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The Winterstorm "Vivian" of 27 February 1990: About the Meteorological Development, Wind Forces and Damage Situation in the Forests of Switzerland

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With 16 Figures

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Summary

During the months January and February 1990 a series of severe cyclones were responsible for enormous wind-induced damage in Europe. The final of this series, on 27 February 1990, cyclone "Vivian" mainly affected the alpine valleys of Switzerland. 5 Millions m^3 of timber were felled by the severe winds, a record number in this century. A complete damage survey of the deforested areas offers in combination with meteorological data an unique data set for a detailed case study of this extreme event.

This paper describes the general meteorological development from the synoptic scale down to the mesoscale of Switzerland and presents a general overview of the damage situation. The main results show that a rare situation of a straight frontal zone stretching over the whole Atlantic Ocean and showing a strong gradient in temperature pointed directly toward Central-Europe. Two waves formed along this elongated polar front and deepend rapidly to depressions. The first low travelled on the southernmost trajectory of the whole storm series and affected Switzerland most. North of the Alps the prefrontal warm air was blocked to the east by the arriving coldfront and had to escape into the complex terrain of the alpine valleys. There, the stormy winds were strengthened by channelizing and "Föhn" effects. The large temperature gradient between the prefrontal and the incoming air masses induced thunderstorm activity which vortices and downdrafts might have enhanced locally. As a result most of the damaged forested areas were found between 1200 and 1600 m MSL on slopes, which were mainly exposed toward the prevailing NW-winds. A comparison of extreme wind speeds for the period 1978–1992 revealed that this event's extreme high speed of 74.5 m/s, measured at a high elevated pass station in the mountains, was exceptional. For lower elevated stations the wind speeds were high but in the range of other observed extreme values. In addition to the severe wind forces the duration of sustained high wind speed was exceptionally long during February 1990.

1. Introduction

During the period between 25 January and 2 March 1990 West-, North- and Central-Europe experienced eight severe extratropical cyclones with winds exceeding Beaufort force 12 ($\geqslant 32.7$ m/s, see Münchener Rück, 1993). The tracks of the centers of the lows can be followed from the east coast of North America until they weaken in North- or Central-Europe (Geipel, 1992). At the end of this period three severe cyclones occurred within four days (26.2.–1.3.92), among them the most severe was called "Vivian", which was the mother cyclone of the two following ones. The stormfield of a "secondary low" of "Vivian" passed across Switzerland on 27 February. In relation to Swiss forests this storm was the most devastating wind storm in this century with gales up to 75 m/s at an alpine pass-station (Grand St. Bernard). Beside the damages in the forests, people were killed and public and private transportation broke down because of windblown trees, many buildings were heavily damaged, trucks were blown off the road and railway wagons turned over. In Germany an estimate of 60 Million m^3 timber was blown down by the severe gales (Geipel, 1992) and for Switzerland the corresponding number was estimated as 4.3 Million m^3 shortly after the disaster, which is 96% of the timber cut on the average in a non-catastrophic year (BUWAL, 1990). The updated number for Switzerland rose in the meantime (1993) to an estimate of about 5 Million m^3 of thrown timber.

In view of the storm's severity, it appears worthwhile to perform a multi-scale analysis from the synoptic scale situation down to the local effects in a Swiss mountain valley, where most forest damage occurred. This analysis was undertaken in the framework of a *N*ational *R*esearch *P*rogram (NRP31), which is entitled "Climate changes and natural disasters". The principal objective of the NRP31 is the detailed study of the consequences of future climate changes on Swiss environment and society in respect to natural hazards. The question arises whether the regional storm activity will change too through the predicted global warming. One approach is to investigate the behavior and activity of severe storms during a time period, which is desirable to be as long as possible for trend analysis and to be able to establish a storm climatology to compare the storm behavior within warmer and colder periods. On the other hand, case studies of the most severe storms are necessary to get the important knowledge about the worst cases, which can be expected in a heavily populated country like Switzerland.

This paper presents an overview of the synoptic and mesoscale development of the storm, especially in Switzerland and its severe damage impact on the Swiss forests. Section 2 gives an idea about the area of interest and introduces the available data. Section 3 reviews the storm's history on the synoptic scale and Section 4 on the mesoscale for Switzerland. In the same section a comparison of the obtained wind forces with wind measurements for the period 1978–1992 are discussed. Section 5 explains the general damage situation in the Swiss forests and Section 6 concludes the investigation.

2. Observational Area and Data

2.1 Observational Area

The storm of 27 February affected a large area of Europe. Figure 1 shows the area covered by the synoptic scale map of the DWD (*D*eutscher *W*etter *D*ienst). The track of the steering low – "Vivian" –

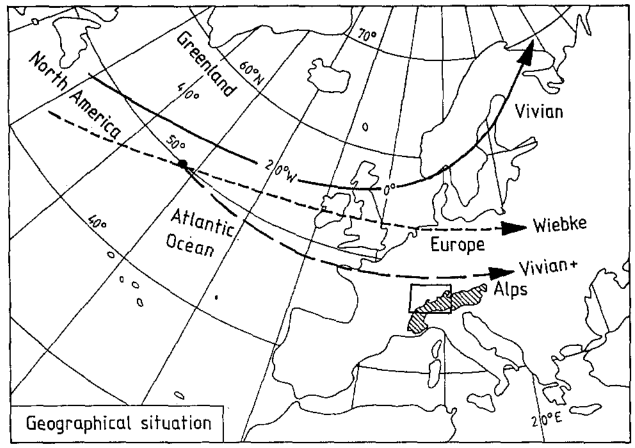

Fig. 1. The synoptic region of Atlantic-Europe related to the observational area of Switzerland (inlay, see Fig. 2). The tracks of the mother cyclone "Vivian" and the secondary lows "Vivian+" and "Wiebke" are displayed

as determined on the surface charts of the DWD – is shown as a continuous line. The track of a "secondary low" of "Vivian" (hereafter named Vivian+), which was responsible for the severe wind situation in Switzerland, is dashed. The second "secondary low" called "Wiebke" followed a track (short dashes) between the mother cyclone "Vivian" and the devastating one just north of Switzerland.

The inlay in Fig. 1 shows the observational area, where the storm's impact on the forests of Switzerland will be discussed. This area is displayed in more detail in Fig. 2. Figure 2a shows the boundary of Switzerland, the range ($r = 60$ km) of the research rader ETH, the locations of the two radars of the Swiss Meteorological Service (SMA), the network of the automatic weather stations (ANETZ) maintained by the SMA, the location of the routine radiosounding station at Payerne. Two ANETZ-stations are numbered 1 and 2 and will be used for the comparison of high gusts and high mean wind speeds during the period 1978–1992 with data available. Figure 2b is a schematic topography of the investigated area mainly detailing the mountain valleys of the Alps, where most of the forest damage occurred. The black areas reveal the main damage locations in Switzerland.

2.2 Data

A combination of data are used to investigate the complex evolution of the event: Since 1979 two 5 cm wavelength weather radars have operated

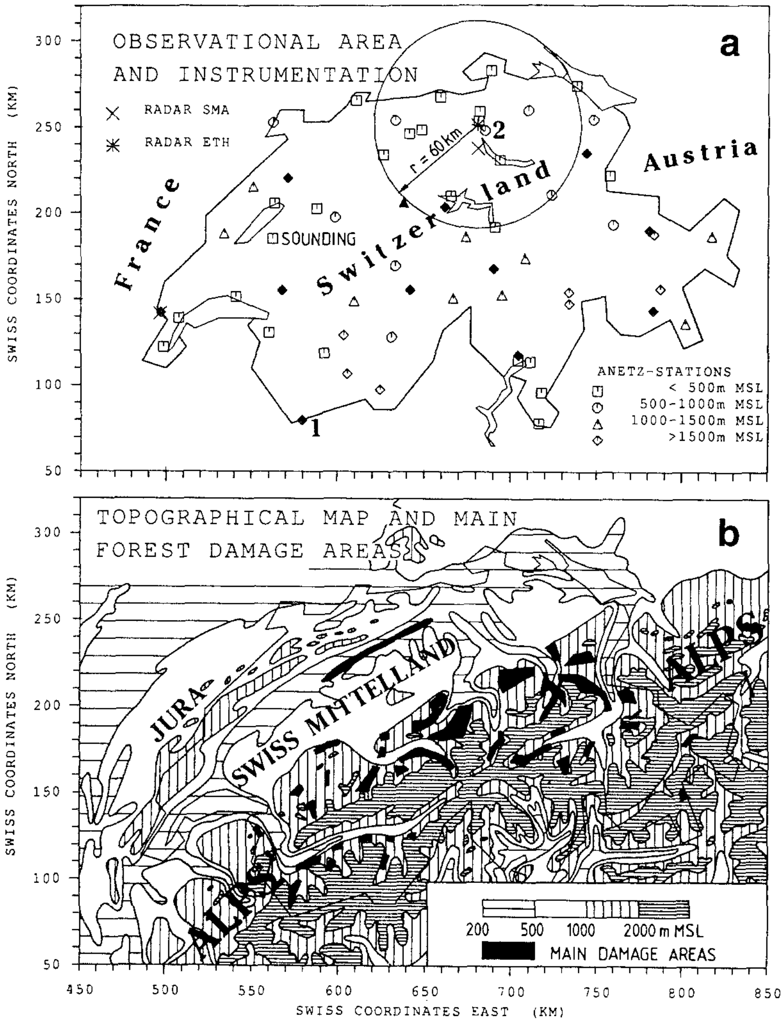

Fig. 2. Observational area. a) The boundary of Switzerland, the range ($r = 60$ km) of radar ETH, the localities of the radars SMA, the network of ANETZ-stations and the location of the site of radiosounding (Payerne) are given. The numbers refer to ANETZ-stations, whose wind measurements are discussed in Section 4.2. b) The topographical situation. The main geographical regions are labelled Jura, Swiss Mittelland and Alps. Black surfaces indicate the main forest damage areas in a very general manner. The scale is given in "Swiss coordinates" (Swiss capital Bern = 600/200 km)

