Comparing historic records of storm frequency and the North Atlantic Oscillation (NAO) chronology for the Azores region

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Received 9 January 2007; revised manuscript accepted 17 December 2007

A HOLOCENE RESEARCH PAPER

Abstract: The storminess of the Azores region was investigated using newspaper records from AD 1836 onwards. The information obtained was rank-ordered for intensity and the time series of storm frequency analysed for interannual- to century-scale variability. The documentary data set was validated by comparison with objective cyclones intensity for the period AD 1958–2000. Results indicate that four periods of contrasting storm frequency are present (AD 1836–1870, 1870–1920, 1920–1940 and 1940–1998). The average storm lasts for 2.3 days and the average secular storm frequency is 3.1 storms/yr. Low intensity events occur four times every five years whereas an extreme storm occurs on average once every seven years. The documentary index of storminess is highly variable at different timescales, which is consistent with other studies of storminess in the North Atlantic. Nevertheless, an objective comparison between late nineteenth- and late twentieth-century storm frequency does not reveal a significant difference. Between AD 1865 and the late twentieth century the winter NAO and storminess indices show a statistically significant anti-correlation pattern at the monthly and seasonal scales. In the late nineteenth century and between AD 1950 and 1970 the NAO index was low and the storminess index high, whilst the opposite occurred from the early twentieth century until the middle 1950s; since AD 1970 both indexes reveal positive trends and are predominantly positive. The NAO mode of circulation is partially responsible for the storminess spatial pattern and temporal distribution over the Azores region since AD 1865 and for about a century, however this relation appears to have weakened since the 1960s.

Key words: Storminess, documentary record, historical evidence, North Atlantic Oscillation, NAO, Azores, storm-tracking.

Introduction

The historical documentary record is an invaluable source to hindcast time series of climate parameters and short-term climatic fluctuations far beyond the period where instrumented data are available (cf. Bradley, 1999 for a critical review). In particular, long records of storminess and related coastal flooding derived from documentary sources may be the only sources to understand the patterns of meso-scale coastal change and to establish relations with meteorological and anthropogenic forcing.

The Azores inhabitants strongly depend on the sea not only as a source of income and means of communication and trade but also because the narrow littoral fringe is one of the scarce land

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 10.1177/0959683608091794

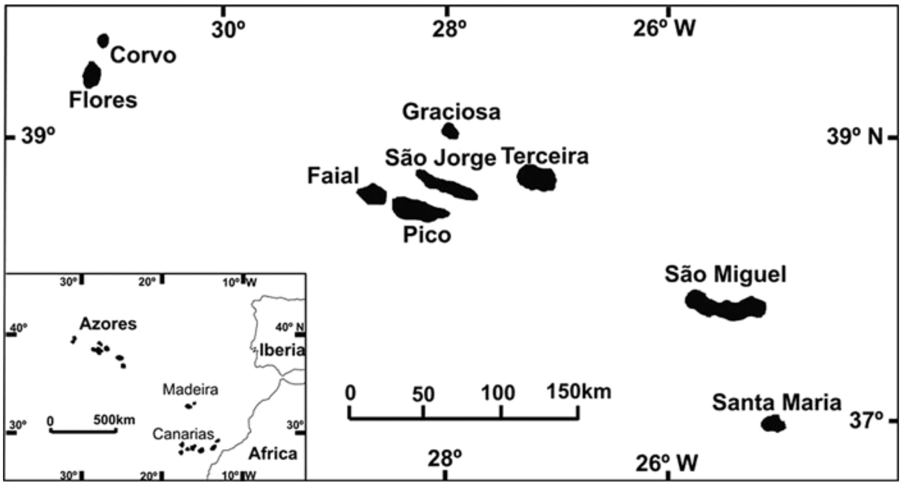


Figure 1 Location map of the Azores islands in the North Atlantic

units that offer potential for settlement, in spite of the hazards arising from storms. It is therefore understandable that storms have been, since the earliest settlements in the fifteenth century, a major concern for people living on these islands and that this concern has been translated into written documents. The compilations of Frutuoso (*c*. 1586) and Lima (1943), among other local monographs, are examples of this concern.

This paper presents a description and analysis of the documented record of storminess for the Azores archipelago on a century timescale, using newspapers as the main source of information. It should be stressed that a recent compilation of Atlantic historical tropical cyclones has used a similar approach (Chenoweth, 2006). Here, the method is applied for searching extratropical storms based on their effects reviewed in contemporary newspapers.

A thorough validation of this historical storminess is a very difficult task. Nevertheless, for the last four decades it is possible to evaluate the documentary storminess based on intense storms detected by objective procedures. Early compilations of storm-tracks were constructed based on the visual identification of cyclones (and respective paths) in synoptic charts (eg, Petterssen, 1956; Klein, 1957; Hayden, 1981). In recent years, subjective techniques based on visual inspection of charts have given way to a wide number of studies applying automated algorithms that can detect and track individual storms (eg, Blender *et al*., 1997; Trigo *et al*., 1999; Hanson *et al*., 2004). Here, the detection and tracking of North Atlantic cyclones is based on an algorithm first developed for the Mediterranean region by Trigo *et al*. (1999) and recently adapted for the entire north Atlantic area (Trigo *et al*., 2004; Trigo, 2005). We present a comparison between intense storminess detected by the subjective (newspapers) and objective procedures for the period covered by this data set (AD 1958–2000). Finally, we intend to investigate the relations between the interannual and interdecadal variability in storminess and the contemporary changes of the North Atlantic Oscillation (NAO).

The study area

The Azores archipelago is located in the North Atlantic between 36°55′ and 39°43′N and 24°45′ and 31°17′W, approximately 1500 km from Europe (Figure 1). It is formed by nine volcanic islands and a few islets scattered over 600 km and roughly aligned WNW–ESE. These rise from the Azores Plateau, defined by the 2000 m bathymetric contour.

