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The blessing of the 'year without summer': Climatic and socioeconomic impact of the Krakatoa eruption (1883) in the South-east of the Iberian Peninsula

Short title: Blessing of the Krakatoa eruption (1883) in the South-east of Spain

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Funding information

This work was partially supported by the Spanish Ministry of Economy and Innovation (CGL 2016-75996-R). SG-G acknowledges the support of the Spanish Ministry of Science, Innovation and Universities through a "Juan de la Cierva Incoporación" grant (IJCI-2016-29016).

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This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/joc.6958

Abstract:

In the current context of climate change–induced warming, interest in analysing the impact of volcanic eruptions on the climate has renewed. The main conclusions from related papers indicate that volcanic eruptions alter the terrestrial radiative balance and cause cooling in the years after an eruption: known as 'years without summer'. These episodes of cyclical cooling have been related to negative socio-economic impacts (such as crop reduction, famine, and social unrest). However, the effect on precipitation has been studied less. Detailed studies on the economic impact of large eruptions are scarce, especially for historical eruptions. This study analysed the effects of the 1883 Krakatoa eruption on temperature and precipitation in the south-east of the Iberian Peninsula and related economic and social effects. It was concluded that this eruption incited a significant decrease in maximum temperatures and stability, an increase in minimum temperatures, a decrease in average temperatures, and a significant increase in rainfall. This climatic context produced a decrease in cereal prices and a reduction in climatic risks (droughts and frosts). Therefore, the effects of the eruption of Krakatoa improved socioeconomic conditions in the south-eastern Iberian Peninsula.

Keywords: volcanism and climate, pre-eruptive window, post-eruptive window, climate variability, socioeconomic impact, cereal prices, climate hazards, south-east Iberian Peninsula.

1. Introduction

The 1883 Krakatoa eruption was the largest volcanic eruption since the eruption of the Tambora volcano in 1815. The intensity of the eruption together with the social, cultural, and scientific context of the time caused this event to have great scientific and social impacts worldwide. In the current context of climate change and analysis of processes and components that cause radiative forcing in the global energy balance (Gerlach, 2011; Burton et al., 2013) volcanic eruptions, especially those of great intensity (VEI>5), have received renewed interest. This is primarily due to their temporary cooling effect because they cause a global decrease in temperatures in the following months and years. These cooler years are the known as ‘years without summer’, and they incite major socio-economic effects in areas distant from the eruption (e.g. Europe and North America) in the cases of Tambora and Krakatoa (Brönnimann and Krämer, 2016; Morgan, 2013: Winchester, 2013). Recently, studies on atmospheric phenomena related to volcanic eruptions of lesser intensity have also been conducted in the Northern Hemisphere. Such eruptions have caused sudden warming in the polar stratosphere with an impact on the polar vortex circulation and its effects on the middle and high latitudes of the northern hemisphere (Butler et al., 2015; Pedatella et al., 2018).

The Krakatoa volcano in Indonesia is located in the subduction zone of the Indo-Australian and Eurasian plates. It entered a phase of continuous eruptions on 19 June 1883, after a series of gas releases registered at the end of May of that year. As of 11 August, the eruptions increased with plumes emitting from several cracks originating in the caldera. The eruptions intensified on 24 August, but on August 26, the eruption entered the phase of maximum activity; on 27 August, the catastrophic culmination was reached with four major explosions that were accompanied by tsunamis that reached the coasts of South Asia, East Africa, and Western Australia (Flammarion, 1875). The combined effects of the pyroclastic flows, volcanic ash, and tsunamis had disastrous results throughout the region. All 3,000 inhabitants of the island of Sebesi, approximately 13 km from Krakatoa, were killed. Pyroclastic flows that travelled over the surface of the water at 300 km/h killed about 1,000 people in Ketimbang on the Sumatra coast, about 40 km north of Krakatoa (Winchester, 2013). The sound of the August 1883 eruption was heard around one third of the planet (Abbot and Fowle, 1913). The magnitude was such that the warming of the ocean and the rise in sea level in the twentieth century was substantially delayed by oceanic cooling resulting from this eruption (Gleckler et al., 2006). The official fatality count recorded by the Dutch authorities was 36,417, and many inhabited areas were destroyed.

Many aspects of this eruptive event have been discussed since the eruption. Climatological and geological studies reported on the foreseeable impact of the eruption on Western society and culture in the late nineteenth century. The event has been widely discussed among scientific elites of the time. A few months after the eruption, the British Royal Geographical Society (1884) published a paper explaining in detail the development of the eruption, its geological genesis, and its immediate impact on the surrounding landscape. This work correctly indicated the great possibility that this eruption could be used to study the impact of major volcanic eruptions on the weather. Four years later, a research committee of the Royal Geographical Society (1888) published conclusions on the impact of the eruption, with special attention to the effects on the luminosity and climate of India in the years following the event.

News and various descriptions of the eruption appeared in press in most Western countries. One month after the great eruption, news of unusual skies appeared in Australia and Hawaii. By November, this effect was evident in the skies of North America and Europe (for a detailed list, see Schröder, 2002). Perhaps the best description of the impact of the eruption was found in a book by Winchester (2013) with the dramatic title 'Krakatoa: The day the world exploded' in which the author analysed the local destruction caused by the volcano and the immediate impact of the tsunami, which was felt as distantly as France (Choi et al., 2003). The consequences of the eruption of Krakatoa had a significant effect among European cultural elites of the late nineteenth century. The most obvious manifestation of the cultural impact of the eruption was noted in the paintings of the time. One of the best examples is the agonised painting of Edvard Munch (The Scream) and the effect of the eruption of Krakatoa in European skies in the years following 1883 (Olson et al., 2007).

Despite the large volcanic eruptions of the nineteenth century, it was not until the end of the century that the effect of the great volcanic eruptions began to be considered as a climate forcing factor, specifically as an inducer of cold periods (Döörries, 2006). The succession of major eruptions (Krakatoa in 1883, Tarawera in 1886, Santa María in 1902 and Katmai in 1912), the growing presence of instrumental meteorological data, and widespread scientific curiosity meant that during the first half of the twentieth century, many empirical studies were conducted on the relationship between large volcanic eruptions and weather. The work entitled 'Volcanoes and Climate' by Abbot and Fowle (1913) was particularly influential. In this paper, the authors used observational data centred on Europe and the United States to detect a decrease in temperatures in the summer after the eruption of Katmai and argued that the greatest thermal impacts were produced during summer. The authors attributed this decrease to the fact that large volcanic eruptions cause a reduction in solar radiation on the Earth's surface, with the consequent temperature decrease. This seminal work created renewed interest that began to generate growing literature on volcanic climate forcing. The meteorologist William Jackson Humphreys published an interesting work in 1913 that used instrumental temperature data reporting that volcanic eruptions between 1750 and 1912 induced a drop in temperatures in the following years. Temperature declines after the eruptions of Tambora in 1815 and Krakatoa in 1883 were especially significant. This result was later collaborated by Milham (1924), who also noted that the greatest fall in heat was observed in the summers. The idea of 'years without a summer' following major volcanic events began to gain popularity. Scientific interest in analysing volcanic forcing as an inducer of climatic variability continues to grow (Wexler, 1951; Panofsky and Brier, 1958; Mitchell, 1961; Lamb, 1970; Schneider and Mass, 1975; Self, Rampino and Barbera, 1981) and is currently widespread and extensively developed (Robock and Mao 1995; Oppenheimer, 2003; Sigl, et al., 2015).

These advances have made it possible to confirm that the climatic response to large eruptions is evident between one and five years after the eruption (Robock, 2000) with a temperature decrease that is consistent over space and time (Wegmann et al., 2014). Volcanic forcing is now considered to be the main factor explaining climatic variability over periods in a decade and the cause of major climatic crises, famines, and socioeconomic unrest during the last 25 centuries (Sigl et al., 2015). However, the effects of volcanic eruptions on precipitation are studied and understood less. Gillett et al. (2004) reported that changes in precipitation have more direct impacts on society and environment than other variables, so it is important to deepen our knowledge of volcanic forcing effects on rainfall. The variable response of precipitation to changes in the radiative balance induced by volcanoes means that the rainfall response to eruptions is not temporally or spatially constant (Fischer et al. 2007), which makes it difficult to find consistent rainfall patterns. Mass and Portman (1989) concluded that no volcanic effect was observed in records of air pressure and precipitation. Iles and Hegeri (2015) reported the diversity of regional effects on rainfall and, consequently, on river flow at the global level. In their research, they pointed to the major reduction in flow (<10%) shown by large rivers in the intertropical regions of northern South America (Amazonas), central Africa, southern Asia, and in central and northern Asia; and, on the contrary, the increased flow rate (>25%) in rivers in south-west North America and southern South America. Prohom (2003) points out that, unlike temperature, the impact of large eruptions on precipitation in the Iberian Peninsula does not show clear spatial-temporal patterns.