24 h a day in Switzerland (Joss and Waldvogel, 1990). The two radars cover a volume of $558 \times 428 \times 12\,\text{km}^3$ in and around the country, there are three image projections (ground view, W–E and N–S cross sections), the pixel size in the ground view is $2 \times 2\,\text{km}^2$ and the vertical resolution 1 km. Each pixel contains the maximum radar reflectivity, which is converted to rainfall rate through the relation $Z = 300\,R^{1.5}$. The range of the rainrate is divided in seven steps indicating intensities $\leqslant 0.3$ to $\geqslant 100$ mm/h. The time resolution of the available images is 10 min. They are stored on 16 mm films for the day under investigation.

A 5 cm wavelength Doppler radar is installed at ETH-Hönggerberg. During the stormy phase of the frontal passage, caused by "Vivian+", three-dimensional observations of the precipitation and windfield were taken every 10 min within a radius of 60 km from the radar site. Technical details related to the radar are given by Schmid et al. (1990).

A Swiss network of automatic weather stations operated by the SMA was maintained since 1978 and currently comprises a total of 72 stations. In the present investigation 63 stations are used (Fig. 2a). The elevation of the stations are given in four intervals and the meteorological variables are available with a temporary resolution of 10 min. For our purposes the pressure, temperature, wind and lightning information will be used. The stations are stratified into "mountain" (given in black in Fig. 2a) and "ground" stations.

After the passage of the storm an almost complete inventory of the damage in the forests was made to get the basic information mainly about the location and size of affected area of total damage down to the level of a single community. The procedure to realize this inventory is described in detail by Scherrer et al. (1990) and Scherrer (1993), but a short summary of the procedure is given hereafter:

The Federal Direction for Forestry in Switzerland decided to undertake the damage inventory to get an overview about the dramatic situation in the forests. Regional forest services delivered the basic damage information for planning the photo-flights. 272 flights of a total length of 2,980 km covered about 18,000 km^2 (more than 40% of the surface of Switzerland) in taking color slides (format 23 × 23 cm). The scale of the images was about 1:15,000. 871 pairs of aerial photographs were interpreted stereoscopally and measured with analytical stereo plotters. The criteria for an area of total damage was taken as follows: At least an area of 0.2 ha (1 ha (hectar) = 0.01 km^2) and the degree of the surviving stock of trees has to be <0.2. With this information detailed maps of the damaged forest were produced. The data are stored for further evaluation in a Geographical Information System and were combined with the underlying topography of the hilly and mountainous landscape of Switzerland.

3. Synoptic Analysis

On 22 February, 5 days before the first of two "secondary lows" of cyclone "Vivian" (Vivian+) affected Switzerland, a high-pressure area (up to more than 1040 hPa) was located over Central-Europe. This situation is illustrated in Fig. 3a, showing the DWD-surface analysis at 12 UTC (local time = UTC + 1h). Therefore, the boundary between the subtropical warm and the arctic cold air masses was found to the NW of the continent. This situation lasted until the 24th of February. At that time (Fig. 3b) an unusually strong frontal zone was forming over the West-Atlantic ocean, and its heading edge is clearly visible as the divergence of the isohypses at the longitudes of 25–40° W. Until the 26 February (Fig. 3c) the frontal zone moved further eastward, with the frontal edge reaching far into Central-Europe. Between 80° W and 0° longitude an elongated area (almost west–east oriented) of parallel isohypses are visible, a straight track for the air, and wind speeds reached about 230 km/h (64 m/s) at 500 hPa level.

On 26 February the anticyclone over Central-Europe weakened rapidly and a high pressure region was established over the Great Lakes. This high was accompanied by the supply of arctic air from Canada and the anticyclone situated over the Azores (Fig. 3d) was associated with the northward transportation of subtropical warm air from the western Atlantic. Together these streams contributed to the building up of the frontal zone that trailed southwestward from the low east of Iceland. This low with its frontal system was named cyclone "Vivian" (V in Fig. 3d). The track of the low is depicted in Fig. 1. Between the 26 and 27 February the frontal zone moved southward from latitude 55° to 50° and reached Central-Europe (Fig. 3e). The winds turned slightly from W to WNW in the alpine regions of Switzerland, so that Switzerland was temporarily at the southern edge of the polar air mass. The first coldfront reached Switzerland in the evening of 26 February. Before the frontal passage, the winds reached the maximum speeds of about 40 m/s and the first accidents and damages with falling trees were already reported.

In the meantime a process developed, which was later responsible for the extraordinary damaging forces in the Swiss forests. Within the West-East elongated polarfront region a wave formed far out in the Western-Atlantic (Fig. 3d). The wave deepend just west of France to become a secondary depression of the large Scandinavien low "Vivian" (Fig. 3e) and moved toward Central-Europe. Its center was just north of Switzerland on 27 February 12 UTC (Fig. 3f). The track of "Vivian+" is shown in Fig. 1 and is labelled "V+" in Fig. 3d–f. The different air masses of the second frontal system are indicated in Fig. 3f as cold and warm air. During that stage warm air was transported from SW to the northern side of the Alps into the Swiss Mittelland (Fig. 2b) and was responsible for the first wave of damaging wind forces. The coldfront, which passed Switzerland in the afternoon from NW to SE, enclosed the warm air in the Swiss Mittelland and blocked the exit to the NE. This warmer air moved into the alpine valleys and led to the very special mesoscale situation, which caused the large windfalls of trees in the alpine area of Switzerland. This phase of the frontal passage will be shown in the mesoscale analysis in Section 4. The passing coldfront moved quickly, as it can be seen from Fig. 3g (28 February, 00 UTC), where the front is already found far in the east over the Balkans.

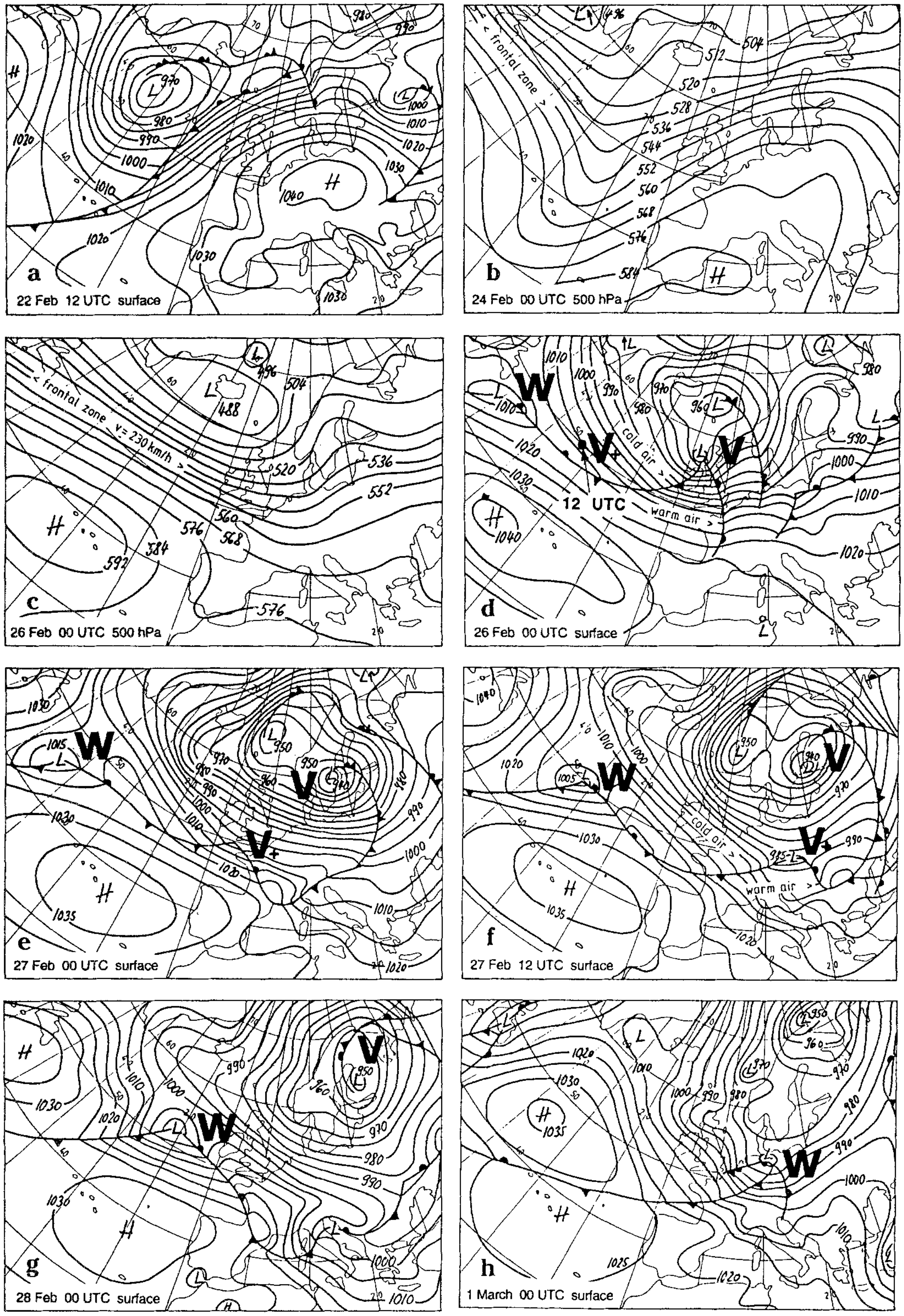

Fig. 3. Succession of significant synoptic situations from 22 February 1990 (a) until first of March 1990 (h). The maps are drawn in using DWD (*D*eutscher *W*etter *D*ienst) weather map information. Time is given in UTC

