Surface Atmospheric Circulation Over Europe Following Major Tropical Volcanic Eruptions, 1780–1995

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We identify monthly circulation patterns of variability over the European continent within the first year after eight large tropical volcanic eruptions since the early 19th century. For this purpose, we apply an empirical orthogonal function (EOF) technique to a gridded sea level pressure data set covering the period 1780-1995. The post-eruption months with above-normal variance represented by the leading two EOFs are retained. Afterwards, we mapped their rotated equivalents to simplify physical interpretation of the results. Following the eight tropical eruptions, four months are identified during the first year fulfilling the criterion of exceptional values of variance in EOF1: January, June, July and September. January shows an anomalously dominant zonal pattern responsible for warmer temperatures over continental Europe. The summer months tend to show a more persistent south-westerly or westerly circulation over the continent, indicating a likely reduction in the strength of the Azores high. The results showing modification of the atmospheric circulation following large volcanic eruptions are consistent with previous studies based on instrumental records for more recent periods. This underscores the robustness of the circulation changes as a response to volcanic forcing. The analysis also demonstrates that empirical orthogonal functions provide a useful tool to detect these dynamical features.

1. INTRODUCTION

The definition of the temporal and spatial nature of climate change is an important issue to help understand the main causes of climatic variations. External forcing factors, such as changes in solar irradiance output and volcanic eruptions are among the natural causes of variability, while atmosphere-ocean interactions (e.g. the El Niño-Southern Oscillation phenomenon) are well known internal factors [*Parker and Folland*, 1988; *Lean et al.*, 1995]. Jointly with natural external forcing, human activities are a continuously increasing source of variability, i.e. the anthropogenic climate forcing factor, altering the radiative balance of the Earth's atmosphere and surface. It is essential to understand how such factors affect the climate system, identifying, if possible, the temporal and spatial responses, and the magnitude of the signal of each.

In this paper we focus on the effects of one of these sources of natural variability: volcanic eruptions. Aerosols injected into the lower stratosphere by explosive eruptions

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10.1029/139GM18

cause stratospheric warming and cooling at the surface for 2 to 3 years following the main events, due to the decrease in incoming solar radiation [*Sear et al.*, 1987; *Robock and Mao*, 1995; *Jones and Kelly*, 1996; *Ammann*, 2001]. In spite of this global impact, there are seasonal and regional differences in the response of the climate system. The first two winters following a large tropical eruption tend to be warmer over the Northern Hemisphere (NH) continental regions, due to advective effects which dominate over the radiative effects, while the opposite is the case in summer, leading to cooling over the same areas [*Groisman*, 1992; *Robock and Mao*, 1992, 1995]. These warm and cool anomalies indicate a dynamic response of the climate system to volcanic aerosols [*Graf et al.*, 1993, 1994; *Kodera*, 1994; *Kirchner et al.*, 1999]. Volcanic particles (dust and aerosols) heat the tropical lower stratosphere affecting the vertical temperature gradient. This, enhances the North Polar vortex in the lower stratosphere, the westerlies in the Northern Hemisphere winter, and the North Atlantic Oscillation (NAO) pattern [*Hurrell*, 1995], also referred to as the Arctic Oscillation (AO) pattern [*Thompson and Wallace*, 1998].

Here we analyze the surface circulation response to this dynamic mechanism created by major volcanic events over Europe during the 19th and 20th centuries.

2. DATA SOURCES AND METHODOLOGY

2.1. Data

In a European Community-funded research project, ADVICE (Annual-to-Decadal Variability In Climate in Europe), monthly sea level pressure (SLP) data were recovered and homogenised from 51 stations across Europe since 1780 [*Jones et al.*, 1999]. The resulting data set consists of monthly reconstructions of gridded (5º latitude by 10º longitude grid containing 60 grid points) SLP data encompassing the region 70ºN–20ºW to 35ºN–40ºE and covering the period 1780–1995. The reconstructions were generally of excellent quality, although in those regions with weak station coverage during the early years, a decrease in data quality was detected, especially for the summer [*Jones et al.*, 1999]. Figure 1 shows the spatial distribution of the grid points over Europe.

