THE LATE MAUNDER MINIMUM (1675–1715) – A KEY PERIOD FOR STUDYING DECADAL SCALE CLIMATIC CHANGE IN EUROPE

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Abstract. The Late Maunder Minimum (LMM, 1675–1715) denotes the climax of the 'Little Ice Age' in Europe with marked climate variability. Investigations into interannual and interdecadal differences of atmospheric circulation between the LMM and the period 1961–1990 have been performed and undertaken based upon sea level pressure (SLP) difference maps, empirical orthogonal function (EOF) analysis, and objective classification techniques. Since the SLP during the LMM winter was significantly higher in northeastern Europe but below normal over the central and western Mediterranean, more frequent blocking situations were connected with cold air outbreaks towards central and eastern Europe. Springs were cold and characterized by a southward shift of the mid-latitude storm tracks. Summers in western, central Europe and northern Europe were wetter and slightly cooler than they are today due to a weaker Azores high and a more southerly position of the mean polar front axes. Autumns showed a significantly higher pressure over northern Europe and a lower pressure over continental Europe and the Mediterranean, an indication of an advanced change from summer to winter circulation. It is suggested that the pressure patterns during parts of the LMM might be attributed to the combination of external forcing factors (solar irradiance and volcanic activity) and internal oscillations and couplings in the North Atlantic.

1. Introduction

The Maunder Minimum (MM; 1645–1715) delineates the coldest phase of the 'Little Ice Age' (LIA, AD 1300–1900) (Pfister, 1999; Wanner et al., 2000), with an increase in climatic variability over the wide parts of Europe. This period coincides with an enhanced concentration in atmospheric ^{14}C (Stuiver and Braziunas, 1993), several large volcanic eruptions (Briffa et al., 1998), a reduced solar activity, and a low number of sunspots (Spörer, 1887; Maunder, 1922; Eddy, 1976; Lean et al., 1995). Solar activity during the MM was near its lowest levels of the past 8000 years (Lean and Rind, 1999). Jones et al. (1998) and Briffa (2000) found a decrease of the Northern Hemisphere (NH) April–September temperatures on the order of approximately 0.3–0.6 °C compared to the reference period of 1961–1990. Within the MM, the Late Maunder Minimum (LMM, 1675–1715) is of particular interest in many parts of Europe since it is one of the few cold periods in recent centuries that persisted for decades. A broad spectrum of high resolution multi-proxy and instrumental data are available for this period (Wanner et al., 1995; Luterbacher et al., 1999; Pfister, 1999; Luterbacher et al., 2000; Luterbacher, 2000).

According to regional time series, winters of that period were characterized by a higher frequency of severe climatic conditions than those of the twentieth century. The winter Central England Temperature (CET; Manley, 1974; Parker et al., 1992) during the LMM was around 1 °C lower than during 1961–1990. Wintertime cooling began in the mid-1670s over the British Isles and the westernmost part of the continent, spread farther east to central Europe, and reached Hungary ten years later (Pfister, 1994a, 1999). The climax of the LIA was reached in the 1690s, with extremely dry winters having recurrent, long-lasting, and strong advection of continental air from the northeast towards western Russia and Europe (Borisenkov, 1994; Brázdil et al., 1994; Pfister, 1994a, 1999; Wanner et al., 1995; Kington, 1995, 1997, 1999; Koslowski and Glaser, 1999; Luterbacher, 2000; Luterbacher et al., 2000). The climate both in the eastern and western Mediterranean was slightly wetter, colder, and more variable than in the recent century (Barriendos, 1997; Rodrigo et al., 2000; Xoplaki et al., 2001). In Portugal, cold relapses happened more frequently than during the recent decades (Alcoforado et al., 2000). After the cold year of 1698, a warming of winters set in 1699, first over the British Isles (Kington, 1999), in 1704 over central Europe, and ten years later over eastern Europe (Pfister, 1999). The springs in central and eastern Europe were the most severe during the last 500 years from 1687–1717 (Pfister, 1999) with a partial decrease of 2 °C in mean temperature compared to the reference period 1901–1960. Indeed, no spring season between 1695 and 1703 exceeded the 1901–1960 average temperature in either England or Switzerland (Pfister, 1994a). Furthermore, the NH summers from 1691–1700 were the coldest of the present millennium (Jones et al., 1998). In Switzerland, no single summer was warm and dry from 1695–1705 (Pfister, 1994a, 1999). The worst summer of this type was 1692, which led to famine in the subsequent years in many parts of France (e.g., Lachiver, 1991), Switzerland, and Germany (Pfister, 1994b). In upland parishes of Scotland, the harvests (mostly oats) failed in seven out of eight years between 1693 and 1700, causing mass emigration (Lamb, 1982). However, though summers were wetter and cooler in western and central Europe than today, no advance of European Alpine glaciers was detected (Holzhauser and Zumbühl, 1988; Wanner et al., 2000). The Lower Grindelwald and Great Aletsch Glaciers (Swiss Alps) showed a series of years with a nearly stable or even a negative mass balance (Wanner et al., 2000). The autumns in general showed the least negative deviations from the twentieth-century conditions (Pfister, 1999). However, most parts of Europe indicated lower mean temperatures.

The above-mentioned long-lasting climatic anomalies must have their origins in a marked change of the atmospheric circulation. Indeed, due to the virtually complete exclusion of human influence, the low solar activity, and a number of explosive volcanoes, the LMM is a unique period for the study of natural climatic variability. How far are the anomalous climatic conditions explained by an internal oscillation in the North Atlantic? How far are they connected to external changes in solar activity or triggered by large volcanic eruptions? These are the main questions that are addressed in this paper.

The paper is structured as follows: Section 2 comprises a short layout of the sea level pressure (SLP) data from the LMM and the period 1961–1990 and introduces objective methods to compare the climatic conditions of the LMM with those of the twentieth century. In Section 3, the seasonal differences in atmospheric circulation between the LMM and the period 1961–1990 based on SLP difference charts, empirical orthogonal function (EOF) analysis, and objective SLP pattern classification are described. The results are synoptically interpreted. In Section 4, significant processes in the lower atmosphere of the eastern Atlantic and the European area are discussed. Additionally, the probable influence of external forcing factors (solar variability, volcanic eruption) and the internal oscillation in the North Atlantic on rapid climate changes during the LMM are analyzed. The conclusions are presented in the last section.