The corresponding windfield on 27 February at 12 UTC surface level (ECMWF-analysis) is depicted in Fig. 4a, where the convergence line over Central-Europe, the line of wind shift (SW to WNW) is clearly visible, which indicates the frontal line. Figure 4b shows the large difference in temperature between the air in the northern and the southern part of the continent, the isolines are given as equivalent potential temperature at the same instant as Fig. 4a but at 700 hPa level. Six hours later at 18 UTC a strong low level jetstream was established over Central-Europe (Fig. 4c), the windfield is displayed at the 700 hPa level. The corresponding field of equivalent potential temperature is depicted in Fig. 4d. The narrow zone with the large temperature gradient moved in the meantime in a southeastern direction and is situated right over Switzerland at 18 UTC. The windfields and the remarkable drop in temperature will be discussed further in Section 4.

After the passage of the second coldfront on 27 February, responsible for the severe weather, the general synoptic situation did not change much and the strong westerly flow from the Atlantic still dominated the weather situation in Europe. A further "secondary depression" of the steering low "Vivian" developed in the Western-Atlantic as a wave on the frontal zone (Fig. 3e), almost at the same location as the first "secondary low" and is labelled W. This latter cyclone was called "Wiebke" (Münchener Rück, 1993; Geipel, 1992). The low moved quickly from the Atlantic to Northern-

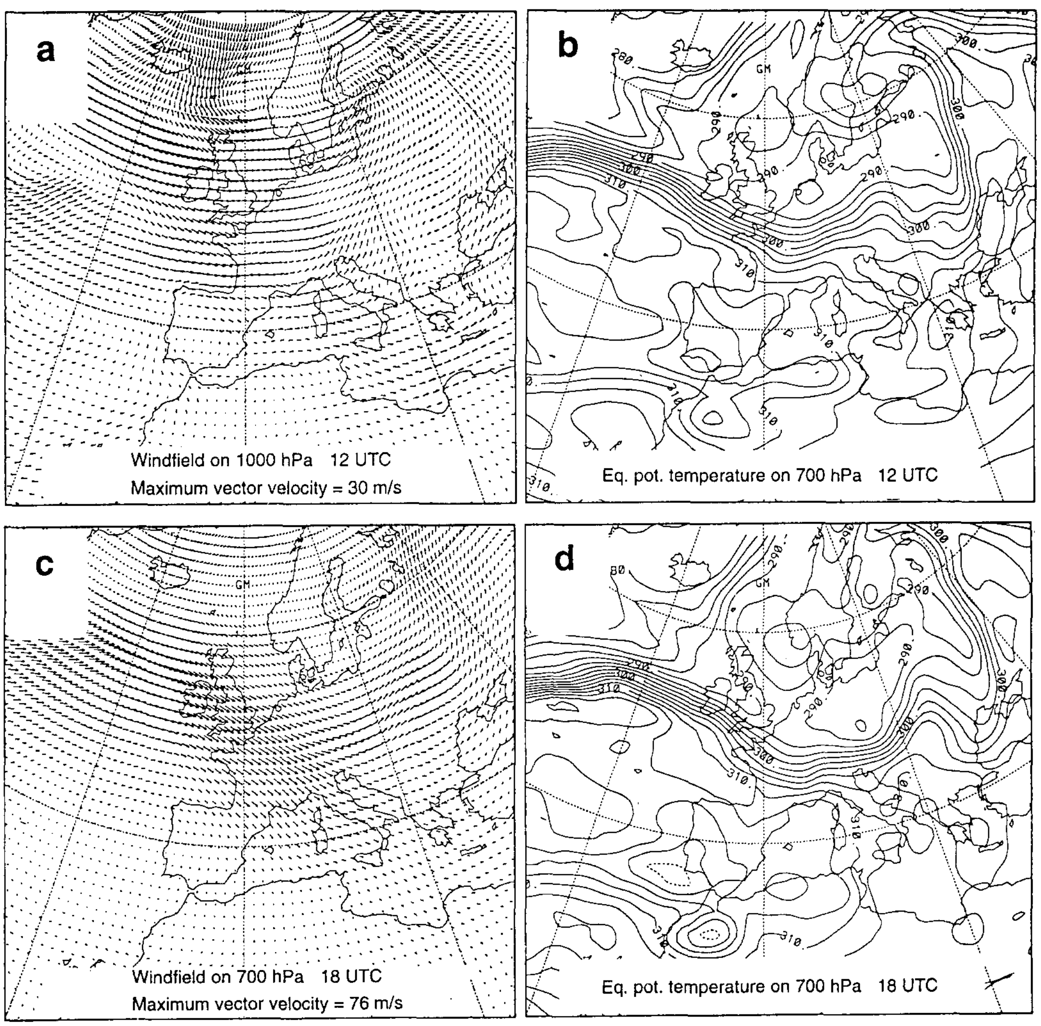

Fig. 4. Weather map of ECMWF-analysis for 27 February 1990. a) Windfield at 1000 hPa for 12 UTC, b) field of equivalent potential temperature at 700 hPa level for 12 UTC, c) windfield and d) field of equivalent potential temperature both at 700 hPa level and for 18 UTC

Germany on a track further north than the low two days before (Fig. 1). The corresponding (third) coldfront passed through Switzerland on first of March (Fig. 3h) and was responsible for minor damage compared with those on 27 February. An important difference was that this latter front passed even quicker and undisturbed because at this time the warmer prefrontal air could leave the Swiss Mittelland unhindered toward the east. This was the definitive end of the series of severe cyclones which battered Europe in the last few weeks. Thereafter an anticyclone formed over Western-Europe and this was accompanied by a modification of the Atlantic stormtracks.

In comparison to the other severe cyclones, which occurred during January and February 1990 over Western Europe, "Vivian +" moved on the southernmost trajectory of all storms and therefore affected Switzerland most. The Swiss reinsurance company investigated the trajectories of storm events for the period 1949–1983 (Schweizer Rück, 1985), which exceeded a windspeed of 30 m/s, calculated from pressure gradients. The trajectories of 271 lows were followed and mapped. The investigation revealed (Fig. 2.5 in Schweizer Rück, 1985) that only about 7% (19 cases within 35 years) of the stormy lows moved on a trajectory as south as the one of 27 February 1990.

4. Mesoscale Analysis

4.1 The Passage of the Severe Coldfront Through Switzerland

To determine the passage of the frontal line at surface level through the observational area (Fig. 2) on 27 February 1990, the data derived from the ANETZ-measurements have been used, namely the change in pressure (decrease – increase), the sudden drop in temperature indicating the arrival of the cold air behind the front and the change in wind direction at the convergence line. Besides this information, the frontal line can also be tracked by the precipitation echos of the SMA radar measurements. On that day the precipitating areas show elongated structures of enhanced reflectivity, so called narrow convective rainbands, which indicate areas of convective activity at the arrival of the frontal line. Recently, Hagen (1992) described such narrow rainbands within a coldfront approaching the Alps in Southern Bavaria from NW on 18 December 1987, using Doppler radar information. The high reflectivity cores are observed along the frontal line, which is the wind shear zone. The same result was obtained by Li et al. (1992) for the actual winterstorm.

In the following presentation a rain intensity of 3–10 mm/h (32–39 dBZ radar reflectivity) is used. Agreement of the derived line with the frontal passage detected by the mesonet is excellent – as long as the front moves over the flatter Swiss Mittelland toward the Alps. As soon as the mountain chain modifies the precipitation fields through blocking and lifting effects the frontal movement is less well defined on the radar measurements to determine the frontal passage. From the movement of the radar echos the speed of the passing coldfront is estimated as 11 m/s.

