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 ten years of Swiss station observations, the computation of this probability uses an empirical gust factor which is a function of the daily gust speed, itself a function of the daily mean wind speed. For this period, each day has been categorised 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 to 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.

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 the building, the bridge or the 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 windspeed is lower than 16 m s^{-1} (Beauford 7), which represent 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 accelerates the winds.

Switzerland is characterised by a very complex topography, a mountain range in the northwest (Jura), a plain stretching from the west to the northeast (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 situations. As investigated by Schüepp (1978), forty 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 Fig. 1 by symbols: west wind storms - W (advective, generally in winter), Föhn storms - F (south wind) and thunderstorms (convective).

Two thirds of the observed storms in Switzerland since 1500 occurred during winter (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 economical sector. 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 focused on the stochastic aspects (e.g. Ragwitz and Kantz 2000; Walshaw 2000; Weggel 1999), whereas some others aimed to link the wind gusts with physical processes and/or atmospheric states (e.g. Krayer and Marshall, 1992).

Fig. 2a-b illustrate 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 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 the observed

likeness of the mean wind gust distribution in Switzerland during "Vivian" and "Lothar" a first working hypothesis can be formulated: the 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 8 strong extratropical cyclones, which swept through Switzerland from February 24-28, 1990. During this period, a deep 968 hPa low pressure center travelled from southern Iceland to the Barents Sea with a maximum deepening rate of 27 hPa within 12 hours on February 26. On February 27, 1990 large parts of Switzerland were hit by the frontal zone of the cyclone "Vivian", which produced violent winds causing strong damage to forests. (Schüepp et al., 1994; Schiesser et al., 1997). 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 (Schüepp et al., 1994). The second severe storm, "Lothar", occurred from December 25-29, 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°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 at 9000 m velocities of nearly $400 \, \text{km h}^{-1}$ (Beniston, 1999).

The question arises whether 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 et al., 2000). Schiesser et al. (1997) 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 are 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 the 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. (1997) is that these westerly wind tracks seem to be shifted northward, hence Switzerland is frequently situated at the southern edge of western 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) (chap. 6, 1996) where different General Circulation Models (GCM) where 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 CO_2 conditions; they found that the larger wind extremes occur in high latitudes where sea ice has retreated compared to the control experiment ($1xCO_2$). 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 strong 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 with prevailing synoptic weather types for groups of climatological stations distributed in Switzerland.

2. DATA

The wind data is provided by the Swiss Meteorological Institute (called MeteoSwiss), which manages a fully automatic network, the **A**utomatisches **Netz**werk, (ANETZ) comprising over 70 stations. The data is not homogenised by MeteoSwiss, however, different tests of plausibility (limits, variability, consistency) are applied and if a correction is necessary, the data series are treated manually (Konzelmann, pers. com., June 23, 2000). After an extensive study by Ehinger et al. (1990) the 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 aberrant data are being 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 to use the data of a maximum number of stations, since many stations of the ANETZ network 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 a method developed by Weggel (1999) to predict the expected value of the daily maximum wind gust speed knowing the mean wind, which is now applied to Switzerland (Sect. 3.1). This method is then extended according to the two working hypotheses formulated in the introduction:

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 (Sect. 3.3).

2. A more accurate form of gust speed prediction is reached when different synoptic situations over the alpine region are considered separately (Sect. 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. 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 normalised 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:

$$G = \frac{U_g}{U} - 1 \tag{1}$$

which is always greater than 0 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, $logG$, as a function of the logarithm of the mean wind speed, $logU$, allows to fit a power function to the data to predict a gust factor, namely G_p.

$$G_p = AU^n \tag{2}$$

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

$$logG = nlogA + nlogU \tag{3}$$

and allows to calculated the intercept, A, and the slope, n, values for individual stations. As shown in Weggel a linear relationship between A and n can be established in the form $n = \varphi A - \psi$ where the slope φ, and the intercept ψ are parameters of this linear fit. As one may expect, steeper negative slopes correspond to higher intercepts so that φ and ψ are smaller than 0. Furthermore, φ and ψ are station dependent.

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

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

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

The standardised 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 standardised value, z, can be expressed as follows:

$$z = \frac{\log G - \log G_p}{\sigma_{\log G}} \tag{5}$$

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 airmass, 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., 1997a). The method characterises 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 5 for the mixed type. Convective situations, normally occurring in summer do not show considerable surface pressure differences and are therefore characterised by generally low wind velocities accompanied by significant vertical movements (convective). Advective situations, normally occurring in winter, in contrast indicate substantial differences in surface pressure and thus strong gradients. Included in

the advective weather type are the mostly wind situations, which produce stormy winds during winter. The mixed type is a group of weather situations characterised of significant vertical as well as 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 Sect. 3.2 and the resulting groups should respond in a similar fashion to a mean wind forcing. Similar grouping was carried out in Jungo and Beniston (2001), where Principal Component Analysis (PCA) and Cluster Analysis (CA) have been applied to a number of Swiss climatological stations in order to group them in function of their interannual minimum and maximum temperature variation. In their study, the PCA and CA have proven to be very convenient grouping tools for climatological stations situated in a complex terrain. For this reason we propose thus such a method to use in the present study. The statistical analyses made use of the software package SPSS (1999).

