LOW FREQUENCY VARIABILITY OF ATMOSPHERIC CIRCULATION OVER EUROPE BETWEEN 1785 AND 1994

With 10 figures and 3 tables

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Zusammenfassung: Niederfrequente Schwankungen der atmosphärischen Zirkulation über Europa zwischen 1785 und 1994
Die dekadenweise Analyse von monatlichen Bodenluftdruckfeldern über Europa und dem östlichen Nordatlantik mittels korrelationsbasierter Druckmusterklassifikation bringt 12 Klassen hervor. Diese zeigen von 1785 bis 1994 starke Schwankungen in den Häufigkeiten und in der Kombination der Druckmuster. Die Schwankungsbreite im Vorkommen der Klassen kann bis zum Faktor 2 betragen. Die Klasse 1 (High-index-Druckfeld über dem östlichen Nordatlantik mit stark positiven NAOI-Werten (North Atlantic Oscillation Index) und Westwindlage bis tief in den Kontinent) erfährt in den letzten Jahrzehnten eine Zunahme, wie sie in der hier analysierten Periode von 210 Jahren sonst nie vorkommt. Nebst den Schwankungen in den Häufigkeiten der Druckmuster herrscht im 19. Jahrhundert in der Atmosphäre ein anderer Zirkulationsmodus als um die Jahrhundertmitte des 20. Jahrhunderts: die Kombinationsmuster häufiger Klassen verschieben sich in diesen zwei Perioden im Winter, Frühling und Herbst. Im Sommer sind die auffälligsten Schwankungen über der Grönländischen See zu finden. Während das Azorenhoch meist vorhanden ist, gibt es Perioden, in denen das Islandtief quasi inexistent oder zumindest nur schwach ausgeprägt ist. Aufgrund theoretischer Überlegungen könnten solche Phasen mit einer schwachen thermohalinen Zirkulation einhergehen. Der verwendete Datensatz NDP-025 (Numeric Data Package) vom CDIAC (Carbon Dioxide Information Analysis Center) weist aufgrund eines Varianzhomogenitätstestes in den Randbereichen des Perimeters Inhomogenitäten zwischen den rekonstruierten und gemessenen Daten auf. Die gefundenen Druckmusterklassen weisen an drei Stationen in der Schweiz (Basel, Genf und Grand Saint Bernard) signifikant von den anderen Klassenmitteltemperaturen verschiedene Temperaturwerte auf. Es zeigt sich insbesondere, daß ein Druckmuster mit dem winterlichen Kältehoch über Osteuropa in Kombination mit einer High-index-Situation über dem Atlantik in den Alpen signifikant tiefere Temperaturen produziert als ein ähnliches Druckfeld ohne das entsprechende Hoch. Der vielverwendete NAOI liefert deshalb in diesen häufigen Situationen (mit winterlicher Osteuropäischer Antizyklone) nur eine schwache Aussage. Da einerseits die Klassenhäufigkeiten und anderseits die Klassenmitteltemperaturen über die Klimarelevanz in bezug auf die Temperatur entscheiden, haben auch relativ seltene Klassen große Auswirkungen für das Klima an den drei Stationen. Dieser Einfluß wird im vorliegenden Artikel für jede Klasse mit Prozenten quantifiziert.

Summary: A decadal analysis of monthly sea level pressure fields over Europe and the adjacent North Atlantic with a correlation-based classification scheme results in 12 classes. These classes show a high variability in the frequencies of their occurrence and also in the combination between the different classes. The range of the frequency changes from one decade to another can differ up to a factor 2. The class 1 high index situation with high positive values of the North Atlantic Oscillation Index (NAOI) with a westerly flow into the continent shows an increasing frequency in the last decades, which is unique in the analyzed period of 210 years. The combinations between the different classes are not the same over the whole period of the 210 years and show differences between the 19th century and the middle of the 20th century: especially in winter, spring and autumn. In summer the most remarkable deviations are found in the Greenland Sea. While the Azores high is present very regularly, the Icelandic low almost disappears for some periods or is at least very weak. From a more theoretical point of view these changes could go together with a weakening of the thermohaline circulation. The used data set NDP-025 (Numeric Data Package) from CDIAC (Carbon Dioxide Information Analysis Center) shows statistical significant smaller variances for the reconstructed period than in the measured period especially in the border areas of the perimeter. The classes have typical temperature means for three stations in Switzerland (Basel, Geneva and Grand Saint Bernard) which differ from each other significantly. Winter temperature with an eastern European anticyclone together with a high index situation are lower compared to a similar pressure situation without the Russian anticyclone. This specific case shows that the NAOI is not very meaningful for Central and Eastern Europe. In some cases the continental signal is almost independent of the NAOI. Depending on the frequency and temperature anomalies of the different classes, these can be subdivided into two groups with high or low climate relevance concerning the temperatures. Indifferent classes have temperatures near the seasonal mean or low frequencies. Their absence has no remarkable effect on the climate. The climate of a period therefore depends on the occurrence of classes with a high climate relevance.

1 Introduction

It is still a very difficult task to separate naturally from anthropogenically induced climate variability.

Nevertheless, internal oscillations of the climate system, of its subsystems and their related feedback mechanisms, are reasonably understood (STOCKER 1996). In this context it is important to know what the
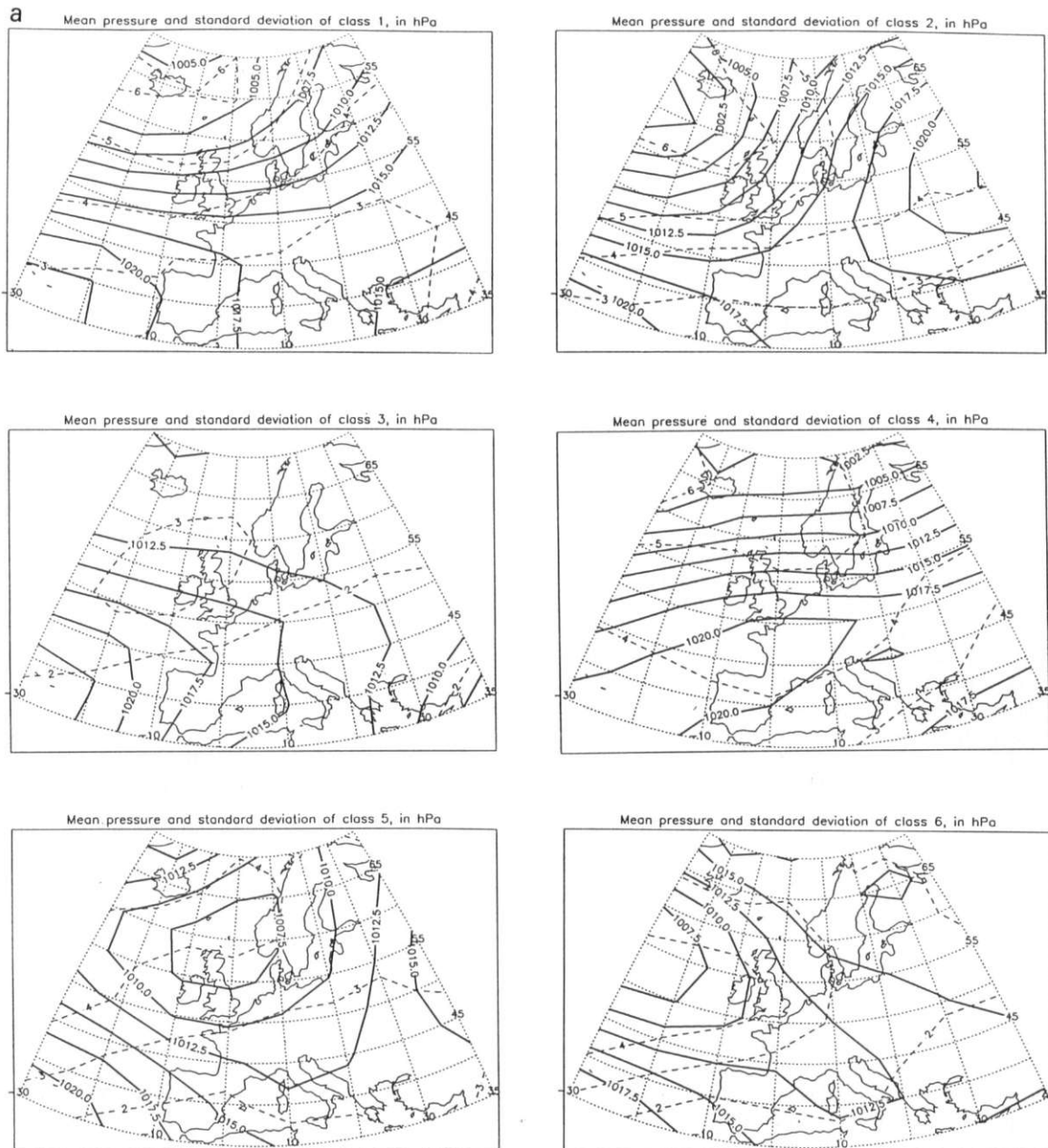
a

