CIRCULATION CHANGES IN EUROPE SINCE THE 1780s

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1. INTRODUCTION

Climatic variability and changes are inherently linked with variability and changes in the atmospheric circulation, the latter comprising causes as well as effects of the former (Hupfer, 1991). Therefore, climate research should always include investigations on the behaviour of the circulation. This is valid within an historical perspective. In view of possible changes in climate that might be expected in the near future due to anthropogenic greenhouse gas forcing, it is of crucial importance to learn about natural variabilities in climate and atmospheric circulation through the extension of empirical research into the historical past.

Since objective circulation analyses require homogenized pressure data, preferably with large-scale grid resolution, most studies have focussed on the last hundred years or even shorter periods (e.g. Barnston and Livezey, 1987; Rogers, 1990; Hupfer, 1991; Jacobeit, 1993; Wanner, 1994; Bartzokas and Metaxas, 1996; Klaus, 1997; Machel *et al.*, 1998; Kapala *et al.*, 1998). For earlier periods, the classical reconstructions by Lamb and Johnson (1966) and Kington (1988) defined the state-of-the-art for a long time. Objective circulation analyses became possible when the first version of a reconstructed gridded SLP data set back to 1780 became available (Jones *et al.*, 1987). Subsequently, enhanced efforts were made to establish an increased number of homogenized pressure time series extending further back into the historical past.

Recently, Jones *et al.* (1997) provided an extension of the NAO back to the 1820s. Schmutz and Wanner (1998) applied a classification technique to the sea-level pressure (SLP) fields from 1785. Case studies of anomalous conditions during the last 500 years were compiled by Pfister (1999), and investigations in the context of the European Community climate research project ADVICE (Annual to Decadal Variability in Climate in Europe) also focussed on the topic of circulation variability extended back to 1780 (Jacobeit *et al.*, 1998; Beck, 1999). These investigations were based on recently improved reconstructions of gridded SLP data (see next section). Here, these reconstructions are used to present the major circulation changes that have occurred in Europe since the end of the 18th century, thus providing an extended frame for representing large-scale circulation variability.

2. DATA

The following analyses are based on gridded monthly mean sea-level pressure data that have been reconstructed back to 1780 for the North-Atlantic-European region by Jones *et al.* (1999) using homogenized long-term pressure time series from various European stations; starting in 1780 with 10 continuous series, increasing to 20 stations in the 1820s (including the important stations of Reykjavik and Gibraltar), and finally reaching a network of 51 stations by the 1860s.

The historical SLP data are available on a 5° latitude by 10° longitude grid over the area from 35 to 70°N and from 30°W to 40°E. For deriving gridded data from the station data, Jones *et al.* (1999) used EOF-regression models calibrated over the period 1936-1995 and verified for the period 1881-1935. Explained variances of above 90% are reached around the central grid points with decreasing values towards the periphery, especially for the earliest period with relatively few station time series. The more structured large-scale circulation during winter explains higher percentages of the variance than in summer. These data represent significantly improved reconstructions compared with earlier assessments (Jones *et al.*, 1999), and define a highly appropriate basis for considering circulation analyses for a longer period of time than previously available data sets would allow.

3. METHODS

Analyses will focus on three different approaches: using major circulation indices; determining large-scale circulation types; and applying principal component analyses (PCA) to the whole grid in order to derive basic circulation patterns and their variations in time.

Calculating circulation indices from gridded pressure data would be most reliable if concentrated on those regions with the highest quality in the reconstructions, i.e. around the central grid points of the analysed area. This has been done by Jacobeit *et al.* (1998) who defined a Central European Zonal Index which was strongly related to regional temperatures in this area (Jacobeit *et al.*, 2000). On the other hand, the major mechanism governing the large-scale circulation variability across Europe is the North Atlantic Oscillation (NAO), and despite its centres of action being situated towards the periphery of the reconstructed pressure grid, an NAO index approximation has been calculated. It needs to be borne in mind that results are less reliable for the time before nearby station pressure series started during the 1820s.

There have been several different definitions of NAO indices: most commonly the difference between normalized station pressure time series is used. However, different stations have been used: Ponta Delgada - Akureyri (Rogers, 1984), Lisbon - Stykkisholmur (Hurrell, 1995), or Gibraltar - Reykjavik (Jones *et al.*, 1997), the latter going furthest back in time until the 1820s. Gridded SLP data are also used: e.g. for determining the moving pressure maxima and minima (Mächel *et al.*, 1998), or for deriving a grid-based principal component representing the NAO (Wanner *et al.*, 2000). A simple approach consists of using fixed grid point averages of normalized SLP (Jacobeit *et al.*, 1998), and here we take the grid points along 30 and 20°W to calculate the differences between normalized SLP averages within the latitudinal sections 35-40°N and 60-65°N (4 grid points for the Azores and the Icelandic centres, respectively). Additionally, cumulating the sum of successive index values leads to the determination of normalized cumulative anomalies. Predominantly rising/falling values in these cumulative anomalies indicate the prevalence of positive/negative deviations, and major turning points in cumulative anomalies indicate transitions between periods dominated by opposite deviations. Therefore cumulative anomalies reveal decadal and interdecadal index variations particularly well (e.g. Mächel *et al.*, 1998).

The second approach of circulation analyses determines large-scale circulation types based on the degree of zonality, meridionality and vorticity of the monthly mean SLP isobars focussing on central grid points where reconstruction models performed well, the 25 grid points from 40 to 60°N and from 10°W to 30°E. Within this area, three SLP patterns have been defined representing typical westerly flow, southerly flow and central low pressure. Spatial correlations with these typical patterns have been calculated for all monthly mean SLP subgrids for the period 1780-1995. Based upon the resulting three correlation coefficients it is possible to classify each of the SLP subgrids into one of ten circulation types corresponding to the Central European Grosswettertypes (Hess and Brezowsky, 1977; Gerstengarbe and Werner, 1993). Low and High pressure types are defined by a maximum coefficient (positive or negative) with the central pressure type. Remaining cases are assigned to the eight main flow types (W, NW, N, NE, E, SE, S, SW) according to the minimum Euclidean distance of their zonality and meridionality coefficients from those defining the main flow types (i.e. the West type is defined by zonality/meridionality coefficients of 1.0/0.0, the Northwest type by 0.71/-0.71, the North type by 0.0/-1.0 etc., and zonality/meridionality coefficients of an actual SLP subgrid are compared with these defining values by means of calculating two-dimensional Euclidean distances, respectively). Seasonal frequencies of the resulting monthly Grosswettertypes have been calculated for 31-year periods (e.g. 1780-1810), iterated with time steps of one year.

Finally, pressure data for the whole grid has been submitted to varimax-rotated PCA, separate analyses for each month. Since we intend to derive basic circulation patterns, T-mode analysis has been applied with variables (SLP grids) differing in time and spatially varying cases (grid points). Since the number of grid points of the reconstructed historical SLP data is restricted to 60, it is not possible to enter all the 216 monthly mean SLP grids from the whole 1780-1995 period into one monthly T-mode analysis. Thus, PCAs have been performed for a series of 60-year periods starting with 1780-1839, continuing with periods each shifted by 12 years until the final period 1936-1995. All those SLP grids with a maximum loading on at least one of the resulting circulation patterns from these overlapping analyses were combined into a new set of variables for a concluding PCA. Thus, we may ensure that circulation patterns resulting from this concluding analysis reflect conditions from the whole 1780-1995 period. In order to generate continuous series of time coefficients, these circulation patterns (T-mode scores of the final extracted principal components) have been subsequently correlated with all the monthly SLP grids from the 1780-1995 period. The background for this procedure is that we have not applied an EOF, but a PCA technique - the former having eigenvectors of unit length, the latter eigenvectors weighted by the square root of their eigenvalues (see Richman, 1986). Thus, the T-mode loadings represent the correlation coefficients between variables (SLP grids entered into the analysis) and resulting PCA scores (circulation patterns). Correlation coefficients between these patterns and the SLP grids from the whole 1780-1995 period therefore represent a completed series of loadings, con-stituting the continuous series of time coefficients required for further investigations.

An essential aspect for pattern analysis is the number of extracted principal components, especially in view of varimax rotations, that have been applied to improve the reproduction of physical relations from the real world (Richman, 1986). According to principles discussed earlier (Jacobeit, 1993), we have only extracted those principal components having at least on one input variable the maximum loading among all the components. In this way, noisy components are rejected and it is ensured that extracted components represent dominant patterns that are realized at least for anomalous conditions.

Changes over time of these patterns are considered with regard to different aspects. The completed series of T-mode loadings (representing the patterns' time coefficients) are indicating more or less weight of a particular pattern within the original SLP grids.