2.2. Selected Volcanic Events

The amount of sulfur into the stratosphere rather than the magnitude of the eruption has the main influence on global climate [*Rampino and Self*, 1984; *Pinto et al.*, 1989]. As a result, records of past explosive volcanism can be constructed from sulfate deposits identified in ice cores [*Hammer et al.*, 1980; *Zielinski*, 1994, 1995]. *Robock and Free* [1995, 1996] designed a new index of volcanic aerosol loading, the Ice core Volcanic Index (IVI), firstly for the period 1850 to the present, and finally for the past 2000 years. This new index correlated well with other indices already available: the Dust Volcanic Index (DVI) [*Lamb*, 1970, 1977, 1983] and the Volcanic Explosivity Index (VEI) [*Newhall and Self*, 1982]. On the basis of the information provided by these chronologies, eight tropical volcanic eruptions were selected (see Table 1).

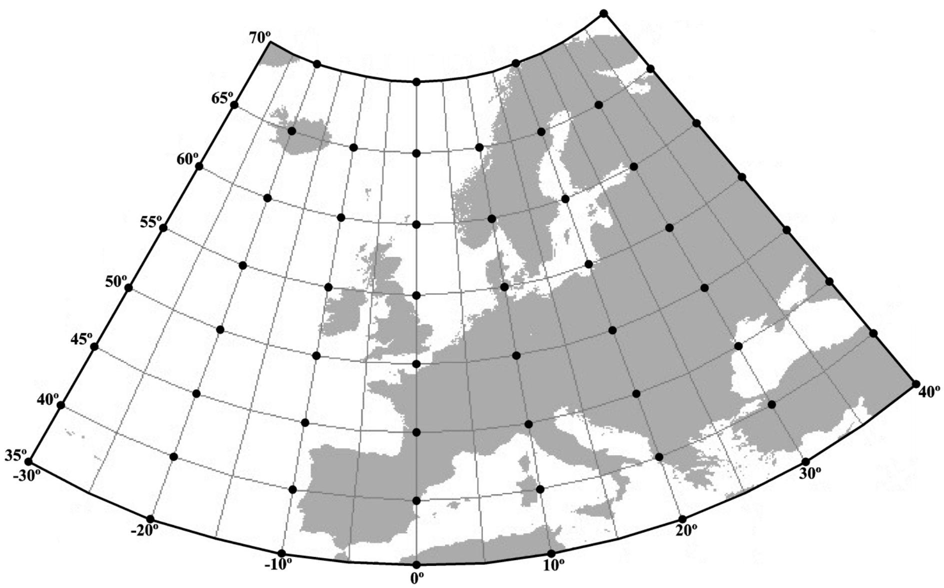

Figure 1. Spatial distribution of grid points containing monthly SLP data used in the analysis (dot points).

Table 1. Tropical Volcanic Eruptions Considered in this Study.

Volcano	Latitude	Longitude	Eruption date	DVI	VEI	IVI
unknown	tropical	?	?, 1808	1500	6	5.6
Tambora	8ºS	118ºE	April, 1815	3000	7	15.0
Coseguina	13ºN	87.5ºW	January, 1835	4000	5	3.2
Cotopaxi	1ºS	78ºW	?, 1856	700	5	na
Krakatau	6ºS	105.5ºE	August, 1883	1000	6	3.7
Santa María	14.5ºN	92ºW	October, 1902	900	6	1.6
El Chichón	17ºN	93ºE	April, 1982	800	5	1.9
Mt. Pinatubo	15ºN	120ºE	June, 1991	>1000	6	4.0

DVI (Dust Volcanic Index), VEI (Volcanic Explosivity Index), IVI (Ice core Volcanic Index).
na, not available

The tropical event of 1808 was revealed from high-resolution analyses of ice cores from Antarctica and Greenland [*Dai et al.*, 1991], although originally assigned to 1809. Documentary [*Chenoweth*, 2001] and coral [*Crowley et al.*, 1997] data suggested the previous year as the most probable eruption year, so 1808 was used in this study. In contrast, the Agung (1963) eruption was not considered because at least two thirds of the aerosol cloud had spread to the Southern Hemisphere [*Volz*, 1970; *Sato et al.*, 1993]. Extra-tropical eruptions were also excluded.

