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Regionalization of Precipitation in Switzerland by Means of Principal Component Analysis

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With 7 Figures

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Summary

The technique of principal component analysis and of cluster analysis has been applied to two sets of precipitation data in Switzerland, one containing 47 stations (1961–80), and the other 101 stations (1981–1993), with the aim of understanding more fully the spatial distribution of precipitation regimes. Seven regions were highlighted in the first case and 13 in the second. The high spatial coherence which appeared is quite remarkable and confirms the usefulness of these techniques for the analysis of the spatial distribution of meteorological variables, even in a topographically complex area such as Switzerland. The two regional distributions obtained not only correspond fairly well to the large, well-known physical regions of Switzerland, but also go much further, separating the Swiss Plateau into 3 clearly differentiated regions, for example. Regional distributions such as those discussed here can have value for climate change issues, and in particular numerical modeling of climate or climate change impacts on forests.

1. Introduction

In the context of climate change research, problems related to the simulation of precipitation are still largely unresolved (IPCC, 1996; Groisman and Legates, 1995) and climate model predictions of precipitation are of lesser quality than those relating to temperature (IPCC, 1996). Difficulties are particularly pronounced in mountain areas. Adequate knowledge of the spatial distribution of precipitation regimes is necessary, however, for a number of climate impacts sectors, such as the capacity of adaptation of vegetation to climate change (IPCC, 1996) or for projections of runoff for hydro-electricity (Breiling and Charamza, 1994). The results described in this paper are planned to be used for instance as a basis for research concerning climate change impacts on swiss forests (Swiss Forest Investigation Programme).

Description of the current distribution of precipitation regimes is made difficult by the high spatial and interannual variability of precipitation in mountains of the middle latitudes (Gregory et al., 1991; Gajic-Capka, 1993; Auer and Böhm, 1994; Beniston et al., 1994). Even the relationship between temperature and precipitation shows important spatial differences and only the decrease of summer precipitation seems to evolve in parallel with the increase in temperature, according to studies conducted in the United States (Zhao, 1991; Zhao and Khalil, 1993) and the Alps (Rebetez, 1996). During winter, in the United States and in the Alps, a signal can be identified which indicates an increase in precipitation when temperatures are highest, but this signal is very weak and is different from one region to another – partly in function of altitude (Schoenwiese et al., 1990; Zhao and Khalil, 1993; Rebetez, 1996).

In order to study the behavior of precipitation during the years of the observational record, and to increase understanding of the relationship between precipitation and global climate warming, it is necessary to obtain a spatial distribution of the climatic characteristics affecting precipitation. However, the distribution of precipitation is very difficult to regionalise due to the concealing of common points between stations by their differences. Principal component analysis (PCA) is particularly well suited to this type of problem. It was applied successfully to precipitation data in various parts of the world (e.g., Willmott, 1978; Briffa et al., 1994; Gregory et al., 1991; Ogallo, 1989). This method allows a particularly good regrouping of stations with similar characteristics and the delimitation of climatic regions in relation to synoptic situations (Ehrendorfer, 1987; Fernandez Mills, 1995; Regenmortel, 1995). Use of PCA in meteorology and climatology began at the end of the 1940s (Preisendorfer and Mobley, 1988) and numerous publications on PCA have appeared since; Preisendorfer and Mobley (1988) give a broad coverage of this technique, emphasizing its value for meteorology and oceanography.

The Swiss Climate Data Base (Bantle, 1989) contains 47 conventional meteorological stations for which data are continuous for the period 1961–1980 (which is the period of at least twenty years containing the most data). We also applied the same analyses for the 1981–1993 period, which is shorter but includes 101 conventional meteorological stations.

2. Method

2.1 *Principal Component Analysis*

Numerous researchers use the Principal Component Analysis (PCA); however some (Richman, 1986; Jolliffe, 1987; Jolliffe, 1990) have shown that confusion can appear in the use and the understanding of this technique. A summary of the method is therefore described below.

The PCA is a widely used technique in meteorology and climatology. When one is faced with a very large dataset, one attempts to reduce its size, while minimizing any loss of information, with the aim of better understanding and interpreting the structure of the data. A typical dataset can be viewed as **n** observations measured for **p** variables. For example, if monthly precipitation for 20 years at 47 different recording stations are available, we would have **n**=240 observations for **p**=47 variables; there are also other types of data, for example **p** meteorological variables measured at **n** stations for a single occasion.