2. Data and Methods

Luterbacher et al. (2000) objectively reconstructed North Atlantic European monthly mean SLP fields for the LMM. The reconstructions consist of gridded (5° × 5° latitude by longitude grid containing 96 grid points) SLP extending from 25° W to 30° E and 35° N to 70° N. Several continuous time series (limited instrumental data, relative temperature and precipitation values reconstructed from documentary proxy evidence, and other proxy information) for the LMM from several European data sites formed the predictors for the SLP reconstructions (Luterbacher et al., 2000). The reconstructions were based on a CCA (Canonical Correlation Analysis (without an EOF truncation) with the standardized station data as predictors and the SLP pressure fields as predictands. The 60 years from 1901–1960 were used to calibrate the statistical model. The statistical relationships were then verified with independent data (1961–1990) to assess the model performance outside the calibration period. In all seasons, the model performance did not reveal any systematic deficiencies and the regression equations developed for the majority of the grid points contained good predictive skill, thus the predicted SLP fields for the period 1961–1990 were in good agreement with the observed SLP distribution (Luterbacher et al., 2000). However, considerable poorer reconstructions at individual grid points were obvious for some regions with little or no data, especially during summertime. Assuming stationarity of the statistical and climatological relationships, the calibrated statistical model (1901–1960) for each season was then related to the data during the LMM in order to estimate monthly mean gridded pressure fields (Luterbacher et al., 2000). Statistical details about the reconstruction technique as well as the model performance can be found in Luterbacher et al. (2000). The reconstructed monthly SLP patterns of the LMM are compared to those of the independent period 1961–1990 (NCAR, 1997), which is considered the independent period since it was not used for the LMM reconstructions.

Three commonly used techniques were applied to investigate the difference in atmospheric circulation patterns between both periods:

- To emphasize the differences in mean SLP during the LMM and the period 1961–1990, we constructed averaged monthly mean SLP difference charts (averaged monthly means of LMM minus averaged monthly means of 1961–1990) and plotted the regions with statistically significant SLP differences according to Student's t test.
- Empirical Orthogonal Functions (EOFs) were used to derive the dominant spatial patterns (i.e., the eigenvectors) and temporal coefficients (scores, i.e., intensities of the eigenvectors) accounting for a substantial fraction of the SLP variances (Preisendorfer, 1988; von Storch and Zwiers, 1999). Rather than conducting the comparison separately between the two periods relative to the means of the LMM and modern times, respectively, we used a joint mean of the LMM and the period 1961–1990 and calculated the EOFs for both periods relative to this joint mean and to the joint standard deviation. This approach is more appropriate for characterizing the systematic differences since the major changes are expected in the mean state. The EOF analysis is based on the correlation matrix, thus giving all grid points equal weights. We show the first three most important joint winter and spring EOF patterns together with the corresponding scores.
- Changes in circulation were also investigated with pressure pattern classifications. The main idea was to identify a number of representative patterns that are expected to characterize the variety of monthly SLP fields. Our classification method was based on a principal component analysis (PCA) (S-mode which concerns SLP varying over space) using a correlation matrix with varimax rotation and a subsequent 'k-means' clustering of the principal components scores. We also applied a method to estimate the statistical confidence for cluster separation (Gerstengarbe and Werner, 1997) in order to improve internal homogeneity of clusters resulting from iterative runs of the 'k-means' algorithm and to extract the optimum number of clusters. Huth (1996) recommended that this method be chosen when all months have to be classified (i.e., very small groups and single months are undesirable) instead of close-to-mean patterns to be included in one rather large group which is a characteristic of the correlation-based classification (Yarnal, 1993). For a detailed description of the method, see Beck and Jacobeit (1997) and Beck (1999). As for the EOF analysis, the classification was based on the combination of both periods rather than each one separately.

3. Results

3.1. MONTHLY SEA LEVEL PRESSURE (SLP) DIFFERENCES BETWEEN THE LMM AND THE PERIOD 1961–1990

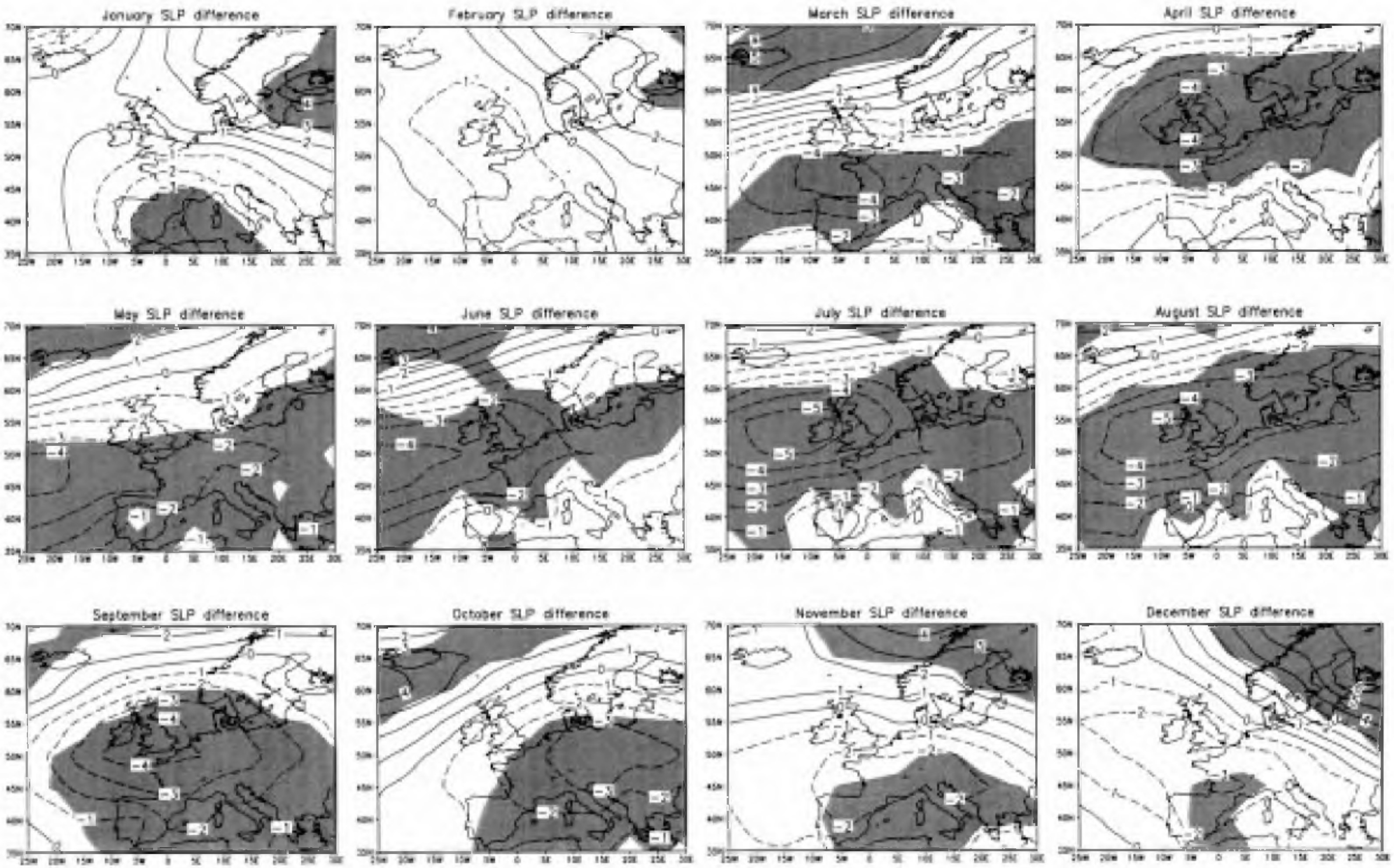
The differences between monthly SLP are analyzed by averaged monthly mean SLP difference charts (LMM minus 1961–1990). These difference maps together with the area with statistically significant SLP differences (95% significance levels according to Student's t test) are presented in Figure 1. The charts show pronounced significant SLP differences for almost all months. The most striking feature of the LMM is the significant positive pressure anomalies over parts of northern Europe. Their center moves from northern Scandinavia and the Baltic area in winter (indicating more blocking situations during the LMM with distinct anomalous cold air advection towards central and eastern Europe) to the vicinity of Iceland from March to October (except for April). This leads to a less pronounced Icelandic Low, implying weaker westerlies over the eastern North Atlantic. Significant negative pressure anomalies are prevalent in a zonally elongated band south of 55° N. The December and January difference maps indicate statistically significant lower SLP over the central and western Mediterranean.