2.3. Methodology

Once the key dates of the eruptions were selected, an Empirical Orthogonal Function (EOF) analysis was performed for the post-eruptive months. EOF analysis is a recognized multivariate technique used to derive the dominant patterns of variability on an original data set of *N* observations and *M* variables, in other words, to simplify this data set (i.e. obtain a new set of variables) for purposes of interpretation and understanding [*Yarnal*, 1993; *Barry and Carleton,* 2001]. It has been widely used in climatology, especially to identify characteristic spatial patterns of variability in temperature and rainfall [*Kelly et al.*, 1982; *Folland et al.*, 1991], and also to identify the volcanic signal in global surface temperature records [*Jia and Kelly*, 1996]. We used the explained variance of every new variable or component of the EOF analysis (i.e. eigenvalues) as a criterion to detect changes in the persistence of the circulation patterns following large tropical volcanic events. Firstly, the non-rotated EOFs were calculated using the S-mode data matrix of 60 variables (grid points of SLP data) and 8 observations (post-volcanic years, on a monthly basis), via correlations of the standardized variables, looking at the resulting amount of variance represented by the first and the second components (EOF1 and EOF2). The second step involved a random selection of 100 sets of eight years each, from the whole data set used (1780–1995), again obtaining (via S-mode data matrix and correlations) the non-rotated EOFs for each set (on a monthly basis), and retaining the percentage of variance of EOF1 and EOF2. The reason for paying attention to the percentage variance of both principal components is based on the principle that the higher amount of variance represented by the first component is related to the most persistent spatial pattern of variability for a certain month. In the same way, the second highest amount of variance (EOF2) is related to the second most persistent spatial pattern, being uncorrelated (orthogonal) to EOF1. By comparing the values of explained variance of EOF1 and EOF2 for the post-eruptive months with the corresponding EOF1 and EOF2 values taken from the 100 random-year sample, we evaluate changes in the persistence of the spatial patterns. By the calculation of the mean and the thresholds determined by the 90th and 10th percentile from the 100 random-year sample, we can detect those months with anomalous persistence of a given pattern above and below the normal values.

Finally, a VARIMAX rotation of EOFs was performed to obtain more coherent and uncorrelated spatial patterns [*Richman*, 1986]. Nevertheless, the opinion in the community is divided on the subject of rotation. While some scientists argue that rotation produces more stable and compact patterns that can be used for ‘regionalization,’ others criticize drawbacks like the arbitrary choice of rotation criterion or the sensitivity of the result to the normalization [*Von Storch and Zwiers*, 1999]. In the present study, the non-rotated and the VARIMAX-rotated EOFs were computed separately from the correlation matrix and represented physically (not shown). Although the rotation did not greatly simplify the spatial patterns obtained, the rotated patterns were used for the physical interpretation of the results.

3. RESULTS

We started the analysis in the first winter following major volcanic eruptions, as most of the events occurred in the first half of the year. Four post-eruptive months were detected showing high levels of anomalous variance represented by EOF1, January (+1), June (+1), July (+1), and September (+1), while December (+1) was the only month showing extremely low levels of anomalous variance (table 2). In order to evaluate whether most of the change affects only EOF1, we also looked for possible anomalies in the variance in EOF2, detecting just two months with high values of variance: May (+1) and June (+1) (table 3). As our research is concerned with identifying those months showing a more persistent pattern, and since most of the changes affect the corresponding first post-eruptive components, we have only plotted the maps for those months exceeding the 90th percentile threshold in EOF1 (figures 2 to 5). Extremely high and low amounts of variance in EOF1 and EOF2 were not found in the second year following the events.

