CHAPTER 6 – DISCUSSION AND CONCLUSIONS

In the preceding chapters, the likely influence of major volcanic eruptions on Iberian and Balearic climate has been analysed. Although the hemispheric and global incidence of the volcanic forcing is clear, the regional scale impact remains unclear, particularly over the south-western corner of Europe. The results exposed confirm that the climate of the Iberian Peninsula and the Balearic Islands shows a detectable response to this forcing mechanism.

6.1. IMPACT ON TEMPERATURE

This is the climate element most extensively analysed, given its easy regionalization and its wider temporal and spatial coverage of the dataset. At a hemispheric scale (NH) and/or global scale, cooling is detected in the two to three years following a large volcanic event. Whilst the individual eruptions show a lot of variability in the timing of the cooling (partly because the eruptions occur at different times of the year), the average of all the events shows significant cooling for many of the months in the subsequent three years.

Our research area exhibits a detectable thermic response, once the Superposed Epoch Analysis (SEA) is applied. The use of this technique allows us to compare the results with those obtained in other areas by using the same methodology. The results indicate a similar response. For tropical eruptions, the total length of the cooling is of three years, quite similar to the response at global and hemispheric scales. Nevertheless, negative anomalies are not continuous in time, showing some periods with maximum cooling and other periods with a null effect or even an opposite sign. The main negative departures are registered in the autumn season within the eruption year. Thus, the temporal proximity to the eruption month seems to be a key factor. Measurements of the global dispersion of the eruption clouds from major tropical volcanic eruptions fix the arrival of the volcanic aerosols to our latitudes in about two to three months following the main eruption [*Bluth et al.*, 1992; *Blumenthaler & Ambach*, 1994; *Olmo et al.*, 1999]. Optical depth reaches the highest values [*Sato et al.*, 1993] and radiative forcing is expected to be more effective also in this period. Taking these two aspects, and the fact that most of the eruptions occur during the first half of the year into account, maxiuml cooling and temporal proximity to the eruption date seems to be correlated.

Detailed analysis of the individual response links the magnitude of the eruption (depending on the geographical distribution of the aerosol cloud, and size, chemistry, volume and optical depth of the aerosols) and their effects on temperature. Thus, the Krakatau, Santa María and Pinatubo events had the more intense radiative impact and the most remarkable temperature response. In contrast, other eruptions having a similar magnitude (e.g. the same VEI values) imply a weaker signal over our area. From this point of view, the Agung eruption (1963) is a paradigmatic case. Figure 6.1. presents the latitudinal distribution of optical depth measurements following five large equatorial eruptions. As is visible in the central graph, the majority of the volcanic cloud was dispersed over the SH, while the NH was out of its influence. This distribution probably accounts for the fact that the cooling over the Iberian sector was of small magnitude and very brief.

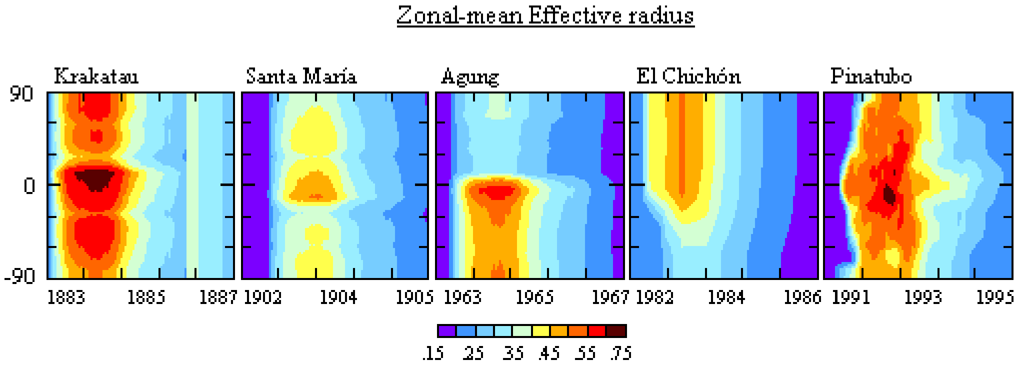

Figure 6.1. Estimated stratospheric aerosol optical depth at λ=0.55 μm as a function of latitude and time, and for five major tropical volcanic eruptions.
Source: http://www.giss.nasa.gov/data/strataer

A similar temperature response is detected following the eruption of the Mexican volcano El Chichón (1982). However, in this case, this response is attributed to the coincidence in time with the remarkable 1982-83 ENSO phenomenon, which produced partial suppression of the expected cooling.