The climatic impact of eruptions is directly proportional to the intensity, location, and seasonality. Regarding intensity, Zielinski (2000) pointed out that volcanic eruptions that inject large amounts of sulphurous gases into the stratosphere may cool the global climate by between 0.2 and 0.3 °C for several years after the eruption. Robock (2000) argues that these sulphurous gases are injected into the stratosphere and become sulphate aerosols with a residence time scale of approximately one year. This aerosol-cloud produces surface cooling but also incites stratospheric warming. In the tropics and medium-latitude summers, these radiative effects are greater than most other radiative forcings because the intensity of solar radiation is greater (Yokoyama, 1981; Arfeuille et al., 2014; Newhall et al., 2018).

Tropical eruptions may affect the global climate system as the volcanic cloud can spread to both hemispheres, while mid-latitude and high-latitude eruptions mainly affect the hemisphere in which they occur (Timmreck, 2012). In addition, tropical eruptions produce more intense alterations. Schneider et al. (2009) indicated that post-eruption winter cooling in Europe is more consistent with exceptionally intense tropical events than with intense eruptions in the mid-latitudes of the northern hemisphere. Stevenson et al. (2017) noted that the time of an eruption has a decisive role in volcanic ash dispersion and in ocean atmosphere coupling and induces differential effects on the El Niño/Southern Oscillation as a result of seasonal differences in atmospheric circulation.

In summary, research on climate volcanic forcing can be divided into three main areas: a) studies based on global (Schneider, et al., 2009; Timmreck, 2012) and/or regional models (Zhang et al., 2013; Wegmann et al., 2014); b) studies based on instrumental data (Angell and Korshover, 1985; Mass and Portman, 1989; Robock and Mao, 1995; Raible et al., 2016); and c) studies based on proxy data from ice (Sigl et al., 2015), tree rings (Esper et al., 2013), palaeoecological records (Payne and Egan, 2019), and multiproxy reconstructions (Fischer et al., 2007).

However, the three previous research aspects have biases that are relevant when analysing the social response to volcanic forcing. The works of the first area present results compatible with physics on a global and regional scale, but it is difficult to analyse these changes at a high spatio-temporal resolution, which limits the ability to analyse the socioeconomic impact derived from volcanic activity. The works of the second area report a situation with a high level of spatial and temporal resolution, but they limit temporal space coverage to areas with a large and old network of meteorological observatories. Accordingly, the focus is mainly on Europe and North America. Moreover, the objective of these works is generally not to analyse the response of societies to these alterations; thus, we know little about the social impact of volcanic forcing. Finally, works based on proxy are usually based on natural proxies but suffer from bias and data limitations associated with human proxies (historical documents, crop data, price data, and so on). Therefore, it is necessary to focus on the human response to climatic alterations induced by volcanoes as a key in understanding how societies adapt to climate alterations. Several studies have researched this aspect. Fei and Zhou (2009) analysed the impact that the Huaynaputina eruption (Peru, AD 1600) had on the increase in catastrophic frosts in North China through historical documents. Similarly, Trigo et al. (2008) analysed the socioeconomic impact caused by the cold period after the Tambora eruption (1815) in the Iberian Peninsula. Oppenheimer (2003) analysed the effect of the Tambora eruption in 1815 and the emergence of pandemics on a global scale. Stothers (2000) analysed the impact of an unknown eruption in 1258 produced on crops and the re-emergence of violence and epidemics in Europe and the Middle East. Oman et al. (2006) pointed to the importance of studying the impact of volcanic eruptions on food supply through alterations in the hydrological cycle.

Regarding the Krakatoa eruption in 1883, only a few studies have been conducted on the socioeconomic impacts associated with the eruption, and in areas far from the eruption. The effects were immediate in the nearby Indonesian islands, both in human victims and in the forced displacement of the population because of the destruction of homes and damage to economic activities (Döörries, 2003; Brata et al., 2013). In contrast, the positive effect of the Krakatoa eruption on soil fertilisation on various islands of Indonesia (Fiantis et al., 2019) has also been noted. In Europe, together with direct atmospheric effects (lower temperatures and changes in brightness), the decline in harvests in some countries, such as the United Kingdom (Self, 2006), has been highlighted.

With the aim to circumvent the aforementioned biases in research of social response to volcanic forcing, it is necessary to establish robust studies in specific areas and positioning society in the centre of the analysis. With this objective, in this paper we use instrumental climate data in a novel manner together with social proxies (flood data and prayers for rain by the Catholic Church) and price series to analyse the impact of the Krakatoa eruption in the south-eastern Iberian Peninsula.

The climate in the study area (driest area with the most torrential rainfalls in the European Union) has led to a long history of social adaptation to climate changes in a struggle against droughts, floods, and heat (Gil-Guirado et al., 2019). This has created an economic system threatened by agricultural and subsistence crises (Espín-Sánchez et al., 2019). The data used enabled the application of robust statistical methodologies to analyse the effect of the eruption on the climate, and the effect of the eruption on the prices of the most commonly eaten cereals (wheat and barley). These results were collated with the series of the main climate risk events in the study area (Zamora Pastor, 2002; Gil-Guirado, 2013). This dual approach identified a clear impact on climate as a result of the eruption (drop in temperature and increased precipitation). However, unlike most of the literature, the derived social effects were positive because they induced a significant fall in cereal prices and a decrease in the number and intensity of climate risk events. This result contradicts the a priori conception that large volcanic eruptions have, in general, pernicious effects on society. The climatic and social peculiarities of each territory must be considered to adequately assess the social response to large events that generate changes in the global climate. Therefore, this type of holistic study is recommended to offer results consistent with the regional scale and microhistory.

2. Study Area

The south-east of the Iberian Peninsula (SIP) has a climate that differs from other European regions. The SIP climate is arid but with torrential annual rains, a pronounced summer drought, and high levels of evapotranspiration. In general terms, these aspects make the SIP one of the regions with the highest climatic stress in Europe (Gil-Guirado and Pérez-Morales, 2019). Geographically, aridity in the SIP is inversely proportional to the altitude and nearness to the mountains because the mountains are zones of humidity where rainfall increases due to the effect of altitude. The province of Albacete, in the interior of this territory, is where the main rivers in the SIP begin, and there are historical and economic links between the coastal provinces of the SIP and the province of Albacete. In this paper, we consider that, from a climatic and historical point of view, the SIP is framed by the four provinces of the south-east peninsula quadrant (Albacete, Alicante, Almeria, and Murcia) (Geiger, 1973). Additionally, to have a greater amount of climatic data and for these data to be spatially distributed, we used rainfall data from Cazorla, a town located in the neighbouring province of Jaén. However, Cazorla presents the rainfall seasonality and teleconnection patterns characteristic of the SIP, while other nearby towns and with available data, such as Granada, are climatically outside the SIP domain. In this regard, while Cazorla presents the seasonal rainfall maximum during the spring, which is a typical pattern in inland areas of the SIP, there is a clear winter rainfall maximum in Granada, which reports rainfall patterns more related to the south-west region of the Iberian Peninsula (Cortesi et al., 2014). Analysing the fractal dimension and the temporal concentration of rainfall, it is also clear that Granada is outside the climatic domain of the SIP. Thus, the fractal dimension of the temporal distribution of precipitation (D) in Granada is clearly separated from the lower D values typical of the SIP climate (Meseguer-Ruiz et al., 2017). In contrast, the precipitation concentration index (CI), which expresses the relative weight of the rainiest days in the total precipitation, is characterised in the SIP by very high values, while in Granada these values are lower (Martín-Vide, 2004). Finally, Granada is also clearly outside the SIP within the rainfall regionalisation and in terms of the association between teleconnections and temporal rainfall variability. In this regard, the SIP, including the north-west border that includes Cazorla, is regionalised within the domain called the "Mediterranean region" (oriented towards the warm and moist flows from the Mediterranean), characterised by a significant negative correlation between autumn and winter precipitation and WeMO (Western Mediterranean Oscillation) index. Granada is fully within the "Atlantic region" (Atlantic flows penetrate this region with no significant orographic obstacles), characterised by a significant negative correlation between winter precipitation and the North Atlantic Oscillation (NAO) index (Martinez-Artigas et al., 2020). Because of all the distortions that these differences could induce, we considered it convenient not to include data from Granada in this study (Figure 1). Hence, there is a clear separation between the SIP climate and the rest of the climates of the Iberian Peninsula. It is important to consider this differentiation because it can be influential in explaining the climatic variability induced by large volcanic eruptions. In this regard, it is important to identify the correlation between the rainfall variability in the SIP and the low-frequency variability patterns. As pointed out by Gonzalez-Hidalgo et al. (2009), in the Mediterranean fringe of the Iberian Peninsula, monthly variations in rainfall may result from the simultaneous effects of different atmospheric modes of low variability. Manzano et al. (2019) identified 6 spatially homogeneous areas in terms of the appearance and duration of droughts in the Iberian Peninsula. SIP is one of these regions, including Cazorla. These authors correlated the variability of droughts in each of the 6 areas identified, with different teleconnection patterns, such as the Arctic Oscillation, the North Atlantic Oscillation (NAO), the Oscillation Atlantic, and the Western Mediterranean Oscillation (WeMO). For the SIP, they only found a significant correlation with WeMO. Specifically, there is a significant negative correlation between the drought variability of October to May and the WeMO index. In this manner, the WeMO oscillation seems decisive in explaining the variability of rainfall in the SIP. WeMO is a low-frequency variability pattern specific to the western Mediterranean basin, defined as the difference in standardised surface pressures between Cádiz-San Fernando (Southwest Spain) and Padua (Northeast Italy). During the negative phase of WeMO, the advection of the easterly winds over the Iberian Peninsula was established. These winds bring moisture and precipitation to the SIP. During the positive phase of WeMO, the prevailing winds have a western and north-western component, giving rise to dry weather in the SIP (Martín-Vide and Lopez-Bustins, 2006).