Several authors (eg, Agostinho, 1938, 1939, 1940, 1941, 1942, 1947, 1948; Bettencourt, 1979; Ferreira, 1981a, b; Azevedo, 2006) previously discussed the climate of the Azores, the large-scale features of which reflect their location within the subtropical high-pressure region of the northern Atlantic. The Azores are usually under the influence of either tropical or polar maritime air masses, a consequence of the seasonal drifting of the high pressure Azores Anticyclone. Whenever this high-pressure centre is dissipated or displaced either to higher latitudes (between Greenland and Scandinavia) or eastern longitudes (over Iberia) the Polar atmospheric front shifts southwards and several low-pressure fronts may sweep the whole archipelago. They typically travel from SW to NE and generate storms that are particularly harsh in the western islands. Occasionally, a low-pressure cell may develop eastwards of the Azores and slowly shift westwards, resulting in storms that are more severe in the islands of the eastern and central groups, such as the catastrophic storm that struck the main Island of S. Miguel between 30 and 31 October 1997, causing 29 deaths (Raposo, 1998; Valadão *et al*., 2002). In general, storms are restricted to those periods characterized by well-defined and deep depressions, ie, mostly during winter and spring months. However, during the Atlantic hurricane season (summer and autumn) several hurricanes can reach the Azores archipelago, albeit sometimes downgraded to tropical cyclones or depressions. These powerful storms can represent an important menace for people, as was the case in 1995, with storms Noel and Tanya, in 1998, with Ivan and Jeanne (Reale *et al*., 2001) and again in 2006 with Hurricane Gordon and tropical cyclone Helene (Babin and Sterner, 2006).

The documentary record

Sources

In the Azores, documents pre-dating the nineteenth century are scarce, biased towards extreme events and provide only a fragmentary record. From the early nineteenth century onwards, several regional newspapers emerged, among which the *Açoriano Oriental* (AOR) and the *Açores* (ACR) are of special relevance because of the high standards of objectivity that guided their editorial policy, and homogeneous and characteristic reporting style that persisted largely unchanged throughout a long time period.

The AOR is the oldest Portuguese periodical, being continuously published from 18 April 1835 onwards (until December 1978 with a weekly frequency and daily afterwards). The ACR was first published on 29 October 1944 and was published daily until January 1979 when it became a weekly paper. In 25 November 1993 its last issue was released and a weekly magazine with the same title replaced the newspaper.

The study of documentary records of storminess in the Azores archipelago relies essentially on information yielded from the leading newspaper AOR, complemented by ACR (see Results section), 11 local monographs and several local papers that were used as supplementary or confirmation sources.

Methodology to retrieve storms from newspapers

The documents mentioned above, published between April 1835 and December 1998, were examined for weather information and descriptive excerpts were transcribed on to card files to build a data base containing a large number and varied suite of weather facts, which were filtered for reliability. The events considered as *most reliable* correspond to contemporaneous events for which eye-witness reports existed. The same classification was given if at least two matching but independent records of the same event existed, regardless of their date of edition. A rating of *poorly reliable* was given to descriptions or mentions of plausible events that linger as vague memories of elderly people but which lacked definite spatial or time coordinates. A rating of *good reliability* was given to all other plausible events that did not fit into either of the previous two classification criteria. The events ranked as *poorly reliable* represent less than 3% of the total record and were discarded from further processing.

All the events falling into the good and most reliable classes were taken into account, forming the resulting series (hereafter the I series). These events were then classified for:

(1) *intensity* – four classes of intensity (Class 4 corresponding to the most extreme events) were defined according to an empirical ranking of descriptive terms used by the diarist and an evaluation of reported damage, following procedures similar to the ones described by Baron (1992) and previously used by Andrade *et al.* (1996);
(2) *duration* – days elapsed between the first report and the dissipation of the storm (the latter is sometimes difficult to identify precisely);
(3) *typology* – type A: marine-related events and effects only (eg, coastal flooding, erosion, overwash, shipwrecks, closure of harbours or cessation of fishing activities); type B: non-marine events and effects only, including heavy rain, frost, thundershowers or gales, with no references to marine influence or effects; type C: lack of specific information; type D: reports containing events and effects of both marine and non-marine influence or effects;
(4) description of damage;
(5) objective information on meteorological parameters, if any (eg, wind direction or speed, wave height and direction, air pressure, precipitation intensity).

A restricted series (hereafter called the II series) was constructed using only records corresponding to types A and D that include explicit mention of effects on the coast. This procedure is useful to evaluate the relationship between the littoral fringe and storm forcing, and the resulting series was compared with the longer and more inclusive I series.

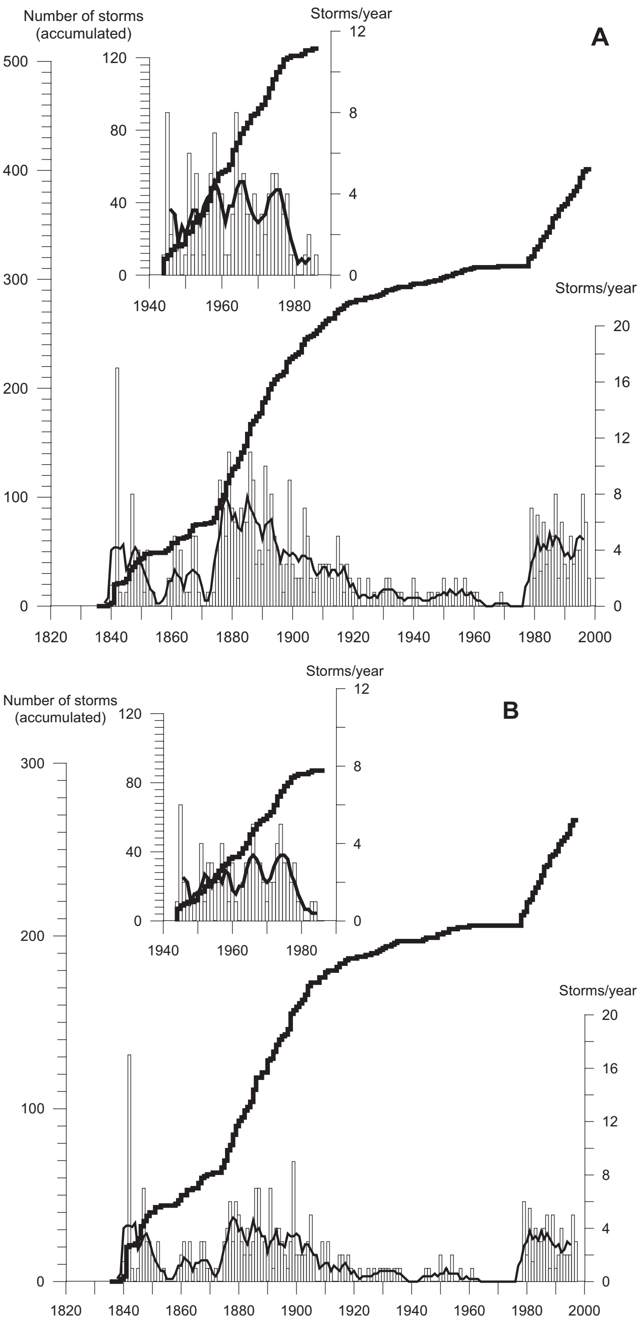


Figure 2 Bar charts of storm frequency, 5-yr running means and step plot of accumulated frequency of storms derived from the newspaper *Açoriano Oriental* (AOR). (A) Series I; (B) series II. Insets: equivalent information derived from the newspaper *Açores* (ACR)

