Atmospheric circulation dynamics linked with prominent discharge events in Central Europe

JUCUNDUS JACOBEIT[1], **ANDREAS PHILIPP**[1] & **MATTHIAS NONNENMACHER**[2]

1 *Institute of Geography, University of Augsburg, Universitätsstraße 10, D-86135 Augsburg, Germany*
jucundus.jacobeit@geo.uni-augsburg.de

2 *Institute of Geography, University of Würzburg, Am Hubland, D-97074 Würzburg, Germany*

Abstract Studies on links between flood events and atmospheric circulation at historical time scales are often constrained by the temporal resolution (monthly or even seasonal) of reconstructed atmospheric pressure fields. Thus, it is necessary to include investigations based on daily resolved data, despite their restricted time spans. In particular, it will be possible to determine circulation pattern sequences preceding prominent discharge events identified from various gauged time series. Based on daily 500-hPa geopotential height fields from the NCEP/NCAR re-analyses, major large-scale circulation pattern sequences for such discharge events in Central Europe are determined by EPCA techniques (principal component analyses extended in the time dimension). Results from different Central European catchment areas are put together for an overview of the most important sequences during winter and summer. They are finally compared with previous results from monthly analyses of historical data.

Key words Central Europe; circulation pattern sequences; discharge; extended PCA

INTRODUCTION

Much progress has been made during recent years in reconstructing historical floods based on documentary data (e.g. Pfister, 1999; Glaser, 2001; Mudelsee *et al.*, 2003; Thorndycraft *et al.*, 2003; Brázdil *et al.*, 2005a,b), and first attempts were carried out to analyse historical flood frequency variability with respect to atmospheric circulation dynamics (e.g. Sturm *et al.*, 2001; Jacobeit *et al.*, 2003a,b, 2004a,b; Wanner *et al.*, 2004). This has become possible in terms of multivariate analyses since the objective reconstruction of gridded sea-level pressure (SLP) fields back to the year 1500 for a large part of the North-Atlantic-European region (Luterbacher *et al.*, 2002). However, these SLP grids have only a restricted temporal resolution (due to the available predictor data for reconstructions) – monthly back to 1659 and even seasonal for the time before. As a consequence, dynamical analyses in this historical context are only able to deal with the first of three groups of factors that are important in the context of flood dynamics: (a) preconditioning factors, such as longer-term varying climatic conditions, which may be reflected in monthly resolved data; (b) initial factors, such as short-term flood producing systems, which operate on daily to sub-daily time scales; and (c) maintaining factors, such as persistent regimes, which determine the evolution of flooding events. This means that historical studies mostly follow the concept of "flood hydroclimatology" (Hirschboeck, 1988) looking at different dynamic backgrounds for the more immediate causes of flood generation. However, this may include important cases with monthly or seasonal mean characteristics other than during intermittent shorter periods of current flood events. Thus, it is necessary, also in a historical context, to investigate more recent data with daily resolution, despite the restricted time periods covered by such data. Results concerning circulation dynamics of flood events have subsequently to be put in the perspective of a historical flood hydroclimatology (see Discussion and Conclusion).

In the present context, the focus is on the initial conditions according to the above-mentioned group (b). Furthermore, not only real flood events are considered, but also prominent discharge events, in order to ensure sufficient sample sizes for the intended multivariate analyses. A prominent discharge event is defined by statistical criteria given in the Methods section. The atmospheric part of the investigation is based on re-analysis data, which are available back to 1948, thus defining the beginning of the study period.

Atmospheric circulation dynamics linked with flood or prominent discharge events may be determined by different approaches. For example, Caspary (1995) has looked at large-scale flow types and their frequency changes during recent decades, Bardossy & Filiz (2003, 2005) applied fuzzy rules to SLP maps to identify flood producing circulation patterns. In this study, a particular technique is used to determine circulation pattern sequences preceding prominent discharge events at various gauging stations. Analyses focus on Central Europe, a region with well-advanced knowledge in historical flood hydroclimatology.

DATA

Time series of daily discharge values from gauging stations of eight Central European catchments (Rhine, Main, Mosel, Danube, Weser, Elbe, Spree, Oder) have been obtained from the Bundesanstalt für Gewässerkunde in Koblenz (Germany). These data (see Fig. 1 for the location of the gauging stations) were processed for the period 1948–2002, thus including the extreme floods of August 2002 in the Danube and Elbe catchments (Ulbrich *et al*., 2003a,b; Philipp & Jacobeit, 2003). The beginning of the study period was determined by the start of the NCEP/NCAR re-analyses data (Kalnay *et al*., 1996; Kistler *et al*., 2001), from which the gridded fields of 500-hPa geopotential heights have been extracted for the North-Atlantic-European area (2.5° × 2.5° spatial resolution). These grids are available with a 6-hour resolution and are used as daily mean values for the subsequent analyses. This smoothing implies a common temporal resolution for all analysed data, ensures a reasonable number of patterns (eight in this case, see Methods section and figures in the Results section) for the daily circulation sequences, and only neglects short-term dynamics which do not alter the principal sequences themselves.

Fig. 1 Location of the gauging stations on Central European rivers included in the topical analyses.

METHODS

A prominent discharge event is defined by a daily discharge value $d(i)$ at a particular gauging station exceeding the following two thresholds:

$$d(i) > m(\max) + sd(\max) \tag{1}$$

where $m(\max)$ and $sd(\max)$ are the mean and standard deviation, respectively, of the monthly maxima of daily discharge values (with respect to a particular month); and

$$d(i) > d(i-1) + sd(d) \tag{2}$$

where $d(i-1)$ is the discharge of the day before and $sd(d)$ is the standard deviation of the entire daily discharge time series.

The latter criterion ensures that only days with a distinctly increasing discharge are considered, excluding, in particular, those days with a high, but not further distinctly increasing, discharge. This means that conditions of triggering instead of those of maintaining high discharge values are the primary focus. The number of such prominent discharge events per season ranges between 21 and 30 for each time series during the 1948–2002 period. These selected anomalies are used as a basic sample for the circulation analyses and are not considered in the present context with respect to temporal variations in the study period.

For the circulation analyses, 500-hPa geopotential height (GPH) grids from the NCEP/NCAR re-analyses have been selected for each daily sequence starting seven days before a prominent discharge event until the event itself. This extended time span has been selected in order to include developments of the atmospheric circulation leading to prominent discharge events at gauging stations which are located in different parts of the corresponding river course (see Fig. 1). As the delay between the main rainfall event and peak runoff depends on this location of the gauging station, a 7-day period before prominent discharge events ensures recording of relevant circulation pattern sequences, even for stations lying relatively far downstream (e.g. Köln in the Lower Rhine basin, see Fig. 1). In order to determine the most important circulation pattern sequences linked to these prominent discharge events, the daily GPH grid sequences have been subjected – separately for each gauging station and each season – to a multivariate technique called Extended Principal Component Analysis (EPCA). In contrast to conventional PCA, this extended version allows each prominent discharge event to be considered not only by one GPH grid, but by a sequence of several GPH grids (eight in this case). This extension in time enlarges the input matrix by these additional GPH grids and leads to the extraction of PC pattern sequences (instead of single patterns for conventional PCA). Thus, EPCA does not process one spatial field for each temporal snapshot, but several spatial fields for a temporal sequence linked with each snapshot. In this respect, there is some similarity to Multichannel Singular Spectrum Analysis (MSSA). However, according to von Storch & Zwiers (1999), a typical difference between these approaches may be seen in the ratio between spatial field dimension (number of grid points) and temporal extension (number of fields within each sequence): the latter is often greater than the former for MSSA, whereas the opposite is usually true for EPCA. With 551 grid points and eight fields per sequence, this study clearly points to EPCA as the appropriate technique. Some examples of EPCA have been provided by Weare & Nasstrom (1982); a more recent one may be found in Compagnucci *et al*. (2001).

The EPCA approach may be applied in both S- and T-mode analyses (see Richman, 1986). The S-mode processes temporal snapshots of a particular quantity (e.g. geopotential heights) for a number of spatial units, and EPCA extends each temporal snapshot to a sequence of snapshots (eight in this case). A previous study on this topic (Jacobeit *et al*., 2003c) has already used this classical S-mode approach. In contrast, the T-mode processes spatial fields of a particular quantity for a number of temporal snapshots, and EPCA extends each spatial field to a temporal sequence of fields (again eight in this case). The T-mode approach has been applied in this study since it has some particular advantages for the focus of this paper: it provides – in its spatial scores – genuine circulation patterns, whereas the S-mode loadings only define centres of variation without definite spatial flow characteristics. Accordingly, Compagnucci *et al*. (2001) suggested that extended T-mode PCA be denoted as "Principal Sequence Pattern Analysis". This coincides exactly with the general aim of this study and allows one to focus directly on the development of flow configurations (instead of spatial patterns consisting of S-mode centres of variation). Furthermore, typical differences between S-mode and T-mode analyses related to GPH grids in connection with prominent discharge events may be summarized as follows:

– S-mode analysis yields five to seven principal components (PCs) with a reasonable physical meaning, but only 60–75% overall explained variance (*EV*); T-mode analysis yields mostly three to four PCs with *EV* of 85–90%.