The synoptic situation at the time when the "second" coldfront entered Switzerland from NNW is depicted in Fig. 3f. A succession of significant stages of the coldfront's further movement toward the alpine ridge is depicted in Fig. 5a–f. The high radar reflectivity zones of the precipitation areas are clearly visible as elongated rainbands with a maximum rain intensity up to 10–30 mm/h (40–46 dBZ). The wind vectors in the Jura mountains and Swiss Mittelland (compare Fig. 2b) indicate the southwesterly flow before the front, except three elevated stations (height: 1670, 1600, 1970m), which already show a wind direction from W to WNW (labelled 1–3 in Fig. 5b). Two other elevated alpine stations (labelled 4 and 5, height: 3580, 2290 m) show a wind direction from NW. This indicates that in higher altitudes the cold air has already arrived and the wind shift has taken place. The other stations within the alpine region show various wind directions and are influenced by the complicated relief of the mountains and inner alpine valleys, depending on the location of the station.

At about 12 UTC the front passed the radar site ETH (Fig. 2a) and volume scans of radar reflectivity and Doppler velocities of the precipitation area were obtained in 10 min intervals. The evolution of the wind direction and speed during the passage is shown in Fig. 6 (modified after Li et al., 1992) as a time-height cross section. The analysis is based on the 10 min volume scans within a circular area of 5 km radius around the radar site. Figure 6 reveals that the wind veered from SW to NW at 1210 UTC, which is in good agreement

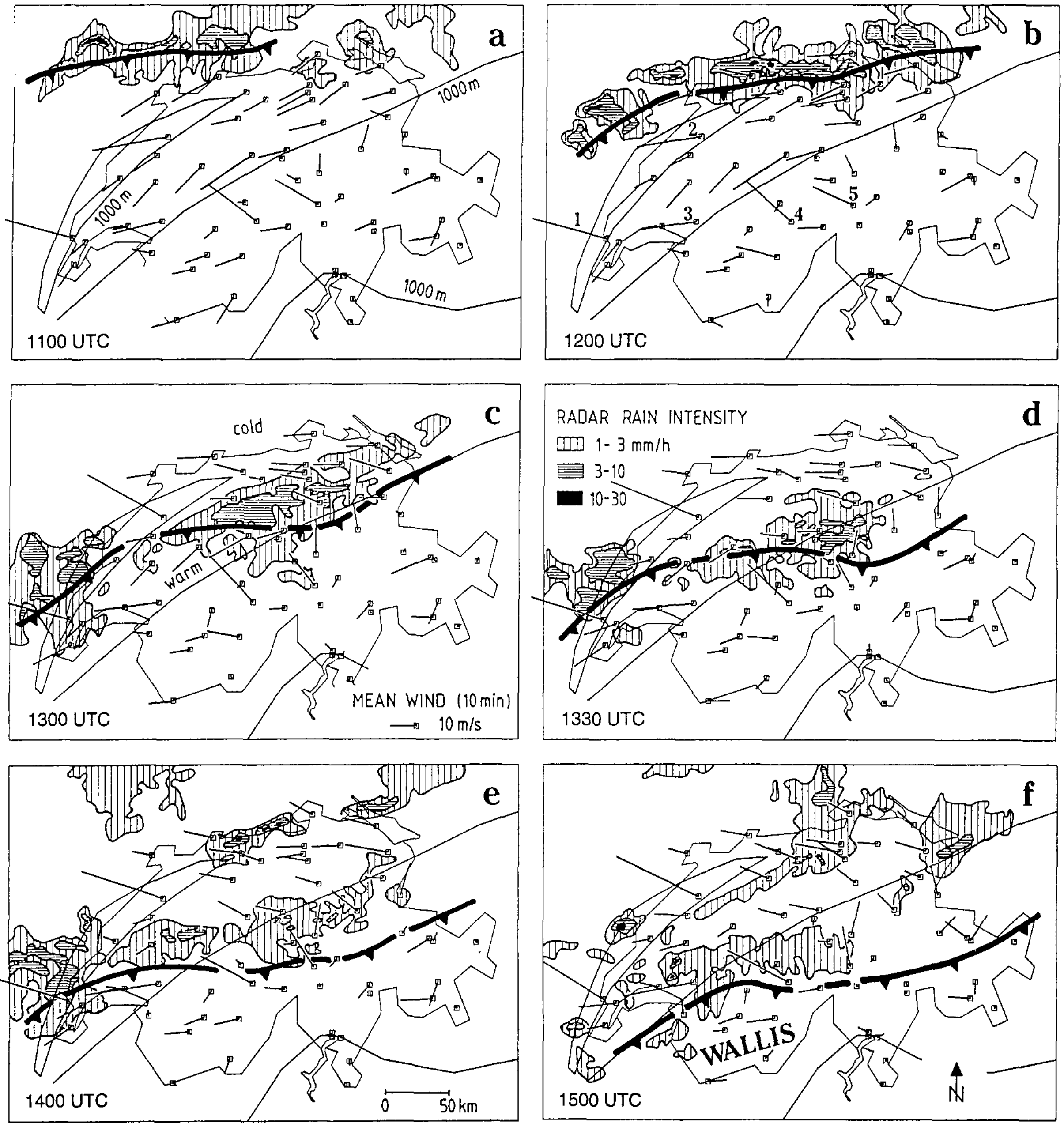

Fig. 5. Succession (a–f) of significant stages during the passage of the coldfront through Switzerland on 27 February 1990. In each figure the boundary of Switzerland, a schematic topography (1000 m isoline, see Fig. 2), the 10 min mean wind vector for each ANETZ-station, the precipitation areas and the frontal line (heavy line) are given. The numbers in (b) indicate ANETZ-stations, which are discussed in Section 4.1. The scale of the radar derived rain intensities is given in (d)

with the mesonet-observations (Fig. 5a, b). The strongest winds are found ahead of the front, e.g. 47.5 m/s at a height of 3 km. At radar level (600 m MSL) a near ground peak gust of 28 m/s was measured at 11 UTC. Weaker wind speeds appeared during the passage of the front but secondary peaks of strong low-level winds occurred after the passage of the frontal line as marked in Fig. 6 (37.5 m/s). In general the wind vectors are more variable after the passage and can be attributed to additional convergence lines, which formed in the unstable air mass behind the main frontal line. Figure 5e and f show the propagation of a secondary line, which still exhibits convective activity, e.g. lightning counts at some ANETZ-stations.

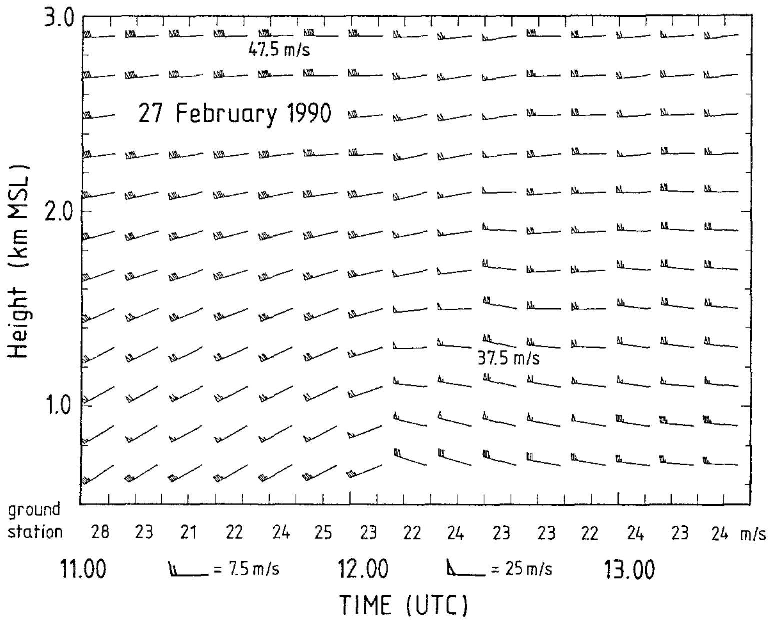

Fig. 6. Time-height cross section of mean wind retrieved from Doppler radar velocities during the passage of the cold front over the radar site ETH. At bottom line the wind speed measurements of a ground station at the radar site are displayed

Another important feature of the front is the angle between the approaching frontal line and the northern slope (indicated as the 1000 m isoline) of the alpine region. Between 12 and 13 UTC (Fig. 5b and c) the line reached the Alps in the east and the air of the warm sector was enclosed between the incoming cold air, the wall of the Alps and also the cold air aloft in the western part of Switzerland. The wind behind the line (Fig. 5c) veered to WNW whereas the wind in the warm sector was still blowing from SW. The front is slightly retarded in the western sector because of the Jura mountains. This retardation is already seen in Fig. 5b and can be further tracked in Fig. 5c through f.

At 14 UTC (Fig. 5e) a second wave of precipitation echos reached the northern border of Switzerland with further convective activity (rain intensity 10–30 mm/h, lightning observations). Around 15 UTC (Fig. 5f) the entire frontal line moved into the mountainous area, also in the western sector, where the prefrontal warmer air was forced to escape into the valleys of the "Wallis", the area is indicated in Fig. 5f. At the same time the front reached the southern slope of the Alps in the eastern part of the country where the "Föhn" (falling wind from direction north) began to influence the wind and temperature regime.