Very often, the **p** variables are highly correlated (particularly if the **p** stations are close geographically). One should therefore select **m** variables (**m** < **p**) which express all information contained in the original matrix. This can be done by creating new variables which are different from the original ones but constructed from them. The simplicity of the PCA technique lies in this restriction to linear functions of the original variables.

A linear function of the **p** variables takes the form:

$$Z = \alpha_1 F_1 + \alpha_2 F_2 + \cdots + \alpha_{\mathbf{p}} F_{\mathbf{p}}$$

where $\alpha_1, \alpha_2, \ldots, \alpha_{\mathbf{p}}$ are constants and $F_1, F_2, \ldots, F_{\mathbf{p}}$ are the precipitation at station$_1$, station$_2$,. . .station$_{\mathbf{p}}$

As one changes, $\alpha_1, \alpha_2, \ldots, \alpha_{\mathbf{p}}$, one obtains different linear functions and one can calculate the variance of any such linear function. The first principal component (PC) is the linear function which has the maximum possible variance. The second PC is a linear function with a maximum possible variance but which is not correlated with the first PC, and so on. The objective of PCA is to find a small number, **m**, of linear functions of a set of **p** variables which successively accounts for the maximum amount of variation in the original variables.

2.1.1 Eigenvalues and Eigenvectors

Suppose that the first PC is:

$$Z1 = \alpha_{11} F_1 + \alpha_{12} F_2 + \cdots + \alpha_{1\mathbf{p}} F_{\mathbf{p}}$$

then the **k**th PC is generally presumed to be:

$$Zk = \alpha_{\mathbf{k}1} F_1 + \alpha_{\mathbf{k}2} F_2 + \cdots + \alpha_{\mathbf{kp}} F_{\mathbf{p}} \text{ for } \mathbf{k} = 1, 2, \ldots, \mathbf{p}$$

The first eigenvector is the set of coefficients $\alpha_{11} + \alpha_{12} + \cdots + \alpha_{1\mathbf{p}}$, contained in the first PC; the same applies to the other PCs. Note that all coefficients $(\alpha_{\mathbf{k}1}, \ldots, \alpha_{\mathbf{kp}})$ are often called loadings (factors loadings). The eigenvalue corresponds to the variance of each PC and is therefore a measure of its importance in explaining variation. The Z_ks may simply be called the PCs or the PC scores (Jolliffe, 1990).

If we have **n** observations from **p** stations, we can compute eigenvalues and eigenvectors of either a covariance, correlation or cross-product matrix of the time series recorded at the **p** stations. In this case, the analysis is a spatial one (S-mode analysis) because the eigenvectors have a component for each station and represent an orthogonal spatial pattern (Molteni et al., 1983). PCAs can also be used in a temporal context (T-mode analysis) or in other contexts (Richman, 1986).

Generally, the inertia matrix in a PCA is either a covariance, correlation or cross-product matrix. Some use the covariance matrix because it retains more information than correlation; the pros and cons of correlation matrices have been frequently discussed (Ehrendorfer, 1987; Ogallo, 1989; Fernandez Mills, 1995) (advantages include equal weighting of all variables).

One of the main problems is to determine the number **m** (the number of PCs) to be retained. There is a large literature on this topic (Jolliffe, 1993), particularly for meteorology (Preisendorfer and Mobley, 1988) or in a more general context (Jackson, 1991). There are several criteria such as "scree test"(Catel, 1966) or the Kaiser test. The criterion proposed by Kaiser (1958) is probably most widely used. Generally if the first factor takes into account a large part of the information, it describes something obvious; the other factors can however bring to light interesting phenomena hidden in the data matrix.

The **m** PCs show the maximum variation of the original variables. Geometrically speaking, it can be said that the **m** PCs span the most informative **m**-dimensional subspace of the **p**-dimensional space spanned by the original variables. However, some of the unrotated components are difficult to interpret because many of their loadings are of a non-trivial size (Jolliffe, 1993). If we are more interested in the joint variability of the **m** PCs than in their individual variability, we can rotate within their subspace and replace them with **m**-derived variables (rotated components). Richman (1986) presents a summary of the multitude of techniques which can be used for rotations in a PCA, in a climatological context. The goal of all these rotational strategies is to obtain a clear pattern of loadings, that is, factors that are somehow clearly marked by high loadings for some variables and low loadings for others: typical rotational strategies are VARIMAX and QUARTIMAX. In the analyses presented below, the orthogonal method of rotation was applied, i.e., the VARIMAX type (Kaiser, 1958), which allows maximisation of the variances of each individual record for the various factors chosen and is preferred by most authors, although in some cases, obliquely rotated solutions can give better results (White et al., 1991). The orthogonal rotation is equivalent to maximizing the variances in the columns of the matrix of raw factor loadings. We have taken into consideration the **m** loadings with the aim of using them in a cluster analysis.