Similarly, as for the NAO index, the normalized time coefficients have been used to calculate their normalized cumulative anomalies, thus allowing us to identify major periods with increased or decreased importance of a particular circulation pattern. Furthermore, the internal characteristics of these patterns, like pressure gradients or spatial dimensions of pressure centres, may have varied over time. Thus, SLP composites have been calculated for each circulation pattern and for each of the 186 31-year periods within the whole 1780-1995 period (starting from 1780-1810 until 1965-1995). Composites have been derived from those original SLP grids having their highest loading (correlation coefficient) on the respective circulation pattern. Composites have been determined as weighted means of these original SLP grids with the corresponding loadings as the statistical weights. Each pair of composites has been compared by means of its root-mean-square value, in order to identify periods with major differences in internal characteristics of a particular circulation pattern. Selected examples of significantly differing SLP composites will be given for the most important patterns.

4. RESULTS

4.1 Seasonal NAO Index

Fig. 1 shows the grid-based NAO index since 1780 for the winter (DJF) and summer (JJA) seasons. The different levels of values compared to those from Jones *et al.* (1997) are mainly due to different reference periods used for normalization. Instead of referring to the modern period 1951-1980, Fig. 1 is based on mean values and standard deviations from the whole period of investigation. Looking at the normalized cumulative anomalies some major periods of differing behaviour are identified. During winter, we get an early period, until the 1850s, with accumulating negative deviations, before an opposite tendency (prevailingly positive deviations) is dominating until the beginning 1930s. The well-known recent evolution is reflected in the cumulative anomalies by a decline from roughly 1950 until 1980, with an increase afterwards which still appears relatively normal (only for the very short period since 1989 are there significantly higher mean values than in the earlier periods, marked by positive deviations).

Contrasting developments are identified for the summer season. Cumulating positive anomalies occur during the early period until the 1870s, with an opposite tendency afterwards and during recent times. But winter and summer seasons do not always tend to inverse relationships, as might be indicated by roughly 40-year periods with changing trends in summer after the 1870s. The early period, until the middle of the 19th century, is clearly characterized by a less intense westerly circulation during winter and a more intense one during summer in relation to the long-term mean conditions. This should imply some changes in circulation pattern characteristics which cannot be revealed by simple indices - thus, types and patterns of circulation will be considered next.

4.2 Monthly Grosswettertypes

Frequencies of monthly mean Grosswettertypes determined as described in the preceding 'Methods' section are shown for winter (DJF) and summer (JJA) in Fig. 2. During winter, only minor contributions, on a monthly scale, of High and Low pressure types occur (not included within Fig. 2). The flow types described by large-scale wind directions have been integrated into groups of different circulation types: SW/W representing conditions with largely zonal advection of maritime air masses towards Europe; NW/N implying a subpolar source region of advected air masses from the North Atlantic (frequently linked with increased snow fall, for example, in the northern parts of the European Alps); NE/E comprising typical situations with cold air directed from the interior continent towards

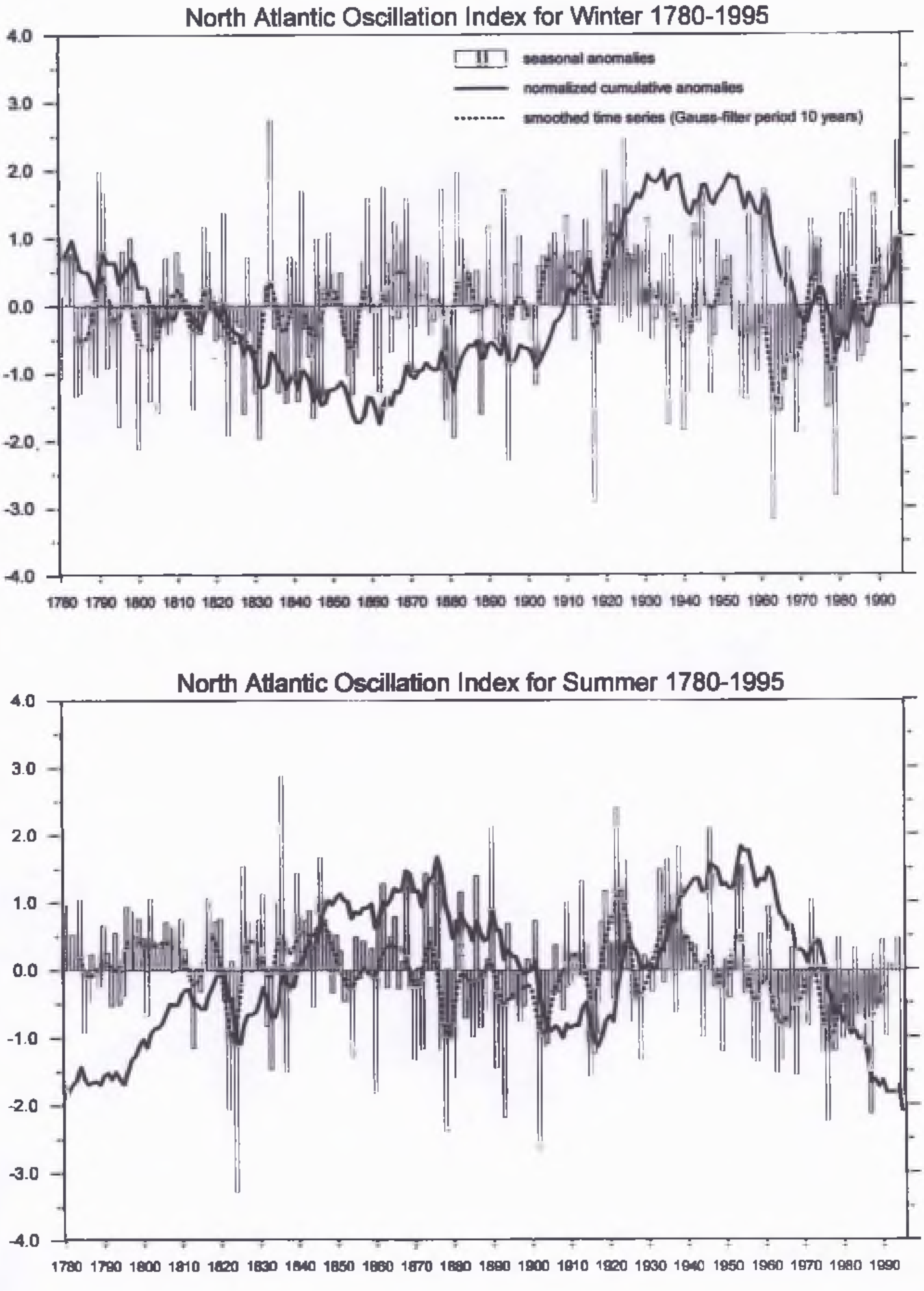
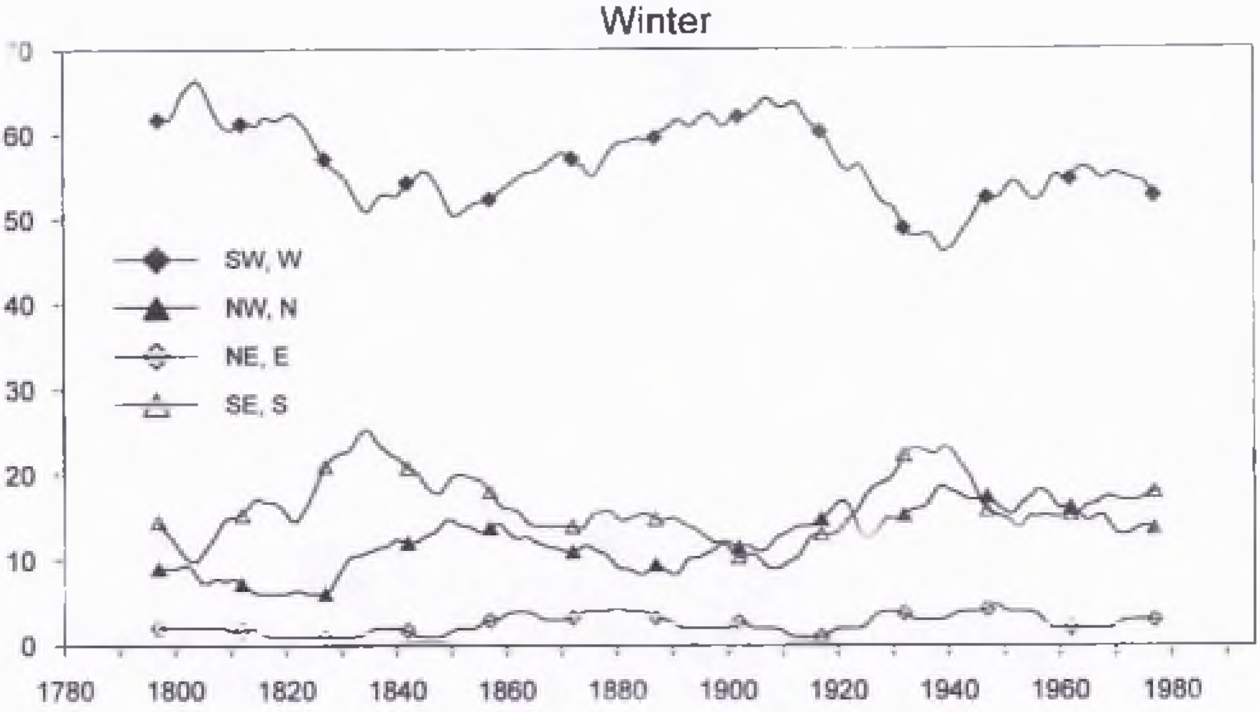


Figure 1. North Atlantic Oscillation Index derived from gridded monthly mean sea-level pressure for winter (DJF) and summer (JJA) in the period 1780-1995.