Time series of storminess

The time series of yearly storm frequency resulting from the documentary compilation show complex patterns and are presented in Figures 2 and 3.

Figure 2A, based upon the I series yielded by AOR, suggests that five periods of contrasting storminess are present. The period AD 1836–1870 is characterized by a distribution of storm frequency with two maxima, separated by a minimum located *c.* 1855. Roughly every 5–7 years a peak in storm frequency is apparent, the largest occurring in AD 1842. Within this period, the storm frequency assigned to the year of 1842 is clearly out of the range of every other value of the series, particularly the month of November with five 'independent' storms being described in the newspapers. In this respect, it is worth mentioning that Chenoweth (2006) refers to an exceptional extratropical storm dated November 1842. Despite its singular character in storm frequency, the calculations and reasoning presented below are not significantly affected by the 1842 value. A second period extends between the AD 1870 and 1920 minima and broadly corresponds to a highly variable distribution of storm frequency, decreasing in time, with similar maximum values being reported in 1879 and 1886. A third period corresponds to the decades of AD 1920–1960 when the storm distribution appears to be quite uniform. Between AD 1961 and 1978 (period 4) there is virtually no record of storms

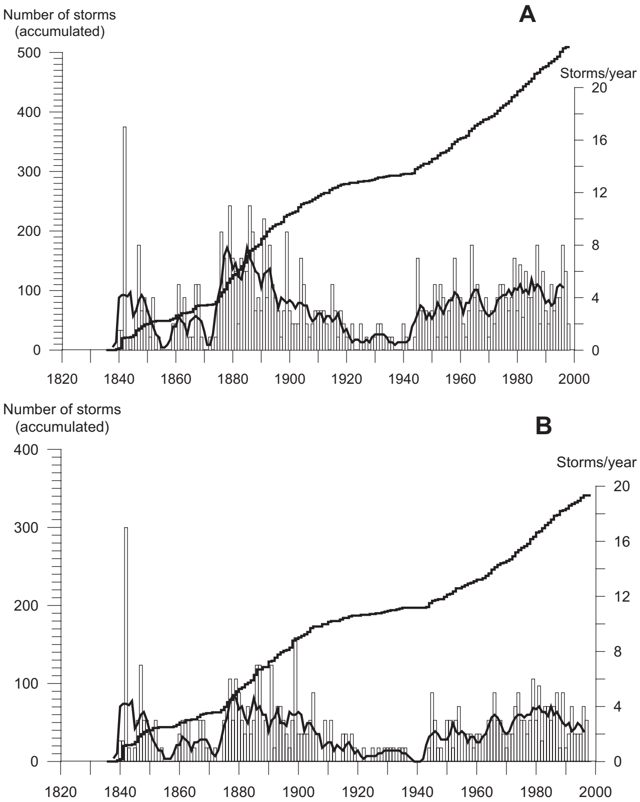


Figure 3 Bar charts of storm frequency, 5-yr running means and step plot of accumulated frequency of storms. (A) Series III; (B) series IV

but from 1979 onwards (period 5) the frequency abruptly increases, matching the decadal averages found in the early section of period 2 yet never reaching comparable maxima.

The pattern of variation of yearly average storm frequency versus time changed considerably both within each of the aforementioned periods and between different periods of the record. The early section of the record (AD 1836–1870) is characterized by a low yearly average (2–3 storms/yr) and strong interannual variability, features that are clearly highlighted by the relatively small slope and stepwise character of the accumulated step diagram. In the first years of the second period the yearly average storm frequency rises abruptly, exceeding 8 storms/yr and then gently but steadily drops after the turn of the nineteenth to twentieth centuries, until a minimum of 1 storm/yr is reached by the end of the AD 1911–1920 decade. The interannual variability in storm frequency is less pronounced then in period 1 and decreases with time. These patterns are clearly depicted in both the 5-yr running mean curve and accumulated frequency step diagram. During the third and fourth periods both the average yearly storm frequency and interannual variability remain essentially low. Finally, the most recent time period is marked by an abrupt increase in both the storm frequency (averaging 4–5 storms/yr) and interannual variability, matching the value attained in the early section of the second recording period.

Figure 2B, corresponding to the II series from the same newspaper (AOR), shows similar patterns of time evolution in both the storm frequency and interannual variability. This suggests that the documentary information was not biased on the source towards any particular type of event, effect or location that might have impressed the reporters, as might be expected to be the case along more populated areas of the islands (eg, the coastal fringe).

The step plot displays a conspicuous inflexion point in both the I and II series, dated AD 1979, following a time interval of about 18 years of virtually no record. This suspicious absence of storminess might be related to a change in editorial policy of the AOR that took place in the late 1970s; this hypothesis was assessed by processing the storminess information collected from the ACR newspaper for the period 1944–1986 (cf. Figure 2A and B), which was incorporated in the previous I and II series avoiding repetition of common events to produce the III and IV series, illustrated in Figure 3A and B.

The analysis of the III and IV series suggests that the third period extends only until the end of AD 1940, when the storm frequency is the lowest. This period is followed by a gradual increase of the frequency (2–3 to 4–5 storms/yr), with low annual variability, the 5-yr running mean curve indicating maxima between AD 1980 and 1985 and this was followed by a decrease in frequency.