2.2 *Cluster Analysis*

Cluster analysis is one of the most widely used statistical techniques of classification. At the start, one has a table of *n* statistical individuals for which the values for *p* variables are known. This is considered as a cluster of *n* individual points in a *p* dimensioned space. If *p* is greater than 3, this cluster cannot be visualised but exists mathematically. A distance between points and a distance between groups of points can be defined (strategy of classification).

The algorithm itself starts with the choice of a distance between individual points and between groups of points. The fundamental algorithm of hierarchical ascending classification proceeds in the following manner: the objects to be classified or the groups of objects generated by the algorithm are called elements.

- at stage 0, there are *n* elements to classify (which are the *n* objects).
- the two closest elements are searched for and aggregated into one new element.
- the distances between the new element and the remaining elements are calculated. The same conditions as in stage 0 are present, but with only (n-1) elements left to classify.
- the two closest elements are again searched for and grouped; the new distances are calculated,

and the process is repeated until only one element remains.

In our case, we first of all selected the manner in which to compute the distances between objects, and selected the "Euclidean distance" method. This is probably the most commonly-chosen type of distance. It is simply the geometric distance in multidimensional space. It is computed as:

$$\text{distance}\ (x, y) = \left[\sum^{i}(x_i - y_i)^2\right]^{1/2}.$$

For cluster, we chose the Ward (1963) method. It is distinct from all other methods because it uses an analysis of variance approach to evaluate the distances between clusters. In short, this method attempts to minimise the sum of squares (SS) of any two (hypothetical) clusters that can be formed at each step. In general, this method is regarded as very efficient; however, it tends to create clusters of small size.

3. Results of the Principal Components Analysis

In order to avoid the trend effect of stations (even if the latter is very weak for such a short period and in particular for precipitation), we applied a preliminary transformation of the data by subtracting each station's trend with the following relationship:

$$X_f = X_i - (\mathbf{a} + (\mathbf{b} * t)),$$

where X_f is the initial value, X_i the new value, **a** is the intercept and **b** corresponds to the value of the slope.

The objectives of the present study are to analyse the pattern governing a region in terms of its precipitation regime and to identify regions of coherent precipitation. In a first phase, we applied the statistical treatment described above to 47 stations (Fig. 1), for which the monthly totals of precipitation for the period 1961–1980 were available; an S-mode PCA is applied to a 47×47 interstations correlation matrix deduced from the 47 synoptic stations and the 240 mean monthly (12×20) precipitation.

We obtained 5 PCs whose eigenvalue is greater than 1 (see Table 1), thus fulfilling Kaiser's criterion (Kaiser, 1958); these 5 factors account for 84% of the total variance.

Figure 2 highlights the diverse correlation coefficients of each site in relation to the 5 factors.

- The first factor shows a strong correlation for the north-eastern sites of the Swiss Plateau and those located in the northern alpine valleys.
- The second factor indicates a strong correlation for the stations South of the Alps and in the southern Grisons.
- The third factor highlights a longitudinal effect: a strong correlation for the sites located in western Switzerland and a very weak correlation for stations in eastern Switzerland and south of the Alps.