Mean pressure and standard deviation of class 1, in hPa

Mean pressure and standard deviation of class 2, in hPa

Mean pressure and standard deviation of class 3, in hPa

Mean pressure and standard deviation of class 4, in hPa

Mean pressure and standard deviation of class 5, in hPa

Mean pressure and standard deviation of class 6, in hPa

Fig. 1a: Mean sea level pressure fields (solid lines) and their standard deviations (dotted lines) for the classes 1–6 (hPa)

Mittlerer Luftdruck auf Meereshöhe (ausgezogene Linie) und die Standardabweichung (gestrichelte Linie) für die Klassen 1–6 in hPa

signature of natural climate variations in the inter-annual to interdecadal scale looks like. Such questions can be studied at least partly with proxydata (WANNER et al. 1994). If a seasonal resolution is needed, only data from the early instrumental period (EIP) are sufficient. They offer the unique possibility to study natural climate variations by correlating the atmospheric pressure

fields with directly measured climate data such as temperature or precipitation. Since the end of the 18th century enough data records have been available for the reconstruction of monthly mean sea level pressure fields over Europe and the eastern North Atlantic. This reconstruction has been done by JONES et al. (1987). The data set is provided by CDIAC (Carbon Dioxide
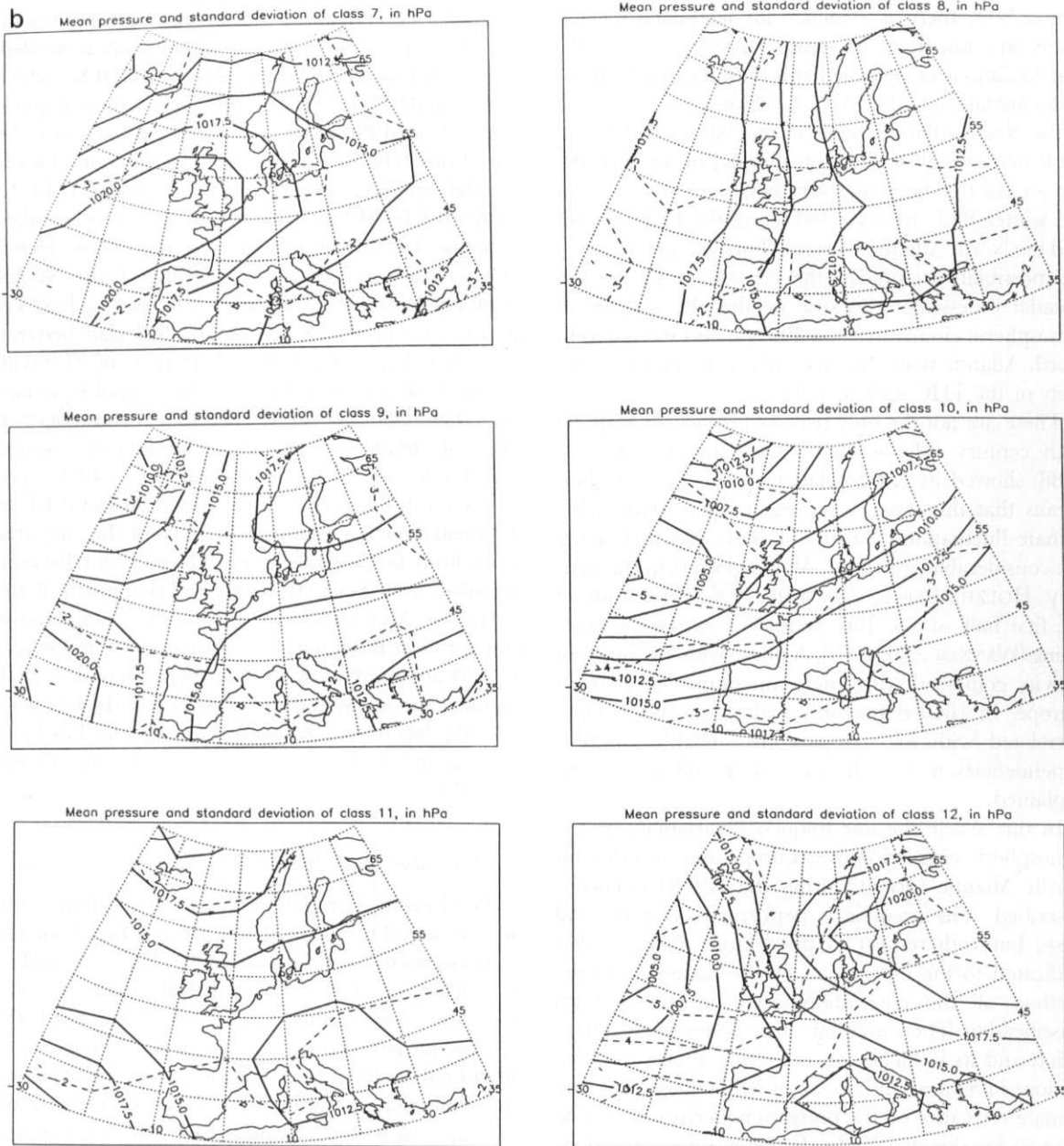
b

Mean pressure and standard deviation of class 7, in hPa

Mean pressure and standard deviation of class 8, in hPa

Mean pressure and standard deviation of class 9, in hPa

Mean pressure and standard deviation of class 10, in hPa

Mean pressure and standard deviation of class 11, in hPa

Mean pressure and standard deviation of class 12, in hPa

Fig. 1b: Mean sea level pressure fields (solid lines) and their standard deviations (dotted lines) for the classes 7–12 (hPa)

Mittlerer Luftdruck auf Meereshöhe (ausgezogene Linie) und die Standardabweichung (gestrichelte Linie) für die Klassen 7–12 in hPa

Information Analysis Center) and is called NDP-025 (Numeric Data Package 25). With this data set an analysis of the seasonal, interannual and decadal variability of the monthly mean surface air pressure can be done back to 1780. The NDP-025 data set will be described in section 2. With data on more than 200 years of monthly mean pressure fields, it is possible to study

atmospheric circulation during a period of mostly minor anthropogenic influence on climate.