3.2. SEASONAL EOF ANALYSIS OF EUROPEAN SLP FOR THE LMM AND THE 1961–1990 PERIOD

Since LMM winters and springs clearly show the largest departures in the climatic behavior over large parts of Europe, the first three joint EOFs (LMM together with the period 1961–1990) of standardized winter and spring SLP anomalies are presented in Figures 2 and 3 together with the corresponding scores. The three eigenvalues share more than 80% of the joint seasonal SLP variability.

Winter

Figure 2 presents the first three EOFs of the joint winter SLP and the corresponding scores for the two periods. The leading winter EOF pattern shows the well-known dipole structure with negative (positive) loadings north of about 55° N and positive (negative) loadings over the Azores. This eigenvalue explains 40% of the joint SLP winter variance and is often referred to as the 'North Atlantic Oscillation' (NAO) (centers of action near the Azores high and the Icelandic low). It is the dominant pattern of atmospheric behavior in the North Atlantic sector throughout the year, although it is most pronounced during winter. It significantly accounts for hemispheric and regional climatic variances (Hurrell, 1995, 1996; Osborn et al., 1999). The associated scores describe its variation over the LMM and the period 1961–1990. The NAO type variability was also present during the LMM. The LMM winter scores show positive values for some winters of the 1680s and the last five winters of the LMM. The corresponding SLP patterns (not shown) indicate enhanced zonality (positive NAOI) over western Europe (Luterbacher et


January SLP difference
February SLP difference
March SLP difference
April SLP difference
May SLP difference
June SLP difference
July SLP difference
August SLP difference
September SLP difference
October SLP difference
November SLP difference
December SLP difference

al., 1999; Luterbacher et al., 2000). Some of these winters (e.g., 1686) were rather mild over wide parts of Europe (Pfister, 1999) and were connected with positive NAO indices (Luterbacher et al., 1999). More LMM winters show negative scores, i.e., the winters 1675–1680, generally the 1690s, and the first decade of the eighteenth century. The respective SLP maps (not shown) go along with a reduced zonal circulation over the eastern North Atlantic (negative NAOI) (Luterbacher et al., 1999; Luterbacher et al., 2000). The most severe winters – 1684, 1695, 1709, unmatched in the twentieth century – show the most negative scores connected with extreme coldness and dryness, especially north of the Alps.

The period 1961–1990 includes a more meridional phase, roughly between 1961 and the early 1970s, with mostly negative scores connected with blocking and cold and dry winters over parts of Europe (negative phase of the NAO). A distinctly zonal phase (positive scores) with enhanced westerlies (positive phase of the NAO) was prevalent from about 1974.

The second EOF of the joint LMM and 1961–1990 winter SLP accounts for 29% of the joint winter SLP variance. It is characterized by a monopole pattern with simultaneous lower (higher) SLP. LMM winters with positive scores (negative values in the corresponding loading pattern) can be found during the first 5 years. From around 1685, a clear upward trend towards positive scores emerges, thus a tendency for winters with below normal SLP especially over western and central Europe around the turn of the century. The period 1961–1990 is characterized by a downward trend of the scores until the mid-1980s (mostly connected with lower SLP over wide parts of Europe) and an upward trend for the last years. The third EOF accounts for around 15% of the joint winter SLP. It shows a contrast between western and eastern Europe with positive (negative) loadings west of approximately 5° E and negative (positive) loadings eastwards. No trend is obvious in the scores of either periods.

Spring

Figure 3 shows the first three EOFs of the joint spring SLP and the corresponding scores for the two periods. The loading patterns as well as the shared variances are very similar to winter. The corresponding scores of the leading EOF for the LMM indicate only a slight downward trend towards negative values. However, distinct negative scores are obvious for the first five LMM years. These springs were unique and were connected with a remarkable southeastward shift of the North Atlantic low pressure system towards central Europe. These springs have very positive scores in EOF two and negative scores in EOF three, an indication of below normal SLP from the eastern North Atlantic towards central Europe. The scores for the first

Figure 1 (facing page). Averaged monthly mean SLP difference patterns (LMM minus analysis 1961–1990). The contours are drawn at 1 hPa intervals. Continuous lines mark positive deviations, the dashed lines negative deviations. The regional distribution of the corresponding *t* variable (according to Student's *t* test) is denoted in shaded grey (above 95% confidence level).

