SEA STORMS IN THE ADRIATIC SEA AND THE WESTERN MEDITERRANEAN DURING THE LAST MILLENNIUM

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Abstract. Data regarding the frequency and occurrence of sea storms in the Adriatic Sea and the Western Mediterranean during the last millennium have been extracted from historical written sources. The Adriatic Sea shows two anomalous periods of high storm frequency: the first half of the 1500s and the second half of the 1700s. In the 1500s the storms were more frequent in autumn, while in the late 1700s they occurred at high frequency in winter. In the Western Mediterranean, storms had a higher frequency in the first half of the 1600s, with two lesser periods of high frequency in the 1400s and at the end of the 1700s. Although both records show a maximum frequency of sea storms during the Spörer Minimum (1416–1534) of solar activity, sunspot series yield no, or poor, correlation during the other periods of lowest activity, i.e., Oort Minimum (1010–1090), Wolf Minimum (1282–1342), and Maunder Minimum (1645–1715), suggesting that a teleconnection between sea storms and sunspots is improbable or masked in this region. No teleconnection was found either between the El Niño-Southern Oscillation (ENSO) and surges flooding Venice or the Western Mediterranean storms or between Venice surges and the Northern Atlantic Oscillation (NAO).

1. Introduction

This study is focused on sea storms because these storms have caused such widespread devastation in Venice and Barcelona that they have been accurately documented in the historical past. In contrast, wind observations were more rarely recorded, and even where semi-quantitative descriptions exist, it is often difficult to distinguish actual meteorological information about strength from mere poetic license. Thus, the floods and shipwrecks described in accounts of sea storms seem a better indicator of storm severity than the qualitative records of high winds. The immediate effects of these severe storms on buildings are primarily mechanical: the dislodgement of tiles and the destruction of chimneys and steeples, for example, although wind-driven rain is also important as it transports sea spray. Heavy precipitation on the coast causes a severe impact on the environment and on monuments (Camuffo, 1992; Moropoulou et al., 1995; Zezza and Macrì, 1995; Gustafsson and Franzen, 1996). In Venice, typical rainwater contains 143 meq l^{-1} of chloride (GSCCPANI, 1985); considering that the average yearly precipitation

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is 770 mm (reference period: 1921–1968), the yearly deposited chloride is 11 meq cm^{-2} yr^{-1}. However, concentrations can be very much higher during sea storms. The sea salt concentration increases linearly with the wind speed when this is below 10 m s^{-1}; above this speed, the efficiency increases geometrically with the number of breaking waves, the dimension of the whitecaps, as well as the wind force. At 20 m s^{-1}, it increases to the third power and at hurricane speed to the fourth power of the wind speed (Blanchard and Woodcock, 1980).

2. Generation of Sea Storms

The Adriatic Sea is a nearly closed basin, whose main axis is directed SE–NW. It is protected at all but the southern end by mountain chains. When low pressure passes over the western and central Mediterranean and then moves to NE, it generates the Sirocco which blows from SE along the main axis of the Adriatic Sea. This is the main source of transport of sea water towards Venice which is in the NW corner of the Adriatic basin. The Sirocco, blowing along the major axis of the Adriatic Sea, interacts with the Alps and generates Bora-type winds which blow from the northeast in strong gusts at the northern edge. The middle part of the Adriatic basin is affected, to a lesser extent, by some gaps in the Alps which surround the northern and the eastern sides. The Sirocco dominates storm generation for two reasons. Firstly, the expanse of sea over which the wind blows and generates waves (i.e., the *fetch*) is much greater for the Sirocco (blowing along the major axis of the sea) than for the Bora (along the minor axis). The major and the minor axes of the Adriatic with respect to these winds are 5:1. Secondly, for dynamic reasons the Sirocco always generates a high pressure ridge when it crosses the Alps. Thus, it generates a wind called *dark Bora*, causing the typical thick cloud cover (Camuffo, 1990).