Climate parameters such as air pressure are strongly related to SST (sea surface temperature) and its changes, but in a very complex manner (e.g. PALMER a. SUN 1985, KUSHNIR 1994). Even though it is still an open question how the North Atlantic ocean feeds back the

atmosphere, there is evidence for feed-back mechanisms on a low frequency scale (WANNER et. al 1997). The variations of oceanic fields on interdecadal time-scales are linked to the THC (thermohaline circulation) in the North Atlantic. SUTTON and ALLEN (1997) and MCCARTNEY (1997) show on decadal to interdecadal time-scales that huge and very persistent anomalies in the winter SST are advected along the Gulf Stream and the North Atlantic Current. These anomalies open the possibility to predict the climate in Europe on decadal time-scales. Because of this the analysis of atmospheric circulation over Europe and the adjacent North Atlantic may also give indications of the variability of the THC back to 1785.

These are not the only reasons for focussing on the 19th century. The so-called Little Ice-Age (GROVE 1988) showed its last oscillation in this century. This means that this century represents quite remarkable climate fluctuations. Worthy of particular mention is the considerable growth of Alpine glaciers in this century (HOLZHAUSER a. ZUMBÜHL 1996). The study of the first half of the 19th century is extremely interesting (WANNER et al. 1997): A phase with low sun-spot activity coincided with low temperatures in 1816 in Europe. In 1840 remarkably higher sun-spot activity correlated with low temperatures. Highly complex dependencies in the climate system still wait to be explained.

In this article the low frequency variability of the atmospheric circulation over Europe and the adjacent North Atlantic Ocean during the last 210 years is described. The analysis is performed on a decadal basis, but with respect to the seasons. Chapter 2 is dedicated to the description of the data-set and the method of the correlation-based pressure pattern classification. The variability of the atmospheric circulation and its influence on the temperatures of three stations in Switzerland are analyzed in chapter 3. The climate relevance of the pressure patterns will also be discussed in this chapter. In chapter 4 some conclusions are drawn. In Appendix A the correlation-based pressure pattern-classification method is critically examined.

2   Data and methods

2.1 Dataset NDP-025

Only a few ready-to-use sets providing long-term series with sea level pressure (SLP) data are available for the eastern North Atlantic and Europe. In order to study the low frequency climate variability in the

decadal scale, a data-set with at least monthly resolution that covers more than hundred years is needed. The reconstructed NDP-025 data-set of CDIAC, which was created by JONES et al. (1987), meets these requirements. The SLP-data are reconstructed back to 1780. Data from 1785 to 1994 are used in this study for the decadal analysis. Therefore, 21 decades could be analyzed. The SLP-data from 1981 to 1994 were taken from the Data-Set 010.1 (Trenberth's North Hemispheric Sea Level Pressure, monthly) of the NCAR (National Center for Atmospheric Research). JONES et al. (1987) reconstructed the monthly SLP-data between 1780 and 1872 using statistical relations of SLP with precipitation and temperature. The derived equations were then calibrated from 1900 to 1974 and verified with data from 1873 to 1899. The data-set covers a region between 70°N/30°W and 35°N/40°E. The grid-point distance is 5° in the meridional and 10° in the zonal direction. Temperature data of the long time series from Basel, Geneva and Grand Saint Bernard are taken from SCHÜEPP (1961) and the annals of the SMI (Swiss Meteorological Institute). The temperature time series in Basel starts in the year 1755, in Geneva in 1753 and on the Grand Saint Bernard pass in 1818 (actually already by the end of 1817). In the following analysis, data from 1785 to 1994 are used for Basel and Geneva and data from 1818 to 1994 for the Grand Saint Bernard.

2.2 Correlation-based classification method

Based on the correlation-based classification method, the monthly mean SLP-fields (see Fig. 1 for the exact perimeter) are classified in 12 classes. According to WILLMOTT (1987), KIRCHHOFER (1974) basically used the same method when he minimized the squaresums between different geopotential patterns of 500 hPa data. YARNAL (1993) gives a good description and evaluation of this classification method. With this technique each of the monthly SLP-fields is compared to the others by means of the correlation coefficients of the corresponding grid points. A threshold value for the correlations has to be given by the investigator. The pressure pattern with the highest number of correlations higher than this threshold value is considered as a key pattern. The next key pattern is found using the same procedure but without the already classified SLP-fields. Each of the months will be classified. This first step has the aim to find the key patterns recursively. After the selection of all key patterns all months are reclassified again by looking at the highest correlation to one of the selected key patterns. If a specific month has no correlation to one of the key patterns which is

higher than the threshold value, it will not be classified. Depending on this threshold value, the unclassified patterns increase or decrease. On the other hand, the homogeneity of each class also depends on the threshold value. Typically, there is a trade-off between unclassified patterns and within-group-homogeneity when the number of classes is held constant.

A threshold value of 0.7 is used for the following examinations, because it is the best compromise between the percentage of the classified months and the number of key patterns. This value is also in good agreement with FRAKES and YARNAL (1997). This means that in each class the correlation coefficient between each of the class members is higher than 0.7. In addition, the correlations of the columns and rows respectively are positive.

One of the big advantages of this method is its simple and direct interpretation. With modern computers, the results of such a classification are available in a few minutes and easy reproducible. Like every method, this procedure is also associated with some problems. Appendix A will give a short evaluation of the method used.

3   Results

3.1 Results from the pressure pattern classification

The mean SLP-fields of each class are depicted in Figure 1. The most frequent classes, 1 to 4, together have a cumulative frequency of 75%. The remaining classes, 5 to 12, have a total share of 18.8%. 6.2% of the patterns are not classified. Figure 2 shows the seasonal distribution of the four most frequent classes (numbers 1 to 4 in Fig. 1) from 1785 to 1994.

The most frequent monthly pressure pattern is represented by class 1. It can be found in all seasons. A strong zonal flow with a west-southwest component in the central and northern part of Europe is established based on the predominant pressure systems in the upstream North Atlantic region: the Icelandic low and the Azores high. A considerable variability of the air pressure in the Icelandic area can be observed (Fig. 1). Class 2 stands for the typical winter pattern (SCHMUTZ 1996). Its likewise also high frequency in spring and autumn is a late (early) signal of the continental cold air anticyclone over eastern Europe and Russia. In contrast, class 3 can be considered as a typical summer situation. The Azores high is very strong, has moved north, and reaches far into the European continent. The signal of the Icelandic low in the eastern North Atlantic is clearly weaker. This is in good agreement with the findings of GRIBI (1995), which state that
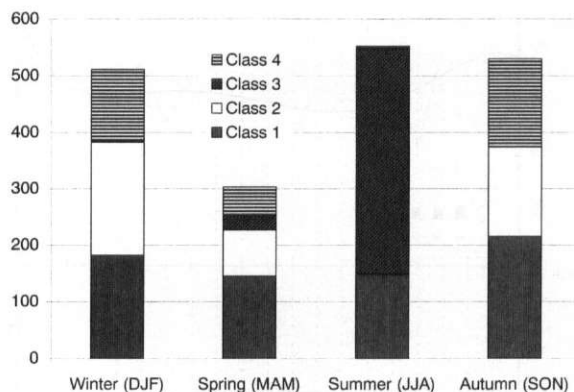

Fig. 2: Seasonal distribution of the four most frequent classes
Jahreszeitliche Verteilung der vier häufigsten Klassen

the Icelandic low has its western-most position in the Labrador Sea in summer. A high pressure ridge reaches the Alps in class 4. In addition, the pressure in the Icelandic region is relatively low. There are two major effects for Europe: the northern part has a strong zonal flow with presumably wet and mild air masses advecting from the North Atlantic. The Mediterranean part of Europe is dominated by a blocking anticyclone. This class is characteristic for winter and autumn.