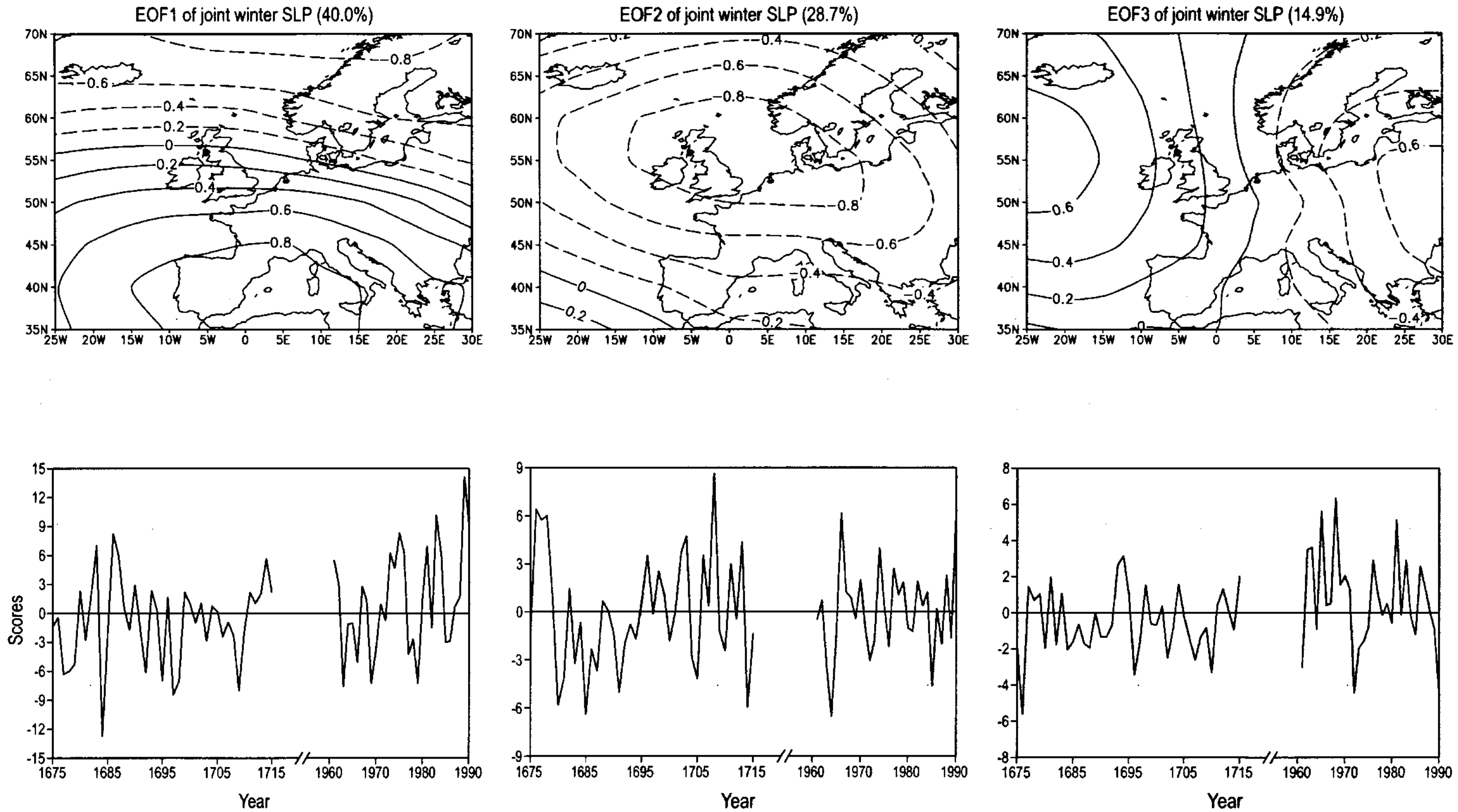


Figure 2. Above: The first three joint (LMM together with 1961–1990) EOFs of winter [DJF] SLP anomalies. The first EOF shares 40%, the second 28.7%, and the third EOF 14.9%, respectively, of the joint winter SLP variance. Continuous lines indicate positive values, while dashed lines mark negative values. The isopleth interval is 0.2. Below: The corresponding scores. For clarity, the monthly (DJF) scores were averaged to one seasonal winter value for the respective years.

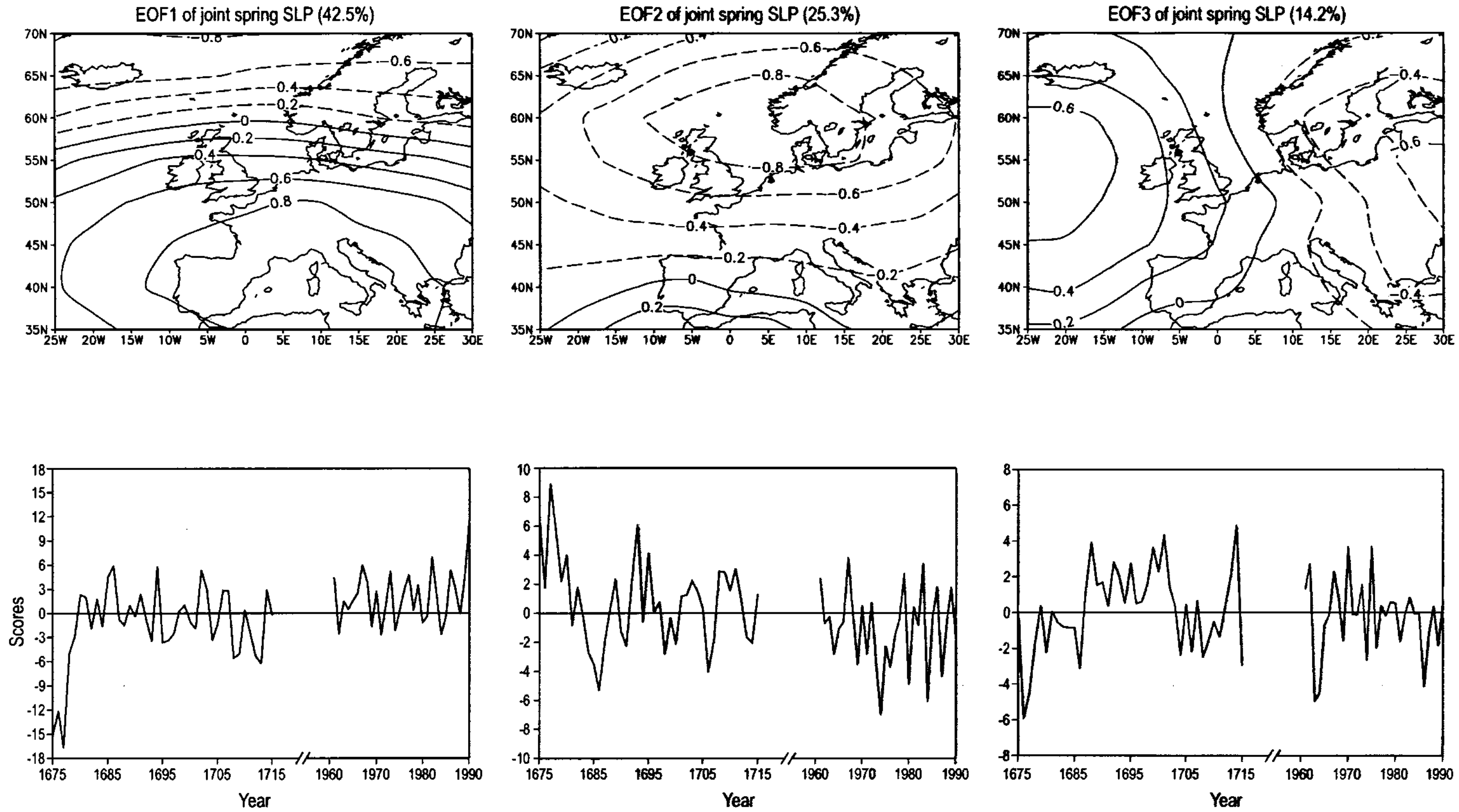


Figure 3. Above: The first three joint (LMM together with 1961–1990) EOFs of spring [MAM] SLP anomalies. The first EOF shares 42.5%, the second 25.3%, and the third EOF 14.2%, respectively, of the joint spring SLP variance. Continuous lines indicate positive values, while dashed lines mark negative values. The isopleth interval is 0.2. Below: The corresponding scores. For clarity, the monthly [MAM] scores were averaged to one seasonal spring value for the respective years.