– The highest individual *EV* accounted for by the first PC always remains below 20% for S-mode analysis, but may exceed 40% for T-mode analysis.

Obviously, T-mode analysis condenses information more effectively and emphasizes leading configurations. This confirms its character as an appropriate approach for identifying major sequences of flow configurations leading to prominent discharge events.

In order to maintain a high degree of correspondence with real conditions in the atmosphere, resulting pattern sequences will not be shown in terms of extended PC scores, but rather as original grids from that 8-day sequence having the highest loading on the corresponding PC sequence. This representative pattern sequence includes the main characteristics of the corresponding PC sequence and recurs in a similar way during other original sequences being highly and predominantly correlated with the PC sequence.

RESULTS

Examples are presented for the summer and winter seasons in a particular way: since all results from the entire gauge-related analyses are too extensive and include considerable redundancy (similar pattern sequences from different analyses), some kind of selection has to be applied. Reproducing full results for selected gauging stations would still include redundancy (e.g. westerly pattern sequences recurring frequently for different stations), whereas particular sequences from neglected stations might be missing altogether. Therefore, selected circulation pattern sequences from different gauge-related analyses are put together for a representative and non-redundant overview. This compilation includes the most important seasonal sequences linked with prominent discharge events in the study area and leaves out those sequences that are only a slight modification of previously extracted sequences. Correspondingly, *EV* percentages specified in Figs 2–10 do not refer to the reproduced ensemble of seasonal pattern sequences, but to the corresponding gauge-related analysis from which they have been extracted for the following overview.

Summer

The circulation pattern sequence in advance of the extreme flood event in August 2002 proved to be, in general, a dominant factor for prominent discharge events in Central Europe, since it is the most important variable for the leading extended principal component of pattern sequences affecting this area (Fig. 2). It includes a cut-off low from an Icelandic trough moving to the northern Mediterranean and a cyclone track towards the northeast known since the late 19th century as van Bebbers cyclone track number Vb. It is also important for Austrian, Czech, Slovak and Polish river catchments and is quite often linked with distinct flooding events. Another prominent example from July 1997, affecting the Oder, Vistula and Morava river basins, was due to similar large-scale dynamics shifted only slightly more to the east. This type of flood-producing circulation pattern sequence is also known from other seasons, especially during the transitional periods.

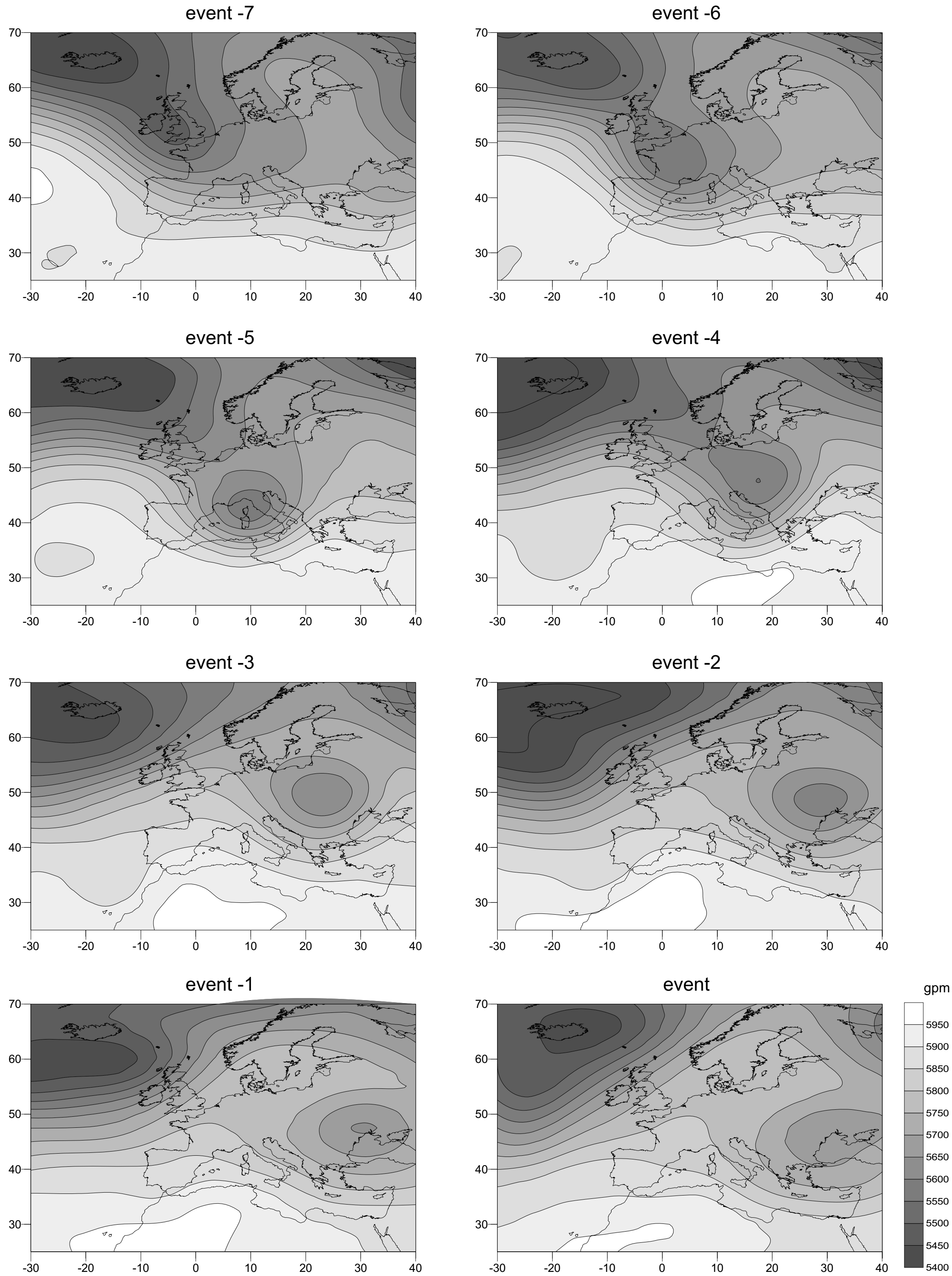

Fig. 2 Daily circulation pattern sequence (500-hPa level) starting seven days before a prominent discharge event in summer (units are geopotential height metres, gpm). This sequence from August 2002 has the highest loading (r = 0.77) on the first extended principal component (43.4% of explained variance, *EV*) derived from all sequences in advance of prominent discharge events during the summer seasons 1948–2002 at the Elbe River in Dresden (eastern Germany, see Fig. 1).