3.2 Decadal variability of the pressure patterns

In order to interpret the low frequent changes of the different pressure patterns, they are aggregated to decades. Analyses are carried out for each season. The decadal variability of the four main classes for the 21 decades between 1785 and 1994 is represented in Figure 3. Even with this low time resolution, a considerable variability in the different pressure patterns can be found. There are periods of one decade or more with very distinct circulation modes: class 1 for instance, representing a typical zonal flow pattern, shows a dramatic rise in frequency in the last decades compared to the 19th century, where classes 2 to 4 were more frequent. KLAUS (1993) suggests that this development coincides with increasing temperatures in the southern hemisphere compared to the temperatures in the northern hemisphere. This phenomenon is attributed to the anthropogenic greenhouse warming effect, to the variability in the aerosol concentration and to the unusual variations in the in solar activity in the second half of this century.

The range of the frequency changes from one decade to another can differ up to a factor 2. The three decades from 1815 to 1824, 1825 to 1834 and 1835 to 1844, for example, show very strong fluctuations
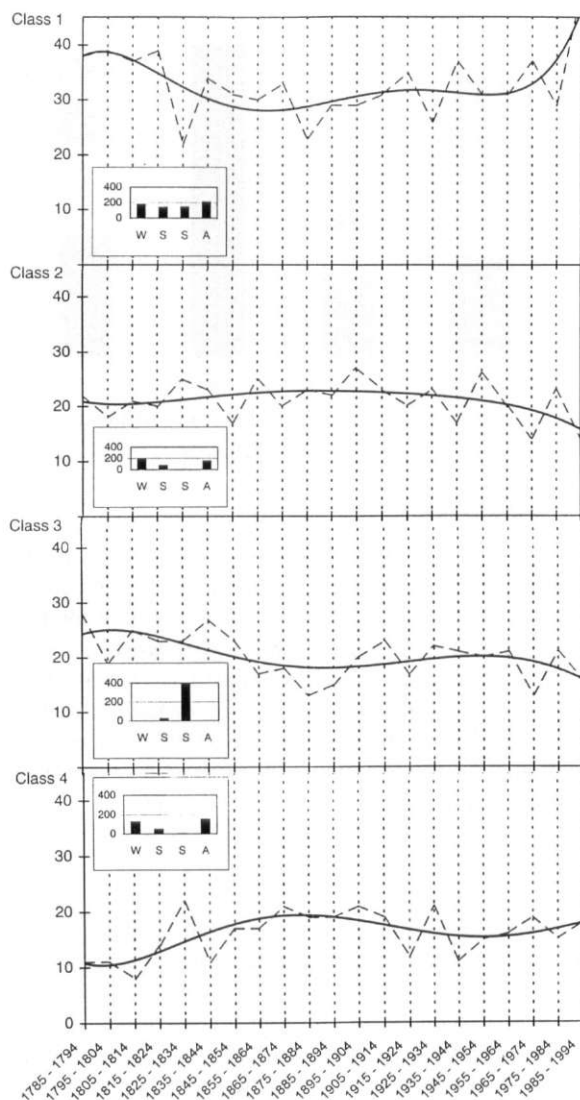
Fig. 3: Decadal variability (absolute frequencies) of the four most frequent classes, including the histograms with the related seasonal distribution

Dekadale Variabilität (absolute Häufigkeiten) der vier häufigsten Klassen, beigefügt sind die entsprechenden, jahreszeitlichen Verteilungen

Fig. 4: Absolute decadal frequencies of the the two most frequent classes (1 and 2) in winter

Absolute, dekadale Häufigkeiten der zwei häufigsten Klassen (1 und 2) im Winter

The most important features of the decadal analysis are decribed for each season in the following paragraphs:

Winter (D, J, F)

Although class 1 and class 2 have a similar North Atlantic Oscillation Index (NAOI; WALKER 1924, VAN LOON a. ROGERS 1978, WANNER et al. 1996) they show one important difference: the strong influence of continental cold air masses in class 2 in winter. The NAOI is a well-known instrument for measuring the zonal flow over the North Atlantic and Europe. This specific case shows that the NAOI is not very meaningful for Central and Eastern Europe. In some cases the continental signal is almost independent of the NAOI. While class 1 results in mild winters in Central Europe, class 2 leads to lower temperatures (SCHMUTZ 1996).

Figure 4 shows the frequency changes of both classes for 21 decades. From 1785 to 1934, both classes show an almost perfect negative correlation. The Icelandic low is well established in almost all decades because both classes show it in its typical form. Depending on the predominating class, the Azores high extends to the northeast (class 1) or remains in the southwest, in the Atlantic (class 2). As mentioned above, the third important SLP system (eastern European anticyclone) reveals very strong seasonal changes. Two temporal minima of this high (represented by class 2) can be observed in the beginning of the last century and in the current century. In contrast, it is observed more frequently in the second half of the 19th century.

Around the middle of the 20th century the anticorrelation of classes 1 and 2 changes into a clear positive correlation. Afterwards, both classes fluctuate in phase. In this later period the variability of the atmospheric circulation shows clearly different structures than be-

(Fig. 3). The second half and the end of the last century represent an interesting phase in the atmospheric circulation over Europe. The zonal classes 1 and 3 (typical for summer) are less frequent, and classes 2 and 4, with a more meridional flow regime in Europe, take their place. It is interesting to note that the homogenized temperature time series of Grand Saint Bernard (Fig. 8) shows negative anomalies for this period (see WANNER et al. 1997). We will discuss the link between temperature and circulation in chapter 3.3.
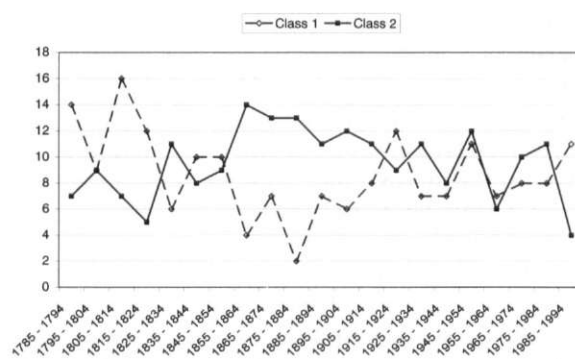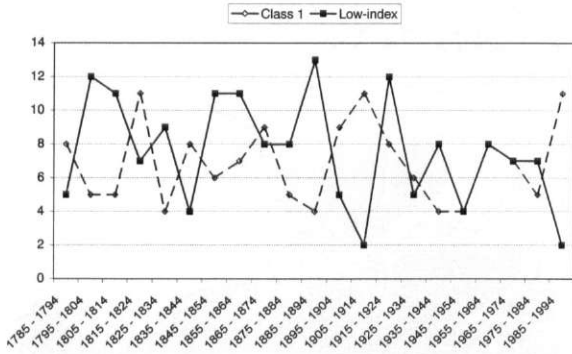
Fig. 5: Absolute decadal frequencies of the high-index class 1 with the low-index classes 5, 6, 8, 10 and 12 in spring

Absolute, dekadale Häufigkeiten der High-Index-Klasse 1 mit den Low-Index-Klassen 5, 6, 8, 10 und 12 im Frühling

fore. Because of the in-phase-variability of the Icelandic low and the eastern European anticyclone, other classes become temporarily more important. A higher frequency of class 10 is a typical consequence. This pressure pattern shows a remarkable southward shift of the North Atlantic low pressure system in the range of approximately 15° latitude (see Figs. 1 and 4). It results in a dominating south-westerly flow over southwestern and central Europe.