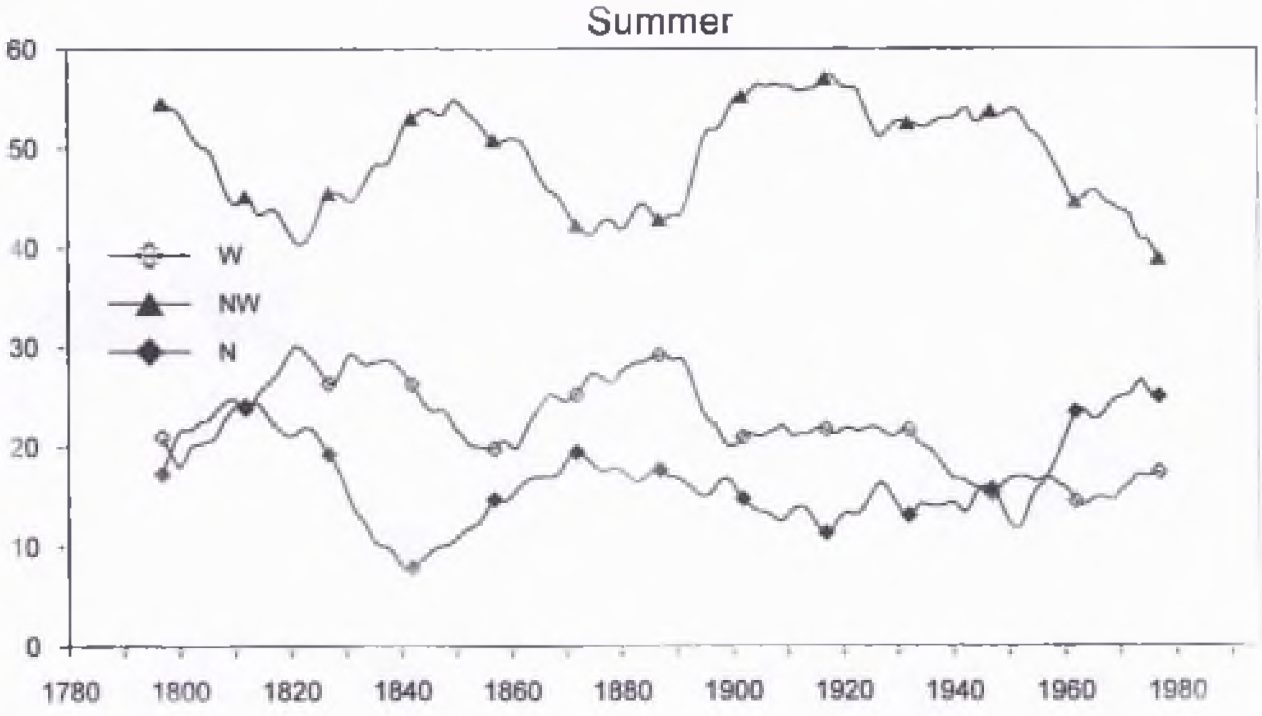


Figure 2. Absolute frequencies of selected monthly European Grosswettertypes for winter (DJF) and summer (JJA), calculated for 31-year periods with time steps of one year.

Central Europe; SE/S covering further meridional circulation types with a greater variety of air masses reaching large parts of Europe.

SW/W types decreased during the first half of the 19th century, and increased during the second half (Fig. 2), before another minimum was reached around 1940. SE/S types including considerable parts of SLP patterns with anticyclonic steering from the eastern continental area generally depict an inverse evolution, whereas NE/N types only slightly increased at the end of the 19th century and around the 1940s. Especially during the first half of the 19th century, SE/S types distinctly exceeded NW/N types. Together with the decrease in SW/W types this indicates a modified circulation regime for the last period of the Little Ice Age, with greater importance of anticyclonic influences on Central Europe.

During summer, NW and N Grosswettertypes reveal inverse frequency changes (Fig. 2), thus preventing integrations into groups of circulation types like those for winter. Since most of the Grosswettertypes account for only small percentages on a monthly scale during summer, Fig. 2 only reproduces particular frequencies of those Grosswettertypes of some importance for this season: W, NW, and N. For the westerly type there is an increased frequency during parts of the first half of the 19th century, in accordance with similar increases that have been identified on a daily scale for months with anomalous SLP distribution patterns during the same early instrumental period (Jacobeit *et al*., 1998). After another peak at the end of the 19th century, the W type frequency in summer decreases during the 20th century with recent values clearly below the level of the earlier periods. The inverse frequency changes of NW and N types seem to be linked to the W type variation, such that higher values of the latter tend to follow increased N and decreased NW type frequencies. This link does not hold in the other direction, especially during the last decades when another convergence of NW and N types takes place with a low level of W type frequency. In general, the first half of the whole study period indicates a greater interdecadal variability among these main types, whereas the second half reflects more long-term trends (decreasing frequencies for W and NW, increasing tendency for N).

4.3 PCA Derived Circulation Patterns

Results from monthly T-mode PCAs are only shown for January and July representing high-season conditions for winter and summer. Figures 3 and 6 give the resulting basic circulation patterns represented by normalized SLP fields of those months with the absolute highest loading on the corresponding principal component. Figures 4 and 7 show the normalized time coefficients extended over the whole investigation period as described in the earlier 'Methods' section. Figures 5 and 8 show some examples of internal pattern changes given as SLP composites and their differences.

For both the January and July analyses, four principal components have been extracted, explaining some 96 and 97%, respectively, of the original variance during the whole study period (1780-1995) (see Table 1 for details concerning the particular components). According to the criteria for extraction mentioned in the earlier 'Methods' section, a fifth pattern in January would emerge. Since it is the dominant one only for two January months, it will not be considered for the following studies referring to the whole period of 216 years. Furthermore, since negative loadings only occur with minor amounts (> -0.5) never constituting a reflective pattern, the reproduced SLP fields of Figures 3 and 6 are, in fact, representing the basic circulation patterns of January and July, respectively.

Table 1. Variances (%) explained by principal components 1-4 of Figure 3 (January) and Figure 6 (July) during the period 1780-1995.

