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## DAILY WIND GUST SPEED PROBABILITIES OVER SWITZERLAND ACCORDING TO THREE TYPES OF SYNOPTIC CIRCULATION

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### ABSTRACT

The nowcasting and prediction of strong winds are still far from adequate, using either statistical or numerical modelling approaches. During the last decade, Switzerland has been struck by two extratropical storms, namely the February 1990 storm 'Vivian', and the December 1999 storm 'Lothar', that caused severe damage to infrastructure and to forests. Although numerical weather prediction models captured in both cases the cyclone tracks on the synoptic scale, the severity of local gusts was not properly predicted over the Swiss territory. To help predicting such phenomena, a combined approach to diagnose the wind gust speeds over Switzerland is described. The diagnostics aim at computing the probability of exceeding a gust speed based on the mean wind in relation to the prevailing synoptic weather type for a limited number of groups of climatological stations distributed throughout Switzerland. Based on 10 years of Swiss station observations, the computation of this probability uses an empirical gust factor that is a function of the daily gust speed, itself a function of the daily mean wind speed. For this period, each day has been categorized into three weather types according to the Schüepp classification. Principal component analysis and cluster analysis are performed in order to group climatological stations having similar characteristics in daily wind gust velocities. The results show that the gust factor provides an accurate method to compute the daily wind gust speeds at each Swiss climatological station for the given period. When combined with the three weather types and group of stations, the proposed diagnostics are an efficient method to predict the distribution of wind gust speeds. The gusts associated with the 'Vivian' and 'Lothar' storms are then diagnosed for each specific group where more than 85% of the stations responded similarly to their specific group members, which is highly satisfactory in this case. Copyright © 2002 Royal Meteorological Society.

KEY WORDS: climate variables; gust factor; complex terrain; winter storms; synoptic weather types; region; statistical techniques

### 1. INTRODUCTION

The severity and potentially destructive nature of a storm are, to a large extent, unpredictable, especially over complex terrain. It is assumed that in some cases the frequency of the fluctuation of pressure in wind gusts is close to the natural frequency of different constructions or of trees in a forest, which can provoke a partial or total collapse of a building, a bridge or trees exposed to these gusts (Beniston, 1999). In a study conducted by Schmidtke and Scherrer (1997) this effect was found to be significant, causing extensive damage to forests even if the wind speed is lower than  $16 \text{ m s}^{-1}$  (Beaufort 7), which represents a critical value for damage to be caused. The authors also found that, on a local scale, the topography has a strong influence on the gust velocity and, combined with windward slopes and ridges, can cause channelling and shooting effects that further accelerate the winds.

Switzerland is characterized by a very complex topography: a mountain range in the northwest (Jura), a plain stretching from the west to the northeast (Swiss Plateau), the Alps in the southwestern, central and eastern part and the beginning of the Po plain to the south. Furthermore, winds are influenced by synoptic

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situations. As investigated by Schüepp (1978), 40 weather types may be defined over the Alps, which can then be combined into three general groups: convective, advective and mixed. With this information in mind, Schmidtke and Scherrer (1997) presented three basic storm types with destructive character occurring in Switzerland as indicated in Figure 1 by symbols: west wind storms, W (advective, generally in winter); Föhn storms, F (south wind); and thunderstorms (convective).

Two-thirds of the storms observed in Switzerland since 1500 occurred during the winter half year (October to March) (Pfister, 1999). The last decade was marked by two severe winter storms, namely 'Vivian' in February 1990 and 'Lothar' in December 1999, which caused serious damage to forests and buildings in different regions and countries of Western Europe. In both cases, the local gust speed and the extent of the damage could not be well estimated in advance of the event. Forests in mountainous regions often have a protective function in order to prevent landslides and avalanches; furthermore, on the Swiss Plateau, forestry represents an important economic activity. A better estimation of local wind gust speeds would help insurance companies to define zones of elevated risk, foresters to adapt tree populations in forests to the wind regime, and civil engineers in their construction plans. Although estimates of the largest wind gusts are required by civil engineers, the knowledge of the atmospheric conditions fostering the development of the gusty nature of the wind is also important for atmospheric scientists. Several studies have focused on the stochastic aspects (e.g. Walshaw 2000), Weggel 1999; Ragwitz and Kantz 2000, whereas some others aimed to link the wind gusts with physical processes and/or atmospheric states (e.g. Krayner and Marshall, 1992).

Figure 2(a) and (b) illustrates the distribution of the daily wind gust speeds averaged for the February 1990 'Vivian' and the December 1999 'Lothar' episodes. The strong wind gust centres, which are situated mostly at

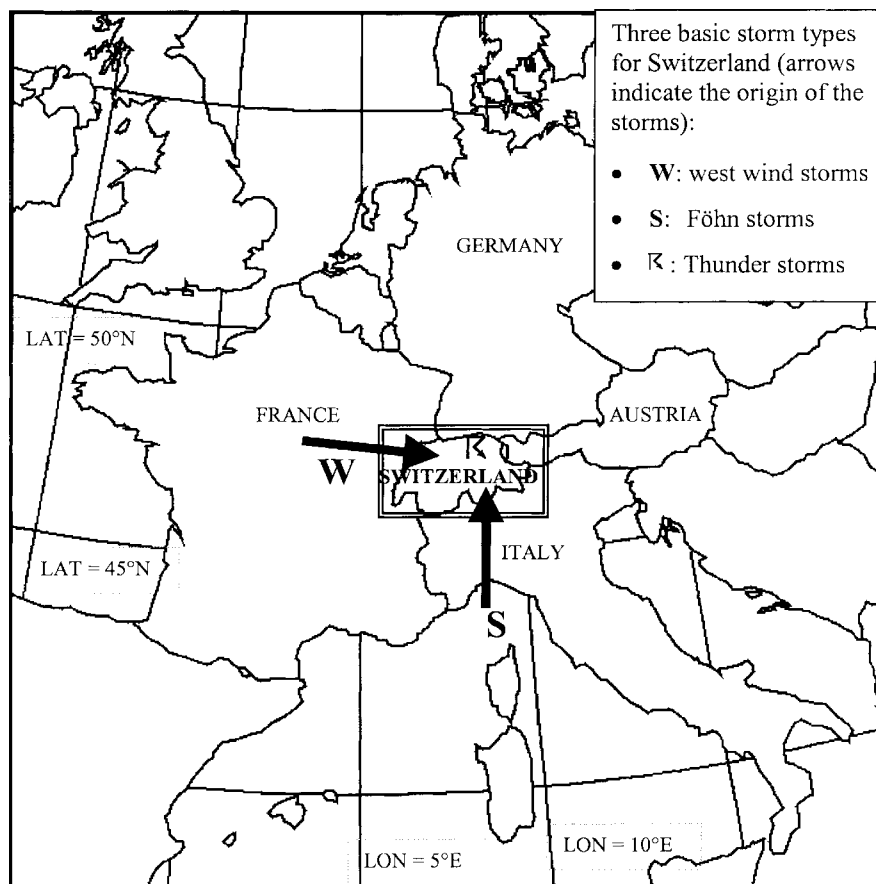


Figure 1. Map of Western Europe. Switzerland is in the inset, which delimits the section of the Swiss maps used in Figures 2 and 6