The strongest signal is detected in January (+1) (see Figure 2). The first EOF for this month, accounting for 64% of the variability in the pressure field of the domain, represents a mode with a dipole structure, with strong weights in the extreme northeast of opposite sign to those in the southwestern half. The positive phase of this spatial pattern is associated with strong westerly/northwesterly flow across Europe, while the negative phase represents a reduction of the zonal component of the circulation. This kind of circulation, typical of the mid-latitudes and well-established in winter, might be linked to the NAO [*Walker and Bliss*, 1932; *Barnston and Livezey*, 1987; *Hurrell*, 1995; *Slonosky et al.*, 2000], and to the AO [*Thompson and Wallace*, 1998]. Nevertheless, in the post-eruptive Januaries this pattern seems to be more persistent, showing a detectable strengthening of the Azores high, as there are no negative values to the south and, as a result, increased tropospheric westerlies at 60ºN. This is consistent with previous studies of NH tropospheric mid-latitude circulation after violent volcanic eruptions that reported a strengthening of the polar stratospheric vortex and geopotential height anomalies of the 500 hPa layer [*Graf et al.*, 1994; *Kodera*, 1994]. This mechanism is explained by the heating of the tropical lower stratosphere by absorption of terrestrial and near-IR radiation, resulting in an enhanced pole-to-equator temperature gradient and in a more gentle surface temperature gradient [*Robock*, 2000; *Stenchikov et al.*, 2002]. The stationary NAO or AO pattern dominates the winter circulation, creating the winter warming shown by observations [*Groisman*, 1992; *Robock and Mao*, 1992, 1995; *Jones and Kelly*, 1996] and modeling [*Graf et al.*, 1993; *Mao and Robock*, 1998], over NH continental areas.

Two summer months were detected with anomalous persistent patterns represented by the first eigenvectors: June (+1) (Figure 3) and July (+1) (Figure 4). In June, the pattern seems to show a strong southwesterly circulation over the British Isles that has been identified as the 'European monsoon' by *Kelly et al.* [1997]. This pattern is established in mid-June and consists of the southwards displacement of

Table 2. Results of the EOF1 Analysis.

Months	Variance represented by EOF1 and for the post-volcanic months, %	Average variance represented by EOF1 obtained from 100 sets of 8 years randomly selected, %	90th percentile threshold fixed by EOF1 obtained from 100 sets of 8 years randomly selected, %	10th percentile threshold fixed by EOF1 obtained from 100 sets of 8 years randomly selected, %
DEC (0)	40.9	43.8	50.8	37.6
JAN (+1)	**63.6**	**48.8**	**58.0**	**39.8**
FEB (+1)	49.6	50.0	58.3	40.6
MAR (+1)	50.7	47.4	55.4	38.6
APR (+1)	40.8	43.0	51.4	36.0
MAY (+1)	41.9	41.5	48.2	35.3
JUN (+1)	**52.7**	**42.1**	**49.4**	**33.3**
JUL (+1)	**48.5**	**40.4**	**46.0**	**34.4**
AUG (+1)	40.3	42.4	50.2	35.2
SEP (+1)	**51.7**	**41.6**	**49.4**	**35.1**
OCT (+1)	45.7	42.0	47.8	36.1
NOV (+1)	45.6	44.3	51.4	38.2
DEC (+1)	*37.4*	*43.8*	*50.8*	*37.6*

First column shows post-eruptive months, where 0 indicates the year of the eruption and +1 the first year following the eruption. In bold, those months exceeding the 90th percentile threshold from the EOF1, and in italics those months below the 10th percentile threshold (see text for additional information).