	PC1	PC2	PC3	PC4	Total
January	50.5	28.2	11.7	5.4	95.8
July	30.5	28.8	21.4	16.2	96.9

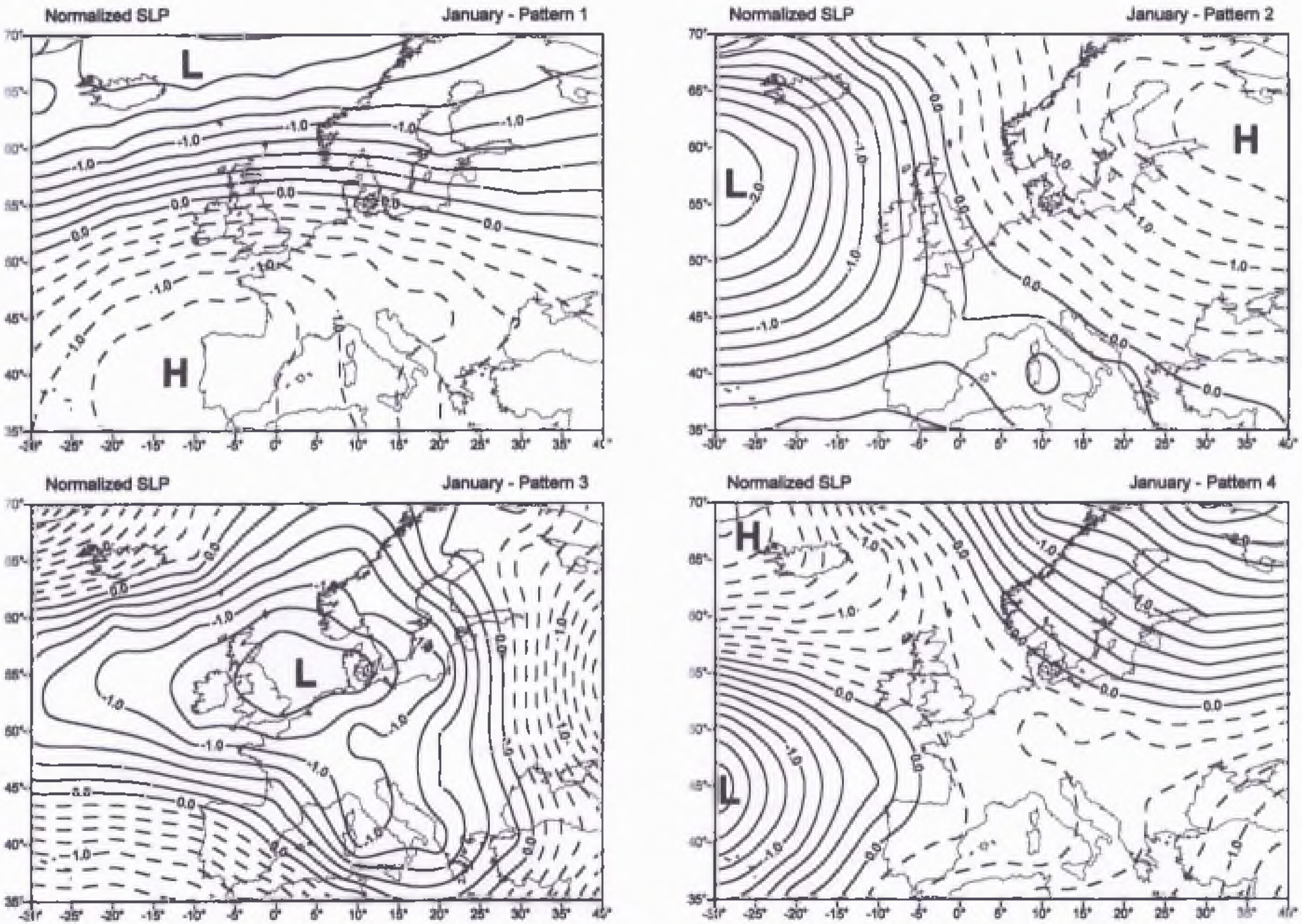


Figure 3. Circulation patterns for January derived from T-mode PCA of monthly mean North-Atlantic-European SLP grids of the period 1780-1995.

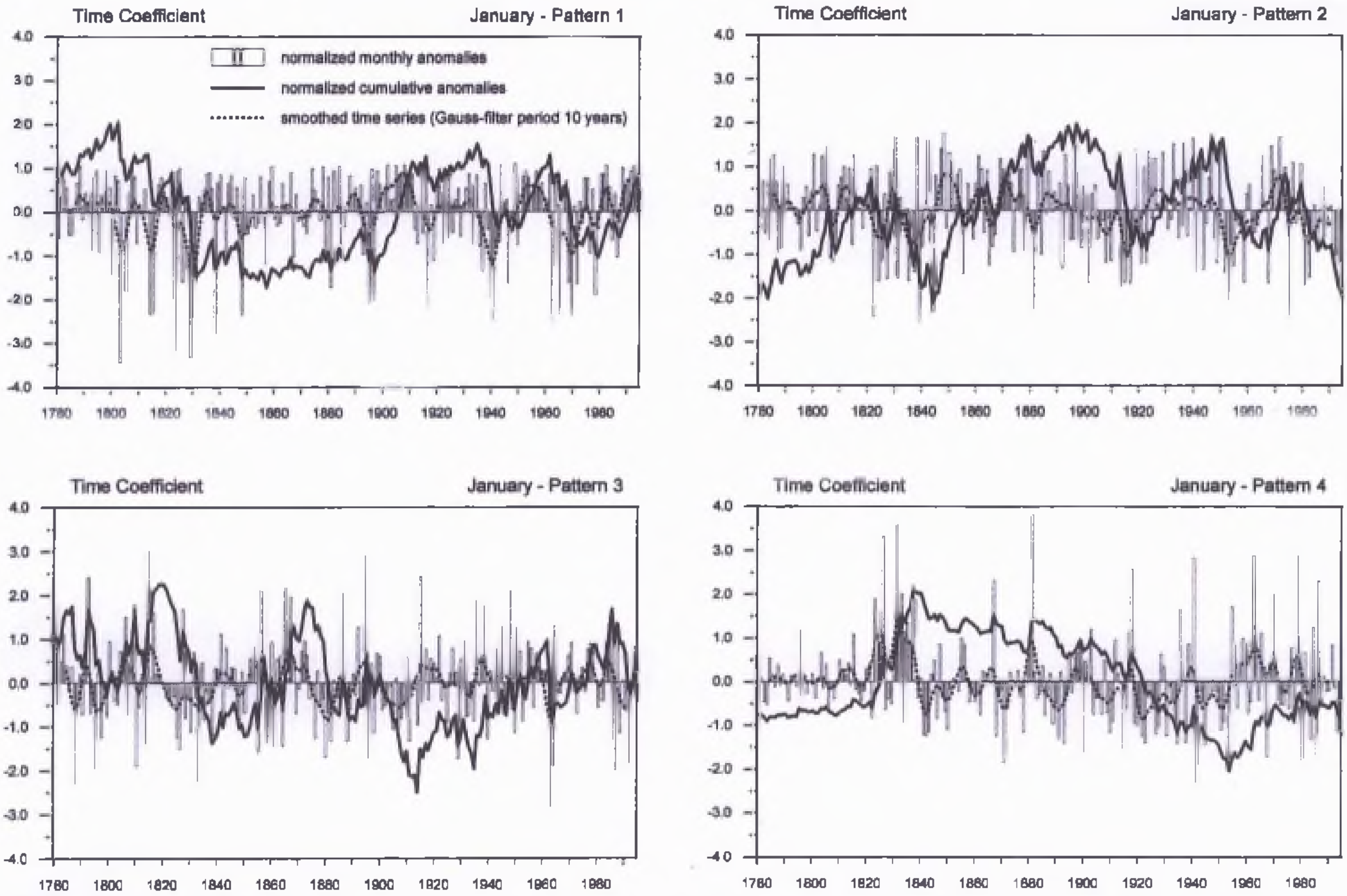


Figure 4. Normalized time coefficients (monthly, smoothed, and cumulative time series January 1780-1995) for the circulation patterns of Figure 3 (see next but one page).