Spring (M, A, M)

Spring is the season with the highest pressure variability. Every class appears regularly. Therefore, the absolute frequencies of all classes are smaller in this season. The main reason for the frequent changes in the pressure patterns is the transition situation between winter and summer. The fingerprints of both seasons can be found. Class 2 (winter) appears quite frequently but class 3 (typical summer pressure pattern) also
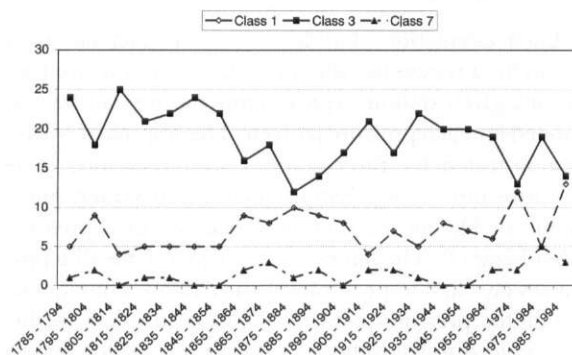
influences the circulation regularly. Figure 5 compares the cumulative frequencies of class 1 with the more meridional circulation (low-index-types). Classes 5, 6, 8, 10 and 12 together build this low-index-group. Again, a phenomenon similar to the one mentioned in the discussion of the winter circulation above can be found when this group is compared with the zonal circulation (class 1). Zonal and meridional circulation show a negative correlation in the 19th and first half of the 20th centuries. Then this relation changes into a positive correlation in the second half of the 20th century. Low frequencies of both types are further compensated by unclassified months and months with weak pressure gradients (class 11).

Summer (J, J, A)

Classes 1 and 3 have already been described in chapter 3.1. Both cover a substantial amount of the summer pressure fields. The time series can be seen in Figure 6. The substantial difference between them is the strength of the pressure gradient between the Azores high and the Icelandic low, and the orientation of the former. Figure 6 can be seen as a time series of these changes. On the basis of model and observational studies for the Atlantic area, it is known that the basinwide decrease of the pressure gradients, and the weakening of the zonal flow and of the baroclinicity go along with an increased THC and a northward shift of positive SST-anomalies in the high latitudes (MANABE a. STOUFFER 1988, DESER a. BLACKMON 1993). Although class 3 is typical for summer (most model and observational studies are conducted with winter data), it is possible that this pressure pattern is an additional indicator for the THC in the North Atlantic. Did a remarkable weakening of the THC occur in the second half of the last century according to Figure 6? Nevertheless, the maximum of

Fig. 6: Absolute decadal frequencies of the three most important classes (1, 3 and 7) in summer

Absolute, dekadale Häufigkeiten der drei wichtigsten Klassen (1, 3 und 7) im Sommer
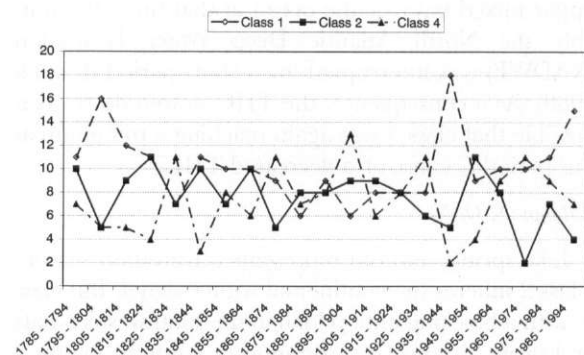

Fig. 7: Absolute decadal frequencies of the three most important classes (1, 2 and 4) in autumn

Absolute, dekadale Häufigkeiten der drei wichtigsten Klassen (1, 2 und 4) im Herbst
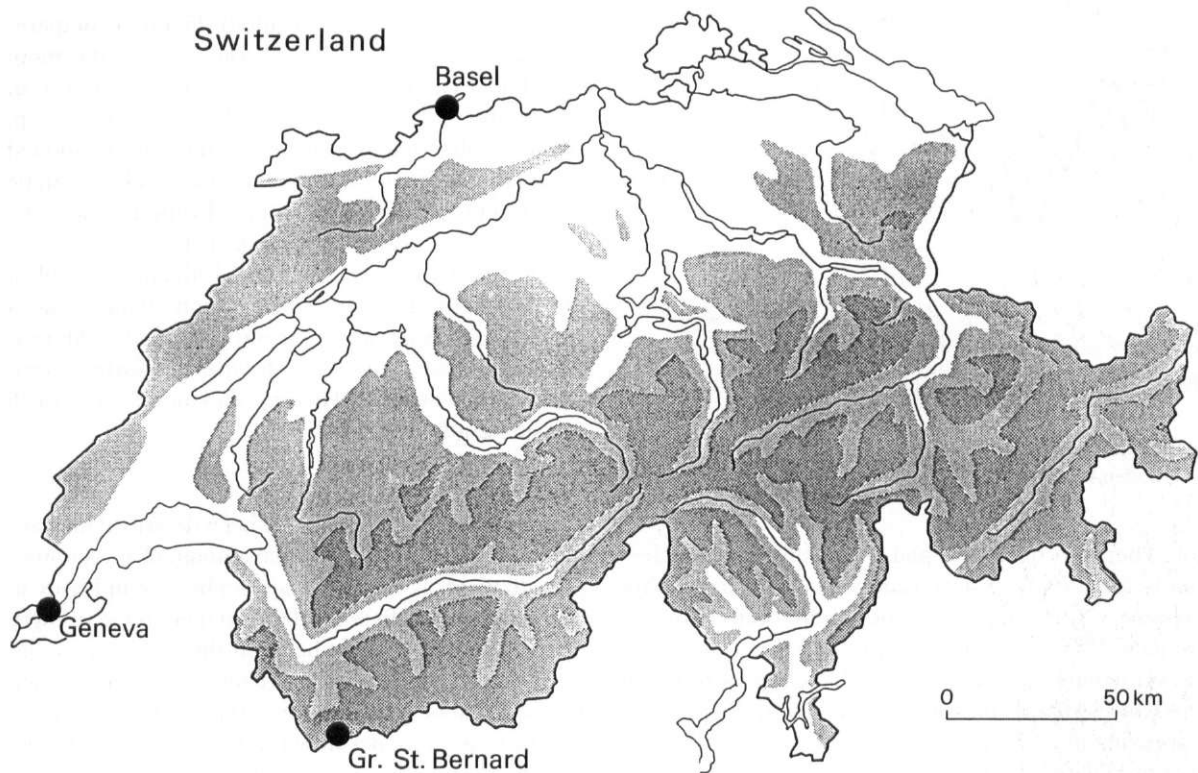
Fig. 8: Topography and geographical locations of the three stations used to estimate the temperature relevance of the circulation classes. Shaded areas are above 800 msl or 2000 msl respectively

Topographische und geographische Lage der drei Stationen, welche zur Abschätzung der Temperaturrelevanz der Zirkulationsklassen benützt wurden. Schattierte Flächen sind höher als 800 Meter, beziehungsweise höher als 2000 Meter ü. d. M.

class 3 goes along with the intensification of the THC in the 1920's and 1930's (DESER a. BLACKMON 1993). In the late 1960's and early 1970's a large pool with negative SST anomalies was observed in the North Atlantic. This phenomenon is denoted as the 'great salinity anomaly' because of the low salinity in the upper mixed layer of the ocean at that time. Presumably the North Atlantic Deep Water Formation (NADWF) was interrupted for a short period (LAZIER 1988). As a consequence, the THC slowed down. Is it possible that class 3 was again reaching a minimum at this period because of a decreased THC?