Venice is sometimes flooded by exceptionally high tides (locally called *Acqua Alta*) raised by a combination of forcing factors (Camuffo, 1993) which are listed as follows. (i) The key factor is the Sirocco. When it blows for several days along the major axis of the Adriatic, it causes water to accumulate at Venice. It is reinforced by the Bora. (ii) Another factor is the barometric effect (i.e., the sea water is raised where the air pressure is lower and vice-versa) which is associated with the spatial distribution of the atmospheric pressure over the Mediterranean Sea. (iii) Rapid changes in the atmospheric pressure pattern cause free oscillations in the Adriatic Sea (i.e., *seiches*) where the first and the second resonant periods are both close to the dominant tidal periods (i.e., diurnal and semidiurnal). These seiches may last for several days, always keeping the same phase lag with the tide (Artegiani et al., 1971). When seiches are in phase with the tides, they can double the tidal excursion. (iv) Tides are influenced by the sun and the moon; in this century, the astronomic lunar-solar factor may be responsible for 25–80 cm oscillations (Sterneck, 1919). The tide in the Adriatic is a mixed tide, with the semidiurnal and the diurnal components being important. The maximum tide, called *spring tide*, occurs when the moon, earth, and sun lie along the same line (syzygy, i.e., at the new moon or full moon) and the minimum tide, called *neap tide*, in quadrature. (v) A final factor, called *subsidence* is associated with vertical land movement. This is caused by various isostatic factors such as sedimentation in the Lagoon area, tectonic processes, and anthropogenic activities, mainly the industrial pumping of water from the coastal aquifer in the past. The *Acqua Alta* that occurred on 4 November 1966 reached 194 cm above mean sea level; fortunately, the tide was in opposition with the seiche, otherwise Venice would have been submerged by some 4 m of sea water.

The sea storms on the eastern coast of the Iberian Peninsula have a totally different origin. They are generated by anticyclones over central Europe, with the southern edge lying over the Mediterranean. The subsidence inversion accumulates heat and moisture in the lower troposphere over the sea. In these cases, the instability develops with violent southerly or easterly winds, which form rough seas that are forced onshore at the Iberian Coast. The worst episodes occur in the autumn and the colder months, with heavy precipitation in the coastal zone and the inland hills (Llasat and Puigcever, 1994; Llasat et al., 1996; Martin-Vide, 1997; Barriendos Vallvé and Martin-Vide, 1998).

3. Data

Archival written sources furnish important descriptions of both extreme climatic events (e.g., annals, chronicles) and usual or unusual meteorological phenomena (e.g., diaries). The time resolution may vary, but can be daily in the case of diaries. Mediterranean countries offer a virtually unexploited mine of data, covering, with varying degrees of continuity, the past two millennia. Of course, unknown data wait unexploited in archives (the Italian State Archives alone have documents on 2000 km of shelves) or libraries, but there is no reason for supposing that missing data would substantially modify the results provided here. Naturally, the present millennium, and especially the last 6 centuries, afford more detailed and reliable data than the previous ones.

Data collection was carried out by searching in public and private libraries and archives for some 20 years in Italy and Spain independently, within the framework of different programs. Two databanks were formed, one by CNR-ICTIMA (for Italy and the surrounding seas) and one by Barcelona University (for the Iberian Peninsula and Western Mediterranean). Once stored, the data have been critically examined and validated (Camuffo and Enzi, 1992; Barriendos Vallvé, 1996–1997) by a team of specialists in history and climatology, and subsequently analyzed. In these two databanks, the latest documentary information is dated early or mid-1800s (depending on the type of data) when instrumental observations were widespread; for the subsequent period, instrumental records substituted the

TABLE I

Sea surges called *Acqua Alta* at Venice (period 782–1990)