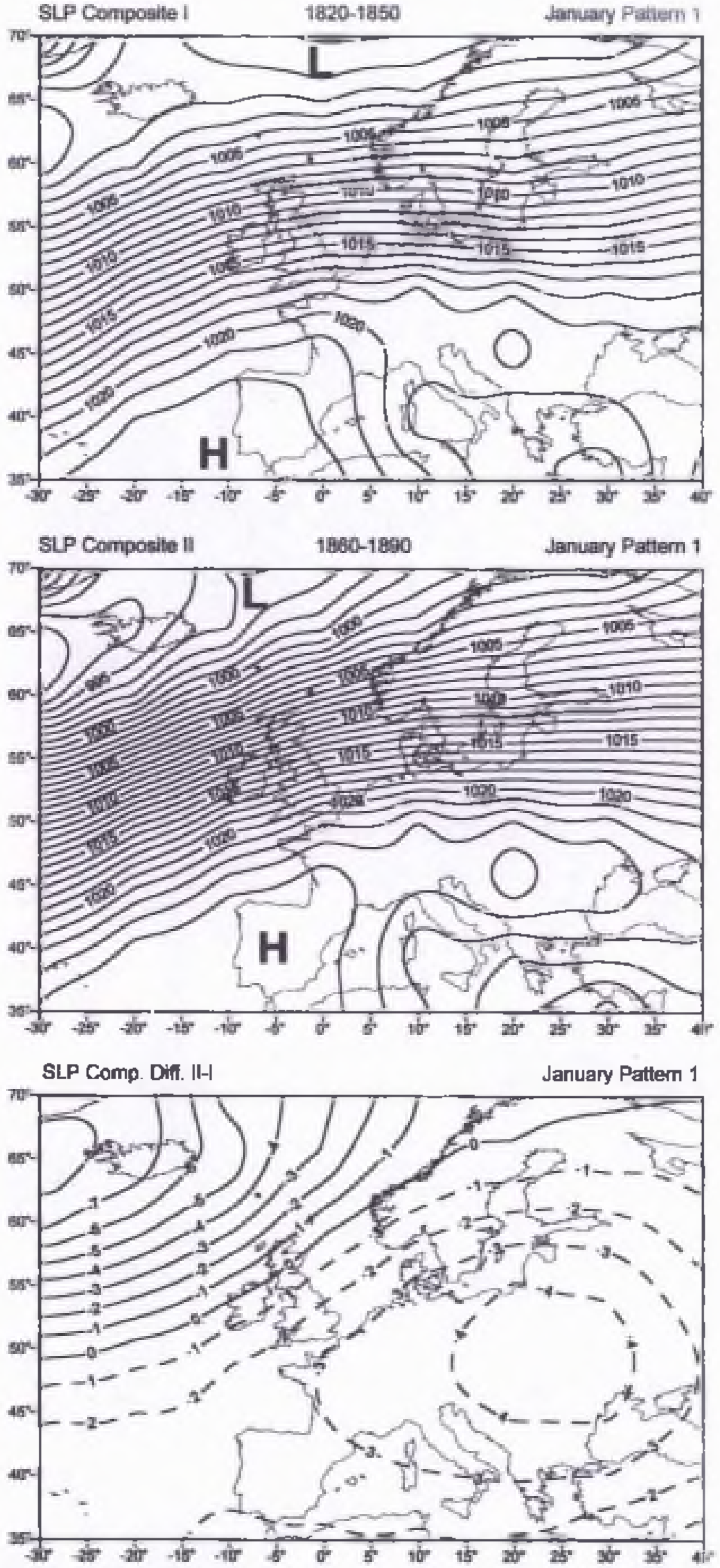


Figure 5. Selected SLP composites (hPa) and their differences derived from monthly mean SLP grids of those January months within the indicated 31-year periods with their highest loading on the indicated circulation pattern from Figure 3.

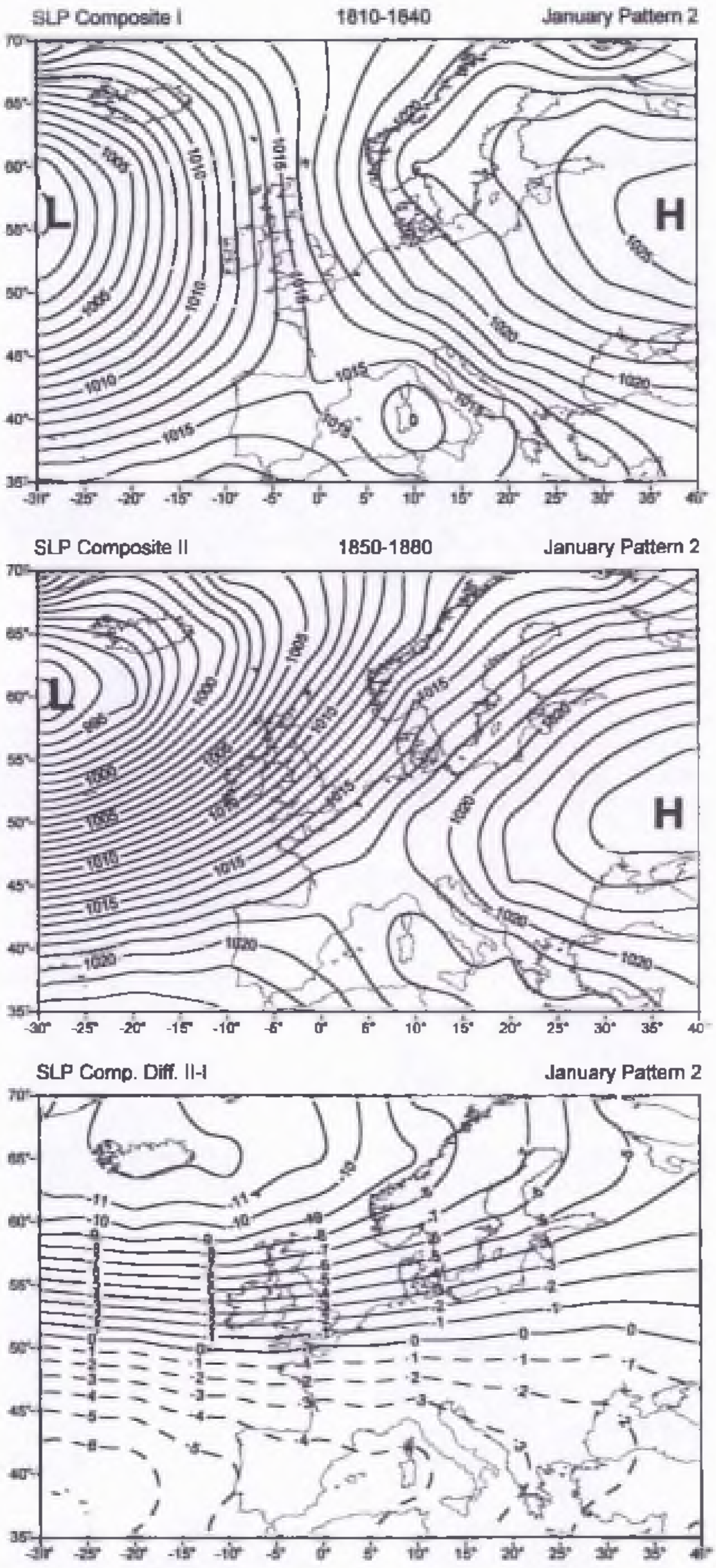


Figure 5. (continued) Selected SLP composites (hPa) and their differences derived from monthly mean SLP grids of those January months within the indicated 31-year periods with their highest loading on the indicated circulation pattern from Figure 3.

January

The high-winter situation is characterized by the following circulation patterns (Fig. 3):

- a westerly flow type with the Azores' high pressure extending towards the western Mediterranean (Pattern 1; representing month, January 1944);
- a Russian high extending as far as Central Europe, whereas the North Atlantic is covered by a strong low pressure system (Pattern 2; representing month, January 1848);
- a distinct low pressure system centred above the North Sea extending over much of Europe (Pattern 3; representing month, January 1814);
- a NAO reversal pattern with high pressure centred over the Icelandic region (Pattern 4: representing month, January 1881).

Most of the SLP variance (78.7%, see Table 1) is explained by the first two patterns; the other two only occur during rather anomalous situations like, for example, Pattern 4 in January 1963 with its NAO reversal (Moses *et al.*, 1987).

Recently, Corti *et al.* (1999) have analysed the northern hemispheric circulation for an extended winter time period (November to April) deriving just four different circulation regimes on the monthly time scales. These regimes do not agree in detail with the patterns described above, since there are differences in the analyses (e.g. concerning space and time domain, the atmospheric level, and particular methods that have been applied). But important regimes discussed by Corti *et al.* (1999) are still reflected in the above patterns: e.g. the positive phase of the NAO (Pattern 1) or the negative phase of the Arctic Oscillation (Pattern 4).

Information concerning circulation variability since 1780 may be drawn from the time coefficients of Fig. 4: the normalized cumulative anomalies show marked periods of dominating positive or negative deviations (i.e. periods of stronger or weaker representation of the corresponding circulation patterns within the original SLP fields). Thus, the westerly flow type (Pattern 1) had a major period of cumulating negative anomalies at the beginning of the 19th century, its Variance Explained (VE value henceforth) dropped to 41.2% between 1803 and 1831 (compared to 50.5% for the whole 1780-1995 period; see Table 1). On the other hand, the Russian high pattern sometimes reached above-average representations during the first hundred years, especially for the periods 1800-1821 (VE=33.8%) and 1845-1879 (VE=36.7%). The interval 1822-1844, during which VE dropped to 24.9%, approximately coincided with the maximum VE for Pattern 4 (18.4% between 1823 and 1837 compared to 5.4% for the whole period since 1780). Since Pattern 4 may be seen as a further westward extension of high pressure compared to its position over Russia in Pattern 2 (see Fig. 3), this sequence reflects a protracted period (roughly the first hundred years from 1780 onwards) with increased occurrence of high pressure influence on Europe culminating with the most westward extensions during the third and fourth decades of the 19th century. For the 1845-1854 decade, explained variances of the Russian high pattern (VE=49.9%) even exceeded those of the westerly flow pattern (VE=35.7%). In the second half of the 19th century, however, important changes occurred within these major circulation patterns (see below).