One in every four or five years is agronomically dry in Murcia, which negatively influences harvests. However, the most frightening events were successions of dry years that produced 'years of hunger' and increased rates of begging and starvation among lower classes (Lemeunier, 1990).

The economy of the SIP until the middle of the twentieth century was peripheral because of its dedication to commercial agriculture and lack of technological development. This situation conditioned dominant types of crops (Espín-Sánchez et al., 2019). Wheat production, a staple for essential foods (bread), was historically insufficient to meet demand. The case of Murcia is one example. In this city, in a year with a normal wheat harvest, just enough was produced to supply the population for three months immediately after harvest; the rest of the time it was necessary to bring wheat either from nearby areas, other provinces such as Albacete, and even other countries (Picazo and Lemeunier, 1984).

3. Sources and Methodology

Three types of sources were consulted (See Table 1): climate data; data on cereal prices in the study area; and data on meteorological risks. In all cases, the data were selected according to the location within the study area and considering a time series of at least seven years before and after the Krakatoa eruption in 1883.

The climatic data were taken from the precipitation and temperature series openly available at the Spanish Meteorological Agency (AEMET, 2020). The precipitation series included continuously accumulated monthly precipitation data from 1851. These series were homogenised by AEMET using the CLIMATOL V.2.0 method from a selected series based on criteria of quality and completeness (Guijarro, 2011; Luna et al., 2012). The temperature series included data from 1863 and was also homogenised and adjusted (Brunet et al., 2006; Brunet et al., 2008). Despite this, it is necessary to consider that quality control and homogeneity tests could be affected by the limited number of series in early periods. These series offer daily data for maximum, minimum, and average temperatures. The ability to differentiate between maximum and average temperatures is useful when studying the climatic impact of volcanic eruptions, as it enables differentiation of conflicting effects that affect the average values, which can be explained from a meteorological perspective. All precipitation and temperature series data available in the four provinces of the SIP were used. Additionally, we used the rainfall data from Cazorla (located in the province of Jaén).

Price data comes from the provincial price bulletins published continuously by the *Gazeta de Madrid* between July 1856 and December 1890. The *Gazeta de Madrid* was the official publication published between 1697 and 1936 (when it was replaced by the Official Gazette of the State – BOE). *Gazeta* is an official source, and the data were validated by the administration. The data offered were the monthly averages in each province for the most eaten cereals (wheat for bread and barley for cattle feed). The data are freely available online through the search engine of the BOE (2020). This data source has been widely used with proven validity in economic history studies (Sánchez-Albornoz, 1975; Barquín Gil, 1999). This is the first time this source has been used to relate the effects of a large volcanic eruption on agricultural production. Because the data uses a provincial average, compared to the local values of precipitation and temperature, the data can introduce scale biases that cannot be ruled out or overcome with the available sources. However, because price values are provincial averages, a realistic approximation is implied to the extent that it reliably represents the economic situation of a society, as local prices may be affected by a socioeconomic situation that is not represented in society as a whole (Barquín Gil, 2000).

Data on meteorological risks can be found in the series on floods and Catholic Church rain prayers in the works of Zamora Pastor (2002) and Gil-Guirado (2013). The data are annual and reflect the annual number of floods and rain prayers. Additionally, the sum of flood intensity and rain prayers was also calculated. Flood intensity is classified into three levels according to its severity from least to greatest intensity: Level 1, ordinary flood; Level 2, extraordinary flood; and Level 3, catastrophic flood. This classification system is widely disseminated in the works of historical climatology (Barriendos et al., 2019). The intensity of Catholic Church rain prayers is classified into three levels from lower to higher drought intensity: Level 1, mild drought; Level 2, moderate drought; and Level 3, extreme drought (Barriendos, 1997). The rain prayers were an instrument in traditional Catholic societies to ask God for rain. Rain prayers have been widely used to measure drought in Catholic countries (Martín-Vide and Barriendos, 1995; Brázdil et al., 2018). Data are available for some important cities within the study area, such as Orihuela (province of Alicante, 19 km north-east of the city of Murcia, and 50 km south-west of the city of Alicante), Caravaca de la Cruz (province of Murcia, 6 km north-west of the city of Cehegín, and 65 km north-west of the city of Murcia), and the city of Murcia.

All data were aggregated at a seasonal level to determine whether the changes detected differed according to the time of the year. For climatic data, precipitation and temperature anomalies for winter (December, January, and February), spring (March, April, and May), summer (June, July, and August), and autumn (September, October, and November) were calculated. Anomalies were calculated as the difference between the precipitation or temperature of a specific season and the average of 15 seasons before and 15 seasons after the eruption (with the eruption year included in the average). Therefore, the averages were calculated for a robust period (31 data points) and anomalies were entered within the same temporal context. The expression for the anomaly calculation is as follows:

$$CA = \frac{SD_{(mm/Tmin/Tmax/Tave)}}{ASD\ (1868 - 1898)_{(mm/Tmin/Tmax/Tave)}}$$

where *CA* is the value of the climatic anomaly in mm of rain or in ºC; *SD* is the value of precipitation (in *mm*) or of average temperature (*Tave*), minimum (*Tmin*) or maximum (*Tmax*) of a specific season in ºC; and *ASD* is the average value for the period from 1868 to 1898 of precipitation (in *mm*) or of average temperature (*Tave*), minimum (*Tmin*), or maximum (*Tmax*) in ºC.

Pricing data were processed in a similar manner to calculate seasonal anomalies. However, the availability of data requires that the average over which the anomalies are applied is 15 seasons before and 7 after the eruption (with the eruptive year season included in the average). The expression for the anomaly calculation is as follows:

$$PA = \frac{SD_{(Tri/Ceb)}}{ASD\ (1868 - 1890)_{(Tri/Ceb)}}$$

where *PA* is the value of the price anomaly in pesetas/hectoliter for wheat and barley; *SD* is the price of wheat (*Tri*) and barley (*Ceb*) for a specific season, and *ASD* is the average value for the period 1868–1890 for the price of wheat (*Tri*) and barley (*Ceb*).

Using anomaly data, we proceeded to calculate whether the anomaly values differed between the period before and after the eruptions. Following the related bibliography (Angell and Korshover, 1985; Manning et al., 2017), we applied Student's t-test for independent samples with a significance level of 95% (p-value <0.05). This test was performed for each location and different post-eruption time windows (between 2 and 10 years). In other words, we applied Student's t-test for the averages of the 8 post-eruption seasons (2 years) of the 12 subsequent seasons (3 years), thus up to 10 years (40 seasons) and compared to the average anomalies of 40 pre-eruptive seasons (10 years). This method allows researchers to determine whether there is a change in averages, where this change increases, and how the changes vary across different post-eruptive time windows.

To analyse the temporal coherence of the results, a homogeneity test was applied to detect significant moments of change that may be related to the eruption. Specifically, the Pettitt test of absolute homogenisation (Pettitt, 1979) has been applied and shows a possible single point of rupture for all available series.

Finally, Pearson's unidirectional correlation (with a significance level of 95%) was calculated between climatic anomalies and price anomalies between all locations. The spatial coherence of the results was evaluated.

4. Results

4.1. Temperature variability induced by the Krakatoa eruption (1883) in the SIP

The data of temperature anomalies in the meteorological stations in Murcia and Alicante show a clear variation in the temperature values as a consequence of the eruption. However, this alteration has differing magnitudes in the series analysed and differentially affects the seasonal anomalies of maximum, minimum, and average temperature. Figure 2 shows the seasonal and annual temperature anomalies for various pre- and post-eruption time windows. The major differences in the anomalies can be seen in the maximum temperatures with a clear decrease in the post-eruption averages. This decrease can be seen both in Murcia and Alicante and affects both the annual and seasonal values; it is most noticeable in the autumn and summer in Murcia, with negative anomalies of maximum temperature close to or greater than 1.5 ºC. However, anomalies in minimum temperatures show no obvious changes in Murcia but a significant increase in Alicante. This increase is evident both in annual and seasonal values, although there are maximum values in the three-year post-eruptive window. Increases are close to or greater than 1 °C in the annual, spring, and summer values in Alicante. Regarding abnormalities in average values, the greater maximum temperature decrease in temperatures, compared to the increase in minimum temperatures, shows the dominance of the negative anomalies in the post-eruptive time windows. This can be seen in Murcia for both annual and seasonal values. In the case of Alicante, there is a considerable rise in the minimum temperature index, and the average values show no clear pattern, except for an evident temperature decrease during autumns.