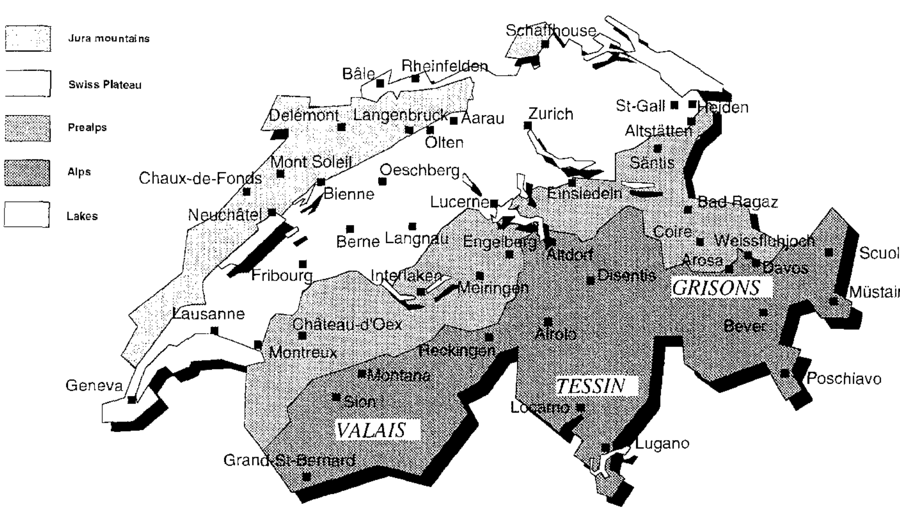

Fig. 1. Map of the area with 47 stations for the 1961–1980 period

Table 1. *Eigenvalues and Percent of Variance Explained*

Factor	Eigenvalue	% Explained	Cum. percent
1	28.68	61.01	61.01
2	4.68	9.97	70.98
3	3.22	6.85	77.83
4	1.84	3.91	81.74
5	1.07	2.28	84.02

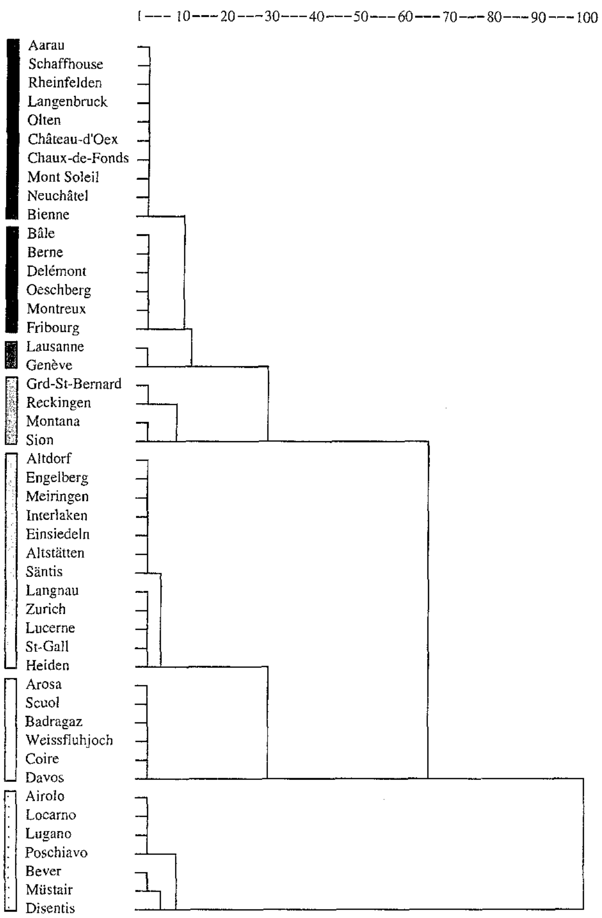

Fig. 2. Principal components for precipitation at 47 stations for the 1961–1980 period

- The fourth factor shows a strong correlation for the stations located in the canton of Valais and also for sites located in the alpine valleys close to the Valais.
- The fifth factor shows strong correlation for the Grisons sites, and more particularly for those located in the northern part of the Engadine Valley.

In order to obtain several different groups within which stations with the most similar characteristics are grouped, we used the cluster analysis, employing the correlation coefficient of the stations with the 5 principal components.

The results of the regrouping (Fig. 3) allow us to distinguish the particular affinities between spatially close stations (excepting Château-d'Oex) and lead us to separate Switzerland into various regions, namely:

- the Jura and foot of the Jura (Schaffhausen, Rheinfelden, Langenbruck, La Chaux-de-Fonds, Mont Soleil, Aarau, Olten, Bienne, Neuchâtel) and also Château-d'Oex
- the central-western part of the Plateau (Basel, Delémont, Oeschberg, Berne, Fribourg, Montreux)
- the central and western part of the Lake Geneva basin (Lausanne, Geneva)
- the Mountain-, valley-, slope-, and pass sites in Valais (Grand-St-Bernard, Sion, Montana, Reckingen)
- the central and eastern part of the Swiss Plateau, valleys north of the Alps (Langnau, Interlaken, Meirigen, Engelberg, Altdorf, Lucerne, Einsiedeln, Zurich, Säntis, St-Gall, Heiden, Altstätten)
- the northern part of the Grisons (Bad-Ragaz, Chur, Arosa, Davos, Weissfluhjoch, Scuol)
- South of the Alps and the southern part of the Grisons (Lugano, Locarno, Airolo, Poschiavo, Müstair, Bever, Disentis)