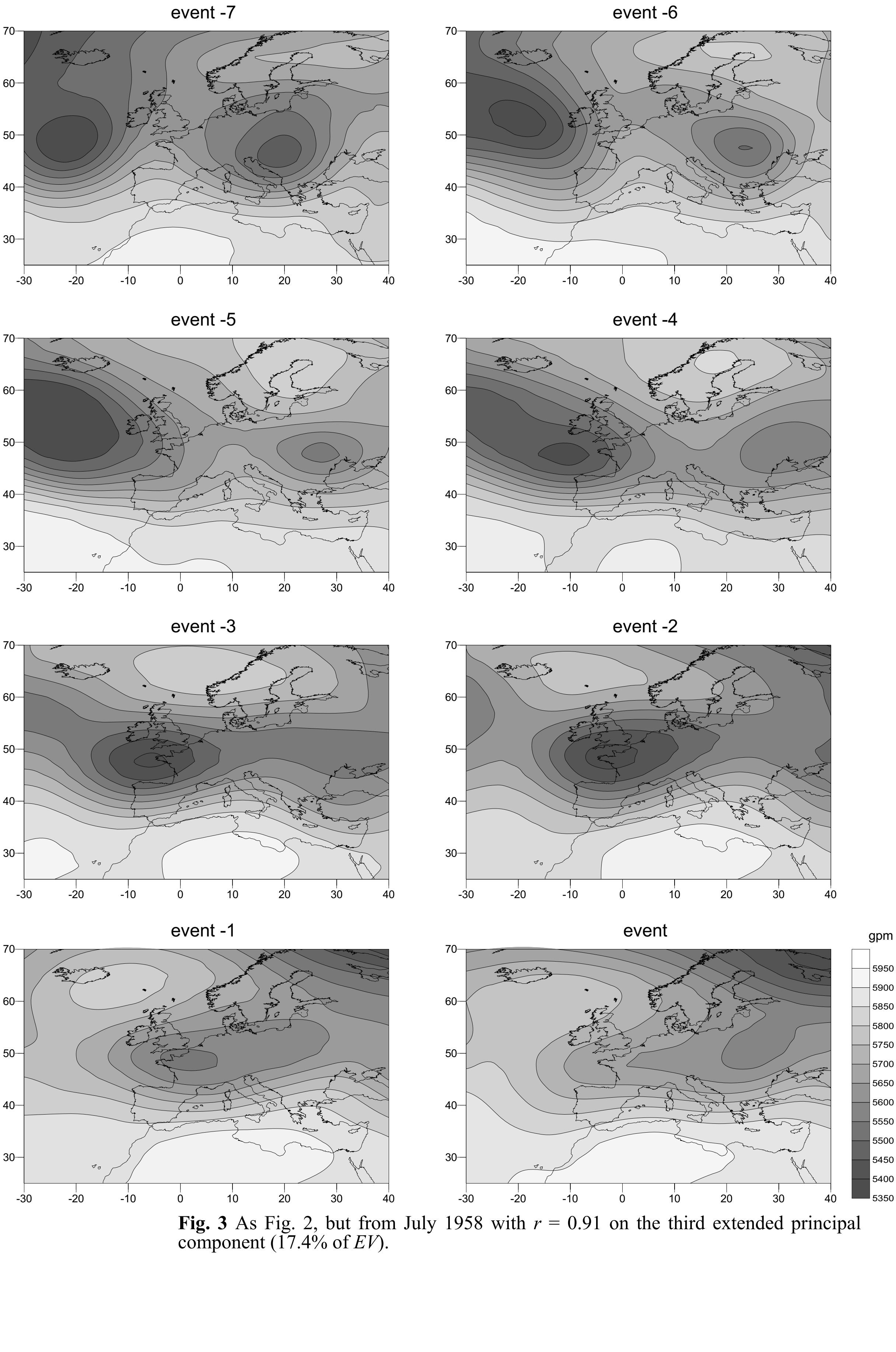

Fig. 3 As Fig. 2, but from July 1958 with r = 0.91 on the third extended principal component (17.4% of *EV*).

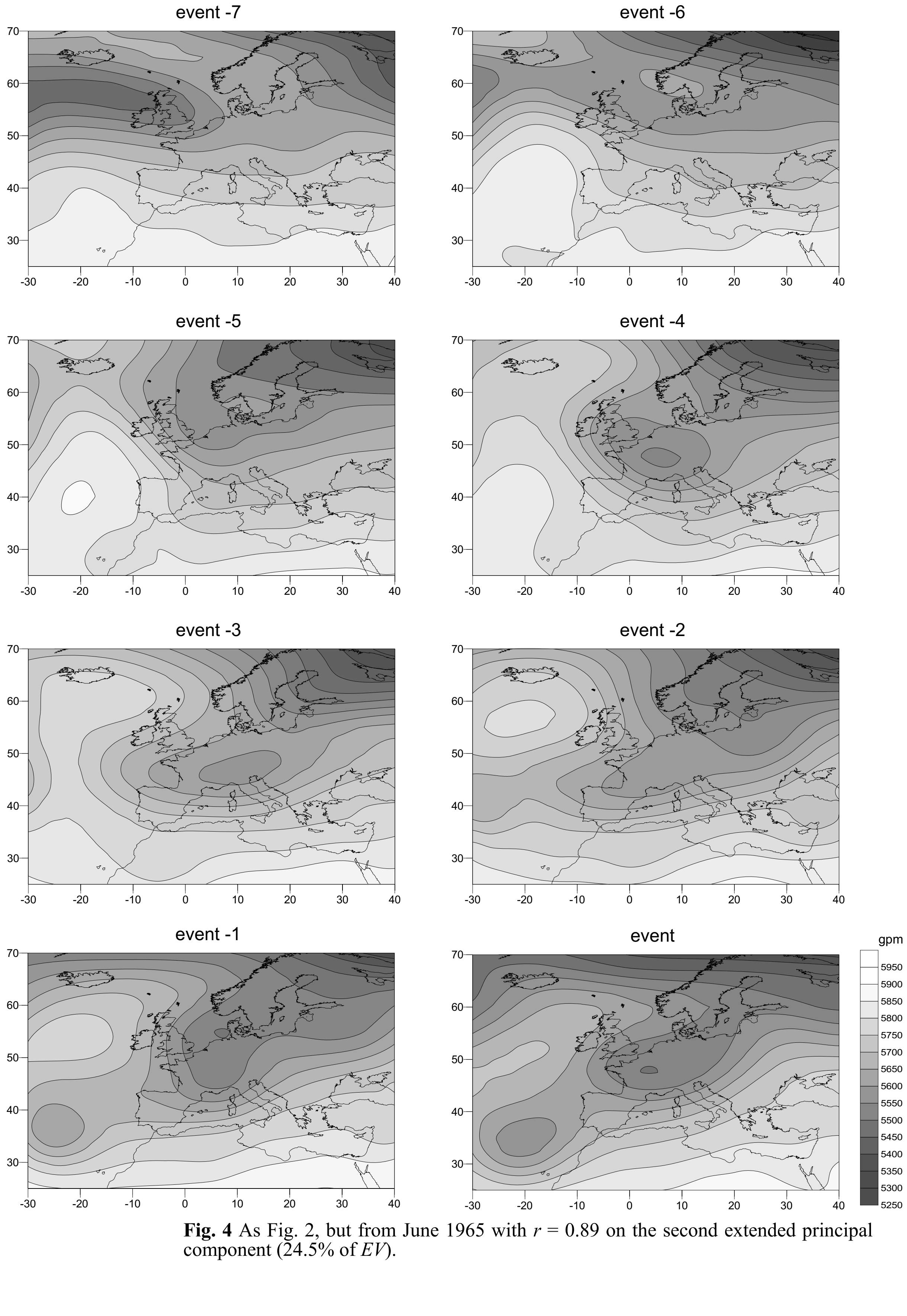

Fig. 4 As Fig. 2, but from June 1965 with $r = 0.89$ on the second extended principal component (24.5% of *EV*).

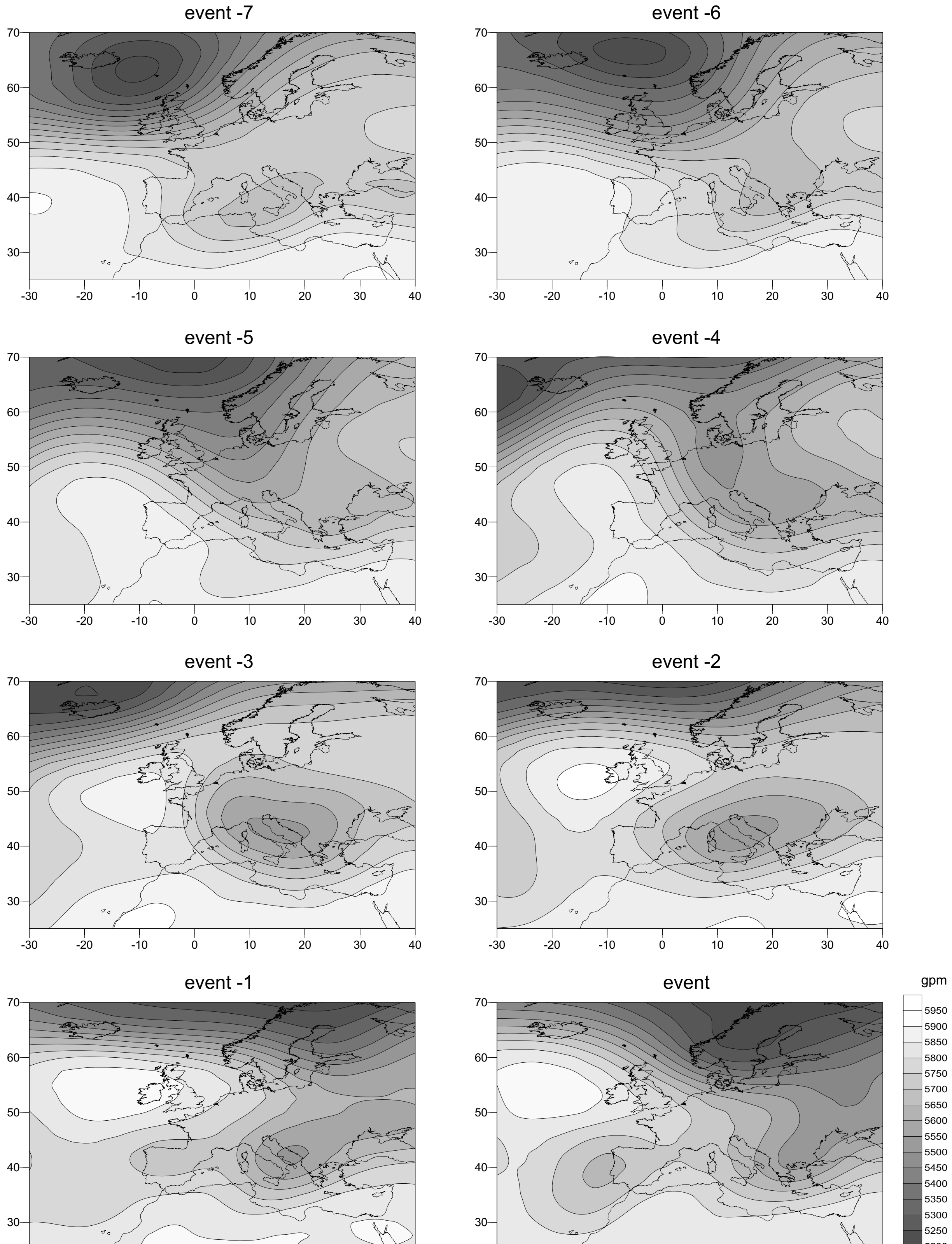

Fig. 5 As Fig. 2, but referring to the Danube River in Achleiten (southeast Germany, see Fig. 1). Sequence from June 1959 with $r = 0.79$ on the first extended principal component (27.6% of *EV*).