Once the Student’s t-test was applied to seasonal anomaly values and various post-eruptive time windows, we confirmed some patterns mentioned above. In relation to seasonal temperature anomalies (Figure 3 Panel A), the difference between the average of seasonal anomalies for 5 years after the eruption versus the average of seasonal anomalies for 16 years prior to the eruption, reveals a significant decrease in maximum temperatures for all seasons and in both analysed locations. This decrease is of greater magnitude during autumn (in Alicante the difference between the 16 pre-eruptive autumns and the 5 post-eruptive autumns is −2.3 °C and −2.1 °C in Murcia). In the case of minimum temperatures, significant increases were observed in Alicante and during spring, summer, and autumn (with differences between the 16 pre-eruptive seasons and the 5 post-eruptive seasons of between + 1.3 ºC for the springs and + 1 ºC for autumns). This increase in minimum temperatures was less than the decrease in maximum temperatures. For average temperatures, a significant increase in Murcia was detected during the summer, particularly during autumn (with differences between the 16 pre-eruptive seasons and 5 post-eruptive seasons of −0.7. °C in the summer and −1 °C in autumn). Accordingly, the ‘year without summer' can be confirmed in the case of Murcia. However, the most important decreases in temperatures occur in the autumn at the two locations studied.

Figure 3 Panel B shows there is a significant decrease in maximum temperatures in both Murcia and Alicante for the average of seasonal anomalies between 2 and 10 years after the eruption. The differences between the average of seasonal anomalies for the 16 years prior to the eruption is greater than −1 °C and begins to lose intensity from the eighth year. Minimum temperatures show a significant increase for the entire period analysed in Alicante. In this city, the maximum anomaly was observed for an average of two years after the eruption and begins to decrease from that moment. In the case of Murcia, the minimum temperature shows a post-eruptive average significantly higher for the period between 6 and 10 years after the eruption. Finally, average temperatures only show significant changes in Murcia. This change is considered a decrease of more than 0.5 °C compared to the average before the eruption.

4.2. Rainfall variability induced by the Krakatoa eruption of 1883 in the SIP

When analysing the precipitation data of the six selected locations, a clear increase in rainfall was observed following the 1883 eruption of Krakatoa (Figure 4). The annual values show increases above 20% for post-eruptive periods of 3, 5, 7, and 10 years. That is, following the eruption of Krakatoa, rainfall was around 20% higher than the average for the period 1868–1898. The greatest annual increases are seen in the 3- and 5-year post-eruptive periods and for the cities of Murcia and Albacete. At the seasonal level, winter exhibited poorly defined patterns that may be simply due to variability in precipitation. Summer exhibited the highest percentage increase, especially for the 3-year post-eruptive period. However, summer is the dry season in the study area; thus, these changes may be due to the variability in summer rains. Furthermore, spring exhibited increases in precipitation greater than or close to 30% in all seasons. However, the greatest changes occur during the autumn because it is the wet season in the SIP and the average increases exceed 50% in almost all seasons.

This is confirmed by analysing the significance of seasonal changes. The 5-year post-eruptive average does not show significant changes during winter and summer. In contrast, statistically significant rainfall increases were observed during spring and autumn in almost all studied cities. These increases are greater than 60% during the autumn in the east of the SIP (Murcia, Albacete, Alicante, and Cehegín in descending order) and exceed 50% in the springs of the eastern third (Murcia and Alicante, respectively) (Figure 5).

The increase in rainfall after the eruption of Krakatoa was significant and consistent throughout the SIP and between two and ten years after the eruption (Figure 6). All significant changes detected were more humid. The greatest accumulated rainfall anomalies have been detected in Murcia, followed by Cehegín and Albacete. The increase in rainfall was most limited in duration in Alicante and Cazorla. However, these cities saw the greatest increase in rainfall for the two-year post-eruptive window with a seasonal increase of 90% and 111%, respectively, for the eight seasons between autumn 1883 and summer 1885 (Figure 6 Panel A).

The greatest impact on rainfall occurred in the two years after the eruption, when the average increase in seasonal rainfall in the SIP was 86% (Figure 6 Panel B). The positive precipitation anomalies continued with less magnitude and a decreasing trend. In the 5-year post-eruptive window, there is a slight increase in the magnitude of the positive precipitation anomaly, which decreases again for successive post-eruptive windows.

4.3. Impact of the Krakatoa eruption (1883) on cereal prices in the SIP

Both wheat and barley prices suffered a significant negative anomaly for the analysed post-eruptive windows (Figure 7). The largest price drops occurred in the provinces of Almeria and Murcia for both wheat and barley. These provinces have the lowest rainfall in the SIP and therefore suffer the greatest limitations for cereal production under conditions of normal rainfall. The province of Albacete exhibited the lowest decrease in the price of wheat and no significant changes in the price of barley (Figure 7 Panel A). This province has the highest rainfall in the SIP. This finding may be because in normal rainfall conditions acceptable grain harvests can be achieved and thus an increase in precipitation does not directly improve production. This can be confirmed by the fact that the price of barley does not change since barley requires less rainfall than wheat.

The fall in prices in the various post-eruptive windows varied between wheat and barley (Figure 7 Panel B). For wheat, the decrease increases as the time window increases. For barley, the behaviour is very similar to the behaviour of the anomalies in precipitation, with a greater decrease in the 2-year window and a slight subsequent increase (the 6-year window in this case). For barley, it is assumed that the increase in rainfall facilitated production in the driest provinces (Murcia and Almeria), which explains the considerable correlation between the behaviour of rainfall and that of barley prices. In the case of wheat, the lack of specialisation in its cultivation in the most arid provinces could have influenced the fact that these provinces did not start planting wheat until after a few years of increased rainfall, which would explain the delay in price falls.

4.4. Time consistency of the climatic-economic alterations of the eruption

After homogeneity analysis, the most noticeable finding was that all significant alterations (except for one) occurred in the year of the eruption (1883), in the year before, or in the two subsequent years (Table 2). This fact indicates that the significant changes detected in the previous sections are likely caused by the eruption. The greatest consistency in these changes was found in the change in maximum temperatures. In 1883, there was a shift towards colder conditions. This change was detected in annual and spring, summer, and autumn values. The shift to higher minimum temperatures is less persistent and is detected in 1883 for the annual values of Alicante and in 1885 for the annual and autumn values in Murcia. An abrupt change to more humid conditions was only detected in the autumn of 1883 in Albacete.

Cereal prices also demonstrated a move towards lower prices in 1883 and 1884. This confirmed the relationship between climatic variables and price, which in turn confirmed that price falls are due to the Krakatoa eruption. The steep decline in prices is especially evident in autumn, summer, and annual values. This decrease in prices was particularly significant in the provinces of Almeria, Murcia, and wheat.

However, despite considering that these homogeneity breaks may be causally related to the eruption, it is advisable to be cautious when making this statement. In particular, considering the high sensitivity of non-parametric homogeneity tests such as Pettit's test, determine that the breakpoint detected can fluctuate randomly around the true date of breakpoint (Yozgatligil and Yazici, 2016). In this regard, the central interest of this analysis is to show how possible homogeneity breaks approximate the moment of the eruption.

4.5. Spatial consistency of the climatic-economic alterations of the eruption

Given the connection between climatic change and declining prices in the SIP, the question arises as to which direct relationships can explain this connection.

The most remarkable of all is the very high negative correlation between rainfall anomalies and price anomalies (see Table 3). That is, when rainfall increases, cereal prices decrease. These correlations are greater in drier provinces (Murcia and Almeria), where there is a greater dependence on positive precipitation anomalies for good harvests. There are significant positive correlations between temperature anomalies and price anomalies. Higher temperatures mean higher cereal prices. Higher maximum temperatures produce a drop in cereal production (Battisti and Naylor, 2009; Grumm, 2011).

The low correlations between the climate of Alicante and the prices of cereals in the SIP are also noteworthy. This is probably due to the fact that Alicante has historically been a province with little cereal specialisation (Peris Albentosa, 1995).

4.6. *Extreme weather events in the context of the 1883 Krakatoa eruption in the SIP*

With the available data (Zamora Pastor, 2002; Gil-Guirado, 2013), we can assume that after the Krakatoa eruption there was a significant reduction in the social impact of droughts, measured as a reduction in the number and intensity of rain prayers held in Catholic churches (Figure 8). In Murcia, an average number of 1.1 prayers per year were made from 1868 to 1883. In the period from 1884 to 1898, this value fell to an average number of 0.5 prayers per year. For these same periods, the average intensity decreased from 1.9 to 1.1. The same occurred in Caravaca, where the average pre-eruption number and intensity of rain prayers of 0.3 and 0.4, respectively, fell to zero in the post-eruptive period. A decline was also evident in Orihuela (from 0.4 annual prayers to 0.1 and from an intensity of 1.3 to an intensity of 0.2)

However, as expected, there was an increase in the number and intensity of floods after the Krakatoa eruption. Thus, in Murcia, the annual average number of floods was 0.9 for the period 1868–1883, and this increased to an average of 1.5 in the period of 1884–1898. The intensity increased from an average of 1.5 to 2.4. The same occurred in Caravaca where the number of floods and their intensity increased after the eruption. In Orihuela, however, there was a decrease in the number of floods but a slight increase in intensity. There were no significant increases in catastrophic flooding (intensity level 3), and ordinary and extraordinary floods (levels 1 and 2) increased the most.