From these two events, one question rises: can the climatic effects of an eruption be calculated? From the data exposed above, we should use the term “estimate” rather than “calculate”, as so many factors are involved that we can only guess that each eruption is different. Moreover, such uncertainty increases as we go back in time, when key aspects as the chemical composition of the aerosol cloud or its geographical distribution are often unknown. Nevertheless, in all the eruptions with likely climatic impact, similar characteristics are detected, and in the future, the information from satellites will provide precise information on their consequences on climate.

In the analysis of the temperature response, NH high-latitude volcanic eruptions are next analysed. As mentioned above, these events generate climate effects only detectable over the hemisphere of origin. Their effects differ from those of tropical eruptions in certain aspects. First, the total length of the cooling is clearly shorter and limited to 1.5 years. Furthermore, the response is more rapid and abrupt, and the effects are detected just in the second month following the eruption date. This effect is quite logical as the aerosols cloud reaches the mid latitudes in a few days. As happened with tropical events, it is difficult to detect a seasonal response due to the temporal location of the events between March and June. In this case, only four eruptions were considered and so the results may not be very conclusive.

We aimed not only to detect the mean response of the Iberian temperature to the volcanic forcing, but also to identify the areas within the Iberian Peninsula and the Balearic Islands with the highest sensitivity. The results have shown that the central and, above all, the southern part of Iberia (and more precisely, the southeast) seem to be the most sensitive areas to the cooling in the post-volcanic period following tropical events, while the north tends to show a less definite response. With regard to this spatial distribution, some hypothese are suggested:

- As we deal with equatorial/tropical events, at least during the initial period, the optical depth may be greater over the latitudinal zones closer to the volcanic source and the later uniformly dispersed over the mid latitudes. This may explain why the south experiences a more marked cooling.
- Another theory linked to dynamical processes can also be proposed. The northernmost part of Iberia is mainly influenced by the most common circulation at mid-latitudes, the zonal circulation or the westerlies (mainly in the ‘cooler’ half of the year). In contrast, the southernmost sector receives a marked influence of the subtropical high, thus remaining for several months out of the zonal circulation and of the associated oceanic flux. For this reason, the radiative forcing is expected to be more effective or clearer over the south, while in the north this effect will be obscured or mitigated. In addition, another process should be taken into account: the observed dynamic post-volcanic forcing and the resulting winter warming over

continental areas of the NH. As a result, a final hypothesis can be suggested: the Iberian and Balearic sector is a transition area between the domain of one and other forcing mechanisms; to the north, the dynamic forcing obscures the radiative forcing during most of the post-volcanic period, while in the south the radiative forcing becomes dominant. The more clear configuration of this dipole structure in the response during the first two post-volcanic summers, may support this theory, as this is the period when the Azores high domain is almost absolute over the southernmost part (see figures 3.21. and 3.23.).

The likely seasonal component of the volcanic signal on temperature seems to be more remarkable in autumn as this is the season experiencing the strongest cooling. In contrast, spring does not show a detectable response in any of the post-volcanic years. The fact that the summer seasons do not exhibit a marked cooling may contradict the hypothesis that "years without a summer" are characteristic of all post-volcanic periods. As mentioned above, the impressive "year without a summer" was attributed to the unusual climatic conditions over most of Europe and North America during the summer of 1816, following the large volcanic eruption of Tambora. Nevertheless, there are more and more evidences tending to tone down the weather conditions governing that summer, indicating that the unusual conditions were a regional phenomenon not applicable to the all regions or to the whole summer season [*Wilson*, 1992]. The results obtained here seem to confirm these conclusions, and to contradict the correlation between all cold summers and post-volcanic periods.

During the first two post-volcanic winters, remarkable cooling is detected and the morphology of the isolines of standardized temperature anomalies is remarkable. During these two periods, the geography of the Iberian Peninsula seems to play a key role. For example, during the first post-volcanic January, the areas close to the Ebro valley and to the Sistema Ibérico tend to concentrate the most important negative deviations (see figure 3.30.). A similar morphology is shown in the previous month and during some months in the second post-volcanic winter, but with weaker intensity. Taking into account that the minimum temperatures are more affected by the cooling than the maximum ones, and the topographical characteristics of the area, this response may be due to the presence of a dominant high pressure over the area. Such conclusion is confirmed by the results obtained in chapter five, when the first January following tropical volcanic eruptions appeared as the month with the highest persistence of a pattern showing a dominant subtropical high over the south-western corner of Europe. Additionally, the most marked negative rainfall anomalies also appeared in this post-volcanic month. Thus, we suggest the following hypothesis:

The dynamical volcanic forcing dominates over the radiative
forcing during the post-volcanic winter
(being more intense during the first year)

↓

This forcing originates a circulation pattern in which the subtropical high becomes
more persistent and, probably, stronger over Iberia and the Balearic Islands

↓

The climatic response over the area consists of a decrease in precipitation rates, a
prevalence of clear skies over the coasts and elevated regions, but a probable
persistence of radiative fogs on the valleys

↓

The maximum temperatures over those areas affected by clear skies, are above the
average values, while the cooling is more intense in minimum temperatures

The maximum cooling affecting minimum temperatures rather than maximum temperatures is more marked in the south of Iberia not only in winter, but also in the remaining post-volcanic periods. In contrast, as we travel north, this response tends to equilibrate, and is even inverted in the northeast, where the maximum temperatures experience a maximum cooling (although this is the least sensitive area to cooling). Again the Iberian sector can be regarded as a transitional area, but a more detailed analysis covering some areas of Europe and North Africa should be performed.

As for NH high-latitude eruptions, a similar spatial pattern in the response of temperature is detected, the south of the Iberian Peninsula being again the most sensitive area to the cooling. This result supports the second hypothesis, as in the north zonal circulation is dominant and weakens the effects of the radiative forcing. Unfortunately, the small size of the sample of volcanic events considered (only four in the 20th century) may condition, in this case, the reliability of the results.

6.2. IMPACT ON RAINFALL

Most of studies devoted to the volcanic influence on climate only analyse the likely consequences on global or hemispheric temperatures, while other parameters are left unexamined. This is the case of the precipitation response to this kind of forcing. The huge spatial and temporal variability of the variable and the difficulty to extract the volcanic signal are often taken as a reason for not analysing its response. Nevertheless, in th areas where water as a resource plays a key role in preserving the economic development of the society, like Iberia, this type of studies should be considered.

The results of the investigation confirm that the rainfall distribution over Iberia and Balearic Islands is affected, registering a reduction of the total rainfall during the first year following a large volcanic eruption. The main incidence is detected within the first winter following major tropical volcanic events, when negative anomalies are present over the whole area, the northwest of Iberia being the most affected sector (with a 40% reduction approximately). Although this is the most sensitive area, the western and south-western sectors of the Iberian Peninsula also show remarkable negative anomalies of 30-35% over the average winter rainfall. As winter is the rainiest season of the year over this area, the rainfall deficits registered are comparable to those detected in the northwest and even have more dramatic socio-economic consequences. This period of extended rainfall deficits may be associated with an above normal persistence of an anticyclonic pattern over the south-western corner of Europe, as suggested in the fifth chapter of the research. Over the southernmost part of the area, negative rainfall departures are reported until the second post-volcanic winter and are relevant for their persistence rather than for their magnitude. Within this sector, the southeast is the most sensitive region, with negative anomalies lasting until the spring of the fourth post-volcanic year and only broken by a short period during the second spring. In view of such response, it could be argued that tropical volcanism is an agent that favours drought periods over this area or, in any case, an agent that would not generate rainfall periods. Over the northwest, the volcanic impact may increase rainfall variability, with drier conditions during the winter seasons.

On the whole, the first summer after large tropical eruptions is the only season registering positive rainfall anomalies in some of the months. Thus, if the temperature response did not show a remarkable decrease (arguing against the referred “years without a summer”), the summer season tends to report a global increase in precipitation. Thus, over the southwest of the European continent, the summer volcanic signal may consist of an increase in rainfall rather than of a decrease in temperature.

Wintertime is the rainiest season over most of the west, the south-west and south of the Iberian Peninsula, but this is not the case over the Mediterranean coast and the Balearics, where is autumn the wettest season. For this reason, the rainfall decrease detected in these areas during the post-volcanic autumn months is especially relevant. Apart from the northernmost coast of the Mediterranean coast, the Valencian coast, the Balearics and the southeast are the most affected regions by rainfall deficits. Therefore, the southeast is affected by a double reduction, as the two rainiest seasons (winter and autumn) accounting for 2/3 of the total yearly rainfall, show remarkable negative rainfall departures, which may explain the wide length of the drought conditions mentioned above.