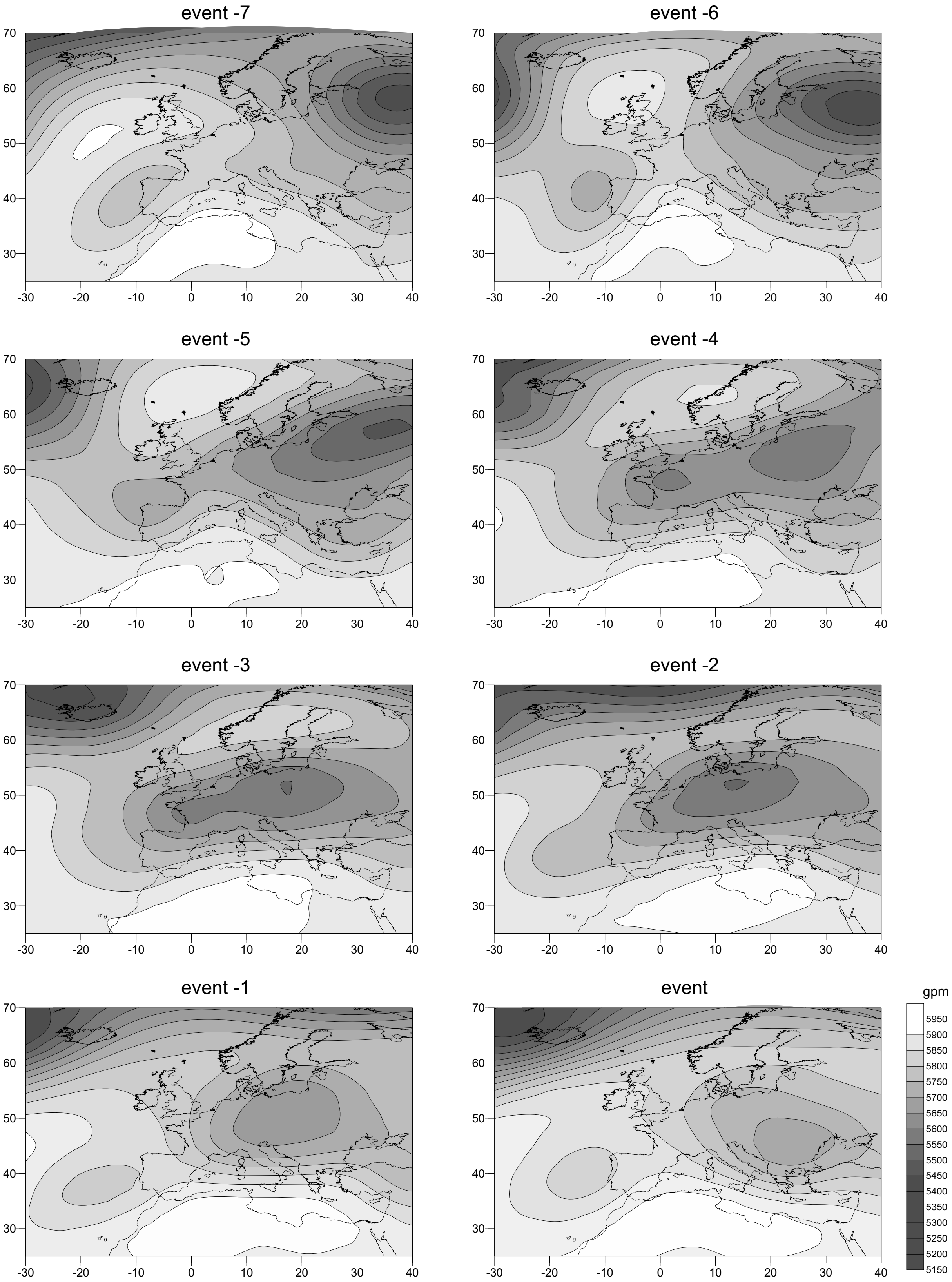

Fig. 6 As Fig. 2, but referring to the Rhine River in Rheinfelden (southwest Germany, see Fig. 1). Sequence from July 1955 with r = 0.79 on the third extended principal component (13.2% of *EV*).

The next type, shown in Fig. 3, depicts a sequence of several cyclones moving from west to east on a rather southerly track with respect to the summer season. This sequence, which occurs in a similar way during all seasons, affects not only the reference catchment of Fig. 3 (Elbe River), but also much of the southern part of Central Europe. In contrast, the third type of circulation pattern sequence, reproduced in Fig. 4, depicting cut-off lows from a cold pool in the northeast, is more important for eastern regions lying ahead of the upper cyclones. This circulation type is only linked with prominent discharge events during the warmer periods of the year.

The next type of circulation pattern sequence, shown in Fig. 5, referring to the Danube River near Passau, includes cut-off dynamics from the northwest, but, in contrast to Fig. 2, without developing a Vb cyclone track. The upper low remains in a rather southerly position and thus primarily affects the southeastern part of Central Europe. However, the last summer circulation pattern sequence (Fig. 6) also has impacts on more western regions (reference gauge on the Upper Rhine section), due to the merging of several lows to a major Central European cyclone of enhanced intensity. Modified NW–SE dynamics will recur during winter (see next sub-section).

Winter

As shown in Fig. 7, the most important pattern sequence for prominent discharge events during this season (not only in central Germany, but also in large parts of Central Europe) is not a pure westerly flow according to the positive mode of the NAO, but a strong cyclonic centre above northern Europe inducing repeatedly northwesterly components with enhanced positive vorticity above Central Europe. Similar patterns do account for a large part of strong precipitation events in this area during winter, as recently shown within the EU-project EMULATE (see http://www.cru.uea.ac.uk/projects/emulate referring to D15). In contrast, Fig. 8 includes – as a main factor for increasing discharge values – a strong low above the eastern Atlantic with Central Europe lying ahead within a distinct southwesterly flow. This implies warm and wet air advection with high precipitation – possibly accompanied by snow melting – and has already been identified on monthly time scales as a major factor for historical flood events, especially in western and central parts of the study area (Sturm *et al*., 2001; Wanner *et al*., 2004). However, it also occurs during the warm season (Jacobeit *et al*., 2004a), often decomposed into a sequence of west–east moving cyclones on a daily scale.

The next two pattern sequences (Figs 9 and 10) include further northwesterly flow configurations (somewhat differing from earlier summer patterns). In contrast to Fig. 7, however, they originate initially (events –7 and –6) from the Icelandic area and subsequently develop into a southeastward advancing low pressure configuration. An important difference between Fig. 9 and Fig. 10 is the longitudinal position of this cyclonic domain, primarily affecting the western and central parts in the former sequence and the eastern region in the latter sequence (compare the different reference gauging stations in both figures). Further pattern sequences for winter include essentially quite similar developments or southerly cyclone tracks already seen for summer (Fig. 3); they are not reproduced once more.