Autumn (S, O, N)

Like spring, autumn represents a transition season. Class 2 inheres the continental winter-signal. But class 4, with a blocking anticyclone in the southwestern part of Europe, is also very common in autumn. Figure 7 shows that the zonal circulation (class 1) became more important in the second half of this century and was dominant by the end of the 18th and the beginning of the 19th century. It is, however, interesting to note that

a less marked low frequency variability in autumn can be observed whereas in the other seasons the interdecadal variations are more pronounced.

3.3 Temperature relevance of the circulation classes for three stations in Switzerland

Each circulation class leads to a distinct air mass origin for a region like the Swiss Alps. This means that, for any given station, typical temperatures can be calculated for each pressure pattern. This approach will be demonstrated for three stations with very long temperature time series: Basel, Geneva and Grand Saint Bernard. The locations of the 3 stations are represented in Figure 8. The temperature means of the different classes give first impressions of the climatic consequences of the pressure patterns. Classes 1 and 10, for instance, lead to westerly or southwesterly airflow in the Alpine region and are clearly associated with positive temperature anomalies in winter (Table 1). In contrast, class 2 shows slightly lower temperatures which are significantly different from classes 1 and 10. This means

Table 1: Temperature anomalies of the single classes related to the seasonal means for Basel and Geneva from 1784 to 1994 and for Gr. St. Bernard from 1825 to 1994. Class 0 depicts the unclassified months

Temperaturanomalien der einzelnen Klassen im Vergleich zu den saisonalen Mitteln für Basel und Genf (1784 bis 1994) und den Großen St. Bernhard (1825 bis 1994). In der Klasse 0 sind die unklassierten Monate zusammengefaßt

Winter

Classes	0	1	2	3	4	5	6	7	8	9	10	11	12
Basel	−2,5	1,1	0,3	−1,4	−0,6	0,6	−0,5	−3,6	−4,9	−5,4	1,8	−4,7	−3,3
Geneva	−1,9	0,8	0,4	−1,0	−0,6	0,7	0,1	−3,1	−4,0	−4,0	2,0	−3,1	−2,1
G.S.Bern.	−2,1	0,3	0,1	−4,2	0,8	−1,1	−1,7	−2,8	−5,1		1,3	−3,8	−2,0

Spring

Classes	0	1	2	3	4	5	6	7	8	9	10	11	12
Basel	−0,5	0,0	−0,9	2,2	−2,1	0,7	1,8	−0,3	−0,7	2,6	−1,9	2,3	−4,6
Geneva	−0,4	−0,1	−1,1	2,3	−2,1	0,7	1,7	−0,2	−0,4	2,3	−2,0	2,3	−4,4
G.S.Bern.	0,1	−0,3	−1,2	1,9	−1,3	0,3	1,5	−0,2	−0,8	1,5	−0,9	2,3	−3,4

Summer

Classes	0	1	2	3	4	5	6	7	8	9	10	11	12
Basel	−0,6	0,5	1,6	−0,2	1,5	−1,2		0,4	−2,4	0,8	−0,8	−1,4	
Geneva	−0,6	0,5	1,1	−0,2	1,9	−1,3		0,5	−2,5	0,5	−0,7	−1,3	
G.S.Bern.	−1,0	0,7	1,3	−0,2	2,0	−1,3		0,5	−3,1	0,2	−1,2	−2,3	

Autumn

Classes	0	1	2	3	4	5	6	7	8	9	10	11	12
Basel	−1,8	1,6	−0,8	2,8	−1,0	−1,7	4,6	2,7	−2,5	2,4	−1,2		−3,2
Geneva	−1,7	1,4	−0,7	3,0	−1,0	−2,0	5,1	3,0	−2,0	2,5	−1,7		−3,2
G.S.Bern.	−2,0	1,2	−0,8	2,8	0,0	−2,1	3,2	2,5	−3,4	2,4	−2,3		−3,0

that the influence of the continental signal is important for the temperatures even though the Russian anticyclone is remote from the stations. Class 8 and class 12 are seldom observed but they have a strong impact on the temperatures (Table 1). Class 12 is an extreme variety of class 2: the high pressure over eastern Europe moves to the northwestern part of Europe. Within the four winters with the hardest ice conditions in the Baltic sea between 1896 and 1956, this class appears 4 times (SCHMUTZ 1996).

Table 1 shows the anomalies of the class-temperature-means related to the mean season temperature. It is therefore possible to estimate the effect of the pressure patterns on different stations. Class 4 shows typical conditions in winter and autumn as well. Grand Saint Bernard (2472 m above msl; Fig. 8) is not affected by the very typical phenomenon of a cold stable air layer over the Swiss midlands and the Region of Lake Geneva during wintertime high-pressure situations (WANNER 1979). On the other hand, Basel and Geneva lie within this cold air layer. In addition, high-pressure situations (class 4) are almost always accompanied by stratocumulus or fog events in the lower basins (WANNER 1979). Table 1 shows the typical temperature anomalies for class 4. The two stations Basel (256 m above msl) and Geneva (375 m above msl) show a very similar influence of the different pressure pattern classes on the temperature anomalies, although these stations are 200 km apart. Altitudinal effects like the above-mentioned cold air separation are the reason for a different influence of the circulation classes on temperature anomalies at the Grand Saint Bernard.

The temperature relevance of the pressure patterns for the station-means is determined by two factors:

− Strength of the temperature anomaly (ΔT_j) (see Table 1).

Table 2: Estimation of the temperature relevance of each class. The frequencies of the classes are weighted with the related seasonal temperature anomalies. For each class this parameter is then compared with the total of all classes (Q_j in %). Class 0 depicts the unclassified months

Schätzung der Temperaturrelevanz jeder Klasse. Die Häufigkeiten der Klassen sind mit den entprechenden Temperatur-anomalien gewichtet. Dieser klassenspezifische Parameter ist mit dem Total aller Klassen verglichen (Q_j in %). In der Klasse 0 sind die unklassierten Monate zusammengefaßt

Winter

Classes	0	1	2	3	4	5	6	7	8	9	10	11	12
Basel	14,0	32,0	10,1	0,2	12,7	1,6	0,7	5,1	5,4	0,9	6,5	1,5	9,5
Geneva	13,0	25,0	14,5	0,2	16,4	2,1	0,1	5,6	5,2	0,9	8,5	1,2	7,4
G.S.Bern.	21,9	10,9	2,0	1,3	28,7	5,2	2,7	4,4	3,2		8,6	2,4	8,9

Summer

Classes	0	1	2	3	4	5	6	7	8	9	10	11	12
Basel	3,3	36,3	0,7	33,5	2,6	3,9		5,5	4,9	5,2		4,1	
Geneva	3,9	36,6	0,5	31,3	3,4	4,8		7,0	5,6	3,0		3,9	
G.S.Bern.	6,6	39,6	0,6	28,5	3,8	4,6		5,2	5,6	1,4		4,1	

– Frequency of the classes (H_j).