From these regroupings, we determined the monthly standardized values for each group. In order to apply this calculation, we used the following transformation formula:

$$Y_{ij} = (X_{ij} - \text{mean}_i)/\text{standard deviation}_{[\text{pop}]}$$

- mean_i is the annual mean of the station (i)
- X_{ij} is the monthly mean (j) of (i) stations.
- Standard $\text{deviation}_{[\text{pop}]}$ is the value of the standard deviation of the entire population, i.e., all stations.

Computation of the standard deviation for all stations allows a comparison of the standardised values between regions, whereas calculation of the standard deviation for each group does not allow this. It is thus possible to compare the annual behavior of precipitation between groups and to show, for example, a stronger or weaker

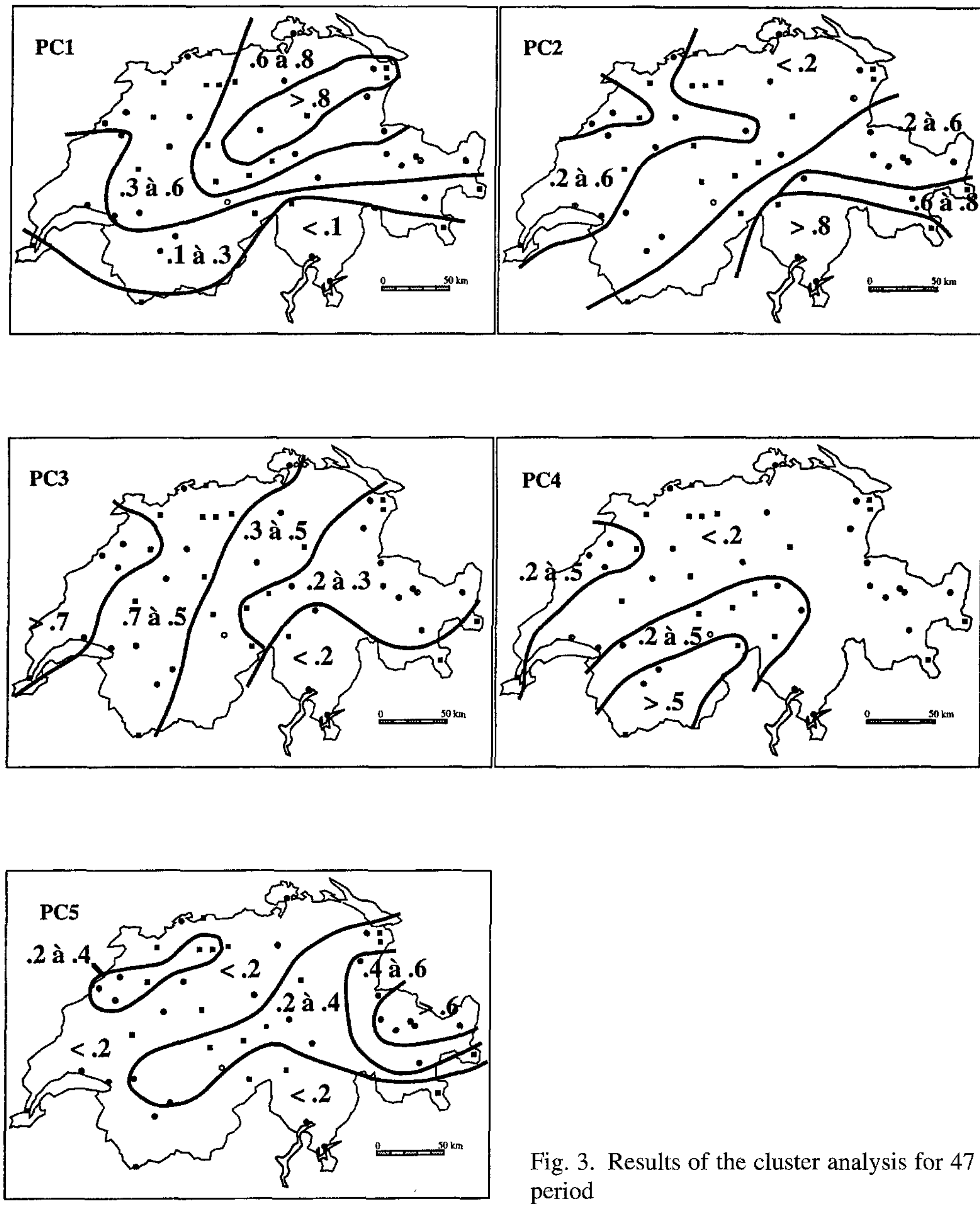

Fig. 3. Results of the cluster analysis for 47 stations for the 1961–1980 period

amplitude of annual precipitation in one region compared to another.

4. Results of the Cluster Analysis

The PCA method allowed reduction of the number of variables from 47 to 5. Application of the cluster analysis method (ascending hierarchical classification) on these 5 variables divides the study area into 7 zones which are characterized by a particular precipitation regime (Figs. 4 and 5).