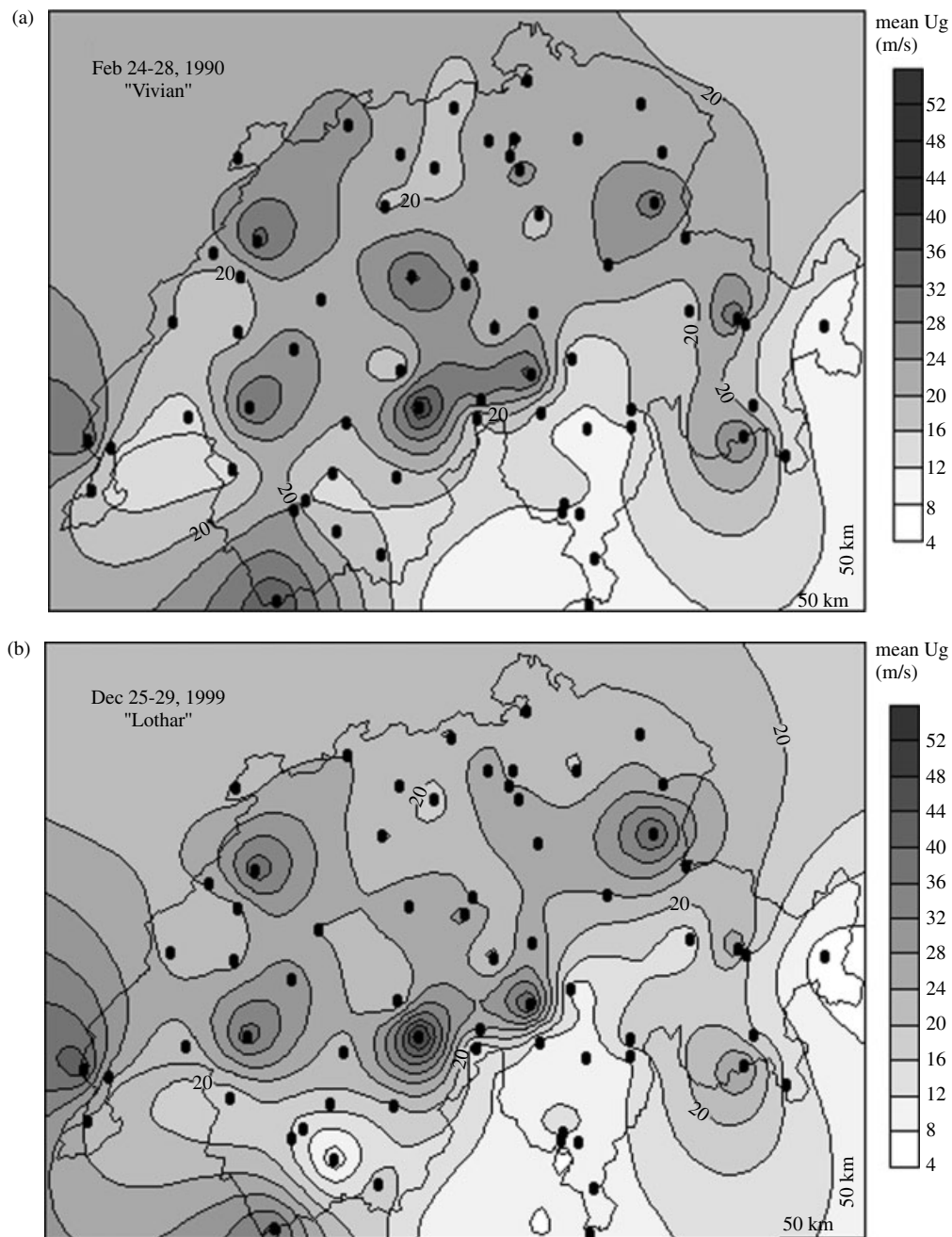


Figure 2. Spatial distribution of the daily wind gust speeds ( $\text{m s}^{-1}$ ) averaged over the period of a winter storm over Switzerland: (a) 'Vivian' (24–28 February, 1990); (b) 'Lothar' (25–29 December, 1999)

high altitudes (1600–3600 m) are well identified and share common features in both cases. However, it is not advisable to make predictions for all possible 'extremes', since only two severe storms were analysed. It may, nevertheless, be assumed that under strong synoptic forcing during advective situations the overall response in terms of wind activity is similar. Considering the chaotic nature of the weather phenomena together with a similar mean wind gust distribution in Switzerland during 'Vivian' and 'Lothar', a first working hypothesis

can be formulated: wind gust speeds can be estimated over different regions represented as groups of several climatological stations exhibiting similar behaviour in terms of wind gusts.

For example, 'Vivian' was a series of eight strong extratropical cyclones, which swept through Switzerland on 24–28 February 1990. During this period, a deep 968 hPa low-pressure centre travelled from southern Iceland to the Barents Sea with a maximum deepening rate of 27 hPa within 12 h on 26 February. On 27 February 1990, large parts of Switzerland were hit by the frontal zone of the cyclone 'Vivian', which produced violent winds causing severe damage to forests (Schüepf *et al.*, 1994; Schiesser *et al.*, 1997a). The maximum gust observed reached more than  $75 \text{ m s}^{-1}$  (Beaufort 12) at the Grand St Bernard pass station, on the Swiss–Italian border. For other stations, located at lower elevations, wind speeds were less intense, but in the range of other observed extreme values (Schüepf *et al.*, 1994). The second severe storm, 'Lothar', occurred on 25–29 December 1999 and consisted of a series of deep cyclones travelling over the Atlantic Ocean. The devastating track of the 'Lothar' storm ranged from west to east approximately along  $49^\circ\text{N}$ , and travelled with a velocity of about  $28 \text{ m s}^{-1}$  (Beaufort 10). The irregularities of this cyclone were the strong wind gusts, as well as its unusual intensification over land. These phenomena can possibly be linked to an amplified interaction between the geostrophic winds reaching velocities of nearly  $400 \text{ km h}^{-1}$  at 9000 m (Beniston, 1999).

The question arises as to whether the observation of extreme events such as 'Vivian' and 'Lothar' tend to cluster in time. This clustering can either be of a coincidental nature under constant conditions of storm probability or related to a gradual increase in storm probability (Frei and Schär, 2000). Schiesser *et al.* (1997a) have carried out a study concerning this topic within a project of the Swiss National Science Foundation. Their initial question was whether during the period of 1864 to 1993 the storms in Switzerland (limited to the northern part of the Alps) have become more frequent and more intense towards the end of the century. The conclusions were that 100 years ago the Swiss climate had been stormier than at present and, furthermore, the period before 1940 can be considered as windier than the past few decades. They also concluded, however, that cyclonic westerly wind situations have increased in number over the past decade. This can be linked to the increasing temperature and pressure gradient between the subpolar and the subtropical regions since the 1980s, generated by the behaviour of the North Atlantic oscillation (NAO). A further conclusion of Schiesser *et al.* (1997a) is that these westerly wind tracks seem to have shifted northward; hence, Switzerland is frequently situated at the southern edge of westerly storm systems and, therefore, less affected by severe winds. This shift is also described in the well-known report of the Intergovernmental Panel on Climate Change (IPCC, (1996: chapter 6)) where different general circulation models (GCMs) were used to detect possible long-term changes in storminess in a warmer world. However, little agreement was found between the models, and conclusions regarding storm events are obviously even more uncertain. Zwiers and Kharin (1998) have evaluated the changes in the wind extremes of the climate simulated by a GCM under double  $\text{CO}_2$  conditions; they found that the larger wind extremes occur in high latitudes where sea ice has retreated compared with the control experiment ( $1 \times \text{CO}_2$ ). However, in the mid-latitudes, the change in return periods of annual wind extremes was found to be marginal at best.