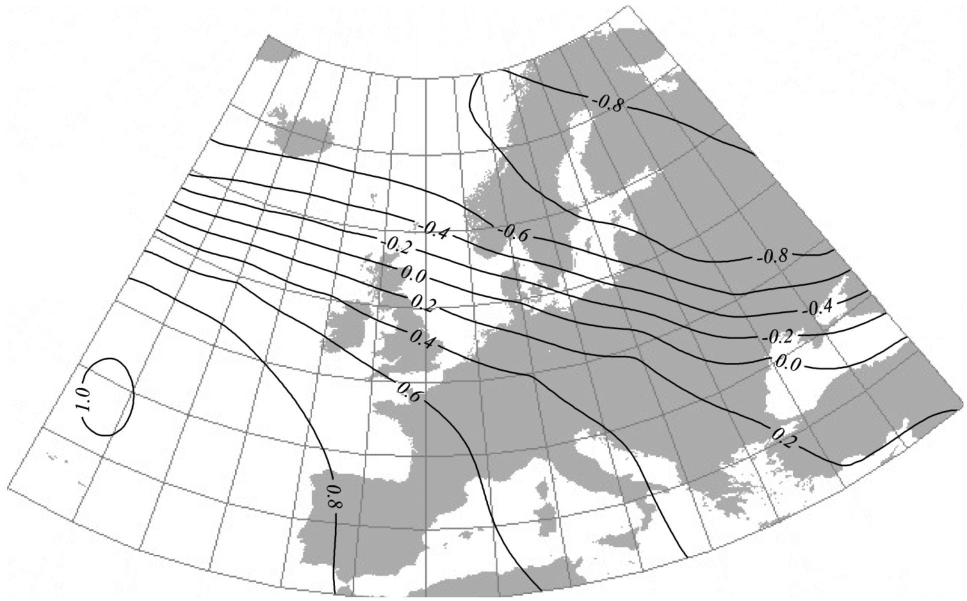

Figure 2. Spatial pattern of rotated EOF1 for January (+1) (64%). Contours represent spatial weights (units are arbitrary).

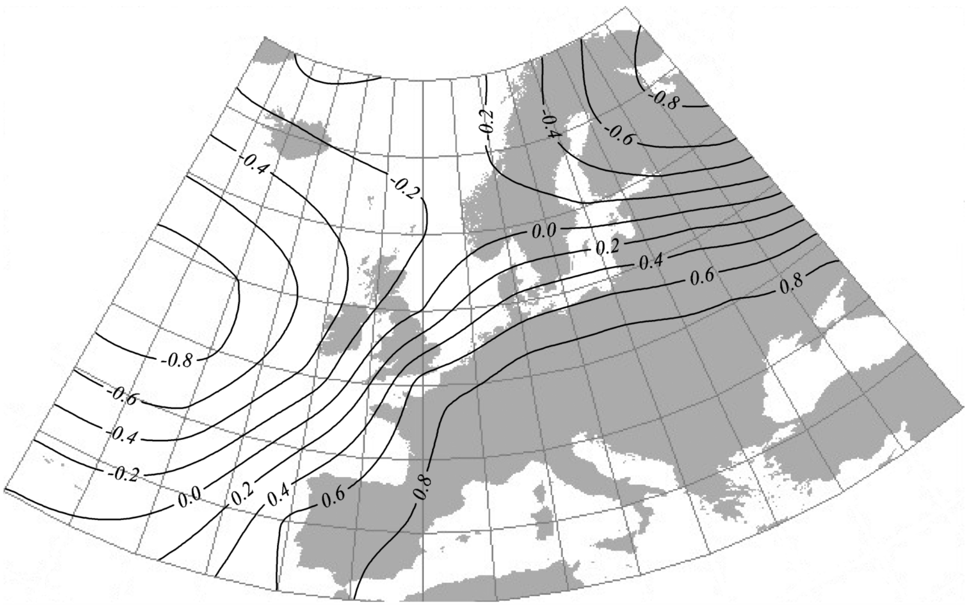

Figure 3. Spatial pattern of rotated EOF1 for June (+1) (53%). Contours represent spatial weights (units are arbitrary).

the upper westerlies, with a formation of stationary wave over the Atlantic. This kind of circulation ensures frequent precipitation over the British Isles. In addition, June is the only post-eruptive month showing significant changes in the amount of variance in the first two components (see tables 2 and 3), indicating that most of the variability is represented by just two spatial patterns. In July (Figure 4) a well-established dipole structure suggesting a reduction of the strength of the Azores high is represented. Such a pattern could be associated with colder summers over central and northern Europe, as has been reported by other studies [*Briffa et al.*, 1990; *Jones et al.,* 1995; *Briffa et al.*, 1998].