5. Discussion

The results regarding a decrease in temperature agree with the results of many studies (Písek and Brázdil, 2006). Self, Rampino, and Barbera (1981) concluded that the great explosive volcanic eruptions of the nineteenth century produced a temperature decrease in the northern hemisphere for between 2 and 5 years. Angell and Korshover (1985) examined the effects of largest volcanic eruptions on global temperatures in the last 200 years using temperature records dating back to 1781 and found that the average temperature for the five-year period after an eruption is usually significantly lower than the average temperature for the five-year period before an eruption. Fischer et al. (2007) analysed the winter and summer climate after 15 major tropical volcanic eruptions during the last half millennium and found that during the first and second years after the eruption, there were significantly cooler summers in Europe and a very weak winter cooling in southern Europe. Timmreck (2012) shows that in the Iberian Peninsula, the first and second post-eruptive winters (with respect to the largest eruptions) are significantly colder. This cooling lasts for between four and six subsequent winters but with less intensity. Prohom (2003) discussed that, between two and three years after a large tropical eruption, there was a decrease in the average temperature in the Iberian Peninsula of around 0.3 ºC. This decrease was particularly important in autumn and winter, with decreased values close to 1.3 ºC. This same work indicates that the decreases were more important in the southern half of the Iberian Peninsula. Finally, Jungclaus et al. (2010) indicated that cooling after the volcanic eruptions of the nineteenth century led to a climate that was almost as cold as at the beginning of the seventeenth century and noted the importance of studying the effect of volcanic eruptions in explaining the variations in preindustrial climate (such as the Little Ice Age). However, it is necessary to consider that between 1780 and 1840, the Dalton solar minimum also induced global scale cooling, which was added to the cooling caused by the large volcanic eruptions of this period (Anet et al., 2014).

Prohom (2003) analysed the response of the mean minimum and maximum temperatures in the Iberian Peninsula to four large volcanic eruptions between 1901 and 1996. This study detected a significant decrease in both the maximum and minimum temperatures. The latter is contrary to our findings; however, it is necessary to bear in mind that in this analysis, the eruption of Krakatoa in 1883 was not considered. The detected increase in the minimum temperature is climatically consistent with increasing precipitation. By increasing the number of rainy days and the subsequent cloudy days, the thermal amplitude is reduced, and the possibility of frost and extreme minimum temperatures decreases (Pastor, 2002). In both Alicante and Murcia, the thermal amplitude (calculated as the difference between the seasonal average of maximum and minimum temperatures) of all post-eruptive time windows is between 1.5 °C and 2.5 °C less than the thermal amplitude of the 16-year pre-eruptive period. If we calculate the thermal amplitude at the seasonal level, we observe that both in Alicante and Murcia, the average thermal amplitude of the five post-eruptive seasons is between 1.1 and 3.3 °C, which is lower than the 16-year pre-eruptive seasonal average. In the case of spring, these differences are −2 ºC in Murcia, −2.5. °C in Alicante, and in autumn, the differences are −2.3 and −3.3 °C. That is, the thermal amplitude falls the most in those seasons where the greatest increase in rainfall occurs. These data confirm that the increase in the minimum temperature is related to the increase in cloudiness, and we can assume that regardless of the statistical significance of the rainfall increases, the Krakatoa eruption induced an increase in cloudiness in the SIP. Oman et al. (2005) found a significant increase in cloudiness in the Iberian Peninsula as a result of the Katmai eruption of 1912.

Wegmann et al. (2014) used climatic reconstructions and model simulations to show that after the 14 strongest eruptions of the last 400 years, there was an increase in summer rainfall in southern

Europe in the year after the eruption. Fischer et al. (2007) observed a tendency towards humid conditions in some parts of the Mediterranean after large volcanic eruptions. Rao et al. (2017) point out that the rainfall response is magnified between late spring and early summer (April to July). Pauling et al. (2006) showed a tendency towards dry conditions in the Iberian Peninsula in the winter after large volcanic eruptions. Prohom (2003) agreed with our findings by indicating a significant increase in autumn rainfall in the SIP, specifically in the second and third autumn after a large volcanic eruption. This situation occurred within an overall context of rainfall decrease caused by large tropical eruptions in the Iberian Peninsula. This highlights the exceptional nature of the situation in the SIP and underscores the importance of evaluating possible differential impacts on cereal prices that could have produced these rainfall differences in the whole of Spain.

Regarding the possible causes of the changes detected, numerous authors found results in line with ours (Prohom, 2003; Anet et al., 2014; Paik et al., 2020) and reported that the explanation for the changes detected in precipitation would be both radiative and dynamic. In general, Fischer et al. (2007) pointed out that the precipitation response on the regional and seasonal scales is complex and strongly dependent on circulation changes, while at the global scale, mean precipitation was reduced as a consequence of lower shortwave radiation. Prohom (2003) reports that during the first post-eruptive January, the positive phase of the NAO is reinforced, thus reinforcing the zonal wind flow and motivating an increase in winter rainfall in the north-east of the Iberian Peninsula, compared to a decrease in rainfall in the SIP. In contrast, during post-eruptive summers, dynamic variability increases, a situation that could explain the increase in summer and autumn rainfall in the SIP, insofar as the dominant dynamic pattern in the SIP is characterised by the stability induced by the action of the anticyclone of the Azores in the south of the Iberian Peninsula. Anet et al. (2014) note that due to large tropical volcanic eruptions, the hydrological cycle can be disturbed by a slowdown of the Hadley and Ferrel cells on time scales of 1 to 3 years after the eruption. Simultaneously, the NAO is pushed into a positive phase in winters after a volcanic eruption, leading to increased precipitation in northern Europe and a negative precipitation anomaly in southern Europe. In contrast, Paik et al. (2020), through a set of simulations, detect that large tropical eruptions reinforce the positive phase of the ENSO (El Niño). This causes a decrease in summer rains in the areas affected by the monsoons of the northern hemisphere. However, in the Mediterranean region, there was a significant increase in rainfall between 1 and 2.5 years after the eruption. Iles et al. (2013) found that the land precipitation response to large volcanic eruptions remains significant for 3 years and reacts faster than land temperature, correlating with aerosol optical depth and a reduction in land-ocean temperature contrast. The response to this forcing manifests on a global scale in an increase in drought in humid regions, while dry regions increase precipitation. Consequently, the authors point to significant increases in precipitation between one and 4 years after the eruption in the western Mediterranean. This increase is notably intense and significant between May and October. Along the same lines, Wegmann et al. (2014) state that the reduction in summer monsoons in Asia and Africa caused by large volcanic eruptions induces an increase in summer precipitation (June to August) of south-central Europe in the year following the eruption. The dynamic explanation is related to the weakening of the weaker monsoon circulations in the northern branch of the Hadley circulation and alters the atmospheric circulation over the Atlantic-European sector.

For the decline in grain prices, it is necessary to note that some outside factors (including legal and administrative changes, wars, and epidemics) may affect prices. However, no relevant changes in this regard were detected. The protectionist Cánovas Tariff was implemented in 1891 to encourage national production of cereal products and improve self-consumption and production in Spain (Barbastro Gil, 2002). However, this law was introduced well after prices changed. In addition, the price decline is consistent with the climate impact of the Krakatoa eruption.

Finally, regarding the weather risks situation in the SIP, the literature reveals that there were no social conflicts. The reduction in the number of droughts reduced the level of social tension (Burke et al., 2015). Despite an increase in the number of floods, there was no worsening of conditions that existed before the eruption because the floods were generally light or moderate. Mild and moderate floods were inherent in the social system in the SIP and were perceived as positive to the extent that it was believed that the sediments increased the fertility of crop fields (Maurandi Guirado and Romero Díaz, 2000; Díez-Herrero et al., 2009). Additionally, there were no catastrophic frosts or other adverse situations in the SIP between 1883 and 1898 (Pastor, 2002; Gil-Guirado, 2013; Gil-Guirado et al., 2019). We are unaware of revolts or social conflicts in the SIP between 1883 and 1898.

6. Conclusions

Large volcanic eruptions have direct effects on the climate of areas far from the eruptive focus. Hence, agricultural harvests fluctuate, which results in changes in food prices. Induced climate change are an additional factor of variability in the atmospheric extremes that can trigger risk processes for societies (droughts, floods, cold waves, etc.). The SIP is an especially sensitive area in this regard.