EOF of the 1961–1990 period reveal weak variability over time and no trend or large fluctuation between the phases is indicated. Most of the recent springs show positive scores. Spring is the season with the highest pressure variability due to its frequent pressure pattern changes from the zonal winter circulation to the summer conditions. Thus, positive scores are no indication of enhanced westerlies for the respective spring months, although one or two months can lead to this result (i.e., 1967, 1989). The majority of the scores for EOF two for the LMM are positive (lower pressure during the LMM over extended parts of Europe). The opposite is true for the 1961-1990 period.

3.3. PCA-'*k*-MEANS'-CLASSIFICATION FOR THE TWO PERIODS

For the PCA-clustering classification, five orthogonal PC scores were retained from the initial S-mode PCA, accounting for 90.2% of the total joint SLP variance. The subsequent optimized '*k*-means' clustering was applied to the time series of the respective PC scores and gave an optimal of ten clusters. Although statistical significance of cluster separation, as defined in Gerstengarbe and Werner (1997), could not be reached for all clusters, the final cluster partition comprising ten clusters was optimized towards this criterion in the best possible way (compared to all other partitions). It can, therefore, be assumed as the optimal solution with regard to homogeneity within and separation between clusters. All months of the LMM and the 1961–1990 period are classified in one of the ten clusters. All months from the two periods belonging to the respective clusters are averaged and plotted together with their standard deviations and their relative frequencies (Figure 4). The most frequent four clusters have a cumulative frequency of around 62%. Average seasonal variation (relative frequency) of each cluster separated by the two periods is used to compare and to detect differences in the atmospheric circulation between the LMM and the 1961–1990 period (Figure 5). Thus, Figure 5 shows the percentage of the months within each season and period that correspond to the respective clusters. Two out of five winter months of the LMM, but only 25% of the 1961–1990 period, belong to Cluster 1. The center of the low pressure system is close to Iceland, and the British Isles and Scandinavia are dominated by a strong average southwesterly flow. More winter months of the period 1961–1990 belong to Cluster 8, which is similar to Cluster 1 but with two low pressure centers in the north and a lower average pressure over continental Europe. Differences are also prevalent with regard to Cluster 4 and Cluster 6. More frequent for the 1961–1990 period were situations with a strong Azores high extending to the British Isles and central Europe connected with a northwesterly flow over Europe (Cluster 4). A total of 8% of all LMM and 1961–1990 months belongs to Cluster 6. It is connected with low pressure over the Atlantic extending towards central and even southern Europe. The rather high SLP variability over the northern North Atlantic north of circa 50° N is an indication of the variable path of the storm tracks towards western Europe. The further characteristics of this cluster are the strong Scandinavian high and rather weak Azores high. Every fourth winter month of the LMM belongs to this cluster, whereas it is seldom seen during the 1961–1990 period. The main differences in the spring atmospheric circulation can be seen in Cluster 7. Its annual frequency is 7% (see Figure 4). It is the most frequent cluster for LMM spring months with a relative frequency of 35% (Figure 5). Only a few months from 1961–1990 are classified in this cluster. It shows a remarkable southeastward shift of the North Atlantic low pressure system. On average, its center is over the British Isles. Nevertheless, the standard deviation for this cluster is very high and implies a large variability and thus different positions of the low. Clusters 1 and 10 include 20% of the 1961–1990 spring months, whereas only single months of the LMM correspond to these clusters. Clusters 2 and 5 are typical summer patterns with the Azores high extending to central Europe and a rather weak Icelandic low. These clusters are quite uniform with a small overall SLP variability. A total of 75% (33%) of the LMM (1961–1990) summer months corresponds to Cluster 2. In contrast, the majority of the recent 30 years, but only 10% of the LMM, belong to Cluster 5. For both periods, Clusters 1, 3, and 4 are typical for autumn. It is the season that shows the least deviations between the two periods, except for Cluster 3, which is a signal for an early development of the continental cold anticyclone over western Russia.

4. Discussion

The SLP difference charts, the EOF analysis as well as the classification results clearly show some significant differences in the atmospheric circulation during the LMM in comparison with the independent period 1961–1990. However, it should be borne in mind that this period is too short for a detailed comparison since it does not capture all the different climate conditions for the four seasons.

Figure 1 points to a significantly higher winter SLP during the LMM over north-eastern Europe and lower pressure over the central and western Mediterranean. From the PCA classification results, it can be concluded that the more frequent occurrence of Clusters 1 and 6 are mainly responsible for this feature. Cluster 1 displays an extended high pressure bridge connecting the Azores high with the eastern European cold anticyclone, leading to stronger blocking over central Europe, enhanced moisture advection over Scandinavia, and drier and in some cases colder conditions over continental and eastern Europe (Wanner et al., 2000). Cluster 6 underlines the severe climate conditions during the LMM, with persistent cold air advection from an easterly direction at the southwestern edge of the strong cold high towards central Europe. Such winter pressure patterns seem to be much more frequent for the LMM (especially the first few winters, 1684, the 1690s and 1709), with a very strong anticyclone with its center over the Baltic, an extended trough from the eastern Atlantic towards central or even southern Europe, and a weak subtropical high. These outstanding winters are also visible in the extremely negative scores of the leading winter EOF and the positive scores of EOF 2 (Fig-