It seems evident that, even though research is advancing, it is difficult to predict the location, timing, and frequency of high and devastating wind gust speeds associated with intense storm systems. The fact that many storms occur during westerly wind situations in winter justifies the formulation of a second working hypothesis, which expresses the fact that a more accurate form of gust speed prediction is reached when different synoptic situations over the alpine region are considered separately. The aim of this study is thus to develop a statistical method to predict the expected value of the daily maximum wind gust speed according to the work of Weggel (1999) in relation to prevailing synoptic weather types for groups of climatological stations distributed in Switzerland.

## 2. DATA

The wind data are provided by the Swiss Meteorological Institute (called MeteoSwiss), which manages a fully automatic network, the Automatisches Netzwerk (ANETZ), comprising over 70 stations. The data are

not homogenized by MeteoSwiss; however, different tests of plausibility (limits, variability, consistency) are applied, and correction factors are applied where necessary (Konzelmann, personal communication, 23 June 2000). After an extensive study by Ehinger *et al.* (1990) most data are considered as reliable and about 98% of the information collected in a year can be exploited. The remaining 2% are lost data due to a malfunctioning of the instrumentation. No erroneous data are used in this study.

We use hourly mean and maximum wind speed values. Daily mean values, as well as daily maximum values, have been calculated on the basis of the hourly values. The measures are generally taken at the anemometer level, i.e. about 10 m above the surface.

Data recorded from 1990 to 1999 have been taken into account for this study. This 10 year period is of moderate size for wind analyses and allows one to use the data of a maximum number of stations, since many of the ANETZ stations were not in operation prior to 1990. In addition, the observations of the two severe winter storms 'Vivian' in February 1990 and 'Lothar' in December 1999 are included.

### 3. METHODS

The present study consists of three parts. It is based on applying to Switzerland a method developed by Weggel (1999) to predict the expected value of the daily maximum wind gust speed knowing the mean wind (Section 3.1). This method is then extended according to the two working hypotheses formulated in Section 1:

- (1) wind gust speeds can be estimated for different regions, represented as groups of several climatological stations having a similar behaviour in daily wind gust speeds (Section 3.3);
- (2) a more accurate form of gust speed prediction is reached when different synoptic situations over the alpine region are considered separately (Section 3.2).

#### 3.1. Wind gust probability

This first part of the analysis is based on the work of Weggel (1999). He developed a method to compute the probability of equalling or exceeding a wind gust of a given magnitude by knowing the daily mean wind. This is very useful, since forecasts for extreme values can thus be made quantitatively using the daily mean wind as the only input. The first part of the present work is it to validate this method to Swiss station observations. Statistical methods to calculate extreme wind speeds are found in the literature (e.g. Von Storch and Zwiers, 1998). Palutikof *et al.* (1999) summarized these different methods in a review. In most cases, however, the methods serve the purpose to calculate return periods of violent winds. The current work can be seen as a complement, since it is used to evaluate wind gust speed explicitly as a function of daily mean wind speed.

Weggel (1999) based his calculations on the normalized maximum gust speed, which is the ratio between the daily wind gust  $U_g$  and the daily mean wind  $U$ . He defined a gust factor  $G$  as:

$$G = \frac{U_g}{U} - 1 \quad (1)$$

which is always greater than zero since  $U < U_g$ . The gust factor is an explicit function of the mean wind speed. Therefore, the maximum gust is a smaller fraction of the mean wind speed for higher wind speeds, which implies that  $G$  decreases with increasing  $U$ . Plotting the logarithm of the gust factor,  $\log G$ , as a function of the logarithm of the mean wind speed,  $\log U$ , allows one to fit a power function to the data to predict a gust factor, namely  $G_p$ :

$$G_p = AU^n \quad (2)$$

The loglinear form of Equation (2) can be expressed as:

$$\log G = \log A + n \log U \quad (3)$$

and allows one to calculate the intercept  $A$  and the slope  $n$  for individual stations. As shown by Weggel (1999), a linear relationship between  $A$  and  $n$  can be established in the form  $n = \varphi A - \psi$  where the slope  $\varphi$  and the intercept  $\psi$  are parameters of this linear fit. As one may expect, steeper negative slopes correspond to higher intercepts, so that  $\varphi$  and  $\psi$  are smaller than zero. Furthermore,  $\varphi$  and  $\psi$  are station dependent.

The statistical distribution of  $\log G$  about its expected value as predicted by the fitted regression is first investigated. The differences between  $\log G - \log G_p$ , written as  $X$ , were ranked and assigned a probability  $P$  using the plotting position equation:

$$P(X \geq x) = \frac{m}{(N + 1)} \quad (4)$$

where  $x$  is the ranking variable,  $m$  represents the cumulative count of the ranks and  $N$  is the number of data points in the time series.

The standardized values for a normal probability distribution are calculated in order to estimate the probability  $P(U_g \geq v)$ , with which a gust is equalled or exceeded by a given speed  $v$ . The equation of the standardized value  $z$  can be expressed as follows:

$$z = \frac{\log G - \log G_p}{\sigma_{\log G}} \quad (5)$$

where  $\sigma_{\log G}$  is the standard deviation of  $\log G$ .

### 3.2. Synoptic weather types

A weather-type classification is expected to contain most of the significant elements determining the atmospheric conditions over a certain region, i.e. pressure conditions, origin and dynamics of the air mass, main wind direction, etc. The weather-type classification of Schüepp (1978) is used in many climatological studies concerning the alpine region, and it is reliable for Swiss weather conditions. (Schiesser *et al.*, 1997b). The method characterizes weather types based on the altitudinal and the surface pressure conditions at noon in the central alpine region. It is based on three general groups of weather types, namely convective, advective and mixed. These three groups can be further subdivided into 40 weather situations: 15 for the convective type, 20 for the advective type and five for the mixed type. Convective situations, normally occurring in summer, do not show considerable surface pressure differences and are, therefore, characterized by generally low wind velocities accompanied by significant vertical movements (convective). In contrast, advective situations, normally occurring in winter, indicate substantial differences in surface pressure and thus strong gradients. Included in the advective weather type are wind situations that usually produce stormy winds during winter. The mixed type is a group of weather situations characterized by significant vertical and horizontal winds (MeteoSwiss, 1985). In order to satisfy the second working hypothesis and to link the daily gust factor  $G$  to different weather situations, a division of the observed days into the three major weather types instead of the 40 situations has been found to be sufficient. The daily wind data series of 1990 to 1999 is partitioned into days of convective, advective or mixed weather situations according to the daily database of weather types of Schüepp, provided by MeteoSwiss.