In this work, a novel methodology is used to analyse high-resolution climatic data together with cereal price data and meteorological risks data, in order to examine whether there is a possible relationship between the Krakatoa eruption of 1883 and the variability of this data. Regarding the climatic effect of the eruption of Krakatoa in the SIP, we noted a significant decrease in maximum temperatures, followed by a lesser decline in average temperatures. Minimum temperatures increased, which may be related to an increase in cloudiness also induced by volcanic forcing. These changes are most obvious during autumn; thus, the phrase 'years without summer' in the SIP would be more appropriate if revised to 'years with double winter'. A significant increase in rainfall resulted from the eruption, especially during spring and autumn. This situation of temperature decline and increase in rainfall-induced a significant decrease in cereal prices in the SIP which further facilitated a favourable economic situation for the general population. The situation in relation to meteorological risks was also helped in this regard, as there were fewer droughts and no cold waves after the eruption. However, there was an increase in flooding. The changes observed in climatic variables and prices coincide in time with each other and with the eruption of Krakatoa. Therefore, we can conclude that the Krakatoa eruption of 1883 produced variations in climate that were favourable for society and the economy of the SIP.

However, despite all indications pointing to a double causal relationship (between the Krakatoa eruption of 1883, the temperature decrease and rainfall increase in the SIP, and between the climatic variability induced by the eruption and the fall in the prices of cereals in the SIP), it is advisable to be cautious when stating this fact. In particular, a limited number of data series were analysed. In this regard, it is necessary to further research this phenomenon with more data. In future research, the research team plans to extend the study to other eruptions and provinces.

This work is a first approximation of the link between the climatic effects of major volcanic eruptions and their economic and social impact. These studies are useful for understanding low-frequency climate variability and its relation to the agrarian economy. This motivates an interest in developing new research to analyse the patterns of social-climatic change that occurs in large areas as a result of the great volcanic eruptions of recent centuries.

Acknowledgements

This work was partially supported by the Spanish Ministry of Economy and Innovation (CGL 2016-75996-R). SG-G acknowledges the support of the Spanish Ministry of Science, Innovation and Universities through "Juan de la Cierva Incoporación" grant (IJCI-2016-29016). The authors have no conflicts of interest to declare.

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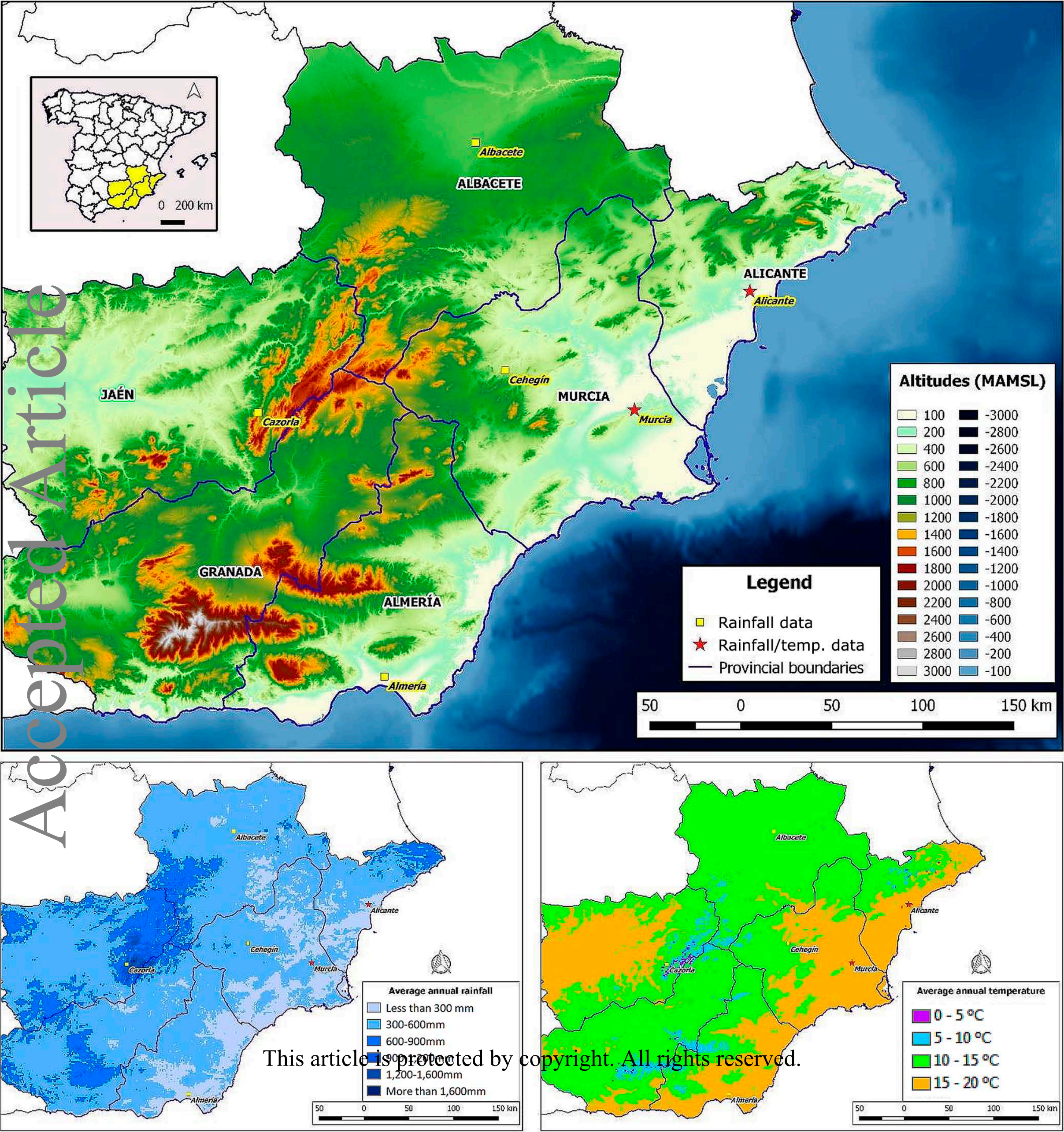
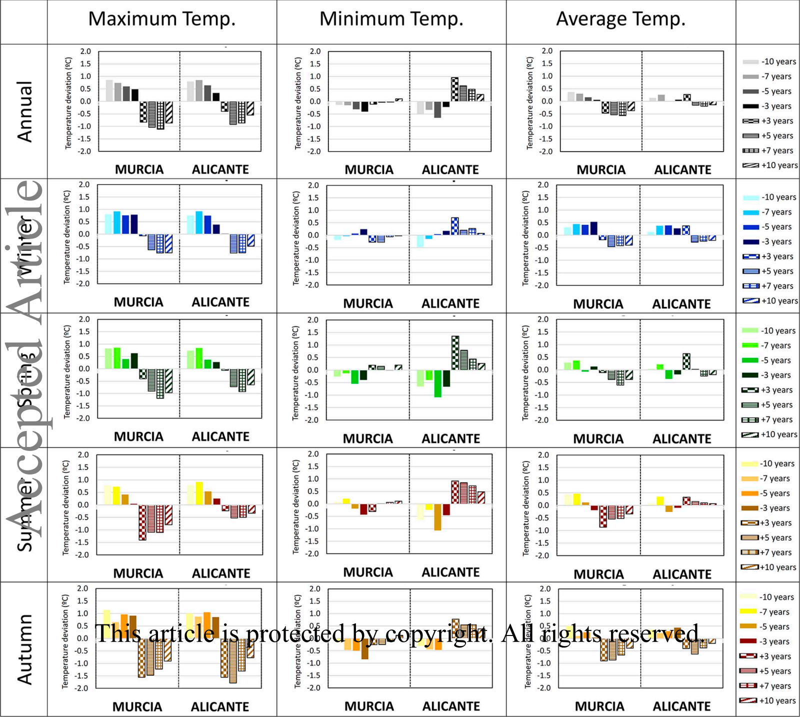
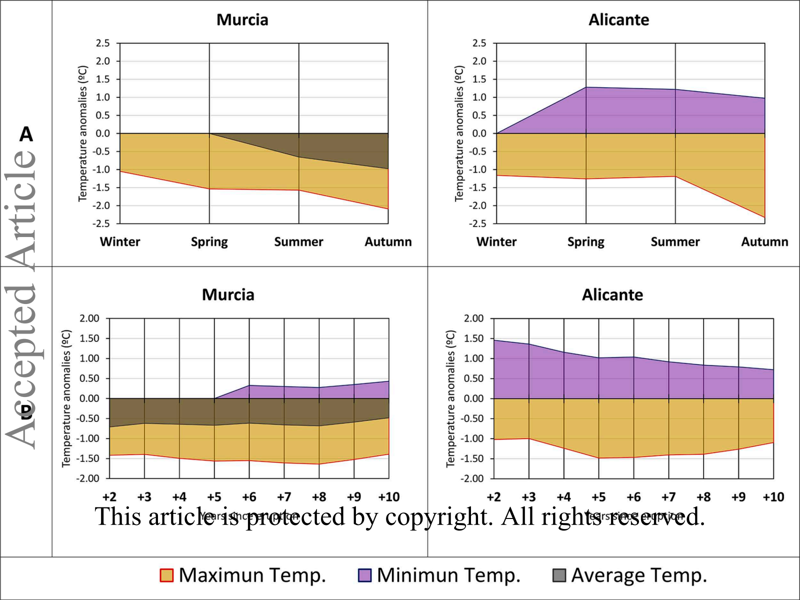
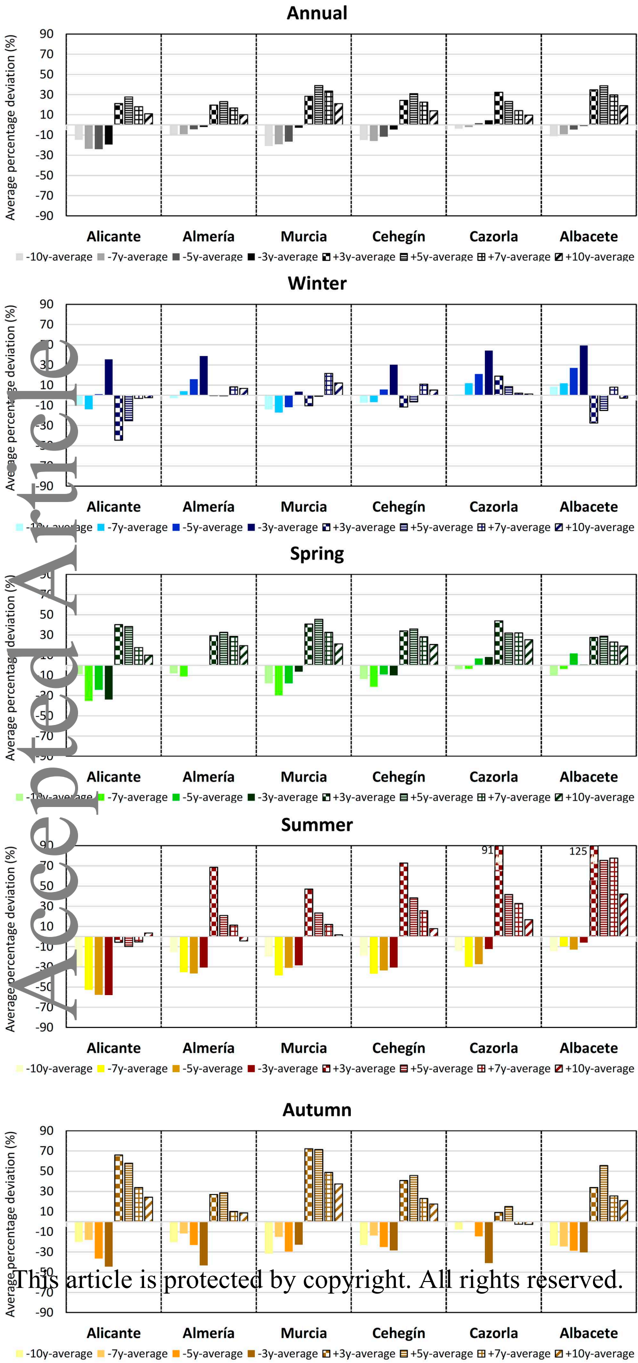
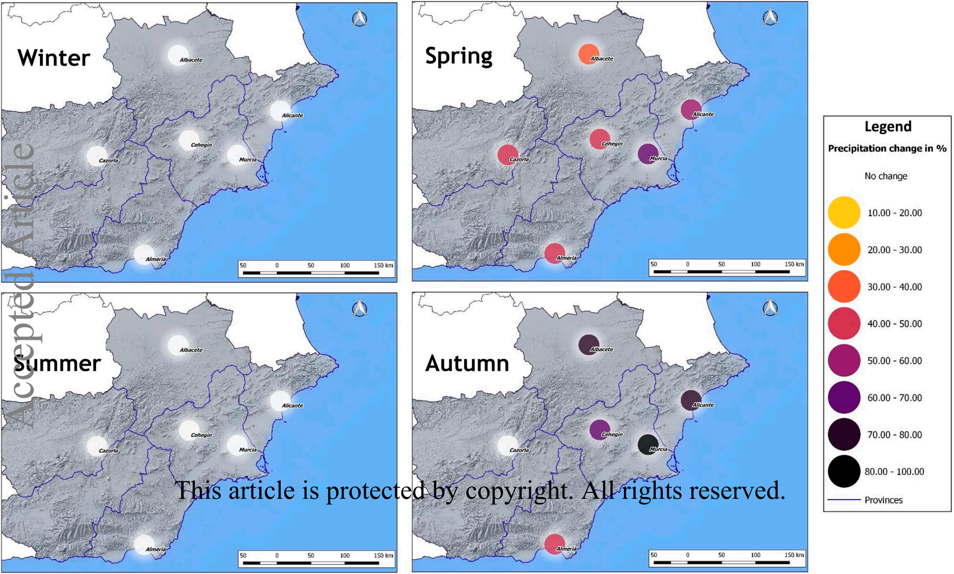