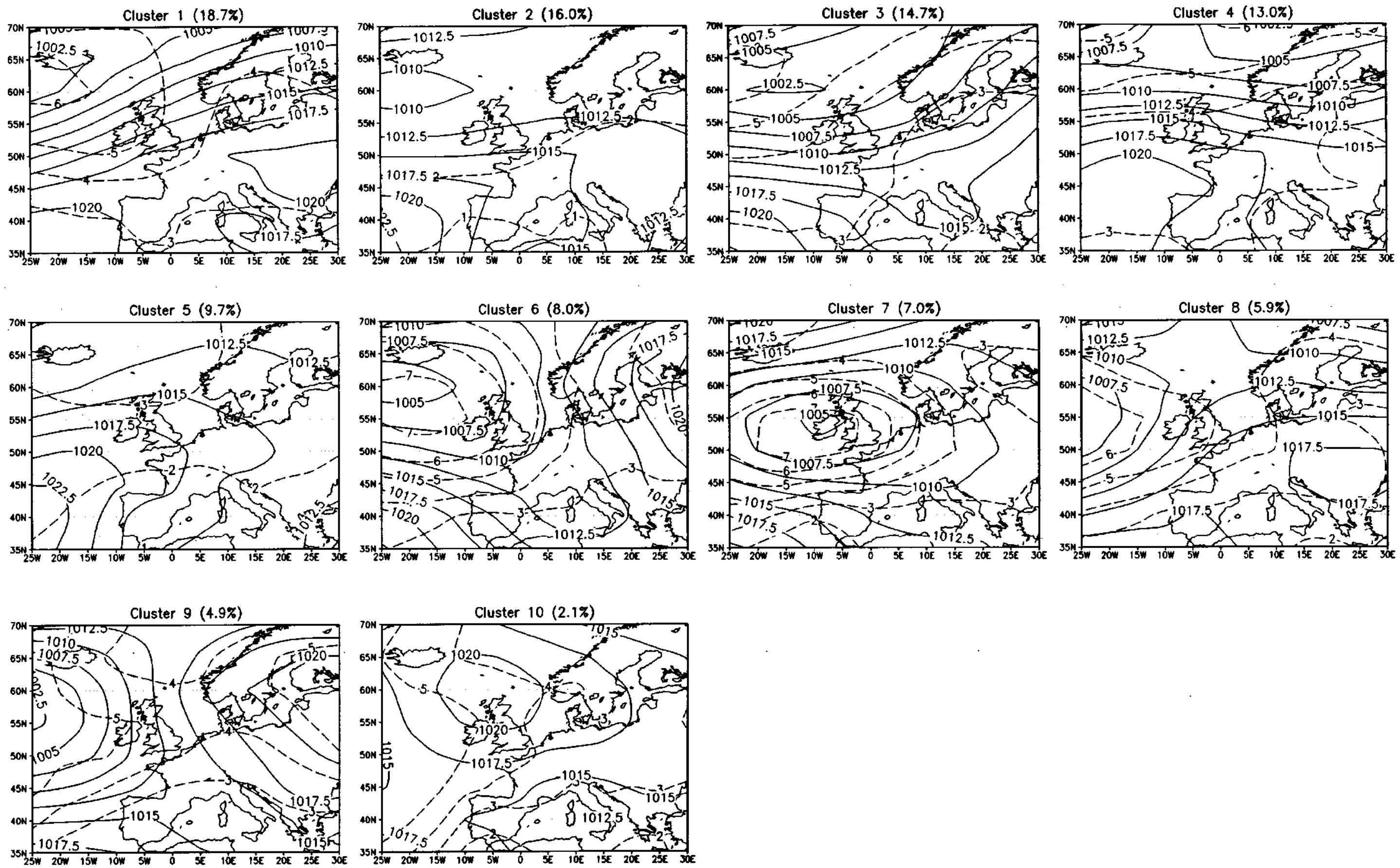


Figure 4. Averaged mean sea level pressure (SLP) fields (solid lines), their standard deviation (in hPa, dashed lines), and relative frequencies (%) (in brackets) of Clusters 1 to 10 for the joint LMM and 1961–1990 period based on PCA-'*k*-means' clustering technique.

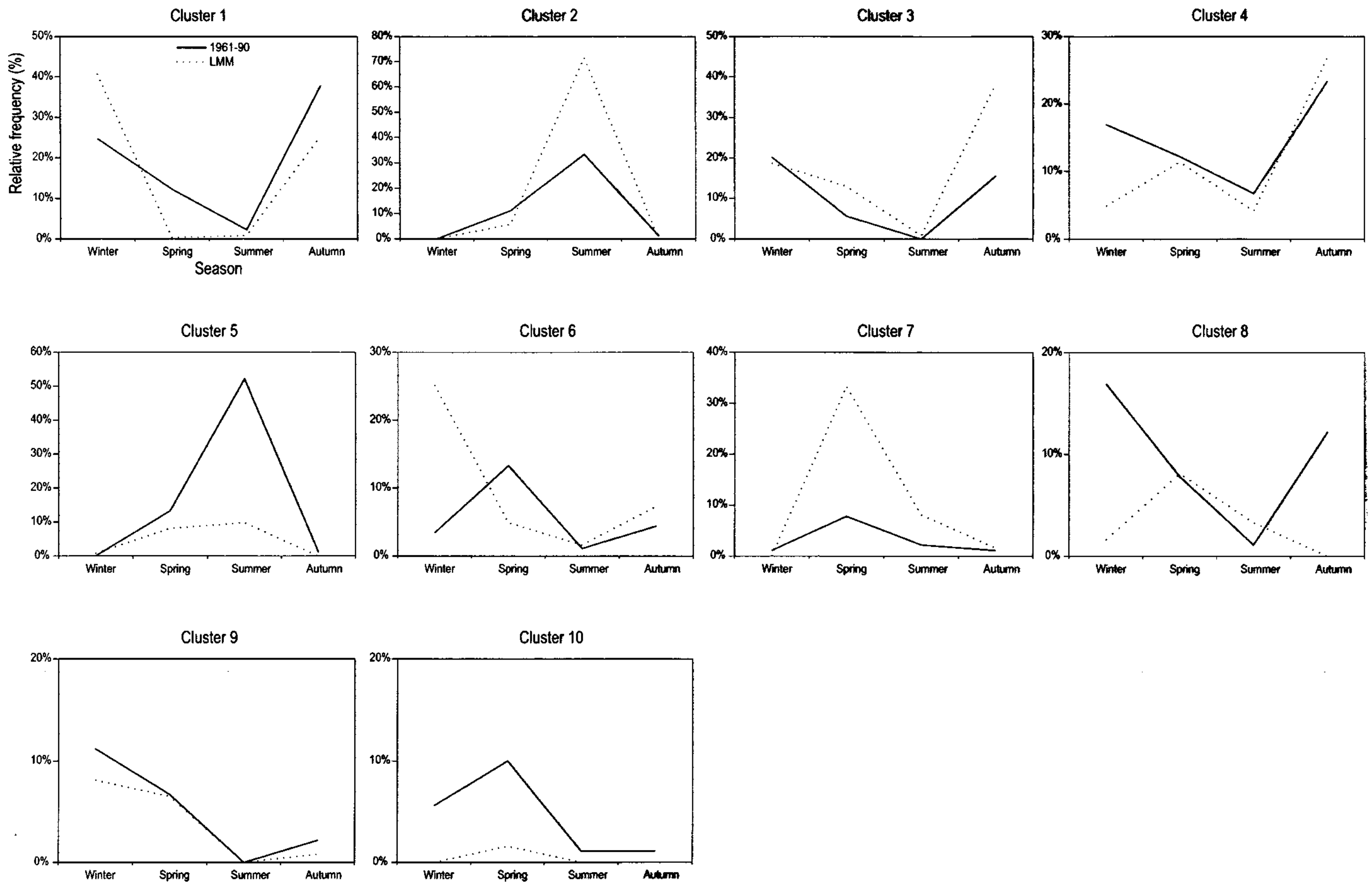


Figure 5. Average seasonal frequency of the ten PCA-'*k*-means' clusters for the LMM (dotted) and the period 1961–1990 (solid). Note the different scales (relative frequency) on the y-axes.