The 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 *logG*, which are then linked to the three weather types. As a result groups are aggregates of stations, which

exhibit a comparable variability to G and its 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, $logG_{\text{matrix}}$, can be reproduced in such a way that each variable is represented as a linear combination of the calculated components, C_l, where l goes from 1 to q. (Bahrenberg et al., 1992). This can be expressed as follows:

$$logG_{matrix} = \alpha_i + \sum_{l=1}^{q}\beta_{il}C_l \;\; , \;\; (i = 1,..., m) \tag{6}$$

where α_i is the regression constant of $logG$, β_{il} is the partial regression coefficient of C_l and m is the number of stations included in data matrix.

The number of components normally extracted is usually smaller than the number of input variables, which constitutes an important reduction of the size of the information while simultaneously 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 single 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

generalisation in order to keep coherent groups of stations and to possibly avoid clusters

including only one or two stations.

4. RESULTS

Equation (1) described above 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. Fig. 3 is the example for the Grand St. Bernard mountain pass station located at an elevation of 2472m. For each station a lognormal distribution of the wind gust factor G is resulting. In Fig. 3 the power function is fitted to the data of Grand St. Bernard and applying Eq. (3) the values for A and n can be calculated for all available ANETZ stations. As shown in Fig. 4, data measured over complex terrain still produce a linear relationship between the coefficients A and n. This equation is:

$$n = -0.2173A + 0.251 \tag{7}$$

where $\overline{\varphi} = -0.2173$ and $\overline{\psi} = 0.251$, when the averages $\overline{\varphi}$ and $\overline{\psi}$ are computed for 10 years of stations observations. Again, there is no reason to believe that φ and ψ are universal as shown in Weggel (cf. Eq. (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), Eq. (7) is a valid approximation for Switzerland and even for the Alpine region.

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

distribution of $logG - logG_p$ 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 confirms 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, where 61% of the days are characterised by convective situations, advective situations were predominant in 34% of the days, and 5% of the whole period are mixed situations. PCA and CA are now applied separately to each of these 3 data series. The daily wind gust factors (Eq. 1) of 70 stations between 1990 and 1999 are considered as variables for the PCA. A 70 by 70 data matrix is now defined. Shown in Table 1 are the number of components extracted, C_l, 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 to the analysis made on temperature data (Jungo and Beniston , 2001) where 3 to 6 components explained 90% to 95% of the variance, the wind data is characterised by much more complex characteristics than temperature data. Although its variance is harder to explain wind data still remains adequate for this kind of analysis. The number of clusters identified with CA for each synoptic type is shown in Table 1. As depicted in Fig. 6a-c, the resulting clusters of stations are obviously not randomly distributed. For each weather type, it can be observed that 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.

Eq. (5) allows computing the standardised 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, Eq. (5) must be modified slightly. In order to calculate z for a group of stations, mean values must be applied:

$$\bar{z} = \frac{\log G - \overline{\log G_p}}{\overline{\sigma_{\log G}}} \tag{8}$$

where $\log G$ is based on Eq. (1), and $\overline{\sigma_{\log G}}$ is the arithmetical mean of the standard deviations, σ, of the transformed data at each station included in a group. To compute $\overline{\log G_p}$, the arithmetical mean of A, and n, namely $\bar{A}$ and $\bar{n}$ are evaluated for each station in a group. Table 2 indicates these mean values computed for each group, which are needed to calculate $\bar{z}$ according to Eq. (8).