0 200 km
Albacete
ALBACETE
ALICANTE
Alicante
JAÉN
Cehegín
MURCIA
Murcia
Cazorla
GRANADA
ALMERÍA
Almería
Altitudes (MAMSL)
100
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
-3000
-2800
-2600
-2400
-2200
-2000
-1800
-1600
-1400
-1200
-1000
-800
-600
-400
-200
-100
Legend
Rainfall data
Rainfall/temp. data
Provincial boundaries
50 0 50 100 150 km
Average annual rainfall
Less than 300 mm
300-600mm
600-900mm
1,200-1,600mm
More than 1,600mm
Average annual temperature
0 - 5 ºC
5 - 10 ºC
10 - 15 ºC
15 - 20 ºC

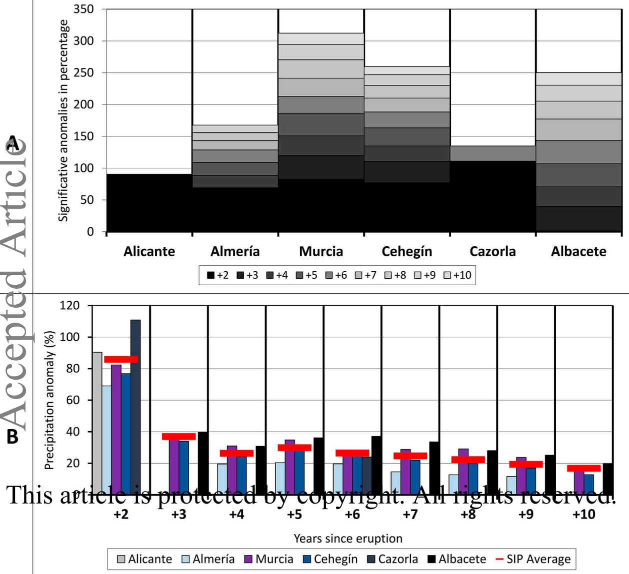


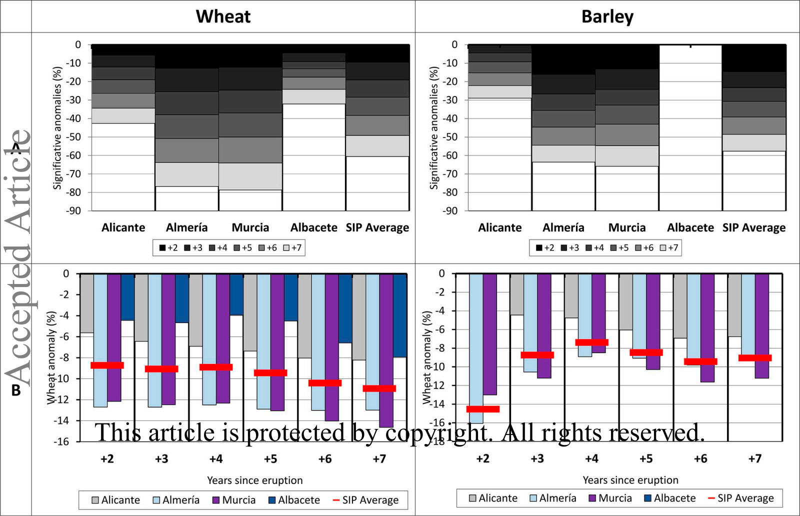
Maximum Temp.
Minimum Temp.
Average Temp.
Annual
Winter
Spring
Summer
Autumn
Temperature deviation (ºC)
MURCIA
ALICANTE
-10 years
-7 years
-5 years
-3 years
+3 years
+5 years
+7 years
+10 years


A
B
Murcia
Alicante
Temperature anomalies (ºC)
Winter
Spring
Summer
Autumn
+2
+3
+4
+5
+6
+7
+8
+9
+10
Years since eruption
Maximun Temp.
Minimun Temp.
Average Temp.