### 3.3. Classification of Swiss climatological stations

The first working hypothesis assumes that we can group climatological stations into a few distinct classes. This classification should be linked to the three different weather types defined in Section 3.2, and the resulting groups should respond in a similar fashion to a mean wind forcing. Similar grouping was carried out by Jungo and Beniston (2001), where principal component analysis (PCA) and cluster analysis (CA) were applied to a number of Swiss climatological stations in order to group them as a function of their interannual minimum and maximum temperature variation. In their study, PCA and CA proved to be very convenient grouping tools for climatological stations situated in a complex terrain. For this reason we propose that such a method be used in the present study. The statistical analyses made use of the software package SPSS (1999).

PCA and CA are being used in the present study in order to aggregate the 63 ANETZ stations as a function of the daily gust factors, namely  $\log G$ , which are then linked to the three weather types. As a result, groups are aggregates of stations that exhibit a comparable variability to  $G$  and their response to the weather forcing. The geographical distribution of the groups should also depend on the complexity of the terrain.

PCA is based on a correlation matrix between station wind time series from 1990 to 1999. The overall variation of the original data matrix,  $\log G_{\text{matrix}}$ , can be reproduced in such a way that each variable is represented as a linear combination of the calculated components  $C_l$ , where  $l = 1$  to  $q$  (Bahrenberg *et al.*, 1992). This can be expressed as follows:

$$\log G_{\text{matrix}} = \alpha_i + \sum_{l=1}^q \beta_{il} C_l \quad (i = 1, \dots, m) \quad (6)$$

where  $\alpha_i$  is the regression constant of  $\log G$ ,  $\beta_{il}$  is the partial regression coefficient of  $C_l$  and  $m$  is the number of stations included in the data matrix.

The number of components normally extracted is usually smaller than the number of input variables, the purpose being to reduce the dimensionality of the data matrix, whilst at the same time retaining most of the variability in the original data. Since the variability at a station is explained by more than one component at a time, the components indicate typical characteristics that groups of stations have in common, such as the topography, the main wind direction and the location.

The following CA attempts to identify homogeneous clusters of stations, which depend on  $G$  and the typical characteristics identified with the PCA beforehand. The method is based on the correlation matrix between  $G$  and the extracted principal components, while the difference between two clusters is as large as possible. The hierarchical method employed here begins by finding the closest pair of stations according to a function of distance and combines them to form a cluster. The number of groups finally taken into account needs to represent a compromise between the degrees of generalization in order to keep coherent groups of stations and to avoid, if possible, clusters including only one or two stations.

#### 4. RESULTS

Equation (1) has been applied to the wind data of 63 climatological stations over a period of 10 years, where  $G$  was plotted as a function of  $U$ . Figure 3 is the example for the Grand St Bernard mountain pass station located at an elevation of 2472 m. For each station a lognormal distribution of the wind gust factor  $G$  is obtained. In Figure 3 the power function is fitted to the data of Grand St Bernard and applying Equation (3) the values for  $A$  and  $n$  can be calculated for all available ANETZ stations. As shown in Figure 4, data measured over complex terrain still produce a linear relationship between the coefficients  $A$  and  $n$ . This equation is:

$$n = -0.2173A + 0.251 \quad (7)$$

where  $\bar{\varphi} = -0.2173$  and  $\bar{\psi} = 0.251$ , when the averages  $\bar{\varphi}$  and  $\bar{\psi}$  are computed for 10 years of stations observations. Again, there is no reason to believe that  $\varphi$  and  $\psi$  are universal, as shown in Weggel (cf. Equation (4), 1999). These values could, however, prove to be useful for further analyses in similar regions with no or insufficient wind data available. In consideration of the high number of stations included (here 63), Equation (7) is a valid approximation for Switzerland, and even for the Alpine region.

To test the statistical distribution of  $\log G$  about  $G_p$ , Equation (4) is applied to the Swiss data with the result that the difference  $\log G - \log G_p$  at all stations follows a lognormal distribution. Figure 5 shows the example of the Grand St Bernard station, which experienced extremely strong winds during the 'Vivian' event. The observed cumulative probability computed with Equation (4) is fitted to a normal cumulative probability distribution. If the resulting dots of the fitting, black in Figure 5, show a diagonal straight line like the grey model line in Figure 5, the observed distribution can be accepted as normal. The example in Figure 5 shows

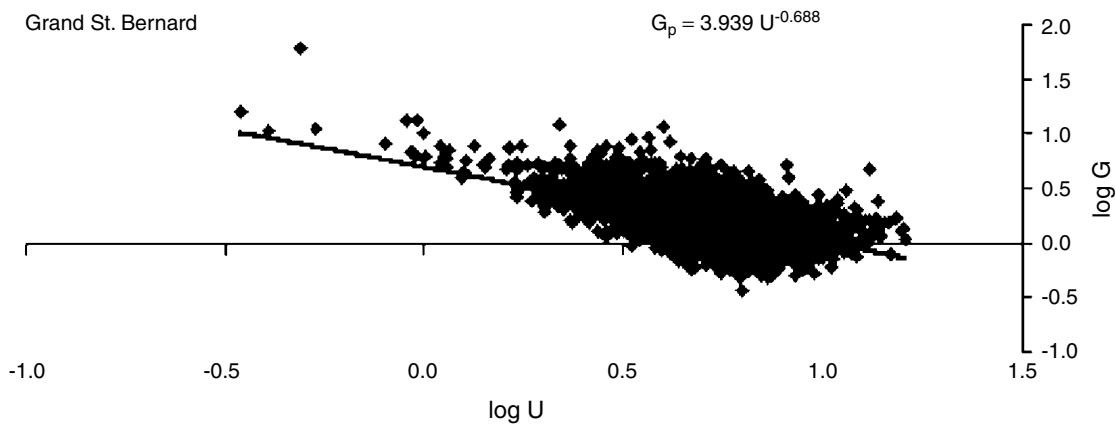


Figure 3. Gust factor as a function of the mean daily wind speed at Grand St Bernard (2472 m,  $07^{\circ} 10''/45^{\circ} 52''$ ) according to Equation (2)

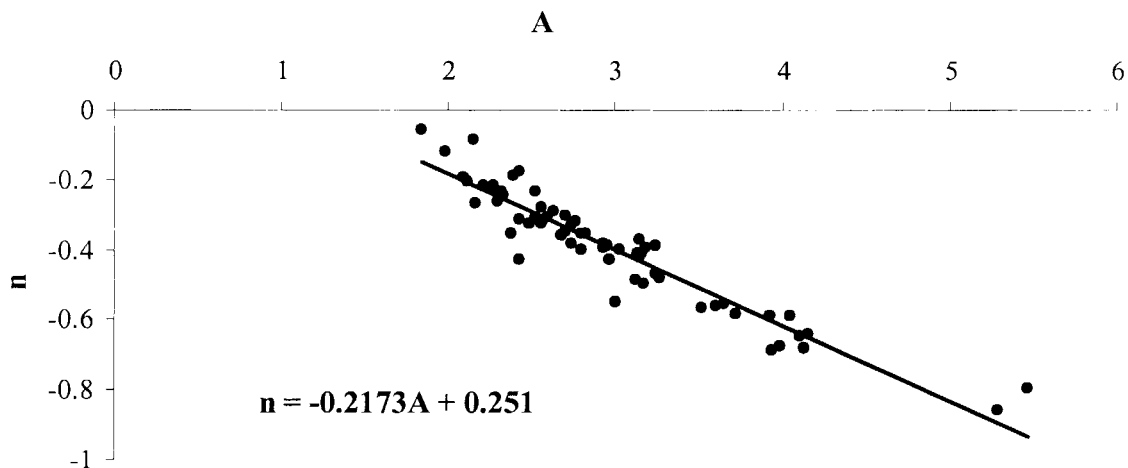


Figure 4. Relationship between  $A$  and  $n$  coefficients of Swiss ANETZ stations over the period covering 1990 to 1999

that the cumulative probability distribution of  $\log G - \log G_p$  is comparable to a normal cumulative probability distribution. An additional Kolmogorov–Smirnov test was made, where the goodness-of-fit between observed values and a normal distribution confirmed the hypothesis of normality.