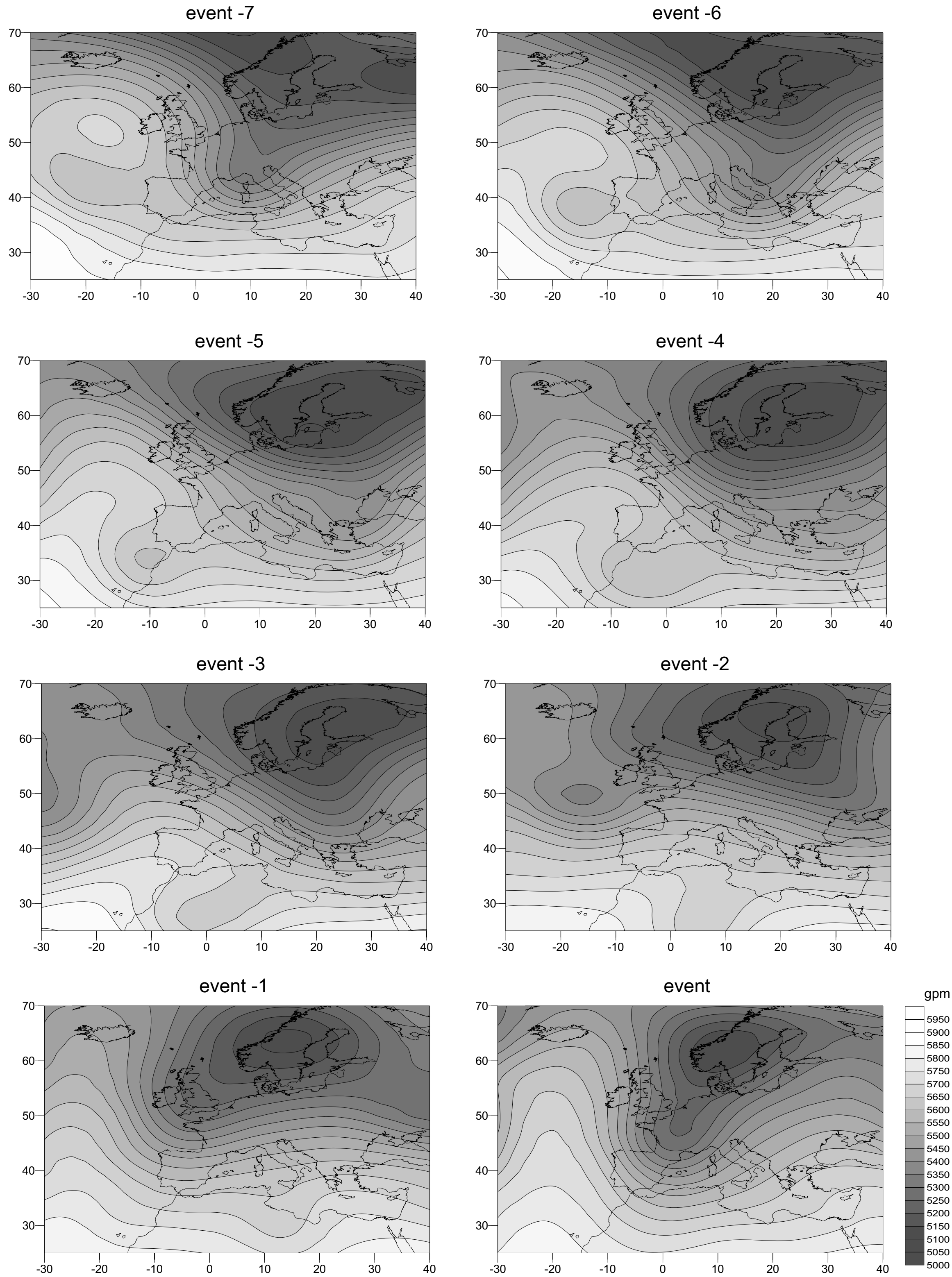

Fig. 7 Daily circulation pattern sequence (500-hPa level) starting seven days before a prominent discharge event in winter (units are geopotential height metres, gpm). This sequence from February 1958 has the highest loading (r = 0.79) on the first extended principal component (31.5% of *EV*) derived from all sequences in advance of prominent discharge events during the winter seasons 1948–2002 at the Weser River in Münden (central Germany, see Fig. 1).

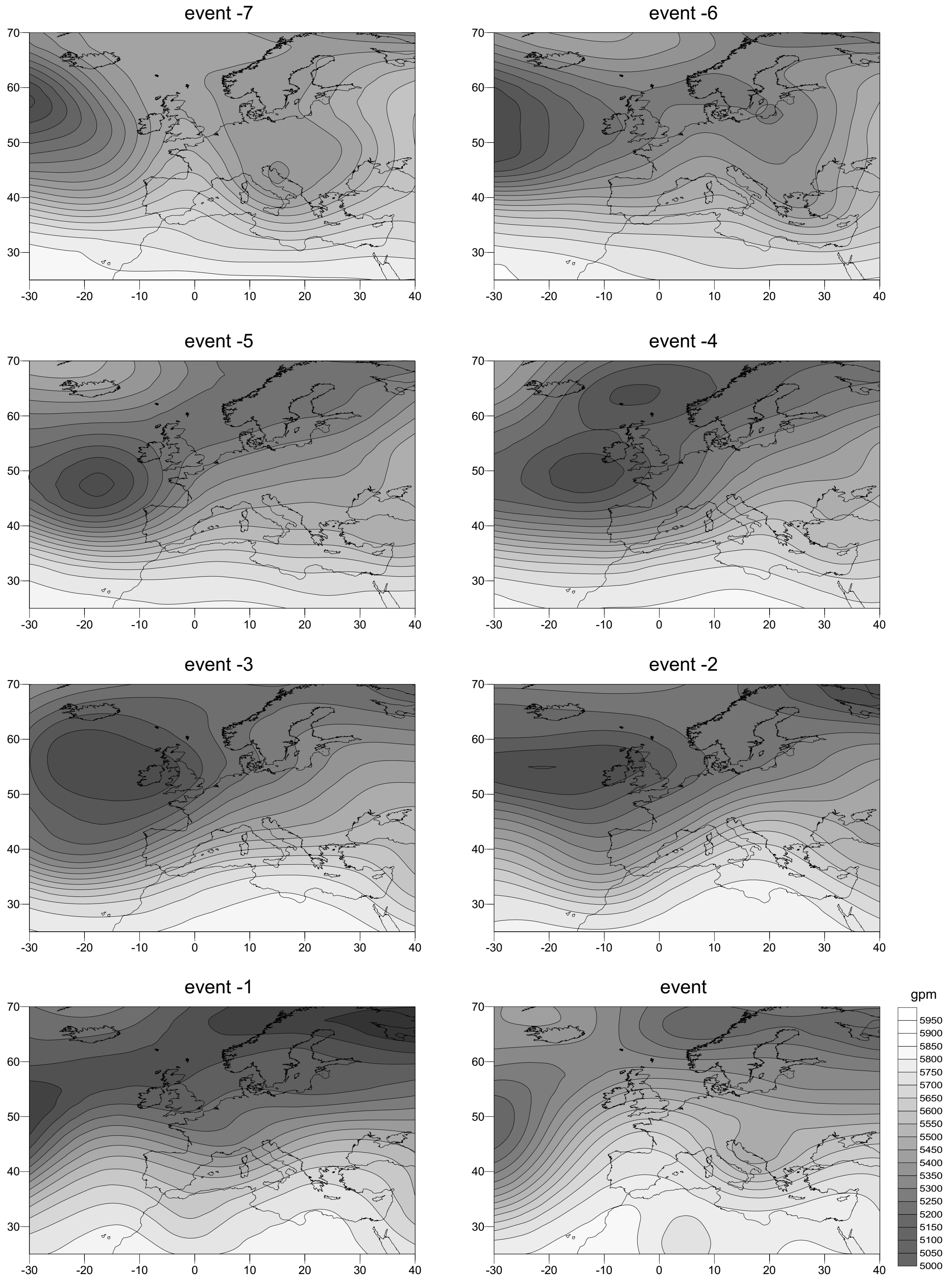

Fig. 8 As Fig. 7, but from January 1982 with $r = 0.89$ on the third extended principal component (27.8% of *EV*).