ure 2). The pressure constellation is connected with widespread coldness and less precipitation over Scandinavia, the Baltic Sea area, central and eastern Europe, and part of the British Isles. Cold air also penetrated into southern Europe and brought low temperatures to the central and eastern Mediterranean (Xoplaki et al., 2001). The persistent low pressure over southern Europe together with cold dry air led to distinct cyclogenesis with considerable amounts of snow and rain in northern and central Italy as well as along the Mediterranean coasts (Xoplaki et al., 2001). Although this cluster was rare – it just appeared 4 times between 1896 and 1956 – it had a relatively high temperature relevance (Schmutz and Wanner, 1998) and supports the difference with the twentieth century. Strong phases of increased ice winter severity in the western Baltics from 1655 to 1710 must have been characterized by frequent blocking situations with a weaker westerly flow over the eastern Atlantic and northern Europe, thus a negative NAO (Koslowski and Glaser, 1999). This is also in agreement with the recent reconstructions by Luterbacher et al. (1999), who found mostly negative winter NAOIs during the LMM.

The SLP difference charts for spring (Figure 1) indicate significantly higher SLP during the LMM over the Icelandic region and the Norwegian Sea and lower pressure generally south of approximately 58° N. The dominant cluster for the LMM (Cluster 7) clearly shows a southeastward shift of the Icelandic low towards the British Isles. This was connected with enhanced (north-)westerlies leading to unsettled, cold, and rainy (1693) or snowy weather over central Europe. The SLP distribution of the months belonging to this cluster is a nice way to demonstrate that reduced zonality (negative NAOI) derived by the simple pressure difference between the Azores and Iceland is not a clear-cut indication of weaker westerlies over western and central Europe.

The main difference in summer climate is shown from the average SLP distribution and the corresponding relative frequencies of Clusters 2 and 5. Cluster 2 accounts for about 75% of the LMM summer months. The corresponding position of the Azores high extends no further than 50° N. As a consequence, low pressure systems from the Atlantic headed for the continent on a more southerly track, thus leading to frequent spells of wet, cool, and windy, but not necessarily cold westerly conditions over western and central Europe. In Cluster 5, where the majority of the summer months from 1961–1990 have been classified, the subtropical high expands more towards northeast compared to the conditions during the LMM.

In autumn, the pressure during the LMM was significantly higher north of about 63° N whereas a lower SLP was prevalent over much of continental Europe and the Mediterranean (Figure 1). This suggests that the change from summer to winter circulation was somewhat advanced. Indeed, some autumn months (e.g., November 1676, November 1684, October 1688, October 1694) were extremely cold in many parts of Europe (Pfister, 1999). The below normal pressure during the LMM can be explained with a higher frequency of the southward expansion of the Icelandic low (Cluster 3 in Figure 5).

The classification of the SLP fields was also conducted for the two periods separately. The clusters for each period were in agreement with the joint classification and the relative frequencies for each cluster revealed similar results.

The causes and mechanisms that might have led to the substantial differences in atmospheric circulation between the two periods will be discussed briefly in the following paragraphs; the anthropogenic influences that may partly underlie the patterns seen in the period 1961–1990 will not be dealt with.

4.1. SOLAR VARIABILITY CONNECTED WITH LARGE-SCALE TEMPERATURE AND ATMOSPHERIC CIRCULATION CHANGE

The effect of low frequency (decadal-to-centennial scale) solar variability is of much relevance, since the accurate assessment of anthropogenic impacts on global change requires reliable estimates of the magnitudes of natural forcing mechanisms (Lean et al., 1995; Overpeck et al., 1997; Mann et al., 1998; Crowley and Kim, 1999; Free and Robock, 1999; Rind et al., 1999; Beer et al., 2000; Crowley, 2000). Several studies point to the fact that the paleo-reconstruction of NH surface temperature correlates highly with historical solar irradiance during the preanthropogenic (pre-1850) period. A direct radiative forcing from the change in solar output (lowering of 0.25% irradiance during the MM relative to present levels as suggested by several authors) could account for a global annual average cooling of around 0.5 °C (Rind and Overpeck, 1993; Wuebbles et al., 1998; Lean and Rind, 1999; Rind et al., 1999; Lean, 2000). However, Overpeck et al. (1997) argue that the lack of a distinct prolonged cold period during the MM in the Arctic argues against a dominant role for solar forcing. In addition, Landsberg (1980), Cullen (1980), and Xu et al. (2000) believe that a decline in solar activity may not have been the cause of the climate severity during the MM, since evidence from numerous local histories, especially from east Asia, suggest that sunspots were not rare in the seventeenth century. Less is known about the relationship between the sun's variability and the SLP distribution. Recently, Shindell et al. (1999) found zonal wind changes between solar maximum and solar minimum with zonal mean SLP increases of circa 0.7 hPa from 30° N to 45° N, with an associated decrease of $\sim$1.1 hPa in the northern latitudes. Haigh (1994, 1996) simulated the relationship between the 11-year solar activity cycles, ozone production, and climatic change. She found a warming of the lower stratosphere due to the absorption of more sunlight at solar maximum, one to two percent more ozone, a strengthening of the stratospheric winds, and a poleward shift of the mid-latitude storm tracks. The opposite effect of the simulations by Haigh (1996) and Shindell et al. (1999) might have played a role in climate during the MM. The slowdown in solar activity may have resulted in a decrease of the stratospheric ozone content on the order of 3% compared to recent values (Wuebbles et al., 1998). Assuming that this decrease leads to an opposite effect of Haigh (1996) and Shindell et al. (1999), a decrease of the latitudinal extent of the Hadley cell circulation follows together with an expansion of the Polar cells and lower SLP (i.e., southward shift of the storm tracks (cf. Figure 1)). Therefore, wintertime hemispheric changes in the thermal structure of the stratosphere may have been affecting tropospheric climate by modifying planetary wave propagation as also proposed by Haigh (2000). However, these hypotheses are in disagreement with Brown and John (1979) and Tinsley (1988), who found that on a longer time scale the climatic changes of the MM can be interpreted as a northward shift of the storm tracks and reduced heat exchange between low and high latitudes. More research is needed to address this topic.