Conditions during the recent century are well-known (Klaus, 1997; Jacobeit, 1997) and will be mentioned only briefly. Fig. 4 shows that there were periods of well-developed westerlies at the beginning of the 20th century (VE=59.7% for Pattern 1 during 1898-1935), again during the 1950s and, especially, for the very recent time (VE=67.7% during 1981-1995). In contrast, there was one major period in between with increased importance of anticyclonic influences. This did not affect patterns with the most westward positions of high pressure (Pattern 4 with only occasional emergence e.g. in 1963 or 1987), but did affect those with extended Russian high pressure (VE=36.7% for Pattern 2 during 1924-

1950) combined with reduced importance (VE=41.2%) of the westerly flow pattern, implying a 18% reduction in VE differences between Patterns 1 and 2 compared to the long-term values since 1780 (Table 1).

The widespread low pressure pattern 3 accumulated negative deviations during the 1820s and 1830s, and for decades around the end of the 19th century (VE=7.8% for the 1874-1914 period), whereas its relative importance increased moderately during the 20th century (VE=12.3% for the 1915-1986 period).

Besides these variations in time coefficients and explained variances, circulation patterns also underwent internal changes illustrated by SLP composites differing from each other with a maximum RMS value within the 19th century (Fig. 5). Comparing westerly flow pattern composites for the periods 1820-1850 and 1860-1890 clearly indicates that, during the 19th century, this pattern shifted northward over Europe in association with significant increases in meridional pressure gradients. This occurred both over the continent, where pressure rose most strongly around Central Europe, and over the North Atlantic where pressure dropped most strongly in the Icelandic region.

The greatest RMS value for Pattern 2 composites included a period (1810-1840), going further back than available station records for Iceland (data close to the Azores had been available since the 1820s). This period was used for comparing with a later period (1850-1880), since important changes for this pattern were located near the central grid points and no other information emerged when using periods after 1820. In addition to another increase in meridional pressure gradients (see Fig. 5, pt. 2; composite differences map), the major change during the 19th century consisted in a southeastward retreat of the Russian high implying that western parts of Central Europe were no longer under its direct influence and became affected by southwesterly components in front of a deepened Atlantic low pressure system. These changes within Pattern 2 were an important stage in the transition from the Little Ice Age circulation to more recent conditions still before an increase in the westerly flow pattern set in at the end of the 19th century.

Since the other circulation patterns of January reach the highest loading within one month only in quite few cases, no further composites will be considered.

July

The high-summer situation is characterized by the following circulation patterns (Fig. 6):

- a zonal flow type with low pressure above the Nordic Sea and a zonal ridge of high pressure to the south (Pattern 1; representing month, July 1928);
- a widespread low pressure system with its centre over southern Scandinavia and the Azores high shifted to a southwesterly position (Pattern 2; representing month, July 1888);
- a diagonal ridge of high pressure extending from north of the Azores towards southern Scandinavia (Pattern 3; representing month, July 1825);
- a meridional ridge of high pressure centered above southern Scandinavia with blocking effects on the Icelandic low pressure system (Pattern 4; representing month, July 1994).

In contrast to the January situation, these patterns have a smaller range in percentages of explained variance (VE values for the 1780-1995 period ranging from 30.5 to 16.2%, see Table 1). This means that none of these patterns is restricted to only a few cases with rather anomalous conditions.

The normalized cumulative anomalies of the time coefficients (Fig. 7) again reveal some major periods of different importance in the circulation patterns. Thus, on a long-term

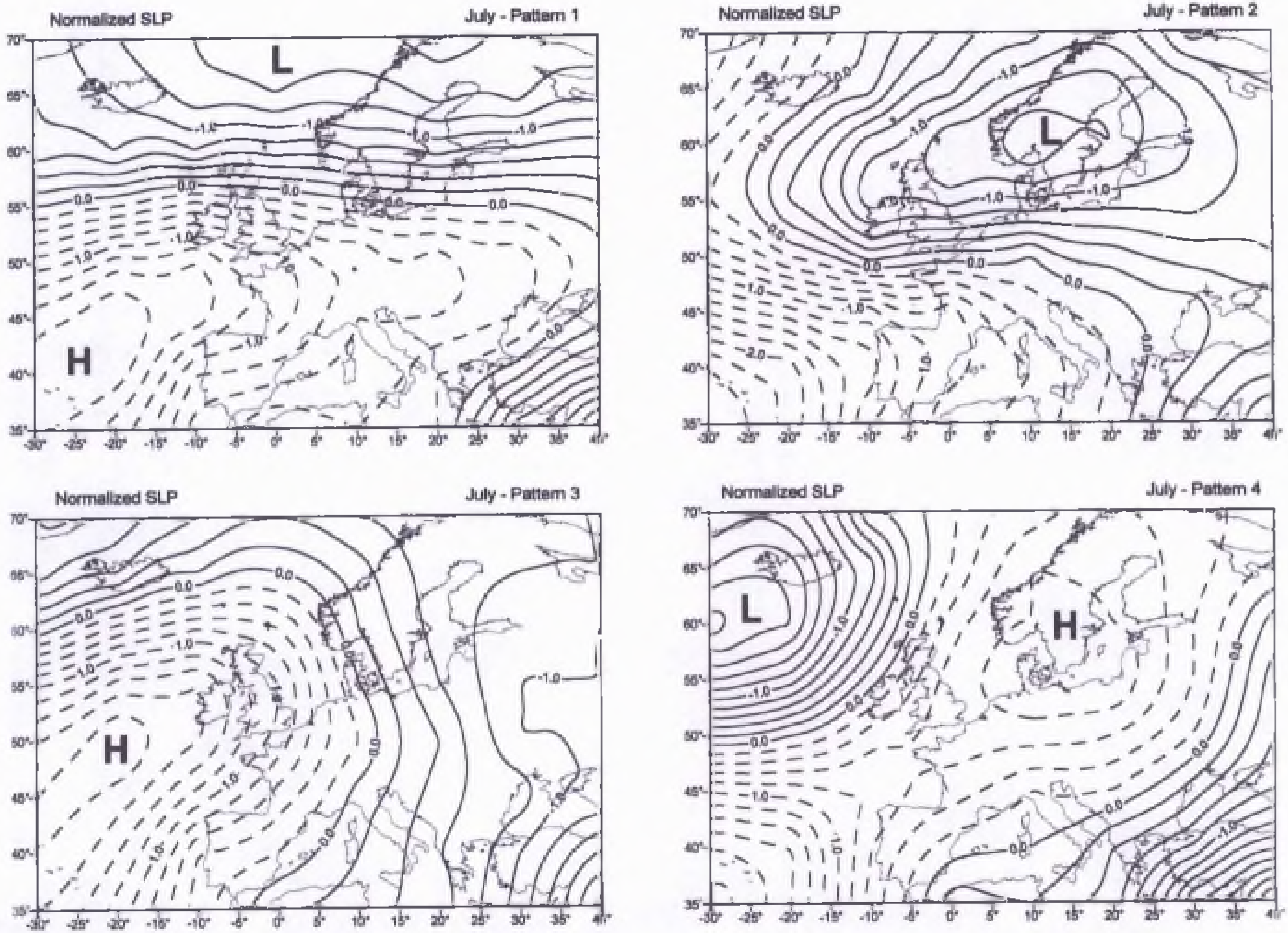


Figure 6. Circulation patterns for July derived from T-mode PCA of monthly mean North-Atlantic-European SLP grids of the period 1780-1995