Results of the comparison of series III and IV are identical to those previously described from the equivalent AOR series. Taking storm frequency as a first proxy of storminess in the Azores, and bearing in mind the geographical and timescales of the present approach, it seems reasonable to use series III as a primary, more comprehensive, data set for further processing, characterization and comparison with other meso-scale meteorological-sensitive indexes.

The long-term variability of storm frequency described by these subjective storm indices for the Azores archipelago are in reasonable agreement with results obtained for other areas of the northern Atlantic basin, such as the data set of Atlantic storms affecting the UK developed by Jones *et al*. (1999) for the period AD 1881 to 1997. These authors obtained an increase in the number of severe gale days over the UK since the 1960s, but no long-term increase when considering the century period (Intergovernmental Panel on Climate Change (IPCC), 2001). A good proxy for cyclone intensity can be provided by wave height and several studies report increased wave height since the early 1970s in the North Atlantic (approximately 2.5 cm/yr) and in coastal areas (Carter and Draper, 1988; Bouws *et al*., 1996; Kushnir *et al*., 1997; WASA Group, 1998). They found no long-term trend during the last 100 years, but a clear rise since a minimum of storminess in the 1960s. This is consistent with our results for the Azores and also with the increase in extreme wind found by Jones *et al*. (1999).

Despite the intense decadal variability presented in Figure 3 it is not clear if there is a significant change of annual storminess between two representative periods of 30 years for the late nineteenth century (AD 1869–1898) and the late twentieth century (AD 1969–1998). Therefore a Student's *t*-test was computed to assess whether the averages for these two periods were statistically different from each other. Referring to the III series (Figure 3A), we found a mean of 4.7 storms/yr for the period AD 1969–1998 and 4.2 storms/yr for the period AD 1869–1898 with no significantly mean difference between the two periods. A similar analysis was performed for series IV (Figure 3B) and the period AD 1969–1998 (1869–1898) reveals an average of 2.9 (3.0) storms/yr, and therefore a non-significant difference was obtained between these two subsets.

Storminess characterization

The information described above covers a time period of 163 years with a total of 509 individual events recorded. Statistics obtained from these data are shown in Table 1.

According to the documentary sources, 1166 days were recorded as stormy and only 28 out of 163 (17.2%) years contain no record of a relevant storm in the time interval AD 1836–1998.

Storms of low intensity, ie, class 1 and 2, represent respectively 30% and 56% of the total number of occurrences, whereas the extreme events (class 4) represent only 5%. The average duration of a storm event is 2.3 days and the longest recorded episode lasted 90 days (November–February 1840/1841) although this remarkable duration is likely to be the result of an inadequate

Table 1 Statistics obtained from the composite III series

Period (1836–1998)	Azores archipelago
Average duration of storms (days)	2.3
Longest duration (days)	90
Average storm frequency (storms/yr)	3.1
Frequency of extreme events (classes 3 and 4)	14%
Average duration of most extreme events (class 4) (days)	1.1
Longest duration of most extreme events (class 4) (days)	2
Average number of most extreme events (class 4)/yr	0.15
Average duration of class 3 events (days)	1.8
Average duration of class 2 events (days)	2.1
Average duration of class 1 events (days)	3.0
Total number of storms	509
Total number of stormy days	1166

description of a stormy season, the diarist not perceiving the succession of distinct low pressure fronts. The minimum reported duration of a storm was one day, and this also reflects the nature of the information source. The overall mean annual storm frequency is 3.1 storms/yr and this frequency would decrease only slightly to 3.0 storms/yr if the year 1842 is removed from the series. This figure may be compared with statistics obtained for the different intensity classes: on average, a low intensity event (classes 1 or 2) occurs four times every 5 years while an upper class storm (classes 3 or 4) occurs on average once every 7 years.

The extended winter (October to March) period accounts for 76% of the total storms recorded. Within this season the months of December to February contribute with equal proportions (20–21%) followed by November (15%), October (12%) and March (11%).

Objective cyclones

Method of detection and tracking

As stated above, the detection and tracking of cyclones used here is based on an algorithm first developed by Trigo *et al*. (1999) and recently adapted for the entire north Atlantic area (Trigo *et al*., 2004; Trigo, 2005). This scheme is performed using 6-hourly geopotential height at 1000 hPa, available from ECMWF reanalyses, on a 1.125° × 1.125° grid, for the period between AD 1958 and 2000. Cyclones are identified as minima in geopotential height fields at 1000 hPa, fulfilling a set of conditions regarding the central pressure and the geopotential gradient. The tracking is based on a nearest neighbour search in consecutive charts, assuming that the speed of individual storms is less than 50 km/h in the westward direction, and 110 km/h in any other. Further details on the cyclone detecting and tracking methodology may be found in Trigo (2005). These thresholds were determined empirically by observing cyclone behaviour in SLP charts (cf. Trigo *et al*., 2004). For the purpose of this study, only cyclones lasting a minimum of 24 h and presenting minimum pressure values below 1010 hPa throughout their life cycle were considered.

Comparison between documentary storminess and objective cyclones intensity

The characterization of cyclone intensity through physical variables in a region around the Azores is presented for the AD 1958–1998 period. The temporal limits of this comparison period are imposed by the availability of both data sets, namely by the starting year of the ECMWF reanalyses (1958) and the end of the storm assessment based on newspaper descriptions described in the previous section (1998). For this purpose it is necessary to select the appropriate physically based variables that can be used to characterize cyclones over the Atlantic and also to check the validity of documentary data. It is not only the frequency of cyclones over the Atlantic that is important but also their intensity, as it has been shown that the actual monetary loss resulting from wind storms rises roughly as the cube of the wind speed (Southern, 1979). The intensity of a cyclone can be estimated by the total power dissipation affecting the surface area affected by a storm and over its lifetime (Bister and Emanuel, 1998). More recently Emanuel (2005) has defined a simplified power dissipation index also proportional to the cube of wind speed:

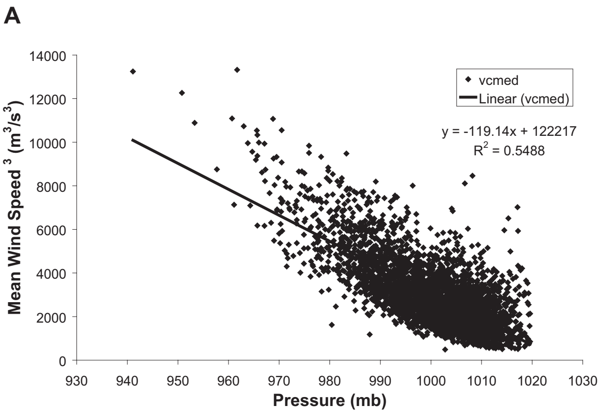
$$PDI = \int_0^{\tau} V_{max}^3 \, dt \tag{1}$$

where V_{max} is the maximum sustained wind speed at the standard altitude of 10 m. Therefore, besides the use of the 'standard' cyclonic central pressure, the average effect of the surrounding wind field was also evaluated, and these two variables have been considered as representing the intensity of the cyclone. Consequently, for every cyclone detected in the selected region the spatial average of the cube of the wind speed over that chosen area has been computed (instead of the V_{max} value that we could not access in this case). It is expected that the relatively small number of cyclones that significantly affected the Azores archipelago present a better characterization than the vast majority of cyclones that cross the North Atlantic sector.

After checking for several window sizes, the selected region with coordinates 30°N to 45.4°N in latitude and 18°W to 33.4°W in longitude was considered, in order to obtain a representative sample of the cyclones that could potentially affect the Azores Islands. As stated above, the combined pair of variables used is the central pressure and the average cube of the wind speed. This relationship is illustrated in Figure 4A for all the cyclones in the work region and in Figure 4B restricted to the subset of cyclones that affected the Azores Islands according to the documentary record. The totality of cyclones for that region present a correlation value of $R = 0.74$ (explained variance of 55%) between pressure and wind speed. The corresponding correlation coefficient value for the cyclones accounted for by documentary sources is significantly higher ($R = 0.85$, ie, with explained variance of 71%). While both values are statistically significant at the 1% significance level, it is possible to conclude that the correlation between the two variables is considerately improved when the cyclone's pool is restricted to those events that were listed in the documentary data set previously described and related to some type of impact in the Azores. For the sake of clarity we will use the terms 'storm' or 'storminess' when referring to those events detected in the news, while the term 'cyclone' is used for low-pressure systems detected objectively with the ECMWF data.

It should be stressed that the entire set of storms (509) empirically detected for the Azores archipelago corresponds to a subset of the total number of storms that have crossed the Azores sector during the same period and that the comparisons discussed above do not provide a full evaluation of the empirical storm detection scheme. A more comprehensive validation would require the detection of each individual storm life cycle, particularly describing the entire storm-track, time and position of maximum strength similar to what is routinely being done at present for Hurricanes (Babin and Sterner, 2006). However, such effort is beyond the scope of the present work.

This fact must be emphasized, particularly when we attempt to validate the strength of these low-pressure systems for the second part of the twentieth century. In other words, the automated procedure applied here between AD 1958 and 2000 to detect and track



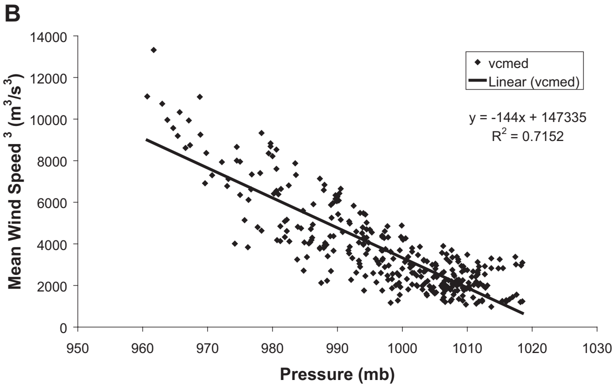


Figure 4 (A) Relationship between pressure and the spatial average of the cube of wind speed (vcmed) for all the cyclones in the work region for the 1958–1998 period. (B) The same as in (A) but only for the cyclones that affected the Azores Islands according to the documentary record. The linear regression line is also represented in both figures (Linear vcmed)

the life cycle of storms is capable of detecting many more extratropical systems around the Azores Islands than those described in the local newspapers. However, these storms described in the news were highlighted by observers/journalists because of their strength and impacts on society. Therefore it is reasonable to expect that, on average, their strength presents a better characterization than the remaining vast pool of cyclones that cross the North Atlantic sector.

The impact of NAO on storminess

The results and discussion presented above suggest that although the meso-scale series of storminess from the Azores displays high variability through time it may show some internal structure that might be correlated with other large-scale regional indexes of climate such as the NAO.

Traditionally the NAO has been defined as the difference in normalized sea level pressure computed between a station in the Azores (Ponta Delgada) or southern Europe (eg, Gibraltar, Lisbon), and another station in Iceland (Stykkisholmur). This index has long been recognized as one major characterizing parameter of the global climate system (Jones *et al*., 1997) reflecting a prominent Northern Hemisphere teleconnection pattern across all seasons, although its value in monitoring global circulation and climate variability outside winter is not yet fully understood. The NAO is associated with changes in the surface westerly winds across the North Atlantic that eventually affect the Azores and the western European shores. In this respect, extreme values of the winter NAO index have been proven to correlate significantly with the intensities and frequency of westerly winds onto Europe (eg, Hurrel, 1995), harshness/mildness of winters in northern and western Europe (eg, World Meteorological Organization (WMO), 1995), temperature anomalies (eg, Hurrel, 1995; Trigo *et al*., 2002) and intensity and frequency of winter daily precipitation over Iberia (Gallego *et al*., 2005). When positive phases of NAO occur during winter months a negative precipitation anomaly was found, not only in Iberia but also in a strong band that spans from west of the Azores to the Black Sea region, with the greatest differences located between the Azores archipelago and western Iberia, and over Portugal (Trigo *et al*., 2004). This relationship between positive NAO phase and low precipitation values is also associated with lower values of river flow regime. This impact has obvious consequences for the water resources management in the region, and in particular it has a huge economic impact because of the associated interannual variability of hydroelectric production within both Spain and Portugal (Trigo *et al*., 2004). Borges *et al*. (2003) also found a decadal periodicity and synchrony between the NAO and wind conditions in the winter over the western Iberian coast, with an association between upwelling-favourable winds and a positive NAO index, which impacted negatively on sardine productivity after the early 1970s.