The occurrence of the maximum wind speed, stratified as "before", "with" or "after" the frontal passage, is shown in Fig. 7 for all ANETZ-locations. Black dots represent the stations with the strongest gusts before the front (up to 63.6 m/s at a mountain station) mostly in the warmer air mass from southwest. Most of the locations in the Swiss Mittelland belong to this category, except sites at the lee of the Jura mountains or the Black Forest (the most northern station), which experienced the strongest winds during or after the passage. This fact can be explained by a "Föhn" effect at the southern steep slope of the Jura mountains at the time the incoming cold air descended toward the lower Swiss Mittelland. An elongated damage area is found along this slope and depicted in Fig. 2b. Some evidence of prefrontal damage is given by newspaper reports in the area of Basel (Fig. 7).

On the contrary most of the alpine stations showed the maximum speed (up to 74.5 m/s at a pass location) after the frontal passage and from various directions that has to be attributed probably to the complex topography. As Golden (1991) stated: "topography can compress and funnel strong air flows accompanying both tropical and extratropical cyclones to produce locally very high wind speeds". At 1420 UTC severe winds are reported for a pass location near Disentis (see Fig. 7), shortly after the passage of the coldfront (Fig. 5e) where two trains were turned over. Nearby the largest damage plots in the alpine forests were found. For comparison maximum wind speeds of 50 and 45 m/s, respectively, were

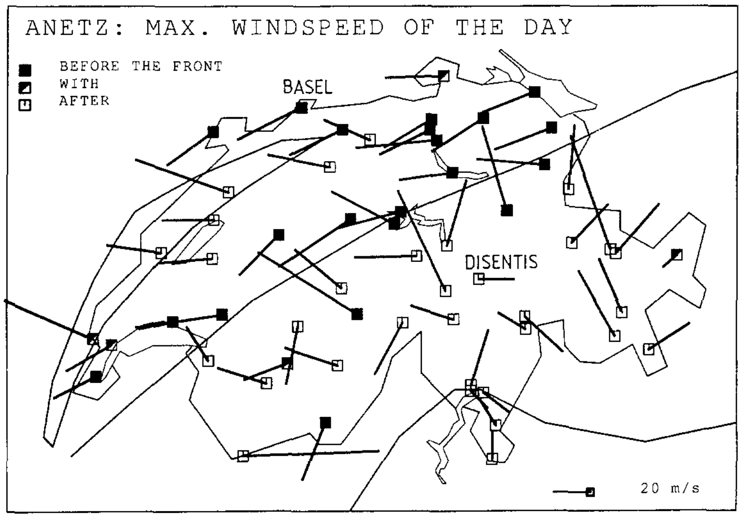

Fig. 7. The maximum wind speed, which was measured at each ANETZ-site, is given for the 27 February 1990. A stratification (before, with, after), according to the passage of the cold front over the station, is used and marked at each location. For the scale see Fig. 5

reported for the violent storms that struck United Kingdom on 16 October 1987 (Burt and Mansfield, 1988) and on 25 January 1990 (McCallum, 1990), respectively.

A further important point of the event is the strong temperature gradient of the two air masses (Fig. 4b and d), which is indicated also by the occurrence of convective cells embedded in the approaching precipitation zones, shown in Fig. 5. Thunderstorms occur in extreme unstable air masses and are quite rare during the winter season in Switzerland. The cooling can be further revealed in using sounding measurements made before and after the passage of the front (00 and 24 UTC) and is observable up to the 500 hPa level. The largest decrease of about 7 K was measured at a height of 4300 m. This decrease in temperature has been modified at ground level through orographic effects and is shown in Fig. 8. There, the spatial distribution of the difference in temperature (ΔT)

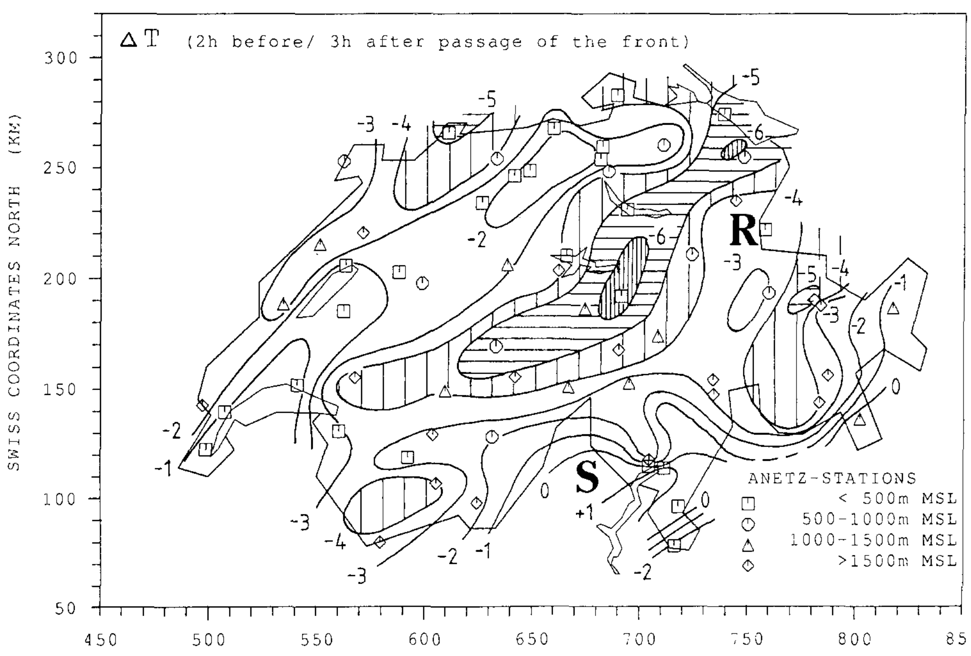

Fig. 8. Spatial distribution of the difference in temperature (ΔT) for the time period 2 hours before until 3 hours after the passage of the frontal line. Temperature decreases $\geqslant -4$ K are hatched. Letter R refers to the geographical region "Rheintal", letter S to the southern part of Switzerland. The scale is the same as in Fig. 2

for the time period 2 hours before until 3 hours after the passage of the front is displayed. A similar decrease of ΔT – as was found in the free atmosphere – is visible in the north of the Jura mountains, in the northern alpine area and at mountain stations. In the Swiss Mittelland the decrease is less because of matutinal colder air and in the "Rheintal" (labelled R) prefrontal colder air, descended from the higher elevated eastern alpine valleys, reduced ΔT as well. On the contrary, the "Föhn" effect brought a slight increase in ΔT in the southern part (labelled S) of Switzerland.

The occurrence of thunderstorms proved that massive vertical exchanges of air have taken place during the passage of the front. In winter situations the advection of relatively cold air in upper levels by the approaching coldfront destabilizes the troposphere and lifting of parcels of warmer air can take place. Updraft and downdraft systems within the advected air mass might modify the wind pattern. Turbulence and vortex phenomenon as known from severe thunderstorms during the summer season can produce severe gusts. Downbursts of cold air (Fujita, 1978) in the downdrafts might be the result, especially if a large temperature gradient is induced by the advected air mass. This gradient can even be increased through orographic effects, i.e. if the air in a mountain valley warmed up through a "Föhn" effect, the descending air originally flown over a pass into that valley, the flow induced through the incoming frontal system. Therefore, for the different damage areas, different wind and gust histories can be expected.

4.2 *About the Measured Wind Forces*

Two European reinsurance companies analyzed the 1990 series of winterstorms in considering the relation between wind speed and damage (Münchener Rück, 1993; Schraft et al., 1993) and presented data about the size of the storm field and the estimated gusts. The observed maximum wind speeds over a large area were about 30 to 40 m/s, which is Beaufort 12. Switzerland was mostly situated at the southern or southeastern border of the storm fields, not directly affected by the strongest wind speeds, except for the particular case under discussion. Schraft et al. (1993) further analyzed the wind speed and the storm duration of several winterstorms between the years 1981 and 1990 and related them to the severity of damage, expressed as the percentage of involved insurance policies from all policies covering storm damage on buildings. They concluded that the maximum gust speed rather than the mean wind speed (10 min values) and the duration of the stormy winds are the most important parameters, which are responsible for storm damage. Since very high wind speeds belong to the relatively rare events in Switzerland a presentation on a monthly basis is considered as sufficient.

Both wind parameters are investigated in the following: 1) the hourly mean wind and maximum gust. This will be done with the help of ANETZ-data and for the available period 1978–1992 to compare the actual case in the context of a longer period. 21 stations are considered in the beginning, six years later the number increased to 63. The stations were stratified into 12 "mountain" stations marked in Fig. 2a, which are exposed to the wind and into a group of 51 stations at lower elevations or situated in alpine valleys, which sites are sheltered from surrounding mountains from the undisturbed wind field, called "ground" stations. 2) To cover the variation of duration of windy periods an analysis of mean wind speeds > 10 m/s was undertaken for the station SMA (location 2 in Fig. 2a).

Figure 9a shows the variation of the monthly maximum hourly mean wind speed and the maximum hourly gust for the mountain stations. The dashed vertical line indicates the year when all 12 mountain stations were in operation. The peak of 74.5 m/s stands out clearly for the whole time-series of the mountain stations, another peak is visible for the month December 1983 with a speed around 60 m/s. Quite a few months show peaks over 50 m/s. The mean wind does not show the most extreme value of February 1990 but an outstanding peak on first on February 1983. Observing the ground stations (Fig. 9b) the gust on 27 February was fairly high but there are other peaks in the same speed range. Instead, July 1985 seems to be outstanding with a lonely maximum over 50 m/s for which a hailstorm was responsible. The mean wind is neither exceptional for the actual day. Such a peak was measured on December 1981 with almost 30 m/s.