- The main separation, which would allow a division of the country into two regions, is between the North and the South of the Alps. The difference between group I and the others is by far the biggest (see Fig. 3). A second important division separates the South of the Alps (group I) on the one hand, the Grisons (group II) and the eastern part of the Swiss Plateau (group III) on the second hand, and the rest of the Plateau (groups V and VI), the Valais (group IV) and the Jura and foot of the Jura (group VII) on the third hand.

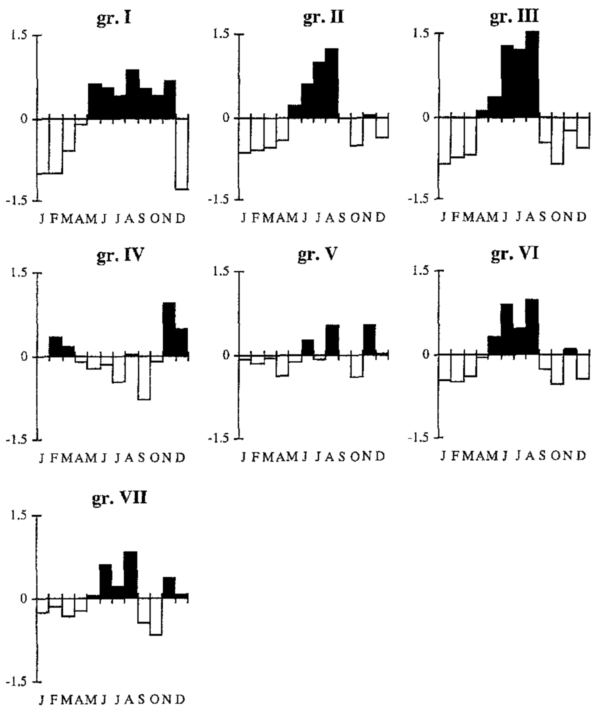

Fig. 4. Mean standardised values for each regrouping

- In the Grisons (group II), the difference between winter and summer is more marked than in the Jura or parts of the Plateau; the months of July are also wetter than June, as a result of summer storms which are more frequent in the Alpine regions.
- In the central part of the Swiss Plateau (group VI), summer precipitation is much higher than in the south-west (group V); this phenomenon intensifies in the north-eastern part of the Plateau (group III). Here again, summer storms explain this phenomenon; the regions closest to the alpine summits experience more summer precipitation than elsewhere. Group III is closer to the eastern Alps' regime than to the remainder of the Plateau (groups V and VI). The central Plateau (group VI) and the western Plateau (group V) are both closer to the Jura regime than to the eastern Plateau regime (group III).
- Valais (group IV) is characterized by a weak amplitude of precipitation throughout the year and by lower precipitation in summer than in winter.