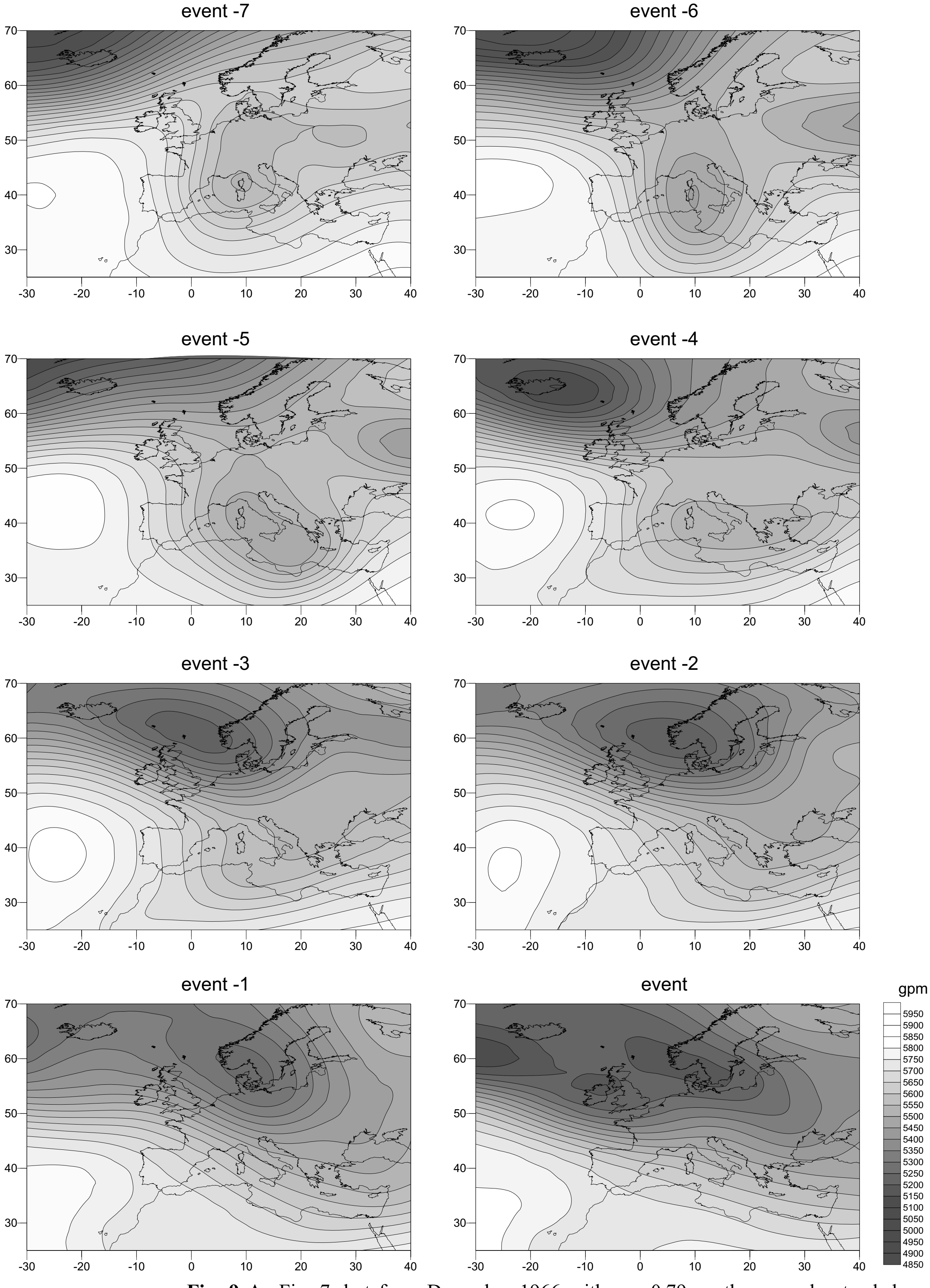

Fig. 9 As Fig. 7, but from December 1966 with r = 0.79 on the second extended principal component (29.7% of *EV*).

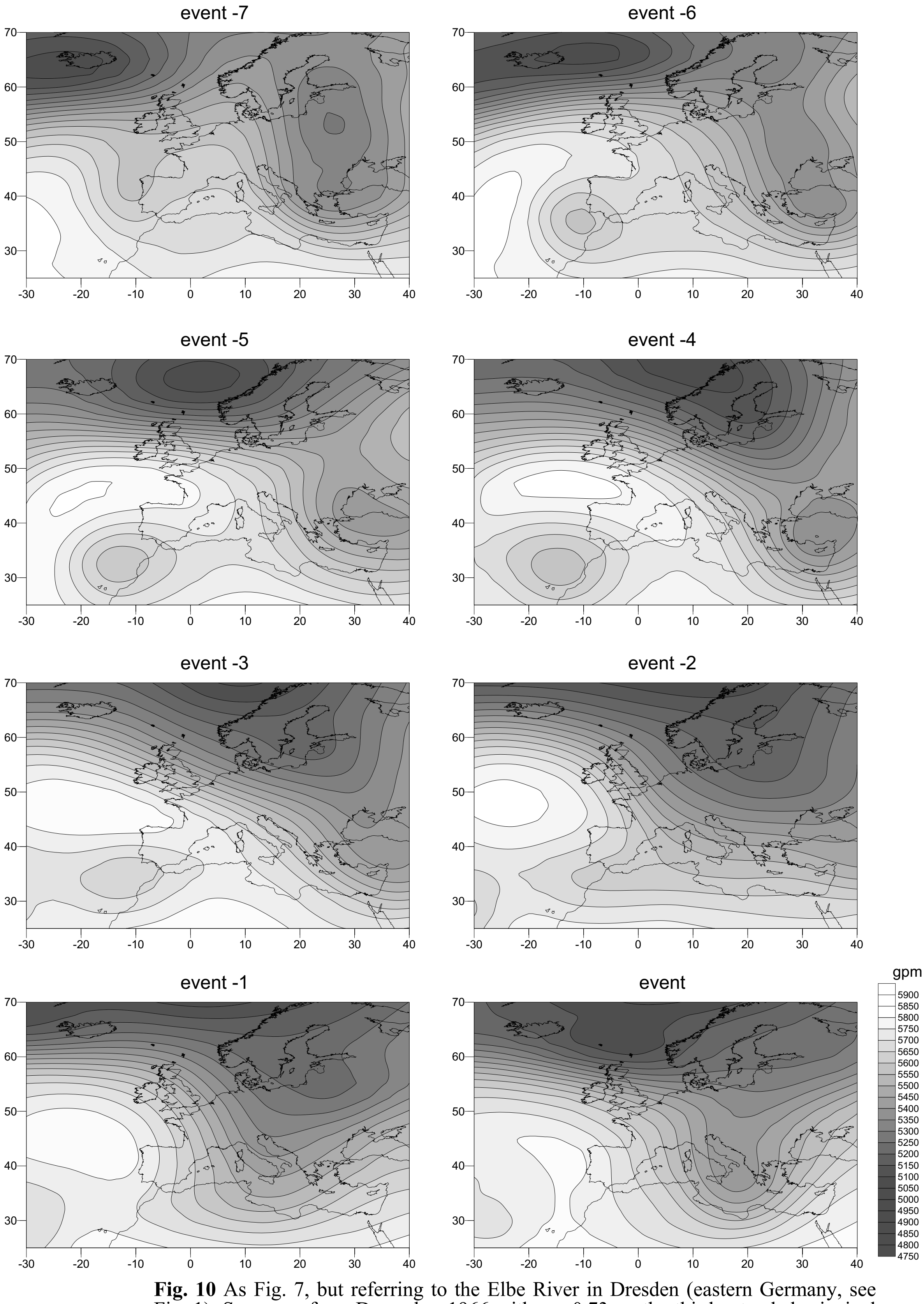

Fig. 10 As Fig. 7, but referring to the Elbe River in Dresden (eastern Germany, see Fig. 1). Sequence from December 1966 with $r = 0.73$ on the third extended principal component (25.1% of *EV*).

DISCUSSION AND CONCLUSION

Extended Principal Component Analysis is an appropriate tool, especially for studies on climate dynamics of prominent discharge events, since it is able to identify the decisive conditions for these events which are mostly operating some days before. Looking only at the day of the event, or at one particular day before, would not reveal the actual conditions as they appear in the dynamical sequences of Figs 2–10. This does not imply, however, that each daily sequence being significantly correlated with one of these pattern sequences, would definitely lead to a prominent discharge event. For example, the sequence of Fig. 11, which also includes a southeastward advancing cyclonic domain, similar (r = 0.71) to the extended patterns represented by Fig. 10, remained without a prominent discharge event due to a more eastern position of the cyclonic amplification. Another example from summer (Fig. 12) depicts a west–east sequence, similar (r = 0.71) to Fig. 3, but again without a prominent discharge event. In this case, a less intense cyclonic vorticity might have been responsible for the lower precipitation and discharge amounts, pointing to the important influence of within-type changes (Jacobeit *et al*., 2003d; Beck *et al*., 2006), which may decide whether or not enhanced discharge or even flooding will occur in the context of a particular circulation pattern sequence.

With respect to historical floods, this issue of within-type changes has been addressed earlier (Jacobeit *et al*., 2003a, 2004a), however, on a monthly scale, indicating particular conditions for basic circulation patterns either to favour or to dampen the development of synoptic disturbances leading to heavy rainfall and flood events. Results from the present study on a daily scale may be compared more easily with findings referring to circulation patterns derived from selected samples of months with the occurrence of historical flood events (Sturm *et al*., 2001; Wanner *et al*., 2004). Remarkably, there are some patterns on the monthly scale which reflect the main characteristics of some daily sequences derived from modern data: the southwesterly pattern ahead of an eastern Atlantic cyclone (Fig. 8) and the cyclonic wave with northwesterly flow towards Central Europe (Fig. 7). Obviously, these patterns may be sometimes strong enough or sufficiently persistent to become decisive for the monthly mean configuration. On the other hand, more transient cyclonic waves, as in Figs 9 and 10, cannot be expected to recur in monthly mean patterns. The same is true for pattern sequences with significantly changing configurations, such as in the case of Fig. 2 including the Vb cyclone track. Thus, more specific information drawn from daily resolved analyses cannot be attributed in a straightforward manner to monthly based results for historical periods unless more detailed indications about circulation dynamics on a sub-monthly scale are available for the entire historical data samples. However, results from daily resolved analyses may help to extend the dynamical background for an appropriate interpretation of historical flood events in terms of circulation dynamics.