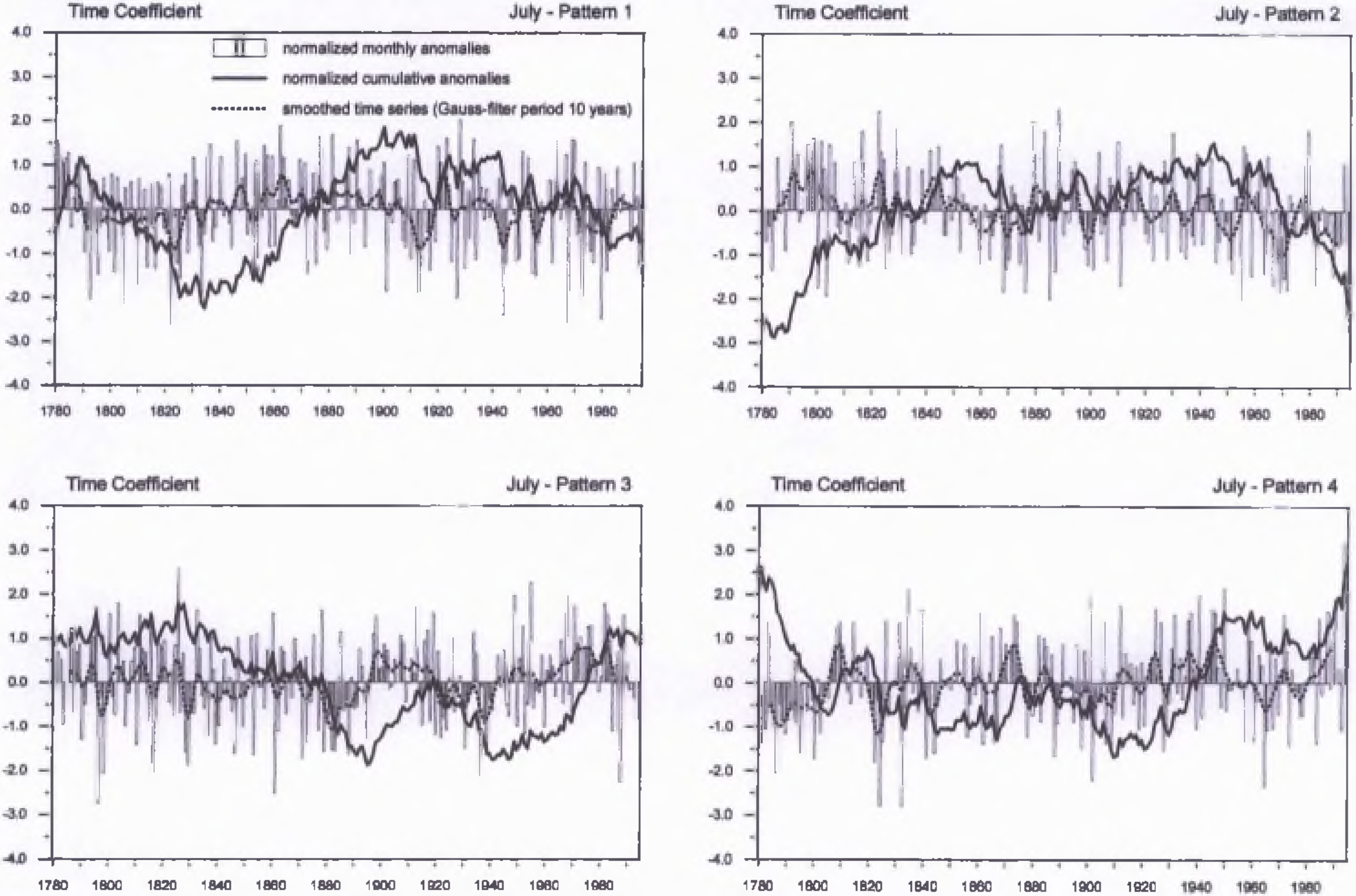


Figure 7. Normalized time coefficients (monthly, smoothed, and cumulative time series July 1780-1995) for the circulation patterns in Figure 6

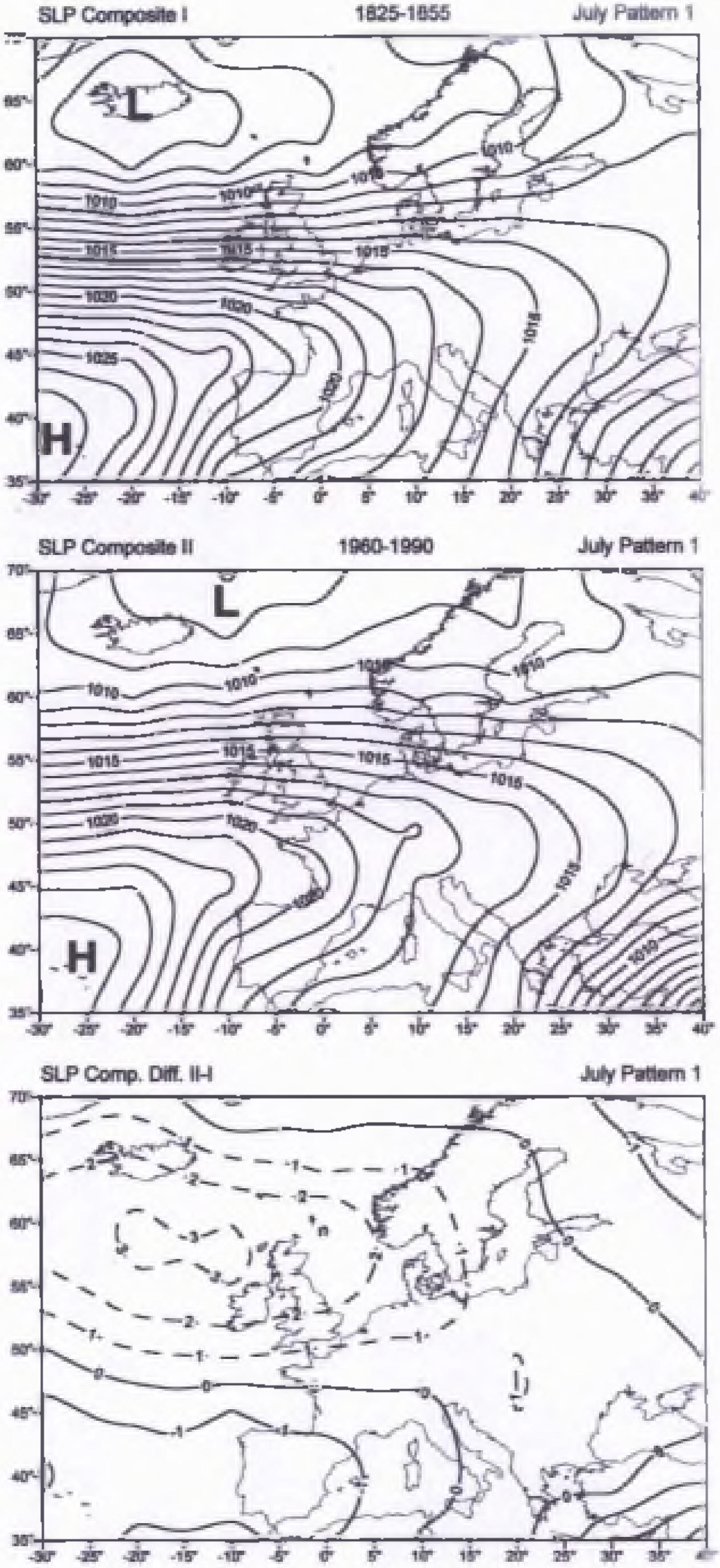


Figure 8. Selected SLP composites (hPa) and their differences derived from monthly mean SLP grids of those July months within the indicated 31-year periods with their highest loading on the indicated circulation pattern from Figure 6.