To show the monthly variation of the two wind parameters for a single location, two ANETZ-stations have been chosen. One elevated mountain station (Grand St. Bernard), which measured the

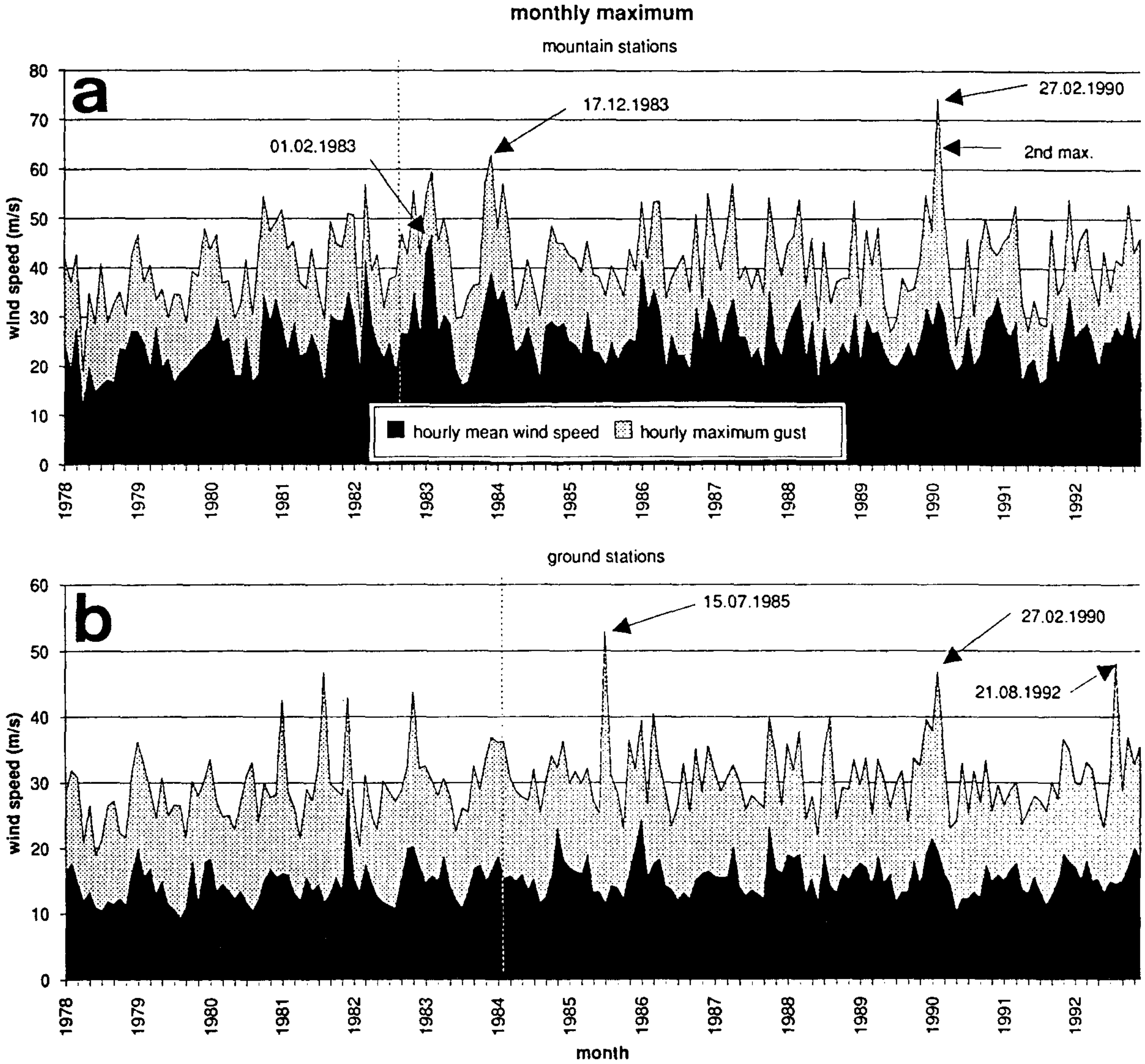

Fig. 9. Time-series of maximum monthly wind speeds (lower curve: the maximum hourly mean wind speed, upper curve: the maximum hourly gust) for a) mountain stations and b) ground stations. For the distinction between the two groups see text

extreme peak value of 74.5 m/s (Fig. 10a) and a ground station (Zürich-SMA) in the northeast of Switzerland (Fig. 10b). The locations are marked in Fig. 2a as 1 and 2, respectively. Figure 10a depicts the values of the elevated station 1 since 1982, the extreme value was registered at 1710 UTC after the frontal passage when the cold air followed rapidly. A channelizing effect of the relief (pass location) could have increased the speed significantly to such an unusual high value if the anemometer worked properly. Other peaks can be found around 50 m/s. However, the mean wind does not show an exception. For comparison the spatial variability of the highest gust can be found in Fig. 7, where the wind vector of the extreme value in respect to the frontal line is given for each station.

For the ground station (2) the 27 February was also an unique event. The highest gust from direction WSW were measured in the prefrontal warm sector just before the arrival of the coldfront. Further the duration of strong winds was exceptional at this station (Fig. 11) were a wind speed greater than 10 m/s was measured during 15 hours. This measure was only exceeded on 14/15 February of the same year with a persistence of the sustained wind of 24 hours. Caused by the long duration of steady strong windflow of the

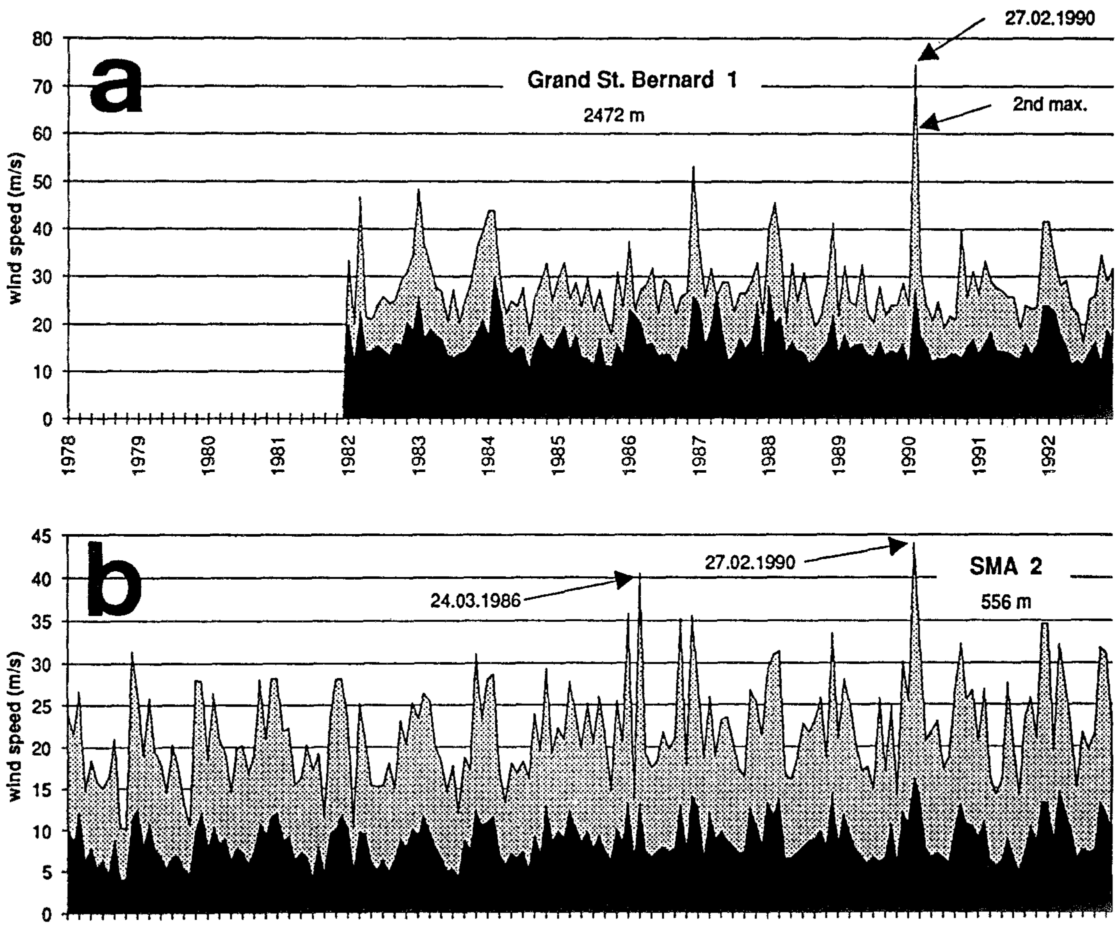

Fig. 10. Time-series of the maximum monthly wind speed for two particular ANETZ-stations: a) Grand St. Bernard, b) Zürich-SMA. The two curves display the same as in Fig. 9