The results from this study have indicated the most important circulation pattern sequences leading to prominent discharge events in Central Europe. They include, for the summer season, the well-known “Vb” dynamics, southerly west–east cyclone tracks, and different cut-off low dynamics (originating in northwestern as well as in northeastern source regions). For the winter season, the main types include a strong cyclonic centre above northern Europe (Central Europe with northwesterly flow), a

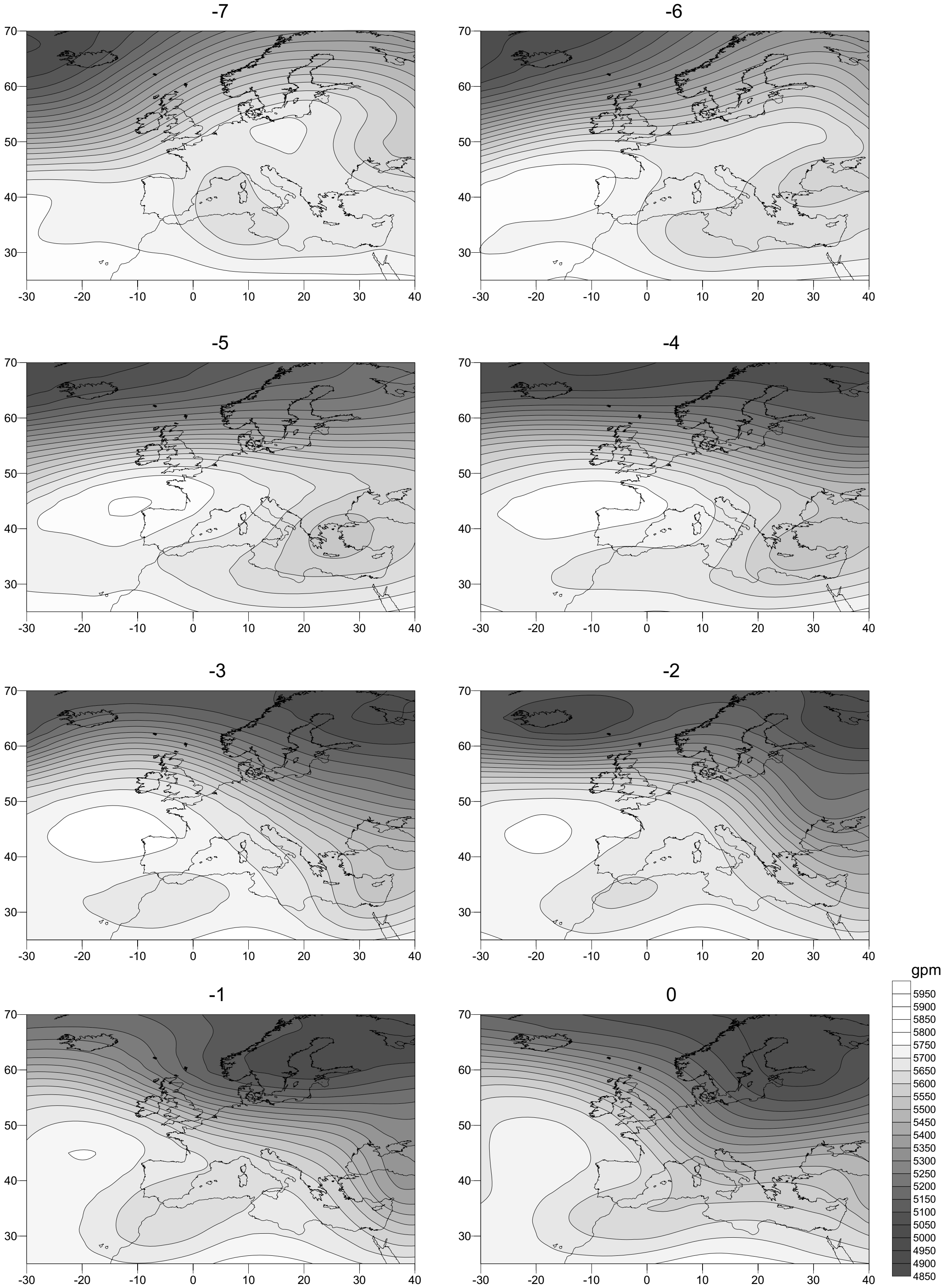

Fig. 11 Daily circulation pattern sequence (500-hPa level) from February 1949 being significantly correlated (r = 0.71 at the 95% confidence level) with the extended principal component represented by Fig. 10, but without a prominent discharge event at the end of the sequence.

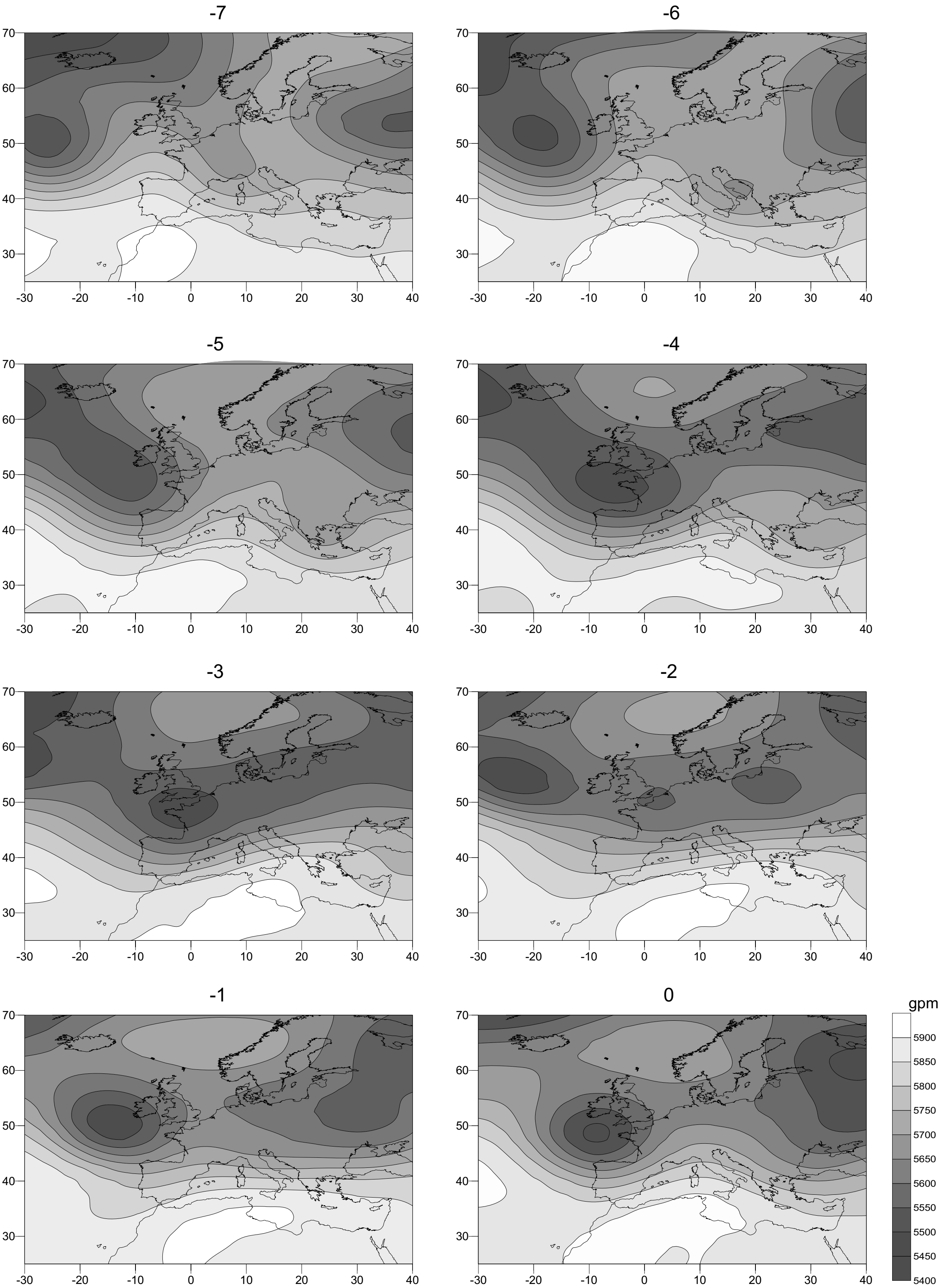

Fig. 12 Daily circulation pattern sequence (500-hPa level) from July 1956 being significantly correlated (r = 0.71 at the 95% confidence level) with the extended principal component represented by Fig. 3, but without a prominent discharge event at the end of the sequence.

strong low above the eastern Atlantic (Central Europe with southwesterly flow), southerly west–east cyclone tracks, and low pressure configurations of varying longitudinal position advancing from northwest to southeast.