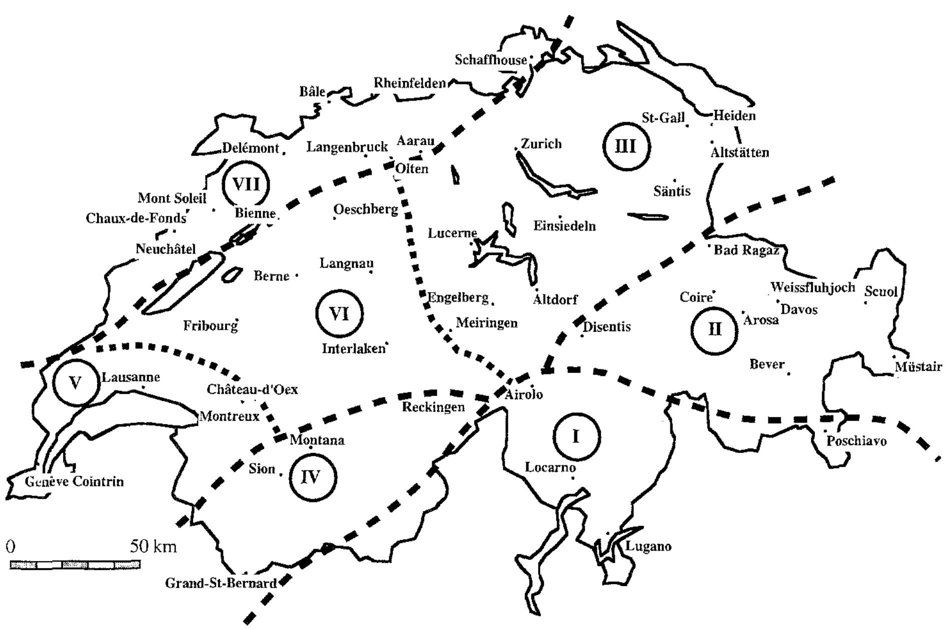

Fig. 5. Limits of the 7 regions for the period 1961–1980

- In the south of the Alps region, winters are much drier than summers, and contrary to most other groups, autumn is very wet as a result of strong precipitation associated with foehn situations.
- The Jura and the foot of the Jura (VII) generally have a dry autumn but can be distinguished from the Plateau in its more abundant winter precipitation. Fronts from the north-west, which are relatively frequent in

winter, are probably the main cause for this difference, as they affect the Jura mountains more than the Plateau, which tends to be sheltered by these mountains.

5. Application of the Method to a Larger Number of Stations and over a Shorter Period

By reducing the number of years of data, a larger number of stations can be used. We applied the same method to the period 1981–1993, which allowed us to use the data from 101 stations (Fig 6). The number of stations increases significantly, particularly in the Alps and south of the Alps. The western Plateau is also much better represented.

The PCA reduces the number of variables from 101 to 10. The results of the cluster analysis showed that the main lines of the division remain the same: a) the south of the Alps, b) the center and east, and c) the west. Finer and more precise distinctions than in the former case can be attempted. The country can be divided into 13 regions (Fig. 7).

- The Hinterrhein, Sils, Lobbia, and Bernina sites confirm that the south of the Grisons, represented in the preceding step by Poschiavo only, is indeed associated with the rest of the south of the Alps region.
- The limited number of stations for the period 1961–80 formerly forced us to reduce Valais to one single region. Now three regions can be distinguished: east, center, and west. The east resembles the southern part of the country. The two other regions are more affected by Atlantic frontal systems and are very weakly distinguishable from one another. The center has less important precipitation events in spring and autumn than the east, but more so than the west.
- The separation of the west of the country is quite different to what it was for 47 stations. Geneva and Changins are associated with the southern Jura and the foot of the Jura, while remaining relatively close to the group formed by Pully, Montreux, Broc, Fribourg, Payerne and Bern, north of the eastern part of Lake Geneva.
- The northern Jura and its foothills, from Fahy to Basel, via Delemont, are part of the same group of stations as those located north of the eastern part of Lake Geneva. This resemblance is associated mainly with the summer months. As in the southern part of the Swiss Plateau,