4.2. ATMOSPHERIC CIRCULATION CHANGE CONNECTED WITH LARGE VOLCANIC ERUPTIONS

Together with solar variations, it is believed that the frequency and magnitude of large volcanic eruptions significantly contributed to decadal-scale climate variability during the ‘Little Ice Age’ (Mann et al., 1998; Briffa et al., 1998; Bertrand et al., 1999; Crowley and Kim, 1999; Free and Robock, 1999; D’Arrigo et al., 1999; Hyde and Crowley, 2000; Robock, 2000; Zielinski, 2000; Crowley, 2000). These authors report that large-scale cooling was caused by explosive volcanism. Recent modeled responses indicate that more than 40% of the decadal-scale variance in the NH mean temperature over the interval 1400–1850 can be shared by explosive volcanism (Crowley, 2000). The NH mid-latitudes seem to be particularly sensitive to large explosive volcanoes, experiencing winter warming and marked summer cooling for at least the following year (Robock and Free, 1995; Robock, 2000). Luterbacher (2000) discussed the expected and reconstructed atmospheric circulation after the volcanic eruptions during the MM (Gamkonora, Indonesia, in 1673 (Volcanic Explosivity Index (VEI) 5?), Long Island, Papua New Guinea (VEI 6) (most possibly in 1673 or 1674; Luterbacher, 2000), Hekla, Iceland, and Serua, Indonesia, in 1693 and Komaga-Take, Japan, and Aboina, Indonesia, in 1694 (Zielinski, 1995)). Luterbacher (2000) found that the years following the respective volcanic eruptions indeed were cooler. However, the corresponding winters were cold in wide parts of Europe, mostly influenced by the cold high over western Russia rather than by the zonal circulation over the eastern North Atlantic. These results may support the findings of Zielinski (2000), who reports that an eruption that occurs during a cooler climatic mode may extend or enhance those cooler conditions (due to other forcing factors such as the sun). This suggests that certain eruptions of the past may have enhanced and likely extended the cool climate (such as the LMM) existing at the time of the eruption (Zielinski, 2000; Luterbacher, 2000). The corresponding summers were cool and wet in western and central Europe connected with rather strong westerlies over the continent and a reduced influence of the Azores high, which is expected after large volcanic eruptions.

4.3. INTERNAL VARIABILITY OF THE ATMOSPHERE-OCEAN SYSTEM IN THE NORTH ATLANTIC AREA

Kushnir (1994) and Kushnir and Held (1996) determined the differences in surface atmospheric conditions connected with warm and cold sea surface temperatures (SSTs) in the northern North Atlantic. The SLP difference fields (warm SST years minus cold SST years) for the cold and warm seasons revealed a positive SLP anomaly from Iceland to northern Scandinavia, whereas anomalous low pressure was prevalent in the middle of the North Atlantic, southeast of the warmest SST values. Similar anomaly charts have been found by Peng and Mysak (1993). Both of these composite SLP patterns are in accordance with our difference patterns (LMM minus 1961–1990, see Figure 1).

Based on these simple analogous cases from the twentieth century, it can be hypothesized that SSTs in parts of the northern North Atlantic might be higher during the LMM compared to the rather cool period 1961–1990 (Kushnir, 1994; Eden and Jung, 2001), which itself has experienced large SST fluctuations in the North Atlantic (such as the freshening and cooling, the Great Salinity Anomaly (GSA) (Dickson et al., 1988) in the 1970s and the 'smaller GSA' (Reverdin et al., 1997) in the early 1980s). Ice-cover anomalies for the Barents Sea and Labrador (which are out of phase with each other; Cushing and Dickson (1976) and Ikeda (1990)) are expected to be attributed to atmospheric pressure anomalies over the Eurasian Basin in the Arctic and northern North Atlantic. Our difference charts show anomalous high pressure and slightly anticyclonic curvature of the isobars over northeastern Europe and likely also over the Barents Sea. If it is supposed that severe ice conditions were prevalent in the Barents Sea during the LMM, as has been postulated by the composite charts from Figure 1 and also shown with the Barents Sea ice edge position (Vinje, 1997), then light sea ice (thus positive SSTs) is expected around Labrador and Iceland. This agrees with Ogilvie (1996), who found that sea ice conditions off northern Iceland occurred less frequently during the LMM compared to the latter part of the twentieth century. Wohlleben and Weaver (1995) found that times with positive SST anomalies in the Labrador Sea are connected with above normal air pressure over Greenland, thus a weaker climatological Icelandic low and a southward diversion of the storm tracks. Our difference patterns are in agreement with our charts and the interdecadal SST and SLP patterns described before.

The hypothesis of above normal SSTs in parts of the northern North Atlantic during the LMM is in disagreement with Lamb (1979), who suggested much below normal SSTs between the Faeroes and southeast Iceland for the period 1675–1705. In addition, Stuiver and Braziunas (1993) and Rind et al. (1999) hypothesized that the North Atlantic region experienced colder conditions. However, recent modeling studies by Etheridge et al. (1998) and Trudinger et al. (1999) indicate that the SSTs were not significantly different for the period from 1550 to 1800. The controversial discussions about the state of the North Atlantic will need more coupled GCM studies in order to gain more insight into the extreme periods in the 'Little Ice Age' such as the MM.

5. Conclusions and Outlook

The synoptical comparison between the LMM and the period 1961–1990 revealed some significant differences in atmospheric circulation. During LMM winters, significantly higher pressure was found over northeastern Europe and below normal SLP over the central and the western Mediterranean. The SLP classification results revealed a much higher frequency of months influenced by the strong Scandinavian high connected with recurrent advection of very cold and dry polar or even arctic air towards eastern and central Europe. Thus, a slightly reduced zonal circulation (negative NAOI values) over the eastern North Atlantic together with a strong influence of the continental anticyclone was responsible for the wintertime cooling over Europe. Over western, central, and eastern Europe, LMM springs were generally cold and summers rather wet and cool mainly due to a southern shift of the low pressure systems and a weaker Azores high. Autumns indicated higher pressure mainly over northern Europe and lower pressure over continental Europe and the Mediterranean, an indication of an advanced change from summer to winter circulation with cooler conditions during the LMM.

The rapid climate change during the LMM can possibly be explained by external forcing factors such as solar variability, volcanic impact, and internal oscillation in the North Atlantic. The summer SLP fields after explosive volcanic events (1673, 1693, 1694) all show stronger westerlies over the northeastern North Atlantic and a reduced influence of the Azores high connected with wetter and cooler conditions. However, a warming of the corresponding winters could not be detected over Europe, probably due to the stronger influence of the cold high over western Russia than the westerly flow over the eastern North Atlantic. These eruptions might have extended the cool climate during the LMM. Compared with several modeling studies, the reduced solar activity during the LMM might be a reason for the southward shift of the mid-latitude storm tracks. Additionally, based on analogous studies from observed data together with evidence from independent climatic indications from the LMM, it might be possible that the SSTs in parts of the northern North Atlantic were higher than during 1961–1990 connected with severe sea ice conditions over the Barents Sea.

Future research will include regime studies, climate forcing mechanisms, and the analysis of the low frequency variability of the atmospheric circulation over the eastern North Atlantic Eurasian area for the last 500 years for which continuous SLP and geopotential height field reconstructions are now available from the authors (Luterbacher et al., 2000b).

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