782/804; 885; 1102; 1105; 1154; 1240; 1268; 1280/86; 1297; 1314; 1321; 1340/43; 1385; 1410;
1423; 1429; 1430; 1437; 1440; 1442/43; 1444; 1445; 1464; 1503; 1504; 1511; 1514; 1515; 1517;
1518; 1519; 1521; 1522; 1523; 1525; 1526; 1527; 1529; 1531 (2); 1532; 1534 1535 (2); 1536; 1539;
1542; 1550; 1559; 1574; 1576; 1599; 1600; 1609; 1625; 1637; 1651; 1660; 1686; 1691; 1696; 1697;
1727; 1728; 1729; 1731; 1740; 1742; 1743 (2); 1746; 1748; 1749; 1750; 1755; 1762; 1767; 1768;
1770; 1771; 1772; 1773; 1777; 1778; 1779; 1780; 1782; 1783; 1784 (2); 1786; 1789; 1792; 1794;
1802; 1805; 1806 (2); 1807; 1812 (2); 1813; 1816 (3); 1817; 1820 (2); 1821(2); 1822; 1823; 1824;
1827; 1939; 1840; 1848; 1861; 1862; 1864; 1867; 1875; 1879; 1882; 1896; 1906; 1910; 1914; 1916;
1920; 1927; 1928; 1933; 1934 (2); 1935; 1936; 1937; 1938; 1946; 1947; 1948; 1950; 1951(3); 1952;
1954; 1957; 1958 (2); 1959 (2); 1960 (6); 1961; 1962; 1963 (5); 1965; 1966 (2); 1967 (2); 1968 (3);
1969 (4); 1970 (3); 1971 (2); 1972 (2); 1973; 1975 (2); 1976 (2); 1977; 1978 (3); 1979 (6); 1980 (2);
1981 (3); 1982 (4); 1983; 1984 (2); 1985; 1986; 1987 (3); 1990 (3)

The figure in parentheses indicates the number of occurrences during one year.

proxy documentary information, except for a number of relevant natural hazards which continue to be monitored. Reliance on instrumentation has meant a change in the collection and transmission of observations about natural hazards and major meteorological occurrences and renders the written descriptions less useful after the early 1800s.

The Adriatic storms which affected Venice are well documented from AD 840 to the present. The *Acqua Alta* data from AD 787 to 1871 have already been extensively presented and commented upon (Enzi and Camuffo, 1995); since 1872, the sea level has been monitored with tide gauges and the data for the instrumental period 1872–1981 have been published by Pierazzoli (1982). The complete list of the sea surges from 782 to 1990 is reported in Table I.

In the early period, the dating is sometimes uncertain, not only for the dating styles which are well known, but for some ambiguous or imprecise information which can lead to an apparent multiplication of the event due to the loss of the original source, which was more or less precisely repeated by later archive documents or more recent authors. A common feature was to mention a number of important events which happened in a certain period with variable duration (e.g., the ruling of the local lord), and take as a temporal reference a key event, e.g., an important battle or the ruling period itself. For instance, one of the most impressive catastrophes, a terrible storm which led to the submersion of Malamocco, the major island forming Venice, is reported by different authors with apparently contradictory dates. This storm is often reported associated with, or prior to, an earthquake which probably occurred in 1106 and probably was not responsible for the island submersion (Boschi et al., 1997). Also, a terrible fire in Venice is found more or less at the same period and is associated with the above events in the same dating. Examples of some authors mentioning this storm and its suggested dating are as follows: 1100/02: Filiasi, *Memorie storiche*; 1102: Anonymous, *Historiae Venetae*; 1102:

Gallicciolli, *Delle Memorie Venete* and Anonymous, *Zibaldone*; 1102: Mutinelli, *Annali Urbani di Venezia*; 1105: Contarini, *Della Veneta Historia*; 1105: Dandolo, *Chronica*; 1105: Dandolo, *Chronicon Venetum*; before 1106 Granzaruolo (reported in Filiasi, *Memorie storiche*); and 1106: (earthquake) Marco, *Chronica Universalis*. After an analysis of the reliability of each author and his access to the original historical documents later destroyed, the best-guessed date seems to be 1105 for the storm and March 1106 for the earthquake, although a definite dating cannot be established. Only after the Middle Ages did the dating become precise and reliable.

