since 1 January 1891, expressed in product-moment and rank correlation coefficients.

	Total period	Period 1	Period 2	Period 3
	1891–2007	1891–1929	1930–1968	1969–2007
Minimum damage reported		$\times 10^1$ m^3	$\times 10^2$ m^3	$\times 10^3$ m^3
Data pairs	22	7	8	7
$r_{Pearson}$	0.61	0.25	0.41	0.93
p-value	0.0027	0.584	0.318	0.0026
$r_{Spearman}$	0.68	0.05	0.70	0.81
p-value	0.0004	0.915	0.053	0.0267

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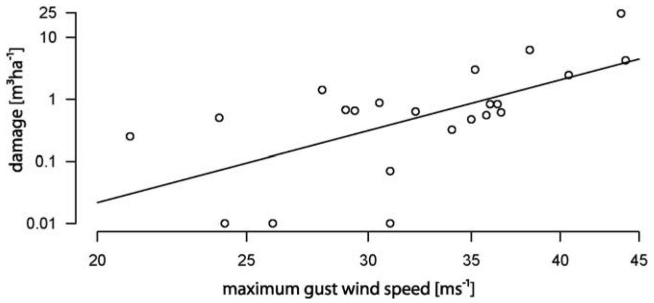

Fig. 5. Maximum gust wind speed during WS events in Canton Zurich (Zurich MeteoSwiss station) and damage per hectare in Canton Zurich, from January 1891 to winter 2006–2007. Regression line: $(\log 10(y) = -10.206 + \log 10(x) \times 6.565$; $R^2 = 0.405$, $p = 0.0015)$.

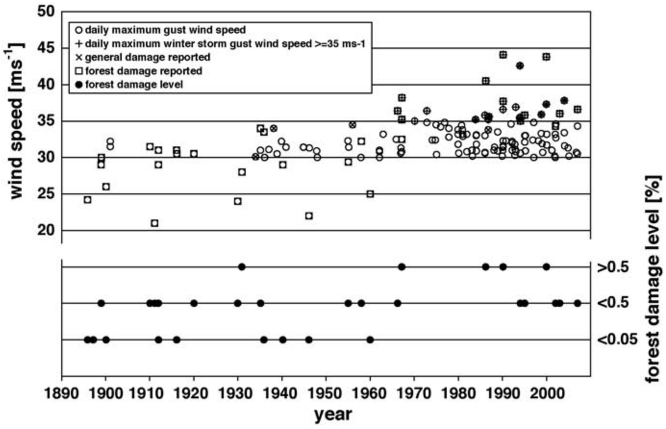

Fig. 6. Maximum gust wind speed during WS events in Canton Zurich (Zurich MeteoSwiss station), daily maximum gust wind speed of >30 m s^{-1}, and damage levels in respect to growing stock in Canton Zurich, for the period form January 1891 to winter 2006–2007.

4. Discussion

Our study showed an increase in severe winter storm damage in both amount and frequency (confirming Bütikofer, 1987; Münchner Rück, 2001; WSL and BUWAL, 2001; Schelhaas et al., 2003). The damage potential, i.e., forest area, growing stock as well as growing stock per hectare has also increased (confirming, e.g., Brändli, 2000; Mather and Fairbairn, 2000). However, our damage adjustment by forest area and growing stock (Münchner Rück, 2001) cannot fully explain the damage increase during the time period 1858–2007. Various authors have suggested that other major influencing variables have also considerably changed (e.g., Mayer and Schindler, 2002; Schmoeckel and Kottmeier, 2008). Our results show that winter temperature and precipitation have increased during the observed period (in agreement with, e.g., Begert et al., 2005; Schmidli and Frei, 2005; Scherrer et al., 2006; Rebetez and Reinhard, 2007). Winter storm damage usually occurred when the soil was ‘unfrozen’ and ‘wet’. We found that this weather type is characteristic for winter storms that are always caused by cyclonic weather situations (e.g., Kraus and Ebel, 2003; Allaby et al., 2006). With one exception, severe winter storm damage in Switzerland occurred when soils were wet. This suggests that the increasing winter precipitation – as regionally predicted in climate change models (Frei et al., 2006; Schmidli et al., 2007) – predisposes forests to higher winter storm damage.

Maximum gust wind speed has also increased during the time period for which data are available. It exceeded 30 m s^{-1} for the first time at the beginning of the 20th century, reached nearly 35 m s^{-1} in the mid-1930s, nearly 40 m s^{-1} at the end of the 1960s and nearly 45 m s^{-1} in 1990.

The observed increase of maximum gust wind speed is decisive due to the fact that wind force, i.e., the destructive energy, increases quadratically when wind speed increases linearly (e.g., Otto, 2000; Hubrig, 2004). The results from the case study region clearly indicate that winter storm damage to forests corresponds to the velocity of the maximum gust wind speed. As a rule of thumb, severe winter storm damage exceeding 2 m^3 ha^{-1} occurred mainly when maximum gust wind speed exceeded 35 m s^{-1}.