The grouping of Swiss climatological stations linked to the three different weather types of Schüepp is tested in the following. The partitioning results in three different series of various lengths: 61% of the days were characterized by convective situations, advective situations were predominant in 34% of the days, and 5% of the whole period were mixed situations. PCA and CA are now applied separately to each of these three data series. The daily wind gust factors (Equation (1)) of 70 stations between 1990 and 1999 are considered as variables for PCA. A  $70 \times 70$  data matrix is now defined. Table I shows the number of components  $C_l$  extracted for each synoptic type. For example, the major part of the variance (57.3%) of the convective type is represented by only 15 components. A number of components  $C_l$  are sufficient to explain about 60% of the variance for each of the three weather types. Compared with the analysis made on temperature data (Jungo and Beniston, 2001), where three to six components explained 90 to 95% of the variance, the wind data are characterized by much more complex characteristics than temperature data. Although its variance is harder to explain, wind data still remain adequate for this kind of analysis. The number of clusters identified with CA for each synoptic type is shown in Table I. As depicted in Figure 6(a)–(c), the resulting clusters of stations are obviously not randomly distributed. For each weather type, it can be observed that

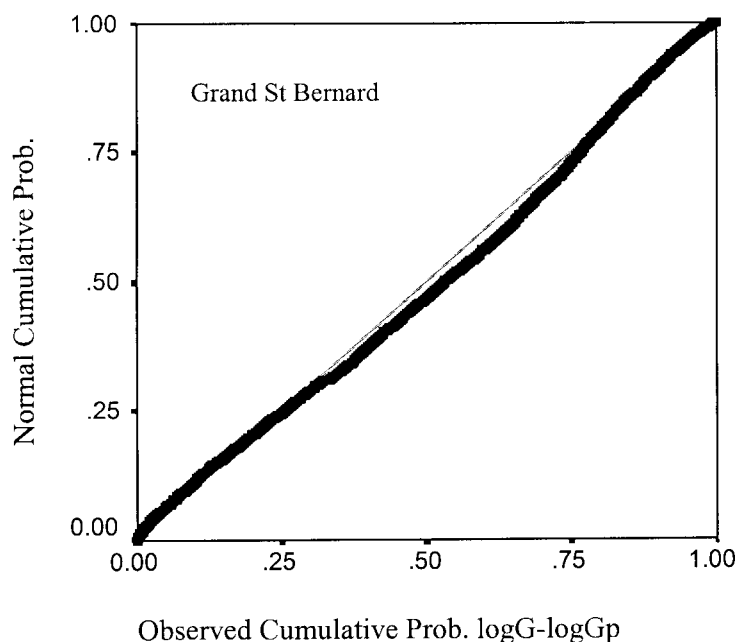


Figure 5. Lognormal distribution of the gust factor [Equation (4)] at Grand St Bernard. The observed cumulative probability is fitted to the expected normal one. The 1 : 1 line is shown in light grey, denoting the perfect normal case

the groups are closely linked to the topography and the location of the stations, to the influence of the Mediterranean climate, which is characteristic of the southern part of Switzerland, and to the main wind direction.

Equation (5) allows computation of the standardized values  $z$  of a normal probability distribution for single stations. Recalling the objective of this study — to calculate the probability of wind gust speeds equalling or exceeding a fixed value during convective, advective or mixed synoptic weather types within different groups of Swiss climatological stations — Equation (5) must be modified slightly. In order to calculate  $z$  for a group of stations, mean values must be applied:

$$\bar{z} = \frac{\log G - \overline{\log G_p}}{\overline{\sigma_{\log G}}} \quad (8)$$

where  $\log G$  is based on Equation (1), and  $\overline{\sigma_{\log G}}$  is the arithmetical mean of the standard deviations  $\sigma$  of the transformed data at each station included in a group. To compute  $\overline{\log G_p}$ , the arithmetic mean of  $A$  and  $n$ , namely  $\bar{A}$  and  $\bar{n}$  are evaluated for each station in a group. Table II indicates these mean values computed for each group, which are needed to calculate  $\bar{z}$  according to Equation (8).

Table I. Results of PCA and CA according to the three synoptic weather types.  $C_l$  are the principal components extracted, the second column denotes the total variance explained with these components, and the third column shows the number of clusters identified using CA. Symbol appearing in Equation (6) is described in the text

| Synoptic type | $C_l$ | Variance explained (%) | No. of clusters |
|---------------|-------|------------------------|-----------------|
| Convective    | 15    | 57.3                   | 7               |
| Advective     | 13    | 61.4                   | 6               |
| Mixed         | 18    | 69.9                   | 8               |