As an example, consider that during an advective weather type we want to determine the skill of the method. The skill is here defined as the percentage of stations included in a group, which actually respond similarly during "Vivian" and "Lothar" episodes. We now assume that the mean wind magnitude $U = 10$ m s^{-1}, and then compute the probability, $P(U_g \geq v)$ for group 1, where $v = 25$ m s^{-1} (Beaufort 9) is a measure of the gust speed. Applying Eq. (1), the gust factor gives $G = (25/10) – 1 = 1.5$ and the predicted gust factor computed with Eq. (2) equals $G_p = 2.698 \times 10^{-0.34} = 1.23$. According to Eq. (8) the standardised 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 m s^{-1} with a mean wind of 10 m s^{-1} is 30.5%,

which is quite significant in this context. In addition, the observations measured during the 10 stormy days of "Vivian" and "Lothar" reveals that at 84% of the stations included in group 1, U_g typically equals or exceeds 25 m s^{-1} when $U = 10$ m s^{-1}. A range of ± 2.5 m s^{-1} has been used here to capture the variability of the observed hourly average wind speed. Examples of observed gust speeds when $U = 10$ m s^{-1} at single stations out of group 1 are: Geneva airport: 29 m s^{-1}; Bern 30 m s^{-1}; Basel 41 m s^{-1} and Zurich airport 30 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 characterised by explosive cyclogenesis.

The probabilities for each group of stations for which the wind gust speed of 25 m s^{-1} is equalled or exceeded during "Vivian" and "Lothar" are shown in Table 3 and indicated with an asterisk in Fig. 7-1 to 7-6. These results are combined to 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 m s^{-1} and to 7 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.

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 4a) as well as with a high U and a high U_g (Table 4b). 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, $\overline{P}$, and its standard deviation, $\sigma_{\overline{P}}$, was determined. Then, the

occurrence probability per group, $P(\overline{A}, \overline{n})$, computed according to Eq. (8), is compared

to the mean station probability, $\overline{P}$. According to Table 4 the difference between both,

ΔP, never exceeds one standard deviation of $\overline{P}$, named $\sigma_{\overline{P}}$. 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 of three different weather types, when the mean wind speed is known. Fig. 7-1 to 7-6 represent 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. Fig. 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 data series increases. At $U_g = 16$ m s^{-1}, a line has been drawn on the graph to indicate the critical gust value for damages. As mentioned earlier, Schmidtke and Scherrer (1997) have observed that gusts of 16 m s^{-1} over complex terrain can cause significant damage to forests. It can be noticed in Fig. 7-1 to 7-6 that there is an 80 to 100% probability for wind gusts to reach 16 m s^{-1} or more if the daily mean wind during advective situations is in the range or 8 and 12 m s^{-1}. As demonstrated with the examples in Sect. 4, daily mean wind speeds around 10 m s^{-1} during stormy situations are frequently observed. The examples with U = 10 m s^{-1}, $U_g \geq 25$ m s^{-1} for groups 1 to 5 and $U = 2$ m s^{-1}, $U_g \geq 7$ 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 3 corroborate this.

If we compare Fig. 6b, where the station location is shown per group, with Fig. 2a and 2b, which show 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 group 3 and 4. The stations in group 3 are mostly situated at passes and summits in the Jura and the Prealps and group 4 unites alpine stations. It can also be noticed in Fig. 7-3 and 7-4, 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 Eq. (1) G decreases with increasing wind speed, i.e., the maximum gust is a smaller fraction of the mean wind speed for higher wind speed. Such a behaviour in groups 3 and 4 emphasises the functional form of G.

6. CONCLUSION

This paper presents a manner of determining the probability of occurrence of daily wind gusts as a function of daily mean wind speed according to three types of synoptic weather situations within groups of Swiss climatological stations. These results demonstrate that the gust factors between maximum and mean wind speeds, which are measured over the complex terrain of Switzerland follow the lognormal distribution of Weggel (1999) applicable to the United States. The achievement to summarise several single climatological stations into groups for the convective, the advective and the mixed weather types of Schüepp separately, represents a convenient approach to compute the occurrence probability of wind gusts over complex terrain according to forecasts of mean wind. The skill of the method is tested and is 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" (Feb 24-28, 1990) and "Lothar" (Dec 25-29, 1999) are included in the data. Although only 10 years of data has been used, we succeeded in a relatively smooth graphical representation (Fig. 7-1 to 7-6) 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 (Schiesser et al.,1997; IPCC 1996, chap. 6) 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 (RCM). Goyette et al. (2001) present short-term results of storm simulations on a local scale (1km) where "Vivian" was successfully simulated. The method proposed in this study will be applied to simulated data in the coming future to investigate the behaviour of the gusty nature of the wind following global climate warming.

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Table captions:

Table 1: 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 Eq. (6) is described in the text.

Table 2: Mean values $\overline{A}$ and $\overline{n}$ and $\overline{\sigma_{log\,G}}$ computed for each group according to the three synoptic weather types.

Table 3: Occurrence probability, P, of a wind gust during the Feb. 24-28, 1990 "Vivian" and the Dec 25-29, 1999 "Lothar" episodes where for group 1 to 5, $U = 10$ m s^{-1} and $U_g \geq 25$ m s^{-1} and for group 6, $U = 2$ m s^{-1} and $U_g \geq 7$ m s^{-1}. The score of the method represents the percentage of stations in a group where observations correspond to these two events.