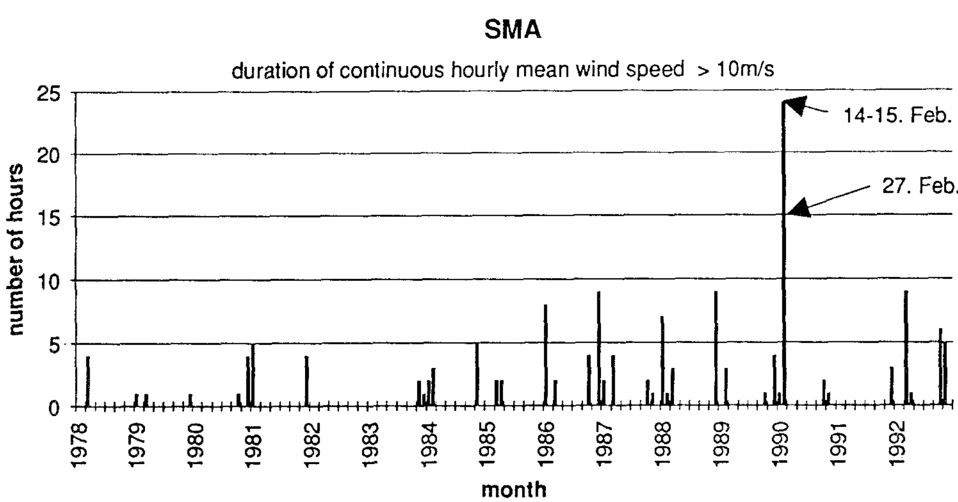

Fig. 11. Duration of continuous winds (> 10 m/s hourly mean wind speed) at ANETZ-station SMA

earlier storm the trees could have been weakened and prepared for the collapse on 27 February. If we consider the monthly maximum gusts in Fig. 10b, an increase of strength can be observed. The speed of 30 m/s was surpassed 15 times since 1986, earlier (1978–1985) this happened only twice. In this context it has to be mentioned that the site did not change over the years and the instrument

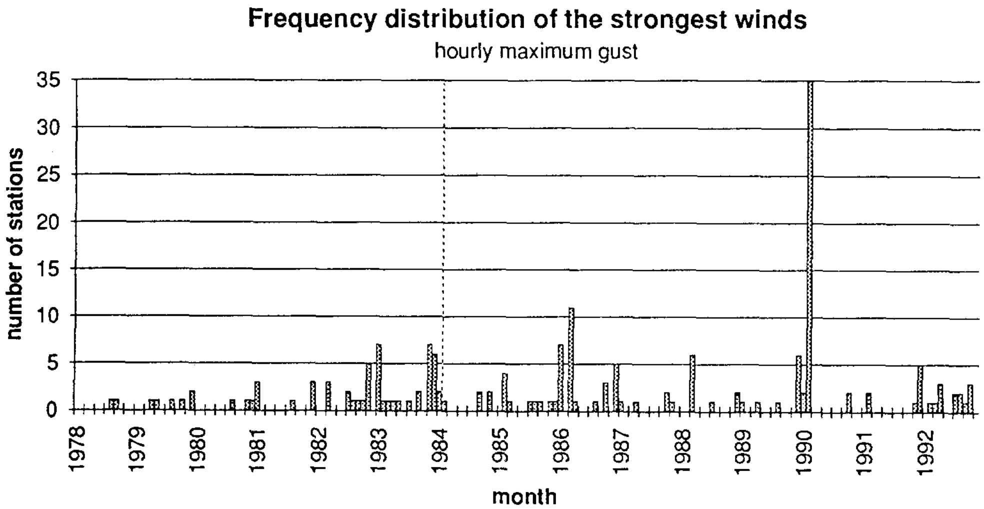

Fig. 12. Frequency distribution (number of stations per month) of the strongest gusts over 15 years. The three most extreme gusts per ANETZ-station are used for the evaluation

was always the same. A higher frequency of strong winds is also true for the mean value. Since 1986 13 m/s was surpassed 13 times whereas before this never occurred. For station 2 the conclusion can be drawn that since 1986 higher windpeaks are obviously more frequent. A similar result can be obtained in observing the duration of mean wind speed >10 m/s (Fig. 11). Starting in 1986, the duration of 5 hours sustained winds was exceeded 8 times, earlier such a value was never measured.

If we consider such trends we have to be aware that the observed time-series (15 years of data) are rather short. Franzen (1991) investigated the changing frequency of gales (exceeding Beaufort force 8) on the Swedish westcoast for a much longer period. The analysis showed that the gale frequency was high from 1860 until 1900, then a decreasing trend occurred from 1875 until 1940 and after an increase was observed until 1989 with a number of about 20 days per year. Another picture found Hammond (1990) for the recent years. After the occurrence of the storm series of February 1990 in the United Kingdom, Hammond performed an analysis of windiness for the month of February and the period 1881–1990. He concluded that since about 1961 a rather decreasing trend of windiness can be observed and February 1990 looks like a lonely peak as demonstrated above for Switzerland.

In Fig. 12 the spatial variation of severe wind events for the period 1978–1992 is shown. For each ANETZ-station the months of the three most extreme wind speeds were determined and the frequency distribution of the number of stations per month, having recorded one of the three wind speeds, are displayed. This evaluation shows clearly the extraordinary event of February 1990. 35 stations (55%) recorded one of the three extreme speeds, indicating that a large area was affected. The next following event, March 1986, registered only 11 stations.

5. Damage Situation in the Forests

5.1 *Forest Damage in Europe*

The storm series of 26 February to 1 of March 1990 caused a huge timber volume of fallen or broken trees in Europe. The absolute numbers in m^3 are listed in Table 1 for the storm-affected

Table 1. *Volume of Damaged Timber and Factor of Annual Cutting for the Storm-Affected European Countries.* The numbers are valid for the storm-series of 26 February until 1 of March 1990

Country	Damaged timber volume Mio m^3	Factor of annual sustainable cutting
West-Germany	65.0	2.0
France	15.0	0.4
Czechoslovakia	11.3	0.6
Great Britain	6.0	1.5
Belgium	5.5	1.8
Switzerland	4.9	1.1
Austria	4.8	0.3
East Germany	2.5	0.2

countries. In whole Europe a total of 115 millions m^3 of timber were damaged, about 30% of the regular annual cutting. In West-Germany it was double (Table 1, factor), in France and former Czechoslovakia half of the regular annual cutting. The break down of the timber market caused an economic catastrophe for the European forestry.

5.2 Forest Damages in Switzerland

In Switzerland timber volume equivalent to one whole year regular cutting was damaged (5 Mio m^3) which was a record so far in this century. Next to it was an estimated damage of about 2.4 Mio m^3 timber fallen during a stormy period in February 1967. Especially the alpine forest is extremely important to protect soil against erosion and to protect traffic lines and houses against avalanches of snow and stones and to regulate water regimes. About 260 million Swiss Francs have been spent in 1990 and 1991 to save the damaged timber and to build safety constructions above endangered objects. Therefore, for the Swiss government it was of great importance to get information about the damaged areas and an inventory of the damage was undertaken (described in section 2.2). It has to be mentioned that in the Swiss forestry community the size of an area is usually given in hectar (ha), equal to 0.01 km^2 and used in the following.

The damage inventory revealed that a total area of 4,928 ha (about 50 km^2) of forest was totally damaged by the storm. It is estimated that about 5 to 10% of the real damaged area is not covered by the inventory because some plots were not or only vaguely reported by the local forest authorities and were therefore outside of the flown tracks. The analysis of the data was done for the whole country as well as for the 551 (out of about 3000) communities hit by the storm. Some results are shown in the following for the whole country.

90% of the storm-areas are smaller than 1.8 ha and represent about 50% of the total area. The largest damaged plot was measured as 60 ha and was found on the terrain of the communities of Disentis/Muster (location see Fig. 7). Figure 13 depicts the distribution for different size classes (given as the mean of the class-intervals) in ha from the totally hit area. In brackets the number of plots in the observed class is also given. Using this data base Schmidtke (1993) showed that the distribution of the damage plot size classes followed the rules of fractal geometry.

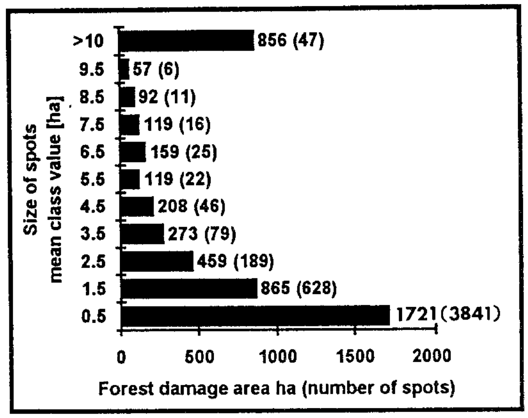

Fig. 13. Forest damages, area in ha (1 hectar = 0.01 km^2) and number of spots per size class

Experiences show influences of soil, water regime, length of trees, tree species, stand structure etc. onto the extention of damage. Wind gusts in the frequency of tree oscillation may cause damage at relatively low wind speeds. Increasing wind speed decreases the influence of these factors (Rottmann, 1986). The extraordinary wind speed of "Vivian+" minimized this effect. Local wind regime and relief parameters were the main factors in case of "Vivian+".