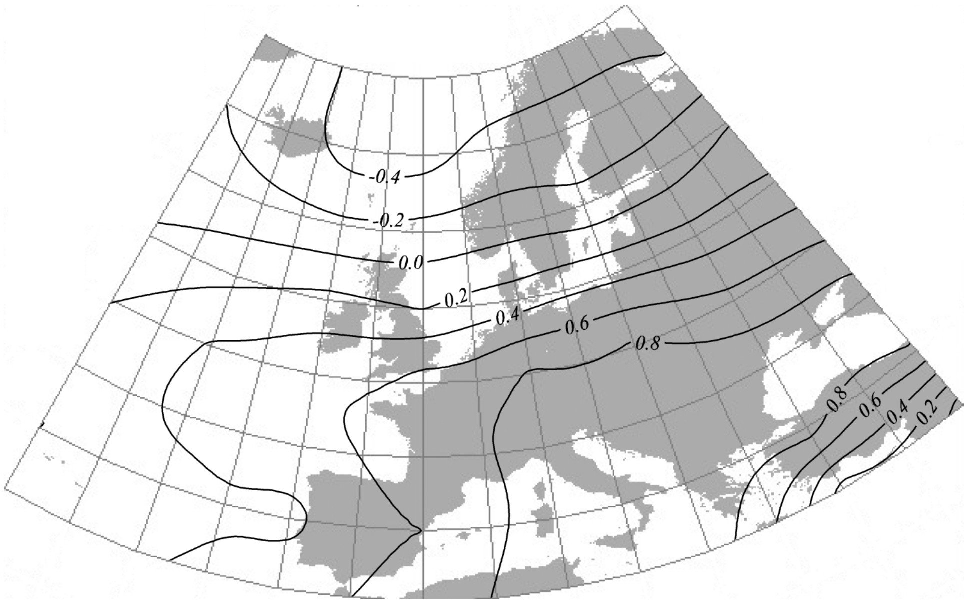

Figure 4. Spatial pattern of rotated EOF1 for July (+1) (49%). Contours represent spatial weights (units are arbitrary).

Table 3. Results of the EOF2 Analysis.

Months	Variance represented by EOF2 and for the post-volcanic months, %	Average variance represented by EOF2 obtained from 100 sets of 8 years randomly selected, %	90th percentile threshold fixed by EOF2 obtained from 100 sets of 8 years randomly selected, %	10th percentile threshold fixed by EOF2 obtained from 100 sets of 8 years randomly selected, %
DEC (0)	28.3	29.2	33.3	24.1
JAN (+1)	22.9	28.1	33.6	21.8
FEB (+1)	34.2	27.8	34.5	21.4
MAR (+1)	28.4	27.5	32.4	22.6
APR (+1)	24.7	26.2	32.2	20.8
MAY (+1)	**30.2**	**25.6**	**30.2**	**21.1**
JUN (+1)	**30.8**	**26.0**	**30.3**	**20.9**
JUL (+1)	24.2	26.5	31.5	21.8
AUG (+1)	24.9	26.4	31.3	22.4
SEP (+1)	24.9	26.0	30.3	21.0
OCT (+1)	26.3	28.0	32.8	23.3
NOV (+1)	25.3	27.6	32.5	23.4
DEC (+1)	26.8	29.2	33.3	24.1

As in table 2 but for EOF2.

EOF1 for September (+1) (Figure 5) shows a less structured spatial pattern. Again, a dipole structure is identified, with strong weights in the central part of the domain and in the Iberian Peninsula sector. This EOF suggests an anomalous northerly or southerly circulation over the western Mediterranean basin.

Finally, as reported before, December (+1) shows very low values of EOF1, probably indicating a less stable dominant pattern.