The NAO index used here was obtained from the data base of the Climate Research Unit (CRU, University of East Anglia, UK) website (http://www.cru.uea.ac.uk/) and refers to the standardized monthly average of the difference in pressure between Ponta Delgada (Azores) and Reykjavik (Iceland) between AD 1865 and 1998.

The positive mode of the NAO occurs when the southern subtropical high-pressure cell is extremely intense, while Iceland registers very low air pressure. In the negative mode of the NAO, both pressure centres are anomalously weak to the point of pressure reversal and the harsh European winters associated with the latter situation may last long in the memory of people (cf. Rogers, 1984). Hurrel (1995) recognized the large interannual variability of the winter NAO index but also identified several longer periods when anomalous (positive or negative) circulation patterns persisted over many consecutive winters. From the turn of the twentieth century until about AD 1930, pressures were persistently higher than normal at the Azores latitude. A second period extends from the early 1940s until the early 1970s, characterized by a downward trend of the NAO. A third period, widely recognized in the literature, extends roughly from AD 1970 until the late 1990s with strongly positive NAO values (Hurrel, 1995; Osborn *et al*., 1999). In particular the NAO index for winter months presents a positive trend over those three decades; as a consequence, its distribution is dominated by positive values, with monthly averages above zero (Jones *et al*., 1997). The December–February winter record corroborates this, showing nine consecutive winters with positive indexes, a feature that is unprecedented since the 1920s (Osborn *et al*., 1999; Trigo *et al*., 2004). Therefore, the monthly values of the NAO index have been normalized using the mean and standard deviation statistics. Afterwards, the extended winter high and low NAO composites were computed using all winters with NAO index greater than 0.5 and lower than −0.5, respectively.

The anomalies of the average number of cyclones detected per winter, per 5° × 5° cell normalized for 50°N, are plotted in Figure 5A and B, for low NAO and high NAO composites, respectively. For the high NAO composite a significant decrease in the number of cyclones between Newfoundland and the Iberian Peninsula is visible, while the dominant cyclone paths are clustered between southern Greenland and the Scandinavia Peninsula. For the low NAO composite the anomalies obtained are basically the reversal of that described for the high NAO composite.

This analysis is similar to the corresponding evaluation on the NAO impact on precipitation and storm density performed in a recent work that focused on landslide occurrence in the Lisbon

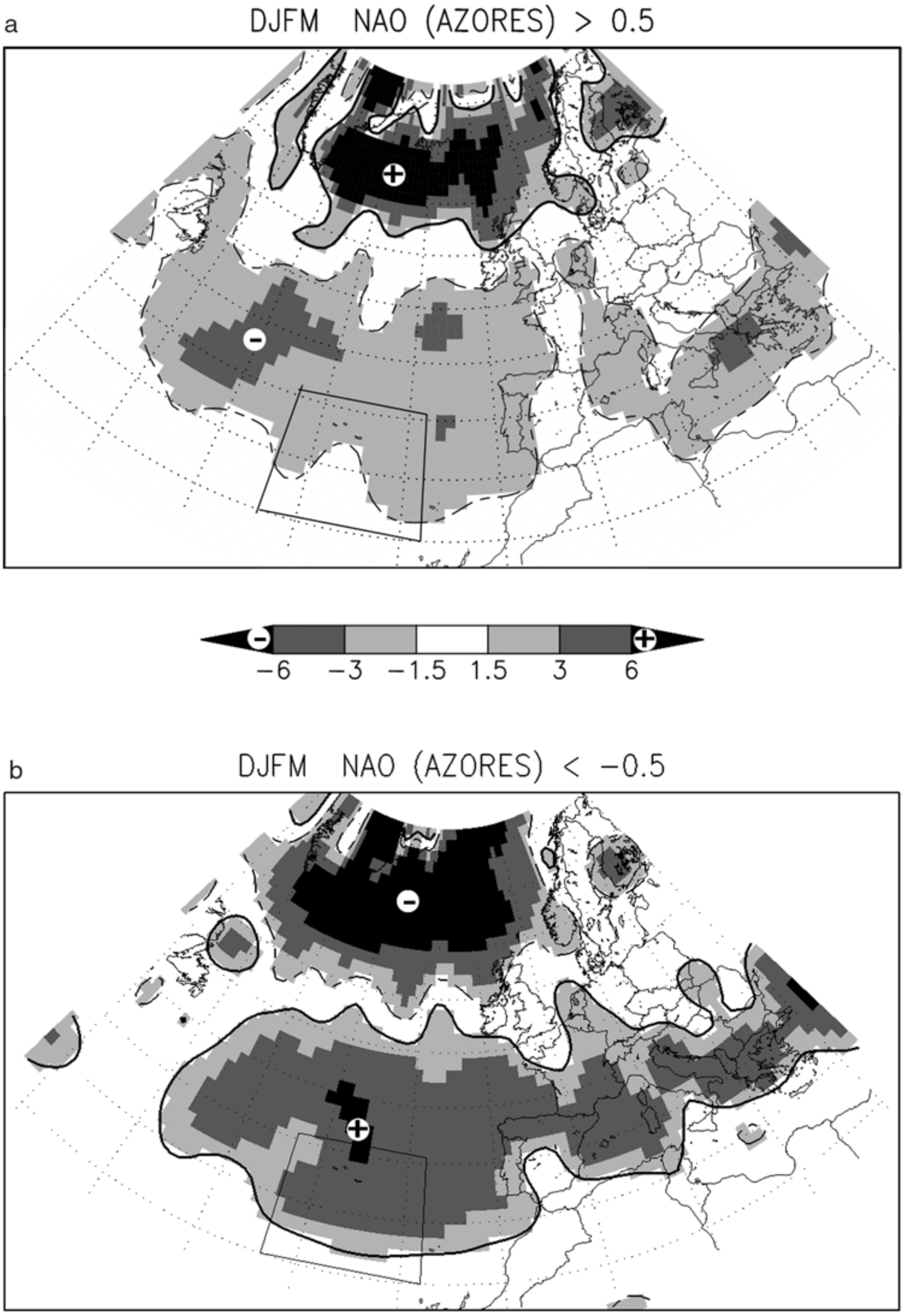


Figure 5 Number of cyclones per winter (DJFM), detected within boxes of 5°longitude × 5°latitude and normalized for 50°N (period 1958–2000). (A) NAO > 0.5; (B) NAO < −0.5. NAO index defined between Ponta Delgada (Azores) and Stykkisholmur (Iceland)

area (Zêzere *et al*., 2005). The differences in patterns obtained for storm tracks (Figure 5, and figure 16 of Zêzere *et al*., 2005) is related to the fact that here we have used the NAO index based in Ponta Delgada and not in Gibraltar.