Although the long wind measurement series consists of data measured at two locations and by different gauges, this series has been repeatedly considered reliable and representative (e.g., Uttinger and Schüepp, 1951; Uttinger, 1968; Schüepp, 1973; Schiesser et al., 1997a,b). Our results of increasing storminess since the 1960s correspond well with the four Central European pressure records Kremsmünster, Vienna, Karlov, and Prague (Matulla et al., 2008). The observed changes in maximum gust wind speed over the investigated period evoke the questions of comparative observations in Central Europe and of possible meteorological causes. Extreme mid-latitude cyclones during the extended winter season (October to March) are the main origin of severe windstorm events affecting Central and Northern Europe (Leckebusch and Ulbrich, 2004). Their occurrence may be linked to the North Atlantic Oscillation (NAO) (Seierstad et al., 2007; Trigo et al., 2008; Pinto et al., 2009) that is the dominant pattern of atmospheric circulation variability in this region during winter (Matti et al., 2009). Strong positive NAO phases are well known to cause more extreme cyclones (e.g., Pinto et al., 2009; Trouet et al., 2009). Our findings of maximum wind speed observations correspond to the increasing severity of storms during the period 1960–2000 (Leckebusch et al., 2008a). Also the temporal pattern of storminess for Austria and the Czech Republic (Matulla et al., 2008) covering the period from the end of the 19th century to the 1990s resembles well the pattern of maximum gust wind speed in Zurich. In Austria, several extreme winter storms in the years 2007 and 2008 produced the most severe forest damage in more than 60 years (Steyrer et al., 2008).

The parameter maximum daily wind speed is claimed to be best for determining changes in wind speed and number of storm events (Rockel and Woth, 2007). For the future climate in Central Europe, extreme wind speed is predicted to increase (e.g., Rockel and Woth, 2007; Leckebusch et al., 2008a,b; Pinto et al., 2009), both in maximum wind speed of extreme events (Leckebusch et al., 2006) and in spatial extent (Leckebusch et al., 2008a).

However, regardless of the significance of the correlation between U_{DMG} and winter storm damage to forests, the dynamic wind field in forests may be the main cause of the majority of storm damage in forests. Results from experiments and modelling effects of dynamic wind fields to trees indicate the relevance of such interactions (Frank and Ruck, 2008; Moore and Maguire, 2008; Rudnicki et al., 2008; Schindler, 2008; Sellier et al., 2008). However, experimental designs and models have focused on single, relatively small trees, or on a limited number of trees that are not preferentially affected by severe winter storms. Due to experimental limitations, only moderate dynamic wind fields that do not cause damage have been estimated. Recording data from dynamic wind fields during severe storms may become available in the nearer future (Moore et al., 2005; James and Kane, 2008). As long as time series of such difficult-to-obtain data are not available, U_{DMG} or other variables of maximum wind speed need to serve as indicators to study the relation between wind and forest damage (e.g., Quine, 1991; Gardiner et al., 2000; Hubrig, 2004; Cook and Goyens, 2008; Gardiner et al., 2008; Kupfer et al., 2008; Islam and Peterson, 2009; Zandenberg, 2009).

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Due to inconsistent or missing data the following forest and site factors often used to describe the susceptibility of forests to storm damage were not considered: proportion of conifers, stand structure, management system, and stand height. Various reports suggest that proportion of conifers and stand structure in Swiss forests have not changed substantially since 1860 (e.g., Weber, 1867; Flury, 1925; Brassel and Brändli, 1999). An increase in mean stand height was assumed to be positively correlated with growing stock (Vanselow, 1948; Kramer and Akca, 1987). Stand height was found to be one of the most important factors explaining forest damage following the storm Lothar in 1999 (Dobbertin, 2005). In contrast, Schütz (2005) concluded that stand height was less important than species composition and stand structure. Concerning site conditions, the question whether changes in soil chemistry reduce forests stability cannot be answered due to a lack of relevant data. However, a few studies have examined the effects of changes in soil chemistry on stand stability. After the Lothar storm, Braun et al. (2003) found more uprooted trees on soils with higher base saturation, but could not show a direct effect of root damage and uprooting. Mayer et al. (2005) found that Lothar caused more damage to stands on soils with lower pH values. However, they found no relationship between storm damage and modelled atmospheric deposition, which may have induced changes in soil chemistry. In summary, beyond several factors not treated in this study, our results show that storm caused forest damage in Switzerland from the middle of the 19th century until today is a function of wind force, growing stock and weather (temperature and precipitation) conditions preceding winter storm events.

5. Conclusions

Our results show that since the 19th century and particularly over the last four decades, wind velocity and strengths of wind fields have increased in Switzerland while forest area and growing stock were also increasing. In the meantime, winter temperature and precipitation have also increased, potentially driving forest stands to be more sensitive to wind storms through wetter and more often unfrozen soils. The combination of all these factors may explain why forests stands nowadays are generally more vulnerable to winter storms than they were in earlier times. Changing growing stock alone cannot explain the observed increase in forest damages.

To combine forestry and damage prevention, more detailed information on wind effects during winter storms is needed. This knowledge would help to better quantify storm vulnerability of forests with respect to topography. It would require the analysis of more long-term wind data series and their relation to nearby winter storm damage records. More localised information on maximum gust wind speed would be a basis for highly resolved wind gust risk maps that could help forest managers to take appropriate preventive measures.

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