Since the data of the inventory was archived in a Geographical Information System, it was possible to combine the recorded damage areas with a digital terrain model, allowing the calculation of three relief parameters for each of the damaged surfaces: 1) aspect to the main wind directions, 2) inclination of the mountain slopes and 3) altitude of the main damage areas. Figure 14 reveals the aspect of the plots in a presentation similar to a wind rose. As a scale two circles of radius 160 and 320 ha are drawn. The line into a particular wind direction represents the absolute value of damaged area compared to the total damaged area. As Fig. 14 clearly shows, most damage occurred on slopes with an aspect toward NW, beginning from SW and ending about NE. The percentage of the other aspects is comparably small. Since the coldfront arrived from direction NNW the results confirm the expectation about the most endangered slopes, which were opposed mainly to the prevailing wind direction. The second measure under investigation was the inclination of the mountain slopes, which distribution according to the damaged surface is shown in Fig. 15. Most of the plots can be found

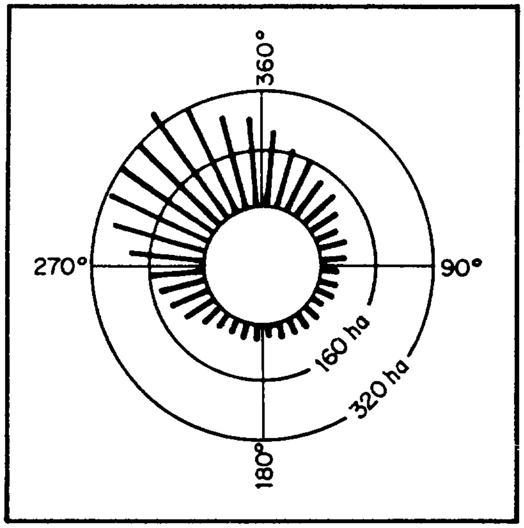

Fig. 14. Forest damages, area in ha (1 hectar = 0.01 km^2) per class of aspect to the main wind directions. As a scale two circles of radius 160 and 320 ha are indicated

on slopes reaching an inclination of 50 to 80%. The distribution of the damaged forest area in respect to the altitude is displayed in Fig. 16. The bulk of the areas is found at an elevation between 1200 and 1600 m MSL.

The absolute surface measures of damaged areas, shown in Figs. 14–16 according to the different relief parameters, are set in relation to the percentage of wooded area in the particular class for whole Switzerland. Table 2 shows the proportionality factor for the different classes of altitude, inclination and aspect to the main wind directions. A factor of 1 means that the damaged area is exactly proportional to the percentage of area in the particular class for the whole wooded area of Switzerland. The elevation of 1401–1600 m MSL, showing a factor of 3.1, was overproportionally hit by the storm's wind forces. Further the forests were overproportionally damaged if the

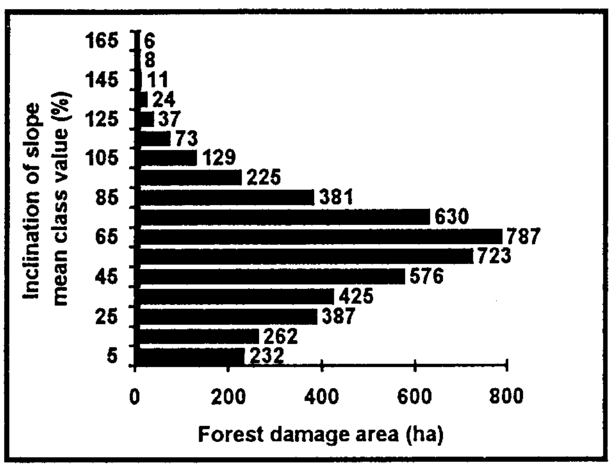

Fig. 15. Forest damages, area in ha (1 hectar = 0.01 km^2) per inclination class

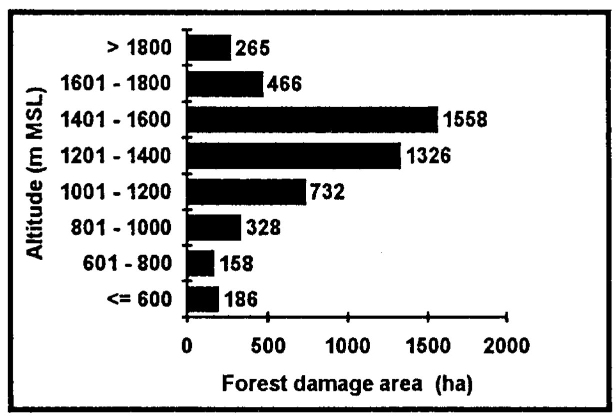

Fig. 16. Forest damages, area in ha (1 hectar = 0.01 km^2) per altitude class

Table 2. *Proportionality Factor Storm Damaged Area Versus Total Wooden Area for Different Classes of Altitude, Inclination of the Mountain Slopes and Aspect of the Relief to the Prevailing Wind Directions.* For the definition of the factor see text

Altitude (m SML)	Prop. Factor	Inclination (%)	Prop. Factor	Aspect to wind direction	Prop. Factor
$\leqslant 600$	0.2	$\leqslant 20$	0.3	North	0.3
601–800	0.2	21–40	0.5	Northeast	0.7
801–1000	0.5	41–60	1.2	East	0.7
1001–1200	1.1	61–80	2.6	Southeast	0.7
1201–1400	2.3	81–100	2.8	South	0.8
1401–1600	3.1	>100	1.6	Southwest	1.2
1601–1800	1.1			West	2.1
>1800	0.7			Northwest	1.9

slopes of the valleys had an inclination of 60 to 100% (factor 2.6–2.8) and if they were exposed to the west (factor 2.1) or northwest (1.9) as seen already from Figs. 14 and 15.

As mentioned in the introduction about 5 Millions m^3 timber was broken or thrown by the cyclone "Vivian+". To give an idea about the spatial distribution of the damage location a schematic map of the main areas is drawn in Fig. 2b. A relative measure about the regions of heavier damage in Switzerland can be extracted from a map of the Swiss forest districts, published by the Federal Department of environment, forests and landscape (BUWAL, 1990). For each district the percentage of thrown timber in comparison to the whole stock of wood available is shown. The highest values of about 2.5% are found in the Central and Eastern Alps and prealpine areas.

6. Conclusions

On 27 February 1990 Switzerland was struck by the most severe winterstorm so far in this century, concerning the amount and the special location (e.g. avalanche protection areas in the alpine valleys) of wind thrown timber. Maximum wind speeds up to 75 m/s were measured on that particular day. The analysis of the general meteorological development showed that a rare combination of meteorological factors were responsible for the special wind conditions in the complex terrain of the Alps. Such factors are: 1) A NW-SE elongated frontal zone straight over the whole Atlantic toward Central-Europe showing a strong gradient in temperature. 2) Within this straight frontal zone waves formed, which deepened to secondary lows, moving on an unusual southern track and were accompanied by strong winds. 3) The warm air of the prefrontal southwesterly flow was blocked in the Swiss Mittelland toward NE by the incoming cold air. 4) The blocked air escaped into the complex relief of the Alps, where channelizing effects, falling winds or downdrafts and local vortices induced by convective activity might have strengthend the wind forces. 5) The long duration of the particular event and the numerous precursors during January and February might have undermined the resistance of the affected trees to the complex local wind regime.

With the help of the automatic meteorological network of the SMA, time-series of the monthly maximum hourly mean wind speed and maximum gust, respectively, were computed for all stations as well as for two selected single stations to compare the obtained wind forces with other events during the period 1978–1992. Considering only the mountain stations, the peak of 75 m/s stands out for the whole time-series of monthly values, the next following peak shows a speed of about 62 m/s. Further, no trend to higher peaks is visible, the high value seems to be exceptional. However, this exception is not seen for the mean hourly wind speed.

Concerning the single investigated ground station the 27 February 1990 event was also exceptional but belongs to a group of higher peaks, which can be interpreted as to be more frequent since 1985, not seen in the time-series for all stations. Since the peak wind forces and the duration of the stormy wind probably play the most important role for the amount and severity of expected damage, the duration of the continuous hourly mean wind speed exceeding 10 m/s was inspected. The obtained duration of 15 hours was exceptionally long, second after a precursory stormy period of 14/15 February 1990 which lasted 24 hours but with less severe peaks. Again the frequency of events with longer duration (e.g. > 5 hours) is higher after the year 1985. These observed two trends to more frequent higher peak values and longer duration would be worthwhile to investigate further.

After the passage of the severe winterstorm, a damage survey in the Swiss forests was undertaken in inspecting aerial photographs of the main damage areas. The location of the single damage plots was combined with a digital terrain model of the hilly and mountainous relief of Switzerland. This investigation revealed that elevations between 1200 and 1600 m MSL were affected most by the storm's wind forces, especially on mountain slopes of an inclination 60 to 100%. The slopes were mainly exposed toward NW, which is in agreement with the prevailing wind directions of the storm.

An extension of this study is under way to investigate in more detail the role of the severe winds in complex terrain. Especially the duration of higher wind speeds during February 1990 is intended to be analyzed further and related to the peak wind speeds for individual alpine regions with heavier damage.

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