Table 4: Occurrence probabilities for wind gusts computed as a mean of single station probabilities $\overline{P}$, compared to the occurrence probability computed per group, $P(\overline{A}, \overline{n})$. The difference ΔP, should not exceed the standard deviation of $\overline{P}$, $\sigma_{\overline{P}}$.

a: $U = 2$ m s^{-1}; $U_g \geq 10$ m s^{-1}. *b*: $U = 20$ m s^{-1}; $U_g \geq 60$ m s^{-1}.

Figure captions:

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

Figure 2: Spatial distribution of the daily wind gust speeds (m s^{-1}) averaged over the period of a winter storm over Switzerland *a:* "Vivian" (Feb 24-28, 1990) and *b:* "Lothar" (Dec 25-29, 1999).

Figure 3: Gust factor as a function of the mean daily wind speed at Grand St. Bernard (2472 m, 07°10'' / 45°52'') according to Eq. 2.

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

Figure 5: Lognormal distribution of the gust factor (Eq. 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.

Figure 6: Resulting clusters of ANETZ stations according to the three synoptic weather types, **a:** convective (7 groups), **b:** advective (6 groups) and **c:** mixed (8 groups).

Figure 7: Isolines of the occurrence probability of a daily wind gust speed knowing the daily mean wind speed. Figures 1 to 6 represent the groups 1 to 6 valid for days with

advective situations. $U_g = 16$ m s^{-1} denotes a critical gust value over complex terrain for forest damages. The asterisk correspond to the gust probability values during storms, noted in Table 3, with $U = 10$ m s^{-1} and $U_g \geq 25$ m s^{-1} for groups 1 to 5 and $U = 2$ m s^{-1} and $U_g \geq 7$ m s^{-1} for group 6.

Table 1

synoptic type	C_l	variance explained	Nb. of clusters
convective	15	57.3%	7
advective	13	61.4%	6
mixed	18	69.9%	8

Table 2

synoptic type	group	$\overline{A}$	$\overline{n}$	$\overline{\sigma_{logG}}$
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
advective	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

Table 3

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%

Table 4a

synoptic type	group	$\overline{P}$	$\sigma_{\overline{P}}$	$P(\overline{A},\overline{n})$	ΔP
convective	1	14.35%	6.33	14.92%	-0.57
	2	5.49%	6.03	5.16%	0.33
	3	5.08%	3.19	4.85%	0.23
	4	3.76%	2.37	3.59%	0.17
	5	11.71%	9.3	12.3%	-0.59
	6	25.58%	12.3	28.1%	-2.52
	7	27.38%	25.5	43.25%	-18.87
advective	1	5.25%	3.16	4.95%	0.3
	2	9.49%	8.65	9.68%	-0.19
	3	12.25%	12.9	14.01%	-1.76
	4	18.55%	16.6	27.43%	-8.88
	5	5.39%	4.72	5.05%	0.34
	6	2.73%	0.96	2.68%	0.05
mixed	1	14.74%	6.31	15.39%	-0.65
	2	12.51%	15.78	19.22%	-6.71
	3	5.05%	3.21	4.75%	0.3
	4	7.3%	8.21	6.68%	0.62
	5	1.62%	0	1.62%	0
	6	5.04%	3.89	4.85%	0.19
	7	30.57%	12.44	33%	-2.43
	8	28.1%	0	28.1%	0

Table 4b

synoptic type	group	$\overline{P}$	$\sigma_{\overline{P}}$	$P(\overline{A},\overline{n})$	ΔP
convective	1	2.38%	1.77	1.74%	0.64
	2	8.97%	9.35	6.94%	2.03
	3	4.21%	3.52	3.36%	0.85
	4	0.86%	0.8	0.6%	0.26
	5	0.91%	0.65	0.73%	0.18
	6	2.99%	2.37	3.22%	-0.23
	7	0.94%	1.19	1.36%	-0.42
advective	1	3.75%	3.4	3.01%	0.74
	2	2.71%	2.79	1.7%	1.01
	3	3.21%	1.99	2.28%	0.93
	4	2.33%	1.79	2.44%	-0.11
	5	4.95%	7.29	3.01%	1.94
	6	19.66%	10.63	18.41%	1.25
mixed	1	1.82%	1.24	1.43%	0.39
	2	3.08%	4.14	2.94%	0.14
	3	3.98%	3.44	3.22%	0.76
	4	1.28%	1.1	1.07%	0.21
	5	6.3%	0	6.3%	0
	6	12.78%	1.45	9.85%	2.93
	7	3.8%	2.71	4.01%	-0.21
	8	0.16%	0	0.16%	0