In order to estimate the influence of pressure patterns on the temperature of a station, the anomalies are weighted with the frequencies of the classes (1). These weighted temperature anomalies (ΔTH_j) are then compared (3) with the sum of all weighted temperature anomalies (2, ΔTH). This quotient (Q_j) gives an estimate of the temperature relevance of class j:

$$\Delta TH_j = \Delta T_j \cdot H_j \qquad (1)$$

$$\Delta TH = \sum_{j=1}^{k} |\Delta TH_j| \qquad (2)$$

$$Q_j = \frac{\Delta TH_j}{\Delta TH} \qquad (3)$$

Table 2 shows the Q_j for winter and summer. Class 1 obviously has the highest temperature relevance in winter in Basel and Geneva. On the Grand Saint Bernard the same class has less impact on the temperature relevance because of the lower temperature anomalies. This example shows that even very frequent pressure patterns may have no strong impact on the temperature anomaly of a station. On the other hand, very rare pressure patterns have a relatively high Q_j score. Classes 10 and 12 are good examples of this fact. They have a high temperature relevance of about 10% over the whole analyzed period, which is clearly above the average. The unclassified months have a considerable influence in winter, while in the summer season this influence is rather small. The reason lies in the high amount of unclassifiable pressure patterns in winter.

These lead to a strong negative temperature influence, which is not the case in summer. The dominance of classes 1 and 3 in summer is also confirmed by this temperature analysis for the three stations in Switzerland. They amount to 70% of the Q_j scores.

All classes with a $Q_j > 10\%$ for the Basel station are listed in Table 3 for each season. It is interesting that classes which are close to the mean temperature of the season, like class 1 in spring, can fluctuate remarkably but do not have any significant influence on the temperature variability.

3.4 Statistical significance of the data set

The SLP data set used is based on a reconstruction of data between 1780 and 1872 (chapter 2: Data and methods). Using the assumption of synoptic climatology (YARNAL 1993), that the classification covers all important pressure patterns in the analyzed perimeter, the

Table 3: Basel: Classes with a Q_j higher than 10%. Class 0 depicts the unclassified months

Basel: Klassen mit einem Q_j höher als 10%. In der Klasse 0 sind die unklassierten Monate zusammengefaßt

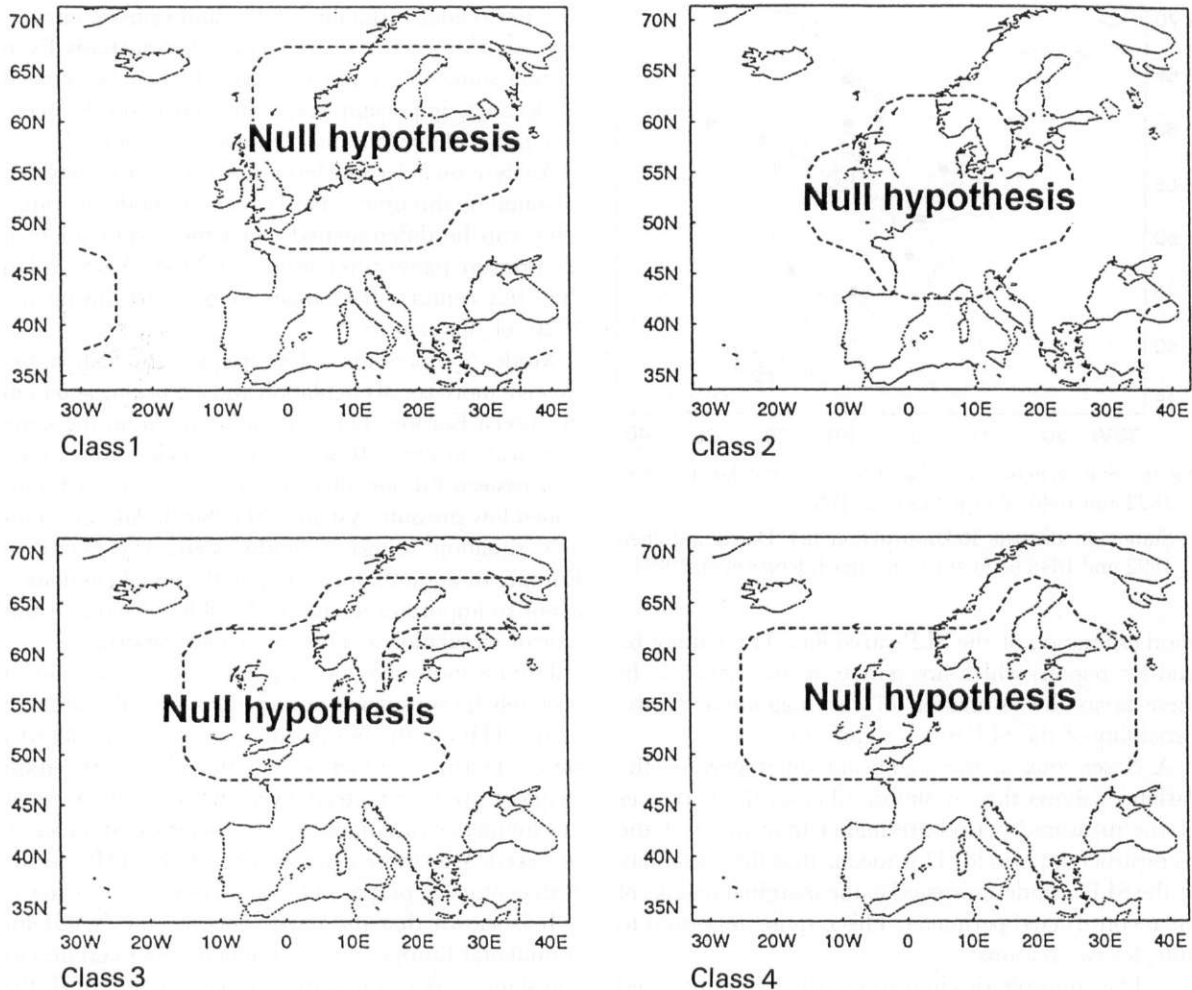|	Basel
Winter	0;1;2;4
Spring	2;6;9;11
Summer	1;3
Autumn	1;2;4

Fig. 9: Classes 1 to 4: Areas with significant data sets, based on a statistical comparison of the variances between the two periods 1780 to 1872 and 1873 to 1994

Klassen 1 bis 4: Gebiete, in denen die Varianzen zwischen den Perioden 1780 und 1872 sowie 1873 bis 1994 verschieden beziehungsweise nicht verschieden sind (Null hypothesis)

climate variability is considered to be seen in the changing frequencies of the different classes. Therefore, not only the grid-point means but also the variances of the reconstructed period have to be in the same magnitude as the measured ones. If this is not the case, one of the two periods shows a greater (smaller) variability. In this way it is possible to estimate how good the reconstruction of the SLP data set is.

The design of the test leads to a one-tailed null-hypothesis: *The variance of grid-point XY from the period 1873 to 1994 is smaller or equal to the variance of the same grid-point XY from 1780 to 1872.*

This hypothesis is tested for all grid-points in each class between the two periods with an $\alpha = 5\%$.