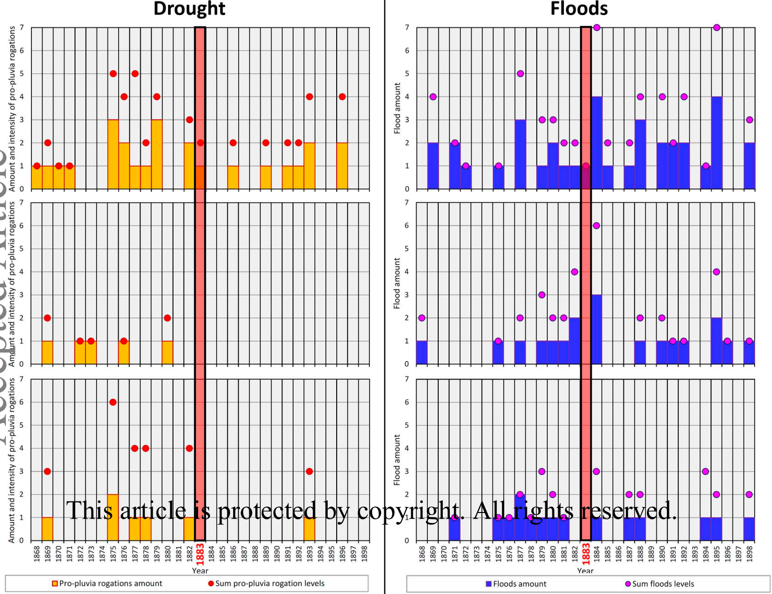

Annual
Average percentage deviation (%)
90
70
50
30
10
-10
-30
-50
-70
-90
Alicante
Almería
Murcia
Cehegín
Cazorla
Albacete
-10y-average
-7y-average
-5y-average
-3y-average
+3y-average
+5y-average
+7y-average
+10y-average
Winter
Spring
Summer
91
125
Autumn


Winter
Spring
Summer
Autumn
Albacete
Alicante
Cehegin
Cazorla
Murcia
Almeria
50 0 50 100 150 km
Legend
Precipitation change in %
No change
10.00 - 20.00
20.00 - 30.00
30.00 - 40.00
40.00 - 50.00
50.00 - 60.00
60.00 - 70.00
70.00 - 80.00
80.00 - 100.00
Provinces


A
Significative anomalies in percentage
350
300
250
200
150
100
50
0
Alicante
Almería
Murcia
Cehegín
Cazorla
Albacete
+2 +3 +4 +5 +6 +7 +8 +9 +10
B
Precipitation anomaly (%)
120
100
80
60
40
20
+2
+3
+4
+5
+6
+7
+8
+9
+10
Years since eruption
Alicante Almería Murcia Cehegín Cazorla Albacete SIP Average



Wheat
Barley
Significative anomalies (%)
Alicante
Almería
Murcia
Albacete
SIP Average
+2 +3 +4 +5 +6 +7
B
Wheat anomaly (%)
Years since eruption
Alicante Almería Murcia Albacete SIP Average



Drought
Floods
Murcia
Caravaca
Orihuela
Amount and intensity of pro-pluvia rogations
Flood amount
Year
1883
Pro-pluvia rogations amount
Sum pro-pluvia rogation levels
Floods amount
Sum floods levels

TABLE 1 Data sources and variables used.

	Place	Variables	Spatial resolution	Time resolution	Source
Climate data	Murcia	Accumulated precipitation (mm) and maximum, minimum and average temperature (ºC)	Point	Monthly	AEMET
	Alicante	Accumulated precipitation (mm) and maximum, minimum and average temperature	Point	Monthly	AEMET
	Almería	Accumulated precipitation (mm).	Point	Monthly	AEMET
	Cehegín	Accumulated precipitation (mm).	Point	Monthly	AEMET
	Albacete	Accumulated precipitation (mm).	Point	Monthly	AEMET
	Cazorla	Accumulated precipitation (mm).	Point	Monthly	AEMET
Prices	Alicante	Wheat and barley (pesetas/hectolitre).	Province	Monthly	Gazeta de Madrid
	Murcia	Wheat and barley (pesetas/hectolitre).	Province	Monthly	Gazeta de Madrid
	Almería	Wheat and barley (pesetas/hectolitre).	Province	Monthly	Gazeta de Madrid
	Albacete	Wheat and barley (pesetas/hectolitre).	Province	Monthly	Gazeta de Madrid
Climatic Risk	Murcia	Number of floods and sum of flood intensity; number of rain prayers and sum of rain prayer intensity	Point	Annual	Zamora Pastor, 2002; Gil-Guirado, 2013
	Caravaca	Number of floods and sum of flood intensity; number of rain prayers and sum of rain prayer intensity	Point	Annual	Zamora Pastor, 2002; Gil-Guirado, 2013
	Orihuela	Number of floods and sum of flood intensity; number of rain prayers and sum of rain prayer intensity	Point	Annual	Zamora Pastor, 2002; Gil-Guirado, 2013

Notes: The peseta was the Spanish currency until 2000; 1 euro equals to 166.386 pesetas.

TABLE 2 Breaks in homogeneity in climate data and prices in the SIP.

		Winter		Spring		Summer		Autumn		Annual	
		T	**RC**	**T**	**RC**	**T**	**RC**	**T**	**RC**	**T**	**RC**
Temperature	Max. temp. Alicante (ºC)			**1883**	-1.3	**1882**	-1.4	**1883**	-1.0	**1883**	-1.1
	Min. temp. Alicante (ºC)					1876	0.3			**1883**	0.9
	Max. temp. Murcia (ºC)			**1883**	-1.4	**1883**	-1.1	**1883**	-1.1	**1883**	-1.0
	Min. temp. Murcia (ºC)							**1885**	0.9	**1885**	0.8
Rain	Rain anomaly in Albacete (%)							**1883**	37.9		
Grains	Wheat anomaly in Almería (%)	**1884**	-10.4			**1883**	-12.1	**1883**	-12.4		
	Wheat anomaly in Murcia (%)			**1884**	-16.8	**1884**	-13.8			**1883**	-15.2
	Wheat anomaly in Almería (%)					**1884**	-9.4	**1883**	-8.2	**1884**	-9.2
	Wheat anomaly in SIP (%)							**1883**	-10.7	**1883**	-11.5
	Barley anomaly in Murcia (%)							**1883**	-11.2		

Notes: **T** is the year of change; **RC** is the rate of change. RC is calculated as the difference between the subsequent and previous average at the time of change (RC = t2-t1). T2 is the average after the moment of change (including the moment of change) and t1 is the average before the moment of change (not including the moment of change). T values are in years. The values of R C are expressed as the differences of averages in % for prices and rainfall and as anomaly in ºC for temperatures. Only values for the variables that present changes with a level of significance equal to or greater than 95% (p-value <= 0.05) according to the Pettit test are shown.

TABLE 3 Correlations between climatic anomalies and price anomalies in the SIP.

	Wheat					**Barley**				
	Alicante	**Almería**	**Murcia**	**Albacete**	**SIP Average**	**Alicante**	**Almería**	**Murcia**	**Albacete**	**SIP Average**
Rain in Albacete	-0.416	-0.548	-0.525		-0.451	-0.518	-0.528	-0.563		-0.475
Rain in Almería	-0.441	-0.575	-0.552		-0.490	-0.549	-0.661	-0.643	-0.399	-0.585
Rain in Cazorla	-0.361	-0.465	-0.428		-0.383	-0.514	-0.627	-0.592	-0.410	-0.543
Rain in Cehegín	-0.451	-0.601	-0.535	-0.367	-0.498	-0.493	-0.634	-0.604	-0.382	-0.558
Rain in Murcia	-0.428	-0.540	-0.498		-0.466	-0.382	-0.525	-0.475		-0.454
Rain in Alicante		-0.452	-0.370		-0.395		-0.436	-0.388	-0.385	-0.421
Max. temp. Murcia	0.493	0.618	0.59		0.48	0.48	0.518	0.476		0.358
Min. temp. Murcia										
Aver. temp. Murcia		0.542	0.472			0.436	0.546	0.434		
Max. temp. Alicante	0.554	0.657	0.616		0.537	0.524	0.545	0.519		0.409
Min. temp. Alicante										
Aver. temp. Alicante										

Key

Precipitation	**Temperature**
Greater than -0.2	Greater than 0.8
Between -0.2 and -0.25	Between 0.8 and 0.7
Between -0.25 and -0.3	Between 0.7 and 0.6
Between -0.3 and -0.35	Between 0.6 and 0.5
Between -0.35 and -0.4	Between 0.5 and 0.4
Between -0.4 and -0.45	Between 0.4 and 0.3
Between -0.45 and -0.5	Between 0.3 and 0.2
Between -0.5 and -0.55	Between 0.2 and 0.1
Between -0.55 and -0.6	Between 0.1 and 0
Between -0.6 and -0.65	Between 0 and -0.1
Between- 0.65 and -0.7	Between -0.1 and -0.2
Smaller than -0.7	Smaller than -0.2

Notes: Correlations are calculated as the relationship between anomalies of temperature and precipitation with anomalies for the entire coincident time period (1868-1890). The values show the Pearson correlation only when the significance level is equal to or greater than 95% (P-value <0.05).