To confirm the results of this study, a significant extension in time beyond the available 55-year period would be required. Daily discharge time series for a sufficient number of Central European gauging stations extend back well into the 19th century, but daily resolved geopotential height data are not available for earlier periods. However, if moving to SLP data, daily reconstructions back to the year 1850 are recently available from the EU-project EMULATE. Thus, future dynamical studies may be based on at least 150-year periods reaching back into historical times which have been analysed so far only on monthly time scales.

Acknowledgements Investigations were supported by the German Research Association (DFG, grant JA 831/1-2) and by the European Commission (EVK2-CT-2002-00161-EMULATE).

REFERENCES

Bardossy, A. & Filiz, F. (2003) Identification of flood producing atmospheric circulation patterns. In: *Palaeofloods, Historical Data and Climatic Variability: Applications in Flood Risk Assessment* (ed. by V. R. Thorndycraft, G. Benito, M. Barriendos & M. C. Llasat) (Proc. PHEFRA Workshop, Barcelona, 16–19 October 2002), 307–312. Centro de Ciencias Medioambientales (CSIC), Madrid, Spain.

Bardossy, A. & Filiz, F (2005) Identification of flood producing atmospheric circulation patterns. *J. Hydrol.* **313**, 48–57.

Beck, C., Jacobeit, J. & Jones, P. D. (2006) Frequency and within-type variations of North-Atlantic European circulation types and their effects on low-frequency climatic variability in Central Europe since 1780. *Int. J. Climatol.* (in press).

Brázdil, R., Dobrovolný, P., Elleder, L., Kakos, V., Kotyza, O., Květoň, V., Macková, J., Müller, M., Štekl, J., Tolasz, R. &Valášek, H. (2005a) *Historical and Recent Floods in the Czech Republic*. Masaryk University, Czech Hydrometeorological Institute, Brno, Prague, Czech Republic.

Brázdil, R., Pfister, C., Wanner, H., von Storch, H. & Luterbacher, J (2005b) Historical climatology in Europe – the state of the art. *Climatic Change* **70**, 363–430.

Caspary, H. J. (1995) Recent winter floods in Germany caused by changes in the atmospheric circulation across Europe. *Phys. Chem. Earth* **20**, 459–462.

Compagnucci, R. H., Araneo, D. & Canziani, P. O. (2001) Principal sequence pattern analysis: a new approach to classifying the evolution of atmospheric systems. *Int. J. Climatol.* **21**, 197–217.

Glaser, R. (2001) *Klimageschichte Mitteleuropas* (*Climate History of Central Europe*, in German). Wissenschaftliche Buchgesellschaft, Darmstadt, Germany.

Hirschboeck, K. K. (1988) Flood hydroclimatology. In: *Flood Geomorphology* (ed. by V. R. Baker, R. C. Kochel & P. C. Patton), 27–49. John Wiley & Sons Ltd, Chichester, UK.

Jacobeit, J., Glaser, R., Luterbacher, J. & Wanner, H. (2003a) Links between flood events in Central Europe since AD 1500 and large-scale atmospheric circulation modes. *Geophys. Res. Lett.* **30**, 1172–1175.

Jacobeit, J., Glaser, R., Luterbacher, J., Nonnenmacher, M. & Wanner, H. (2003b) Links between flood events in Central Europe since AD 1500 and the large-scale atmospheric circulation. In: *Palaeofloods, Historical Data and Climatic Variability: Applications in Flood Risk Assessment* (ed. by V. R. Thorndycraft, G. Benito, M. Barriendos & M. C. Llasat) (Proc. PHEFRA Workshop, Barcelona, 16–19 October 2002), 269–274. Centro de Ciencias Medioambientales (CSIC), Madrid, Spain.

Jacobeit, J., Nonnenmacher, M. & Philipp, A. (2003c) Atmosphärische Zirkulationsdynamik markanter Abflussereignisse in Mitteleuropa. *Terra Nostra* **2003/6**, 209–213.

Jacobeit, J., Wanner, H., Luterbacher, J., Beck, C., Philipp, A. & Sturm, K. (2003d) Atmospheric circulation variability in the North-Atlantic-European area since the mid-seventeenth century. *Climate Dynamics* **20**, 341–352.

Jacobeit, J., Glaser, R., Nonnenmacher, M. & Stangl, H. (2004a) Hochwasserentwicklung in Mitteleuropa und Schwankungen der atmosphärischen Zirkulation. *Geogr. Rundschau* **56**, 26–34.

Jacobeit, J., Glaser, R., Nonnenmacher, M. & Stangl, H. (2004b) Mitteleuropäische Hochwasserentwicklung im Kontext atmosphärischer Zirkulationsschwankungen. In: *Proc. Klimaänderung und Küstenschutz* (ed. by G. Gönnert, H. Graßl, D. Kelletat, H. Kunz, B. Probst, H. von Storch & J. Sündermann) (Hamburg, 2004), 31–41. GKSS Forschungszentrum, University of Hamburg and Hafenbautechnische Gesellschaft, Germany.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R. & Joseph, D. (1996) The NCEP/NCAR 40-year reanalysis project. *Bull. Am. Met. Soc.* **77**, 437–471.

Kistler, R., Kalnay, E., Collins, W., Saha, S., White, G., Woollen, J., Chelliah, M., Ebisuzaki, W., Kanamitsu, M., Kousky, V., van den Dool, H., Jenne, R. & Fiorino, M. (2001) The NCEP/NCAR 50-year reanalysis monthly means CD-ROM and documentation. *Bull. Am. Met. Soc.* **82**, 247–267.

Luterbacher, J., Xoplaki, E., Dietrich, D., Rickli, R., Jacobeit, J., Beck, C., Gyalistras, D., Schmutz, C. & Wanner, H. (2002) Reconstruction of sea level pressure fields over the eastern North Atlantic and Europe back to AD 1500. *Climate Dynamics* **18**, 545–561.

Mudelsee, M., Börngen, M., Tetzlaff, G. & Grünewald, U. (2003) No upward trends in the occurrence of extreme floods in central Europe. *Nature* **425**, 166–169.

Pfister, C. (1999) *Wetternachhersage: 500 Jahre Klimavariationen und Naturkatastrophen (1496–1995)* (*Weather Hindcasting: 500 Years of Climate Changes and Natural Catastrophes*, in German). Haupt, Bern, Switzerland.

Philipp, A. & Jacobeit, J. (2003) Das Hochwasserereignis in Mitteleuropa im August 2002 aus klimatologischer Perspektive (The floods in Central Europe in August 2002 from a climatological perspective, in German). *Petermanns Geogr. Mitt.* **147**, 50–52.

Richman, M. B. (1986) Rotation of principal components. *Int. J. Climatol.* **6**, 293–335.

Sturm, K., Glaser, R., Jacobeit, J., Deutsch, M., Brázdil, R., Pfister, C., J. Luterbacher, J. & Wanner, H. (2001) Hochwasser in Mitteleuropa seit 1500 und ihre Beziehung zur atmosphärischen Zirkulation (Floods in Central Europe since 1500 and their relationship to atmospheric circulation, in German). *Petermanns Geogr. Mitt.* **145**, 14–23.

Thorndycraft, V. R., Benito, G., Barriendos, M. & Llasat, M.C. (2003) *Palaeofloods, Historical Data and Climatic Variability: Applications in Flood Risk Assessment* (Proc. PHEFRA Workshop, Barcelona, 16–19 October 2002). Centro de Ciencias Medioambientales (CSIC), Madrid, Spain.

Ulbrich, U., Brücher, T., Fink, A. H., Leckebusch, G. C., Krüger, A. & Pinto, J. G. (2003a) The Central European floods of August 2002. Part I: Rainfall periods and flood development. *Weather* **58**(10), 371–376.

Ulbrich, U., Brücher, T., Fink, A. H., Leckebusch, G. C., Krüger, A. & Pinto, J. G. (2003b) The Central European floods of August 2002. Part II: Synoptic causes and considerations with respect to climatic change. *Weather* **58(**11), 434–441.

von Storch, H. & Zwiers, F. W. (1999) *Statistical Analysis in Climate Research*. Cambridge University Press, Cambridge, UK.

Wanner, H., Beck, C., Brázdil, R., Casty, C., Deutsch, M., Glaser, R., Jacobeit, J., Luterbacher, J., Pfister, C., Pohl, S., Sturm, K., Werner, P. C. & Xoplaki, E. (2004) Dynamic and socioeconomic aspects of historical floods in Central Europe. *Erdkunde* **58**, 1–16.

Weare, B. C. & Nasstrom, J. N. (1982) Examples of extended empirical orthogonal function analysis. *Monthly Weather Rev.* **110**, 481–485.