Fig. 6. Map of the area with 101 stations for the 1981–1993 period

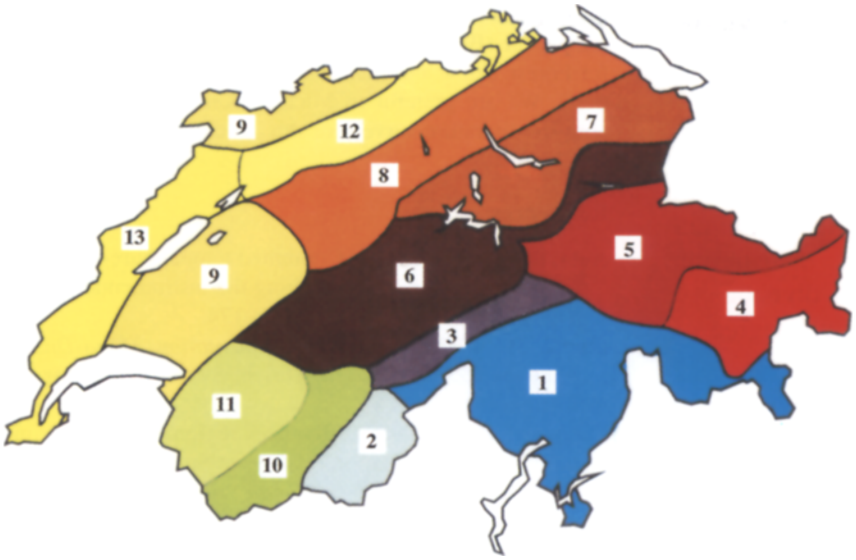

Fig. 7. Limits of the 13 regions for the 1981–1993 period

this part of the Jura is characterized by the summers which are drier than in the eastern part of the Plateau.

- The alpine foothills form two very close regions and are characterized by very rainy summers. They are the wettest regions in terms of total annual precipitation. The northernmost region distinguishes itself from its neighbor by an even more marked annual amplitude.
- Two regions can be identified in the Grisons; the westernmost part of this region has a greater annual amplitude of precipitation (thus bringing it closer to the Swiss Plateau and to the alpine foothills).
- Contrary to the first analysis, where Château-d'Oex was grouped with the Jura stations, it now integrates itself in a group of stations which are geographically close, namely Le Sepey and Gstaad; it is also associated with Montana and Sion – which were formerly grouped with Grand St.-Bernard. We analysed the Château-d'Oex data very closely, in order to verify whether an error in the measurements or a local and exceptional event could explain this link to a geographically remote group in the first analysis. In the second analysis, the data for Le Sepey and Gstaad allow the grouping of Château-d'Oex into a homogenous region.

6. Conclusions

Our analyses have shown that the PCA method is particularly well adapted to the regionalization of precipitation regimes. It allows the grouping of stations with similar characteristics and recognition of climatic regions in the alpine domain. We undertook a first analysis taking into account 47 conventional meteorological Swiss stations, and a second analysis of 101 conventional meteorological stations.

The regions identified by both analyses are largely the same. The first highlighted 7 regions, whereas the second allowed finer and more detailed results, due to a larger number of stations. In this case, 13 regions were identified. It is all the more remarkable to observe such similar results between the time periods 1961–1980 and 1981–1993, as we are in the presence of two periods known to be climatically different (Beniston et al., 1994, Beniston and Rebetez, 1996a; Beniston, 1996), in particular concerning temperatures. The 1981–1993 period (101 stations) was particularly warm, whereas the 1961–1980 period (47 stations) was remarkably cool. Moreover, the 1981–1993 period was associated on average with less precipitation than the former period, although extreme events were more frequent (Rebetez et al., 1996).

The strong geographical link allowing the constitution of groups with similar behavior into homogenous regions is quite marked. This shows the extent to which the precipitation regimes are linked to regional factors, and confirms the conclusions of our analysis of similarity in precipitation events (Baeriswyl, 1996). It should also be noted that the spatial distribution obtained fits into the main physical divisions of the area considered with a quite high degree of precision.

The Château-d'Oex example, associated with geographically remote stations in the first analysis, and associated with surrounding stations when a larger number of stations is taken into account, shows the limitations of this method. It is clearly a function of the number of stations considered, and this number determines the degree of refinement of the results.

Except in certain cases where the limit between two regions is well defined, (e.g., the barrier between the north and south of the Alps), most limits occur between two regions with numerous common characteristics. For example, Geneva is part of the Lake Geneva basin and also the foot of the Jura region, and does indeed exhibit characteristics of both regions. The PCA and cluster analysis methods allow one to determine the strength of the different links between stations and to draw the limits between regions.

The two spatial distributions of precipitation regimes which we have obtained here can be used for analyses of past precipitation and also to some extent to assess possible future precipitation in a warmer global climate. They can constitute a spatial basis for analyses in impacts sectors, such as the capacity of adaptation of forests in particular and vegetation in general to climate change or for projections of runoff for hydro-electricity, among others. They can also be used as a reference base to test the capability of current high resolution regional climate models of reproducing observed climatological regions.

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