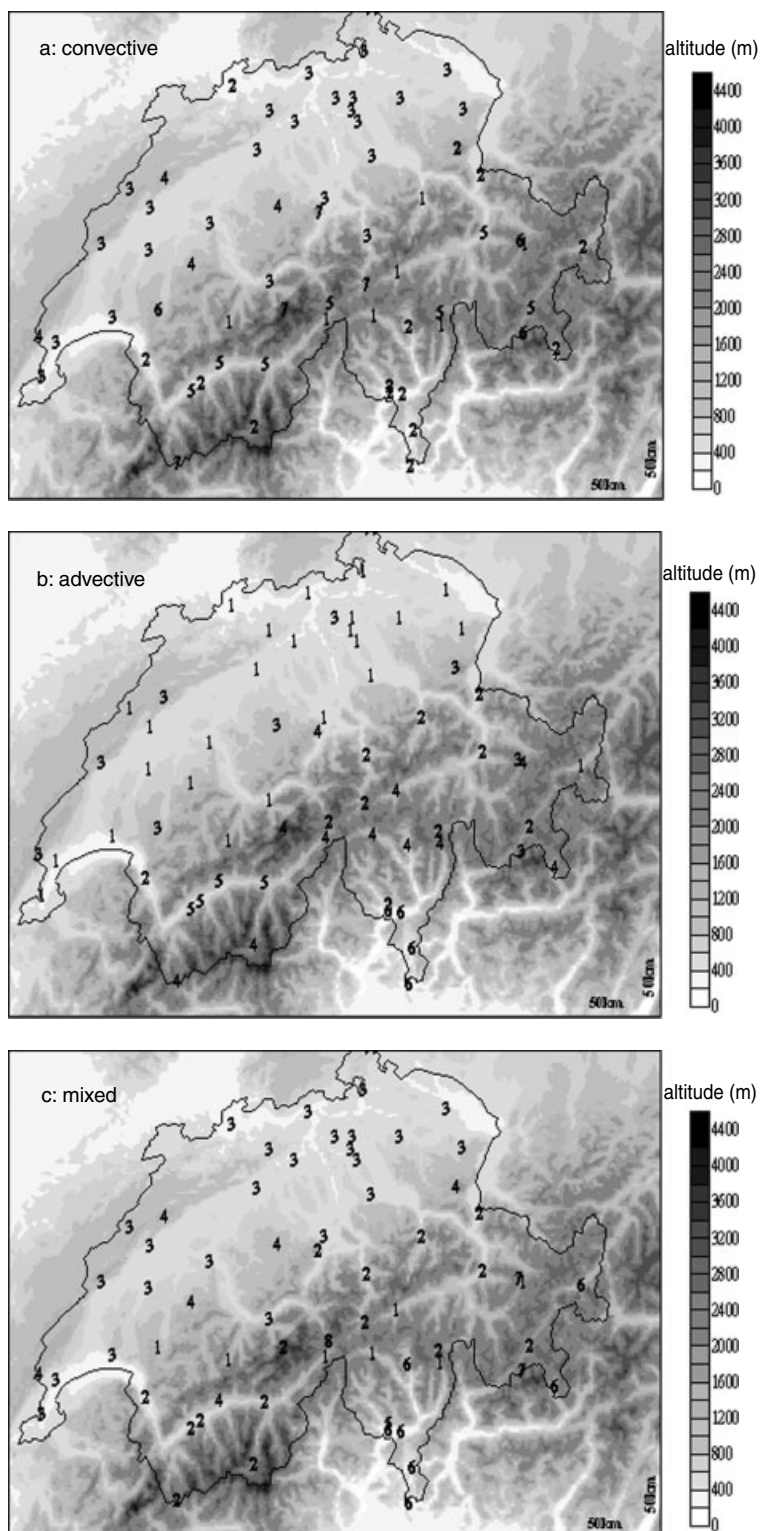


Figure 6. Resulting clusters of ANETZ stations according to the three synoptic weather types: (a) convective (seven groups); (b) advective (six groups); (c) mixed (eight groups)

Table II. Mean values  $\bar{A}$  and  $\bar{n}$  and  $\overline{\sigma_{\log * G}}$  computed for each group according to the three synoptic weather types

| Synoptic type | Group | $\bar{A}$ | $\bar{n}$ | $\overline{\sigma_{\log * G}}$ |
|---------------|-------|-----------|-----------|--------------------------------|
| Convective    | 1     | 3.571     | -0.511    | 0.196                          |
|               | 2     | 2.579     | -0.276    | 0.168                          |
|               | 3     | 2.645     | -0.329    | 0.167                          |
|               | 4     | 2.650     | -0.421    | 0.169                          |
|               | 5     | 3.577     | -0.529    | 0.179                          |
|               | 6     | 4.347     | -0.652    | 0.276                          |
|               | 7     | 6.345     | -0.801    | 0.245                          |
| Adveective    | 1     | 2.698     | -0.340    | 0.166                          |
|               | 2     | 3.233     | -0.442    | 0.173                          |
|               | 3     | 3.324     | -0.501    | 0.215                          |
|               | 4     | 4.486     | -0.595    | 0.215                          |
|               | 5     | 2.741     | -0.341    | 0.163                          |
|               | 6     | 2.159     | -0.136    | 0.160                          |
| Mixed         | 1     | 3.610     | -0.536    | 0.201                          |
|               | 2     | 3.859     | -0.490    | 0.187                          |
|               | 3     | 2.654     | -0.332    | 0.167                          |
|               | 4     | 2.927     | -0.446    | 0.180                          |
|               | 5     | 2.118     | -0.205    | 0.158                          |
|               | 6     | 2.473     | -0.238    | 0.169                          |
|               | 7     | 4.761     | -0.694    | 0.302                          |
|               | 8     | 5.289     | -0.864    | 0.238                          |

As an example, consider that during an advective weather type, we want to determine the skill of the method. The skill is defined here as the percentage of stations included in a group that actually responds similarly during 'Vivian' and 'Lothar' episodes. We now assume that the mean wind magnitude  $U = 10 \text{ m s}^{-1}$ , and then compute the probability  $P(U_g \geq v)$  for group 1, where  $v = 25 \text{ m s}^{-1}$  (Beaufort 9) is a measure of the gust speed. Applying Equation (1), the gust factor gives  $G = (25/10) - 1 = 1.5$  and the predicted gust factor computed with Equation (2) equals  $G_p = 2.698 \times 10^{-0.34} = 1.23$ . According to Equation (8) the standardized value results in  $\bar{z} = (0.176 - 0.091)/0.166 = 0.51$ . Using a table of a normal probability distribution (e.g. Bahrenberg *et al.*, 1990), one finds that  $F(0.51) = 0.695$  so that  $P(U_g \geq v) = 30.5\%$ . In other words, the probability that the gust speed exceed  $25 \text{ m s}^{-1}$  with a mean wind of  $10 \text{ m s}^{-1}$  is 30.5%, which is quite significant in this context. In addition, the observations measured during the ten stormy days of 'Vivian' and 'Lothar' reveal that at 84% of the stations included in group 1,  $U_g$  typically equals or exceeds  $25 \text{ m s}^{-1}$  when  $U = 10 \text{ m s}^{-1}$ . A range of  $\pm 2.5 \text{ m s}^{-1}$  has been used here to capture the variability of the observed hourly average wind speed. Examples of gust speeds observed when  $U = 10 \text{ m s}^{-1}$  at single stations out of group 1 are: Geneva airport,  $29 \text{ m s}^{-1}$ ; Bern,  $30 \text{ m s}^{-1}$ ; Basel,  $41 \text{ m s}^{-1}$ ; Zurich airport,  $30 \text{ m s}^{-1}$ . In other words, 84% of the stations included in group 1 exhibit a similar behaviour in response to an advective synoptic situation characterized by explosive cyclogenesis.

The probabilities for each group of stations for which the wind gust speed of  $25 \text{ m s}^{-1}$  is equalled or exceeded during 'Vivian' and 'Lothar' are shown in Table III and indicated by the asterisks in Figure 7. These results are combined with the scores of stations per group containing real cases corresponding to these theoretical conditions. For group 6, the  $U$  and the  $v$  values have been modified to  $2 \text{ m s}^{-1}$  and to  $7 \text{ m s}^{-1}$  respectively, because west wind storms generally do not affect the southern part of Switzerland; therefore, high wind speeds are not realistic. The highest destruction rate during the storm episodes was found in the regions defined by groups 1 and 5, where a high score is also reached. Group 3, reaching a 100% score, aggregates pass and summit stations, which are frequently exposed to high wind speeds.