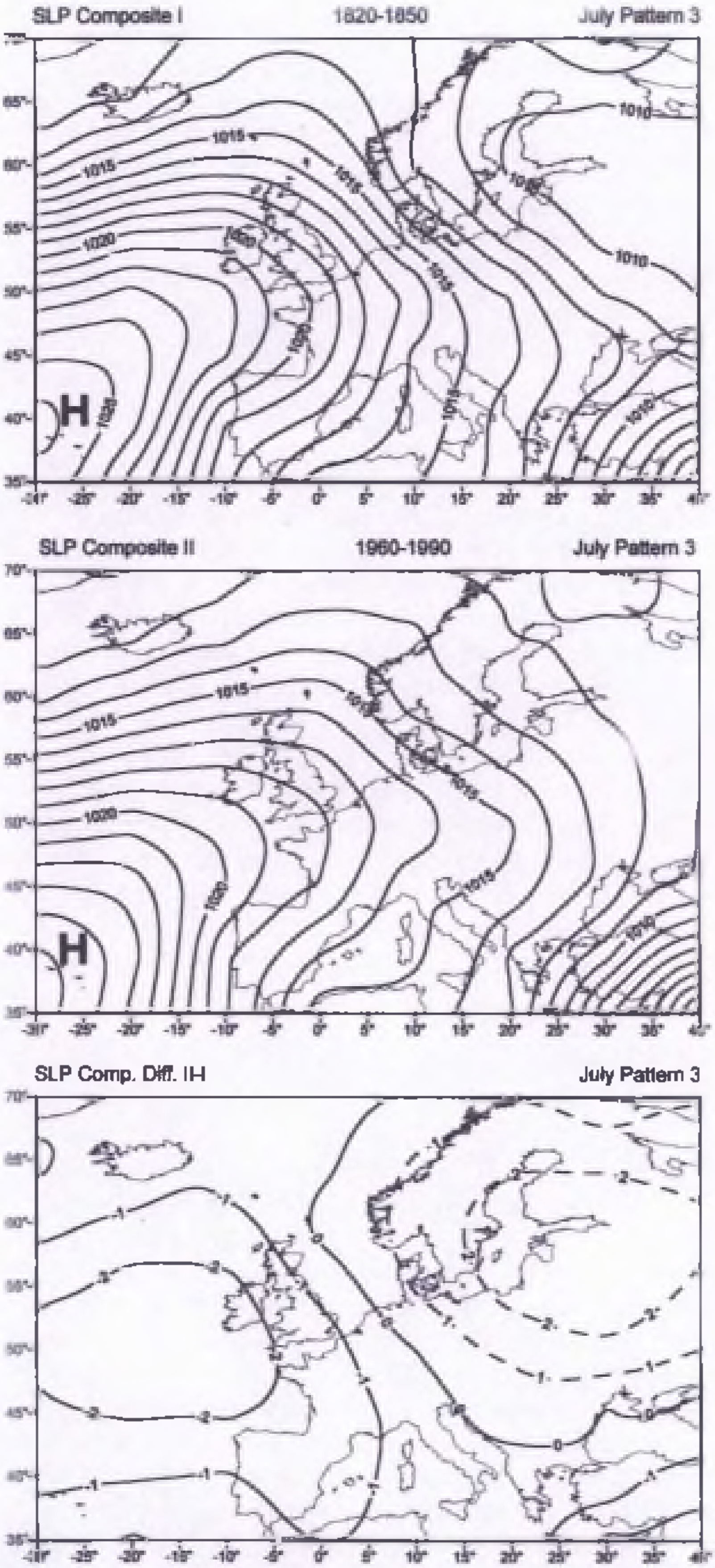


Figure 8. (continued) Selected SLP composites (hPa) and their differences derived from monthly mean SLP grids of those July months within the indicated 31-year periods with their highest loading on the indicated circulation pattern from Figure 6.

perspective, circulation patterns 1 and 3 show periods of inverse association. From the 1830s until the end of the 19th century the zonal pattern 1 accumulated positive deviations in its time coefficient; the Atlantic ridge pattern 3, in contrast, showed negative ones. Accordingly, explained variances differed more distinctly than in Table 1 (e.g. VE=33.6% for Pattern 1 and VE= 17.0% for Pattern 3 during 1828-1895). After a downward trend for the ridge pattern during the first four decades of the 20th century, the most recent period had positive deviations, in contrast to the zonal pattern which preferred negative deviations. This evolution amplified after 1970, with VE values for 1971-1984 of 23.0% (zonal pattern) and 34.7% (ridge pattern).

Another recent decrease in relative importance occurred for the cyclonic pattern 2, especially pronounced during the 1985-1995 period (VE=17.2%), when the meridional ridge pattern 4, in contrast, increased strikingly (VE=29.6%). Opposite conditions in July prevailed during the early period when the cyclonic pattern 2 reached its greatest long-term importance (VE=36.7% during 1790-1825), and the meridional ridge pattern 4 started at a distinctly low level (VE=8.3% during 1780-1802). Remarkably, the westerly pattern 1 (VE=24.0% during 1790-1825) also stayed behind the more pronounced cyclonic mode of Pattern 2 during this early period, before the above-mentioned period of cumulating positive deviations set in during the 1830s.

In respect of internal pattern changes, SLP composites with maximum RMS values between the first half of the 19th century and the second half of the 20th century will be compared for two contrasting circulation patterns; the westerly flow type of summer and the Atlantic ridging towards southern Scandinavia. According to Fig. 8 the zonal pattern 1 attained higher pressure above the central North Atlantic during the modern period (1960-1990) corresponding to a northward shift of the higher-value isobars in this region, and was downstream of the British Isles compared with the conditions some 130 years ago (1825-1855). A similar northward shift occurred within the cyclonic pattern 2 (not shown here), along with its decreased importance during summer in the modern period.

The diagonal ridge pattern 3, with its recently increased importance underwent internal changes at the same times: rising pressure around the Baltic region and falling pressure north of the Azores (Fig. 8) corresponding to a less developed anticyclonic ridge in its source region but extending - with a reduced pressure gradient - further northeastward towards southern Scandinavia, where cyclonic curvature existed during the first half of the 19th century.

5. CONCLUSIONS

Based on gridded monthly mean SLP data reconstructed back to 1780 by Jones *et al.* (1999), calculations of seasonal NAO indices, frequency changes of European Grosswettertypes on a monthly scale, and of PCA derived circulation patterns have been performed allowing an assessment of the major circulation changes that have occurred in Europe during the winter and summer seasons since the end of the 18th century. The first hundred years since 1780 have only been analyzed objectively in a few cases (see Introduction), considering some aspects of large-scale circulation variability. Key changes revealed by the analyses described in the preceding sections may be synthesized as follows.

During winter there was a period mainly in the first half of the 19th century - known as the concluding phase of the so-called Little Ice Age - with weakened westerlies in the North-Atlantic-European region. This is reflected in prevailingly negative deviations of the NAO index until the 1850s, in decreasing frequencies of SW and W Grosswettertypes accompanied by increases in SE and S types, in cumulating negative anomalies of the time coefficient of the zonal circulation pattern for January, and in a more southerly position of this pattern along with lowered meridional pressure gradients. At the same time, high pressure influence in Europe was distinctly greater, caused by more westward extensions of the Russian high (circulation pattern 2 for January) and, in an intervening period (third and fourth decades of the 19th century), by high pressure systems extending towards the Icelandic region (circulation pattern 4). During the second half of the 19th century an opposite regime was established: increasing frequencies of SW and W Grosswettertypes along with decreasing frequencies of SE and S types, and marked internal changes within the major circulation patterns indicating a northward shift of the zonal circulation pattern over Europe in association with significant increases in meridional pressure gradients, as well as a southeastward retreat of the Russian high within the second circulation pattern for January (Fig. 5). Around the turn from the 19th to the 20th centuries, for periods of well-developed westerlies set in for the first decades, for the 1950s, and for the very recent time interrupted by further periods of increased anticyclonic influence from the east.

For the summer season we get very different results. During the first half of the 19th century, zonal circulations prevailed indicated by cumulating positive anomalies in the NAO index, increased frequencies of the westerly Grosswettertype and dominating positive deviations in the time coefficient of the cyclonic circulation pattern 2 for July. These were replaced by similar positive deviations in the westerly pattern 1 during the second half of the 19th century, contrasting to the opposite development of the anticyclonic ridge pattern 3 (Fig. 7). During the 20th century, however, Grosswettertype W reduced in frequency, and roughly the last 50 years most clearly showed the reverse of the 19th century: predominantly negative deviations in the NAO index and in the time coefficient of the cyclonic circulation pattern, whereas the anticylonic ridge pattern accumulated positive anomalies and additionally extended further northeastward than during the first half of the 19th century (Fig. 8). This redistribution from cyclonically to anticyclonically controlled conditions is further emphasised by the long-term downward trend in the cumulative anomalies of the westerly circulation pattern 1 during the 20th century (Fig. 7), as well as by the fact that the meridional ridge pattern 4 which mostly had negative anomalies in the early stages of the whole period, recently has reached its maximum representation. Another indication for a modern increase in meridionality of the summer circulation might be the recent tendency for decreasing NW, but increasing N, Grosswettertypes on a monthly scale (Fig. 2).

In general, the extension of circulation analyses to a period of more than two centuries not only provides a perspective of immediate controls on past climate variations, but also offers an extended range of natural variability to be considered. This is important when judging the nature of recent changes, and of changes projected into the future. For example, looking at the time coefficient of the zonal circulation pattern 1 for January (Fig. 4) reveals that, with respect to the whole period since 1780, the modern changes from low values of the 1960s to high values of the 1990s are not as outstanding as might be judged by referring to shorter periods or to single indices (e.g. for the NAO) which are more restricted to particular areas. The time coefficient for the whole North Atlantic European zonal circulation pattern 1 (Fig. 4) shows even lower values during the first half of the 19th century than during the 1960s, as well as other important periods of positive deviations at the beginning of the 20th century and during the 1950s. Thus, in addition to attempts by analogue approaches to reconstruct past pressure patterns in the 16th century, at least for some outstanding anomalies (Jacobeit *et al.*, 1999), further objective recon-structions as recently provided by Luterbacher *et al.* (2000) for the Late Maunder Minimum period (1675-1715) should be encouraged in order to enable further extensions of circulation analyses into the historical past with additional improvements concerning possible ranges of natural variability.

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