To determine the relationship between the Azores storminess and the NAO index a two-sided rank-based Kendall test was performed between the total number of storms reported in the Azores Islands during the winter months and the corresponding winter NAO index for the AD 1865–1998 period. The null hypothesis of the Kendall test corresponds to the non-existence of any statistically significant correlation between the NAO and the respective number of storms. The alternative hypothesis is the existence of such an association, regardless of whether it is positive or negative. The sign of the association was taken to be the sign of the Kendall statistic, r_k. The investigation of the series at a monthly scale systematically yields negative correlations, although with different strength (Table 2). Results reveal statistically significant (at the 5% significance level) negative relationships for the months of October, December, January, February and March (being significant at the 1% level in October and February). For the extended winter (October–March), this relationship is reinforced, presenting a correlation of −0.34 between NAO and storminess (statistically significant at 1% significance level). In all these cases we have assumed that both time series do not suffer

Table 2 Evaluating the strength of the NAO impact in storminess for the Azores window, during the period 1865–1998, at monthly and seasonal scales

Month	Correlation	Kendall_tau r_k	P-value
Oct	−0.190	−3.26	0.0011
Nov	0.103	1.77	0.0771
Dec	−0.147	−2.52	0.0117
Jan	−0.119	−2.05	0.0408
Feb	−0.264	−4.53	5.965e-06
Mar	−0.080	1.37	0.1704
Win	−0.336	−5.76	8.601e-09

from serial interannual autocorrelation (ie, each year is independent from the previous and following year).

The interannual variability of extended winter storm frequency and the corresponding NAO index is shown in Figure 6A, with both curves normalized to facilitate the comparison. The tendency for negative NAO values being characterized by above average values of storminess in the Azores area is evident, a result in accordance with the negative correlation coefficient value previously mentioned ($R = -0.34$). However, it should be stressed that this anticorrelation appears to diminish in more recent decades. We have computed the Pearson correlation coefficient value using a 30-yr moving window and values are usually negative (below −0.3) but diminishing considerably (even crossing to positive values) between the 1950s and 1980s. Both time series are characterized by significant changes at the decadal scale, as shown through the application of a low pass filter, in this case, a simple 5-yr moving window (Figure 6B). The last three decades of the nineteenth century are characterized by high values of storm frequency and low values of the NAO index. On the contrary, the period extending from the turn of the twentieth century until the middle 1950s is characterized essentially by lower than average winter storm frequency and predominant high (positive) mode of the NAO index. The short period between the middle 1950s and 1970 is dominated by negative values of NAO and positive normalized index of storminess. However, since 1970 both the NAO and the normalized storminess index are predominantly positive with the NAO index revealing a strong positive trend until the early 1990s. It is worth noting that two out of three time boundaries

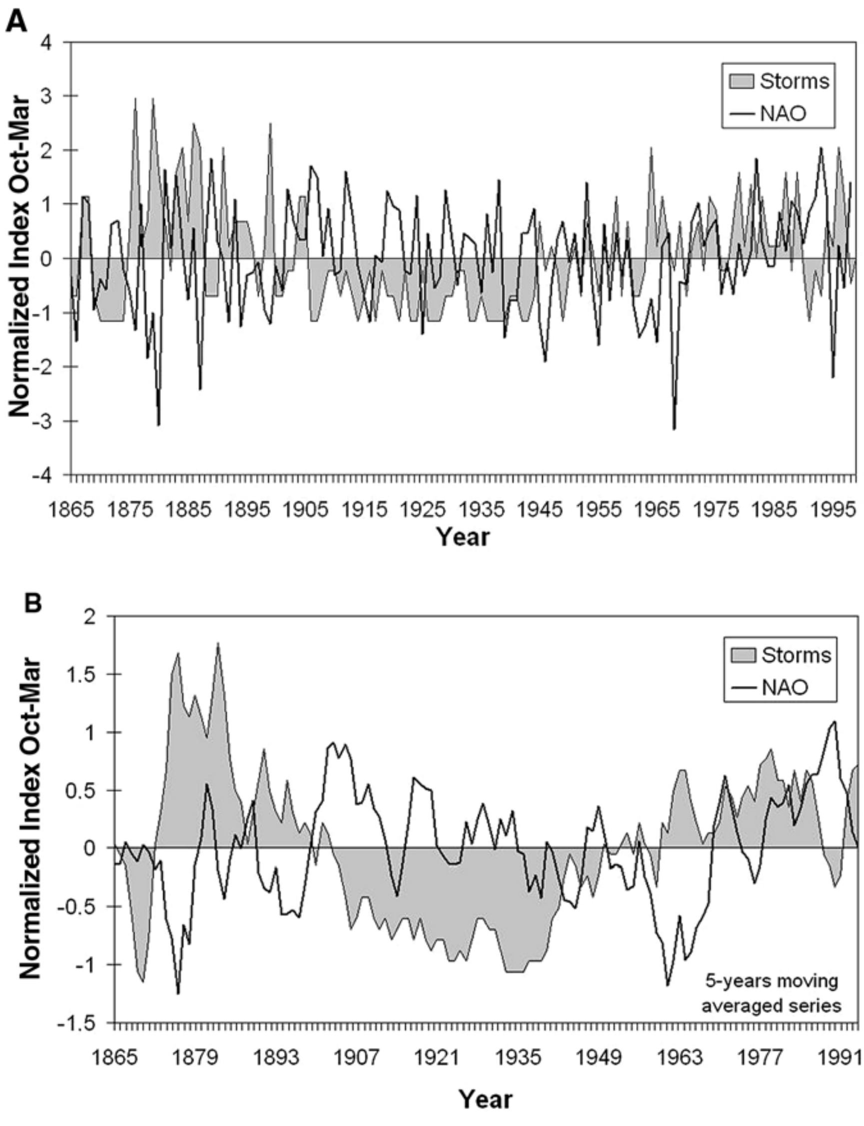


Figure 6 (A) The interannual winter variability of the NAO index and storminess of the Azores (according to the documentary record) between 1865 and 1998. Both data sets were normalized and refer to extended winter (October–March). (B) As in (A) but smoothed with a 5-yr moving window

(*c*. 1900 and 1970) separating periods characterized by coherent anomalous circulation patterns and described by Hurrel (1995), as mentioned above, are also recognizable in the subjective time series of storminess in the Azores (Figure 6B). In addition, a third boundary is dated from the middle 1950s in the storm frequency record that is not directly mirrored in Hurrel's (1995) periods.