4. DISCUSSION AND CONCLUSIONS

Surface atmospheric circulation anomalies over most of Europe following eight large equatorial eruptions were studied. EOF analysis has demonstrated that during the first post-eruptive year, four months show more dominant patterns than normal, as revealed by the high amount of variance represented by the first eigenvectors. The circulation regime for January represents a higher persistence of zonal

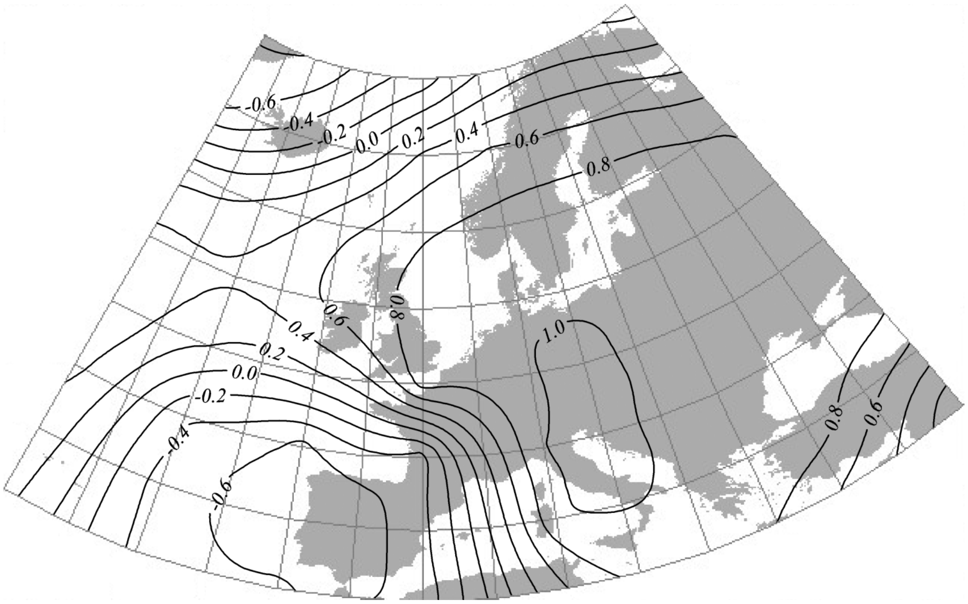

Figure 5. Spatial pattern of rotated EOF1 for September (+1) (52%). Contours represent spatial weights (units are arbitrary).

flow over the region, linked with a strengthening of the Azores high which probably forces a displacement of the axis towards the north (60ºN). This could be associated with a more persistent positive phase of the NAO pattern, as reported by other studies [*Ammann*, 2001]. In addition, this kind of circulation prevents cold air outbreaks and stops polar air reaching Central Europe, but it could also have consequences for rainfall distribution. Dry winters were reported over Iberia following major volcanic events in the 20th century, probably linked to the persistent location of the Azores high over the southwestern sector of the domain [*Prohom and Bradley*, 2002].

In June the circulation pattern suggests a more frequent southwesterly flow over the British Isles, perhaps associated with a more frequent 'European monsoon', while a zonal regime seems to be well-established in July. The dominance of the Azores high, which is reduced in years after large tropical eruptions, would ensure the penetration of more frequent cyclones with frontal systems, causing both cooler and wetter conditions. Finally, a strong dipole pattern is present in September, with negative anomalies over western Iberia and positive anomalies towards the Adriatic sea. This situation would indicate increased cyclonic flows over the southwestern corner of Europe and drier conditions over eastern Europe.

The signals detected in this study are consistent with observations and some model studies (particularly the winter). Thus, the extension of the record back into the early 19th century confirms (at least on average) earlier findings, and therefore strengthens the link from the stratospheric perturbation to tropospheric and surface circulation changes. The results also highlight summer cooling and winter warming over the mid to high latitudes in the European sector. In spite of these promising findings, we caution against making more conclusive statements as a consequence of the small number of volcanic cases considered and the limitations of the EOF analysis. For this reason, it is essential to increase efforts to develop new and better *proxy data* and more precise statistical techniques to detect the volcanic signal above the background noise.

Acknowledgments. This work was partially supported by the Spanish research project CICYT REN2001-2865-C02-01 and by the Scientific Park of Barcelona (University of Barcelona). In addition, the original data collection was undertaken as part of the European Commission project ADVICE, ENV4-CT95-0129. We also thank an anonymous reviewer for comments.

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