Figure 9 shows the results for the 4 main classes. The shaded areas denote the regions where the null hypo-

thesis is not rejected at the 5%-level. This means that there is no statistically significant difference between the periods mentioned above concerning the variability of the SLP for the specific pressure pattern in these areas. The 4 classes represented in Figure 9, as well as the remaining 8 classes (see Fig. 1), show a surprisingly coherent and clear picture. There are significant differences in Eastern Europe, in the Middle East, in the Mediterranean region and over the eastern North Atlantic ocean. The station network for the reconstruction of the SLP data between 1822 and 1846 is shown in Figure 10 (after JONES et al. 1987). The geographical distribution of this network elucidates the reasons for the spatial structure of the significant and non-significant areas. In central and northern Europe, the station density is quite high. The reconstruction leads to a
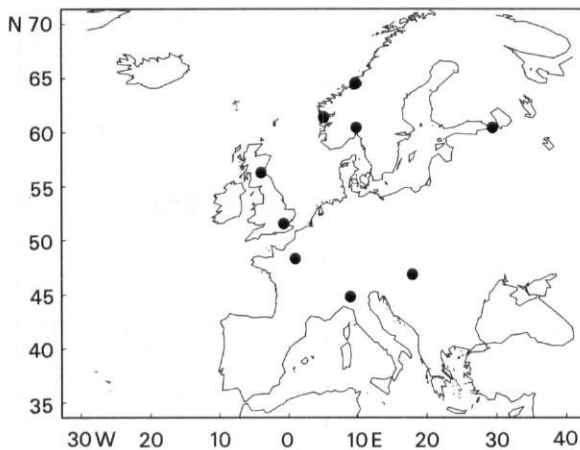
Fig. 10: Station network used to reconstruct the data between 1822 and 1846 (after JONES et al. 1987)

Stationen, die zur Rekonstruktion der Daten zwischen 1822 und 1846 benützt wurden (nach JONES et al. 1987)

good estimation of the SLP-variability. This cannot be said for regions which are remote to this network. In these areas the estimation of the magnitude of the variability of the SLP is non significant.

A closer look at the significant differences of the variances shows that in almost all cases the variances of the measured period are higher than those of the reconstructed periode. This means that the variability of the SLP is underestimated in the marginal regions of the reconstructed perimeter. This is quite important to note, for two reasons:

– The atmospheric circulation, which is represented by SLP-fields in this paper, is important in the whole perimeter (e.g. southern part of Europe).

– Especially the variability in the North Atlantic region, which is the important upstream area of continental Europe, should be reconstructed exactly. This reconstruction mainly concerns the two most important pressure systems in this area: the Icelandic low and the Azores high. Changes in the magnitude and position of these systems are of great importance for Europe (VAN LOON a. ROGERS 1978, WANNER et al. 1997).

4 Conclusions and open questions

The correlation-based classification of the NDP-025 data set of monthly mean SLP leads to 12 classes with fairly consistent circulation patterns. They cover all important patterns in the analyzed perimeter (Europe and the eastern North Atlantic). The classes show typical seasonal cycles. In order to analyze the decadal

to interdecadal variability of the atmospheric circulation, each season was analyzed on a decadal basis. Even though some structures are blurred when aggregated to decades, important variations can easily be seen. The range of the variations reaches a factor of 2.

Analysis on a decadal level shows that variability can be found on this time scale. Two major modes of variability can be differentiated when the combination of the pressure patterns is considered. Mode A is found in the 19th century. It changes to mode B during the 1930s of this century.

Mode A represents a low frequent oscillation between a more zonal circulation and a blocking situation in eastern Europe. This cannot be found on the same time scale in mode B, where the blocking anticyclone over eastern Europe alternates with a southward-positioned low pressure system in the North Atlantic. This new situation brings a southwesterly cyclonicity to Europe. In autumn, for example, the zonal circulation is not so important for mode A, while in mode B this type of circulation assumes increased importance.

From a more theoretical point of view, class 3 can probably be considered as an indicator of the strength of the THC in the North Atlantic in the interdecadal range. During summer season this class is the most frequent pressure pattern, even though it shows clear low frequency variations. The following question has to be asked: Was there a weakening of the THC in the 19th century as proposed by the frequencies of class 3?

It is shown that the importance of the NAOI for continental Europe is overestimated under certain circumstances. With the same positive (high) NAOI, the circulation in northern and eastern Europe can vary drastically. Further, it was demonstrated that the temperatures at three stations in Switzerland (Basel, Geneva and Grand Saint Bernard) are significantly lower when eastern Europe lies under cold surface anticyclones.

The pressure patterns lead to typical seasonal temperatures. Depending on the frequency and temperature anomalies of the different classes, these can be subdivided into two groups with high or low climate relevance concerning the temperatures. Indifferent classes have temperatures near the seasonal mean or low frequencies. Their absence has no remarkable effect on the climate. The climate of a period therefore depends on the occurrence of classes with a high climate relevance.

The variance-homogeneity-test of the data set shows inhomogeneities for the reconstructed period (1780–1872) in eastern Europe, the Mediterranean area and the eastern North Atlantic. These regions have a significant lower pressure variability in the

reconstructed period compared to the observed period. Therefore, the variability of the important pressure centers (Icelandic low, Azores high) might be underestimated by the reconstruction method (JONES et al. 1987).

Appendix A

In this Appendix a general criticism related to the correlation-based classification has to be expressed. In this study this method was used because of its simplicity of approach and interpretation. It is an automatic classification scheme and therefore allows reproduction of the same results. There are subjective decisions to undertake during one classification-run, however. This is why the procedure should be denoted as a semi-objective or – according to YARNAL (1993) – automatic classification. With state-of-the-art-computers it is possible to bring the classification to a level where it meets the demands of the problems to be solved. There are typically two parameters that can be influenced by the investigating person: the number of classes and the threshold value of the correlation coefficient. These have an influence on the proportion of unclassified patterns. There is a trade-off between these parameters and the best mixture has to be found.

However, a far more important problem is connected to this method. This study shows that the exact position *and* the intensity of a pressure system are important to the climate of a region. It is well known that using the Pearson correlation coefficient the data undergo a z-transformation, which is shown in equations (4) to (7).

$$r_{xy} = \frac{cov(x,y)}{S_x \cdot S_y} \tag{4}$$

$$= \frac{\sum_{i=1}^{n}(x_i - \bar{x}) \cdot (y_i - \bar{y})}{n \cdot S_x \cdot S_y} \tag{5}$$

$$= \frac{1}{n} \cdot \sum_{i=1}^{n} \frac{(x_i - \bar{x})}{S_x} \cdot \frac{(y_i - \bar{y})}{S_y} \tag{6}$$

$$= \frac{1}{n} \cdot \sum_{i=1}^{n} z_{xi} \cdot z_{yi} \tag{7}$$

Therefore, pressure fields with similar pressure patterns but different gradients are leveled. It is possible that pressure fields with different gradients are classified in the same class, although they have, climatologically speaking, very different regional impacts. A short but nevertheless impressive example illustrates this fact.

1	2	3	2	4	6	2	3	4
2	3	5	4	6	10	3	4	6
4	5	6	8	10	12	5	6	7

These three matrices have correlation coefficients of $r_{xy}=1.0$. Assuming that they represent three pressure patterns with 9 grid-points each, they are certainly classified in the same class. This is correct when the criterion followed is pattern recognition. Under the additional, important criterion of the steepness of the gradients, the classification says nothing. It is easily shown that the second pressure field has the steepest gradients. A simple classification method that recognizes the patterns and the gradients with the advantages of correlation-based classification is still needed.

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