Table III. Occurrence probability  $P$  of a wind gust during the 24–28 February 1990 ‘Vivian’ and the 25–29 December 1999 ‘Lothar’ episodes where for groups 1 to 5  $U = 10 \text{ m s}^{-1}$  and  $U_g \geq 25 \text{ m s}^{-1}$  and for group 6  $U = 2 \text{ m s}^{-1}$  and  $U_g \geq 7 \text{ m s}^{-1}$ . The score of the method represents the percentage of stations in a group where observations correspond to these two events

| Group | $P$ (%) | Score (%) |
|-------|---------|-----------|
| 1     | 30.5    | 84        |
| 2     | 26.4    | 40        |
| 3     | 23.6    | 100       |
| 4     | 29.1    | 40        |
| 5     | 31.6    | 75        |
| 6     | 25.8    | 100       |

A further test of the skill of the method is done in order to quantify the performance of the method in cases during low  $U$  and low  $U_g$  (Table IV) as well as with a high  $U$  and a high  $U_g$  (Table IV). First, the occurrence probability of these two examples has been calculated separately for each station included in a group and then the mean of all these station probabilities  $\bar{P}$  and its standard deviation  $\sigma_{\bar{P}}$  were determined. Then, the occurrence probability per group  $P(\bar{A}, \bar{\pi})$ , computed according to Equation (8), is compared with the mean station probability  $\bar{P}$ . According to Table IV, the difference between both,  $\Delta P$ , never exceeds one standard deviation of  $\bar{P}$ , i.e.  $\sigma_{\bar{P}}$ . This represents a satisfying result for the skill of the method. Wind gust occurrence probabilities, computed for specific groups of climatological stations, established in this study are as reliable as if they were computed for single stations and then averaged.

## 5. EXAMPLE AND DISCUSSION

Summarizing the results given above, a convenient method is now available to compute the probability of occurrence of a wind gust speed for groups of stations over Switzerland, as a response to three different weather types, when the mean wind speed is known. Figure 7 represents the summary of the results for advective situations. This weather type is of major interest, since westerly wind storms like ‘Vivian’ and ‘Lothar’ generally occur during the winter months under advective conditions. Figure 7 shows isolines of the probability of occurrence of gust wind speeds as a function of the mean wind speed for the six groups (1–6) in Switzerland during advective situations. It is expected that these distributions will become smoother as the record length increases. At  $U_g = 16 \text{ m s}^{-1}$ , a line has been drawn on the graph to indicate the critical gust value for damage. As mentioned earlier, Schmidtke and Scherrer (1997) have observed that gusts of  $16 \text{ m s}^{-1}$  over complex terrain can cause significant damage to forests. It can be noticed in Figure 7 that there is an 80 to 100% probability for wind gusts to reach  $16 \text{ m s}^{-1}$  or more if the daily mean wind during advective situations is in the range of 8 to  $12 \text{ m s}^{-1}$ . As demonstrated with the examples in Section 4, daily mean wind speeds around  $10 \text{ m s}^{-1}$  during stormy situations are frequently observed. The examples with  $U = 10 \text{ m s}^{-1}$ ,  $U_g \geq 25 \text{ m s}^{-1}$  for groups 1 to 5 and  $U = 2 \text{ m s}^{-1}$ ,  $U_g \geq 7 \text{ m s}^{-1}$  for group 6 are indicated by asterisks. These points are gust speeds that have effectively been observed at most of the climatological stations in Switzerland during ‘Vivian’ and ‘Lothar’; the scores shown in Table III corroborate this.

If we compare Figure 6(b), where the station location is shown per group, with Figure 2(a) and (b), which shows the distribution of the mean wind gusts during the ‘Vivian’ and ‘Lothar’ episodes, the strong wind gust centres can be identified as stations belonging to groups 3 and 4. The stations in group 3 are mostly situated at passes and summits in the Jura and the Pre-Alps, and group 4 unites alpine stations. It can also

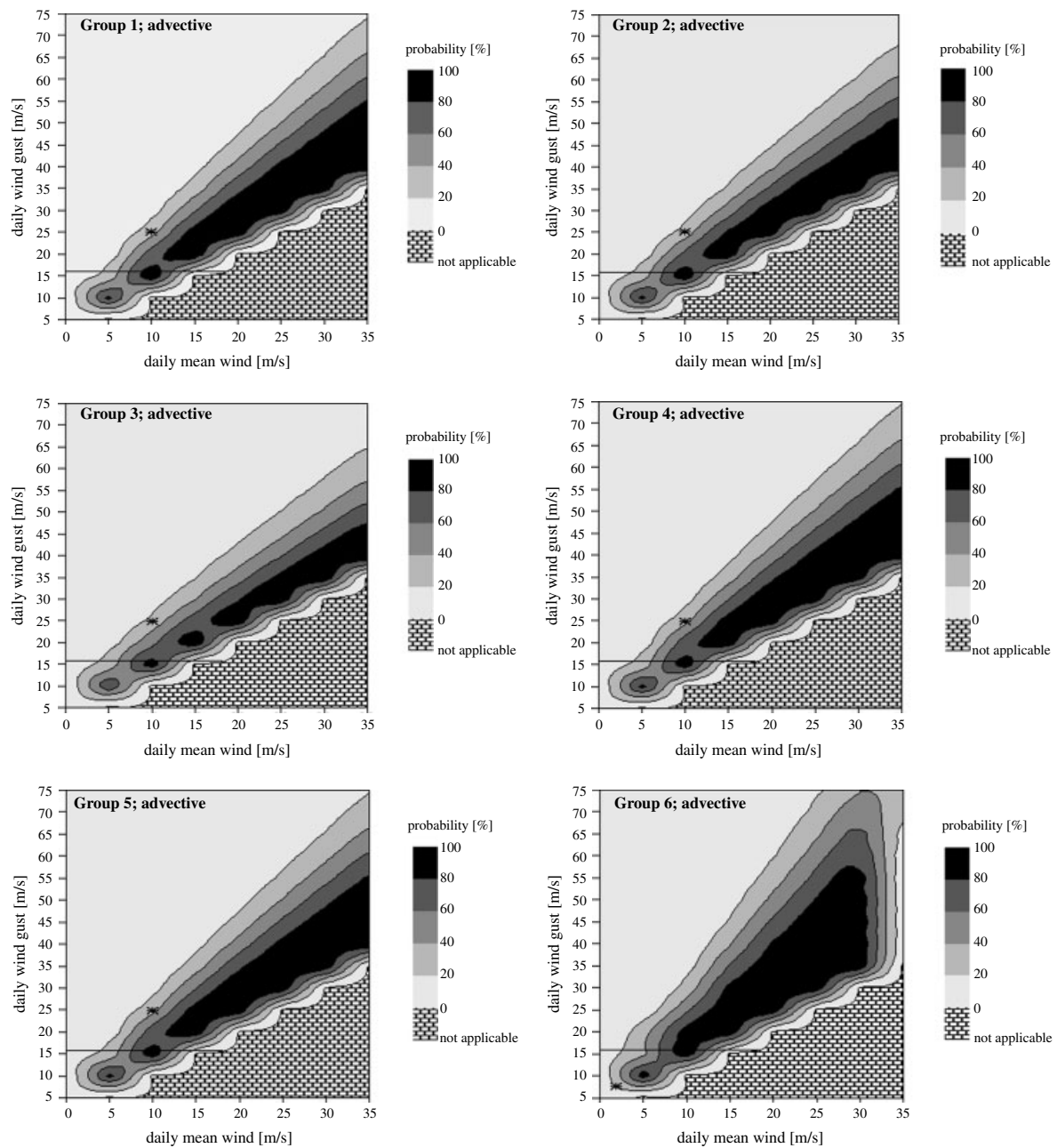


Figure 7. Isolines of the occurrence probability of a daily wind gust speed knowing the daily mean wind speed. Parts 1 to 6 represent the groups 1 to 6 valid for days with advective situations.  $U_g = 16 \text{ m s}^{-1}$  denotes a critical gust value over complex terrain for forest damage. The asterisks correspond to the gust probability values during storms, noted in Table III, with  $U = 10 \text{ m s}^{-1}$  and  $U_g \geq 25 \text{ m s}^{-1}$  for groups 1 to 5 and  $U = 2 \text{ m s}^{-1}$  and  $U_g \geq 7 \text{ m s}^{-1}$  for group 6