For NH high-latitude volcanic events, and bearing in mind the small sample of eruptions, the summer and autumn seasons within the year of the eruptions tend to show positive rainfall anomalies in almost all the area (all the events considered are placed in the first half of the year). For this set of eruptions, the contrast between the north and the south responses is enhanced, especially between the southeast and the northeast. The southeast shows continuous negative departures until the third winter, while the northeast shows positive anomalies over the whole post-volcanic months. Additionally, the distribution of the rainfall standardized anomalies is similar to that observed for the months following tropical events: a first winter with remarkable negative anomalies over the northwest, post-volcanic summers with marked positive anomalies in some areas and autumn deficits over the southeast. This may point to some similarities in the dynamical mechanisms responsible for the anomalies reported.

6.3. SURFACE ATMOSPHERIC CIRCULATION CHANGES

From the analysis of the Iberian and Balearic temperature and rainfall responses to the volcanic forcing, a dynamical forcing may also be generated jointly with the radiative forcing. The results obtained from the Principal Component Analysis (or EOF analysis) have allowed us to identify the months with an above normal persistence of a certain circulation pattern during the period following large tropical volcanic events of the 19th and 20th centuries. The main modifications over the European sector are detected during the first post-volcanic year, thus confirming that the proximity to the eruption date plays a key role in the response. Winter months are those experiencing the most marked response, giving support to the hypothesis that the dynamic forcing is most important during this period.

The spatial patterns obtained are in agreement with the detected temperature and rainfall anomalies. This is especially evident during the first post-volcanic January, when the persistence and reinforcement of the subtropical high over the southwest of Europe involves general and marked negative rainfall anomalies and a decrease in minimum temperatures, while maximum temperatures are less. We would also like to highlight the negative rainfall departures detected during the first post-volcanic autumn over the eastern part of Iberia, which may be linked to a wide anticyclonic area over the Mediterranean basin (October, +1).

The analysis of the volcanic incidence on the NAO index has confirmed previous findings. Thus, the positive phases detected during the first two winters following tropical events may be in agreement with the negative rainfall departures detected and confirm the main role of the Azores high. In contrast, during the third post-volcanic winter, NAO indices turn to negative values, altering the precipitation pattern, which tends to show a distribution close to the most frequent pattern. Nevertheless, it is possible to detect some interesting aspects. Positive indices are dominant for the eruptions following the Cosegüina eruption (1835), but this response is less clear for previous eruptions. *Jacobeit et al.* [2003] indicate that around 1850 the circulation modes over Europe during the winter months show clear changes: from a domain of easterly patterns, they become a domain of westerly patterns, coinciding with the last years of influence of the Little Ice Age. This may also be reflected in the post-volcanic circulation patterns, e.g. the characteristics of dynamical forcing mechanism during the period previous to the mid 19th century.

Finally, the perpetuation of positive NAOi during the winters following large NH high-latitude volcanic events, conditions the distribution of the rainfall anomalies over Iberia and the Balearics. Unfortunately, the short sample of events considered may limit the reliability of the results.

6.4. MORE TO BE DONE…

All studies main to clear most of the doubts about a certain question. However, it is also interesting to leave the doors open and questions to be solved in the future. In this sense, the analysis of the impact of volcanism on Earth climate is inevitably tied to new volcanic events in the future. Nevertheless, our research poses some questions:

- *Improve our knowledge of the role of large high-latitude volcanic eruptions*. These type of eruptions have long been thought to play a minor role in the climate response induced by volcanism, and so many aspects remain unanswered. The precise and lasting chronology of Icelandic volcanic events, of proved influence on the European continent, can be used to improve our knowledge of their climatic influence. Additionally, the tracking and modelling of the eruption clouds generated by these eruptions, may be of especial interest for the aeronautic industry, as they affect the transatlantic air routes.

- *Obtain more precise and complete chronologies of explosive volcanism*. The vast documentary sources present all over the Iberian Peninsula and the Balearics should contain several references of well-known optic phenomena created by large volcanic eruptions (e.g. dry fogs, unusual red sunsets and sunrises). This information can be used to date unknown eruptions and to study specific cases, like the climatic conditions in the aftermath of the major Tambora eruption.

- *Study in depth the dynamic forcing induced by volcanism*. Recently new climatic reconstructions based on *proxy* and instrumental data over the European continent from the 16th century have been developed. The use of this data set could allow us to include new volcanic events within the pre-instrumental period (i.e. the 1601 Huaynaputina eruption). Thus, the dynamical responses during the Little Ice Age could be detected, as suggested in this study.

- *Confirm the role of explosive volcanic eruptions as a generator of drought conditions over the Iberian sector*. Again, by using *proxy* data from pre-instrumental documentary sources and from dendrochronological sources and crossing this information with chronologies of known volcanism, these questions could be solved.

CHAPTER 7 – REFERENCES

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