The results stated above indicate that the evolution of the relation between extended winter storminess and NAO in the Azores region is not random or irregular over time; instead, it encompasses a large time window, roughly extending between AD 1865 and 1960, where the storminess pattern appears to be dominantly explained by the large-scale circulation pattern associated with the NAO. However, this linkage appears to have weakened over the last 40 years.

Discussion and conclusions

Results from the compilation of the newspaper record on storm frequency in the Azores between AD 1836 and 1998 indicate that the frequency of storms, with recognizable impact on the Islands, is highly variable at interannual to interdecadal timescales. The study of cyclones that crossed a region around the Azores over a recent 40-yr period common to the documentary data base indicates that the storm series described in newspapers and related to impacts in the islands indeed mirrors to a large extent the subset of objective cyclones also listed in the documentary sources, therefore providing validation of the subjective data base.

A number of major periods of contrasting storminess were identified. The first period (AD 1836–1870) is characterized by a distribution with two maxima and low yearly storm frequency (2–3 storms/yr). A second period extends between AD 1870 and 1920 and corresponds to an irregular distribution of storm frequency that decreases in time, maximum values reported in 1879 and 1886; the first years of this period record an abrupt peak of storminess (> 8 storms/yr) that drops to 1 storm/yr by the end of the 1911–1920 decade. A third period corresponds to the decades of AD 1920–1940 with uniform distribution and low storm frequency. After 1940 (period 4) a general trend of increasing storminess emerges (2–3 to 4–5 storms/yr on average) with maxima occurring in the middle of the 1980s.

Storms of low intensity represent 86% of the total number of occurrences, the most extreme events contributing with just 5% to the total of 509 recorded events. The weighted average storm intensity is 1.9 on a scale of 1 to 4, the average duration of a storm event is 2.3 days and the storm frequency is about 3 storms/yr on the secular average; a low intensity event occurs four times every 5 years while an extreme storm occurs on average once every 7 years. The extended winter (October to March) accounts for 76% of the total storms recorded. Within this season the months of December to February contribute with equal proportions (20–21%) followed by November (15%), October (12%) and March (11%).

The variability at the decadal and centennial scales of storm frequency of the Azores, as recorded in documentary sources, is in general agreement with other studies of storminess in the North Atlantic area and adjacent coastal areas. In particular the low activity in the early twentieth-century decades followed by the increase observed in the last 40 years (WASA Group, 1998; Jones *et al*., 1999). Nevertheless, despite the intense decadal variability the subjective index used in this study excludes the existence of any long-term trend in storm frequency as shown through an objective comparison of two 30-yr reference periods in the late nineteenth and twentieth centuries, which yields no statistically significant differences in storm frequency.

Generally, periods of higher (lower) than average storminess in the Azores area are characterized by lower (higher) than average values of the NAO index. In fact, objective cyclones studied in this paper cluster in well-defined regions of strong positive and negative departures from the normalized mean in yearly storm frequency, which switch locations in latitude in phase with changes in the signal of the NAO index. In which respects the documentary record, the interannual correlation between the enlarged winter (October to March) NAO index for the AD 1865–1998 period and the total number of storms reported in the Azores islands is negative ($r = -0.34$) and statistically significant. The strength of this correlation is lower and variable at a monthly scale, and is negative in the months of October, December and January to March. The time distribution of the NAO index and storminess over the last 163 years indicates that this pattern of regional climate has been dominant in explaining the internal structure of the subjective storm frequency in the Azores within a time window extending 105 years from about AD 1865. However, since the 1960s the NAO influence may have been considerably diminished. At the present state of knowledge, the reasons determining both the location of time boundaries separating periods of predominance or subsidence of the NAO in driving the storminess over the Azores region and the exact nature of the replacing patterns are unclear. Recent studies have shown that throughout the decades of the 1980s and 1990s, the northern centre of the NAO dipole (the Icelandic low) has moved closer to Scandinavia (Jung and Hilmer, 2001). This shift has major implications for the Northern Hemisphere climate, in general (Lu and Greatbatch, 2002) and for the precipitation field over Iberia, in particular (Rodó *et al*., 1997; Goodess and Jones, 2002; Trigo *et al*., 2004). It is not obvious if this variability is natural or itself induced by climate change. Using a multicentury control run Osborn *et al*. (1999) have shown a remarkable range of interdecadal variability on the magnitude of the association between NAO and Northern Hemisphere temperatures. We should also underline that the Azores area is affected by other important atmospheric circulation large-scale patterns, namely the Eastern Atlantic or the Scandinavian Pattern, that have also been shown to play a relevant role in the entire Mediterranean basin (Trigo *et al*., 2006).

Last, but not least, this study indicates that newspapers may be a relevant source in historical climatology, provided that the documentary time series is checked against a record of overlapping objective climatic data.

Acknowledgements

This paper is a contribution to project STORMS: Storminess and Environmentally Sensitive Atlantic Coastal Areas of the European Union, Contract ENV4-CT97-0488, CeGUL – supported by the European Union. Ricardo Trigo and Alexandre Ramos were supported by Projects VAST (Variability of Atlantic Storms and their impact on land climate) contract POCTI/CTA/46573/2002, co-financed by the Europen Union under programme FEDER, and CLIMAAT (Climate and Meteorology of the Atlantic Archipelagos) Interreg IIIb A3/2.3, co-financed by the EU under programme FEDER. M.C. Gallego thanks Junta de Extremadura – Consejería de Infraestructuras y Desarrollo Tecnológico – and Fondo Social Europeo for providing funds through the grants MOV05A075 and MOV06A0000331. The authors are grateful for the advice and comments given by J. Corte-Real on the subjects and early drafts of this paper and to the referees whose contributions led to improvement of this work.

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