be noticed in Figure 7, however, that groups 3 and 4 show a modest probability for extremely strong wind gust speeds even though it is precisely these groups that are frequently exposed to strong wind speeds. This can be related to the fact that with Equation (1)  $G$  decreases with increasing wind speed, i.e. the maximum gust is a smaller fraction of the mean wind speed for a higher wind speed. Such a behaviour in groups 3 and 4 emphasizes the functional form of  $G$ .

Table IV. Occurrence probabilities for wind gusts computed as a mean of single station probabilities  $\bar{P}$  compared with the occurrence probability computed per group  $P(\bar{A}, \bar{n})$ . The difference  $\Delta P$  should not exceed the standard deviation of  $\bar{P}$ ,  $\sigma_{\bar{P}}$

| Synoptic type | Group | $U = 2 \text{ m s}^{-1}, U_g \geq 10 \text{ m s}^{-1}$ |                    |                     |            | $U = 20 \text{ m s}^{-1}, U_g = 60 \text{ m s}^{-1}$ |                    |                 |            |
|---------------|-------|--|--------------------|---------------------|------------|--|--------------------|-----------------|------------|
|               |       | $\bar{P}$ (%)  | $\sigma_{\bar{P}}$ | $P(\bar{A}, n)$ (%) | $\Delta P$ | $\bar{P}$  | $\sigma_{\bar{P}}$ | $P(\bar{A}, n)$ | $\Delta P$ |
| Convective    | 1     | 14.35  | 6.33               | 14.92               | -0.57      | 2.38   | 1.77               | 1.74            | 0.64       |
|               | 2     | 5.49   | 6.03               | 5.16                | 0.33       | 8.97   | 9.35               | 6.94            | 2.03       |
|               | 3     | 5.08   | 3.19               | 4.85                | 0.23       | 4.21   | 3.52               | 3.36            | 0.85       |
|               | 4     | 3.76   | 2.37               | 3.59                | 0.17       | 0.86   | 0.8                | 0.6             | 0.26       |
|               | 5     | 11.71  | 9.3                | 12.3                | -0.59      | 0.91   | 0.65               | 0.73            | 0.18       |
|               | 6     | 25.58  | 12.3               | 28.1                | -2.52      | 2.99   | 2.37               | 3.22            | -0.23      |
|               | 7     | 27.38  | 25.5               | 43.25               | -18.87     | 0.94   | 1.19               | 1.36            | -0.42      |
| Adveective    | 1     | 5.25   | 3.16               | 4.95                | 0.3        | 3.75   | 3.4                | 3.01            | 0.74       |
|               | 2     | 9.49   | 8.65               | 9.68                | -0.19      | 2.71   | 2.79               | 1.7             | 1.01       |
|               | 3     | 12.25  | 12.9               | 14.01               | -1.76      | 3.21   | 1.99               | 2.28            | 0.93       |
|               | 4     | 18.55  | 16.6               | 27.43               | -8.88      | 2.33   | 1.79               | 2.44            | -0.11      |
|               | 5     | 5.39   | 4.72               | 5.05                | 0.34       | 4.95   | 7.29               | 3.01            | 1.94       |
|               | 6     | 2.73   | 0.96               | 2.68                | 0.05       | 19.66  | 10.63              | 18.41           | 1.25       |
| Mixed         | 1     | 14.74  | 6.31               | 15.39               | -0.65      | 1.82   | 1.24               | 1.43            | 0.39       |
|               | 2     | 12.51  | 15.78              | 19.22               | -6.71      | 3.08   | 4.14               | 2.94            | 0.14       |
|               | 3     | 5.05   | 3.21               | 4.75                | 0.3        | 3.98   | 3.44               | 3.22            | 0.76       |
|               | 4     | 7.3  | 8.21               | 6.68                | 0.62       | 1.28   | 1.1                | 1.07            | 0.21       |
|               | 5     | 1.62   | 0                  | 1.62                | 0          | 6.3  | 0                  | 6.3             | 0          |
|               | 6     | 5.04   | 3.89               | 4.85                | 0.19       | 12.78  | 1.45               | 9.85            | 2.93       |
|               | 7     | 30.57  | 12.44              | 33                  | -2.43      | 3.8  | 2.71               | 4.01            | -0.21      |
|               | 8     | 28.1   | 0                  | 28.1                | 0          | 0.16   | 0                  | 0.16            | 0          |

## 6. CONCLUSION

This paper presents a method for determining the probability of occurrence of daily wind gusts as a function of daily mean wind speed according to three types of synoptic weather situation within groups of Swiss climatological stations. These results demonstrate that the gust factors between maximum and mean wind speeds, measured over the complex terrain of Switzerland, follow the lognormal distribution of Weggel (1999) applicable to the USA. The achievement in summarizing several single climatological stations into groups for the convective, advective and mixed weather types of Schüepp separately, represents a convenient approach to computing the occurrence probability of wind gusts over complex terrain according to forecasts of mean wind. The skill of the method was tested and found to be satisfactory in quantitative terms.

All the computations are based on the period ranging from 1990 to 1999 and the observations of the two severe winter storms 'Vivian' (24–28 February 1990) and 'Lothar' (25–29 December 1999) are included in the data. Although only 10 years of data have been used, we succeeded in a relatively smooth graphical representation (Figure 7) to predict the occurrence probability of a daily wind gust speed knowing the daily mean wind in relation to prevailing synoptic weather types for groups of climatological stations distributed in Switzerland. With the data of the two storm events included, the validity of these graphical results is particularly high for the decade 1990 to 1999.

With the current warming trend of global climate, it is uncertain, however, if these results are valid for future predictions. If the signal of a northward shift of the westerly wind tracks (IPCC, 1996: chapter 6; Schiesser *et al.*, 1997a) proves to be true, then the probability of occurrence of wind gusts may also undergo important changes.

Predictions of this kind are becoming more accurate when simulated with regional circulation models. Goyette *et al.* (2001) present short-term results of storm simulations on a local scale (1 km) where 'Vivian' was successfully simulated. The method proposed in this study will be applied to simulated data in the near future to investigate the behaviour of the gusty nature of the wind following global climate warming.

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