Other relevant sea storms can be found in the Adriatic Sea that caused shipwrecks or other major damage (not including the *Acqua Alta*) in the period of documentary sources from 787 to 1820. Some examples of these descriptions are useful for a better understanding of the document type:

> On 26 October 1322, one of the most tremendous wind storms occurred, with the wind blowing from North and North-East, with snow; it was one of the worst in living memory. It caused damage to several kinds of ships (e.g., *navi*, *galee*) in several parts of the world, especially in the gulf of Venice. The same occurred inland where enormous trees were blown down or broken . . . . (G. Villani, *Cronica*).
>
> In August 1413, a terrible storm occurred, with absolutely unusual hail and rain. Especially the gale overturned and sank ships, uprooted and transported far away trees and a bell tower . . . . (Anonymous, *Cronaca Veneziana o Zibaldone*).
>
> Unfortunately, everlasting memory merits the storm happened in Venice the 10 August 1471. Afternoon, a North-eastern wind started to blow, and sank more than thousand people in the Lagoon which was full of boats, for the St. Lawrence festival that at that time was very popular. In the Canal Artane [the wind] broke and sank 75 boats. (Filiasi, *Osservazioni sopra le vicende . . .*).
>
> 15 July 1500, Wednesday, at 19.00. There was a terrible wind and rain storm, and myself, with other five boats, were sent to the bottom, and I was completely soaked. I had to reach a wall with a ladder. For this storm originated from West and North-West, several boats were destroyed and a lot of people died. (Dolfin, *Annalium Venetorum*).
>
> An important event happened in Venice. On 9 June 1504, near noon, a gale wind with a violent shower made rough the gulf of Venice and overturned many boats, and only the overturning of small *gondolas* in the canals make to perish 500 persons. (Bernardi, *Cronache forlivesi*).
>
> Autumn 1660. In this autumn the public coast was so damaged, that the government was obliged to deliberate with decision and with an extra taxation in order to take measures [to repair the coast] in the best way and in the early position. (Zendrini, *Memorie storiche . . .*).

> 18 March 1771. After a pleasant and mild season that stimulated all the crops, near midnight a terribly chilling Bora wind arrived, with snow and turbulence, that caused sad shipwrecks in the sea, and destroyed all the vegetation. The wind blew with such a gale force, that its sound was similar to a ceaseless thunder, and a number of chimney-pots fell, tiles flew away, and the snow, dusty, dry and with many vortexes, blinded and was breath-taking. (Filiasi, *Osservazioni sopra le vicende* ...).
>
> January and February 1795. The snow, the winds and the extremely troublesome cold weather lasted till the last two days of Carnival. However, the night preceding the first day of Lent and for the whole day, an abrupt gale wind blew, and several ships sank, and many persons perished. It was also referred that 16 ships sank near Messina. (Gallicciolli, *Delle memorie venete* ...).
>
> 10 March 1797. The drizzle of yesterday evening was transformed into an impressive storm with gale wind and heavy rain that lasted for the whole night and in the early morning became snow. The gale wind and the rainfall lasted for the whole day. A ship directed to Parenzo was suddenly reached just out of the port and sank with all the people that were onboard. (Gennari, *Notizie giornaliere*).

A list of these major sea storms in the Adriatic Sea, which caused catastrophic damage (not including the *Acqua Alta* in Venice), is reported in Table II.

Finally, a list of the major sea storms in the Western Mediterranean off Barcelona between 1346 and 1848 (Martin-Vide, 1997) is reported in Table III.

4. Data Analysis

The essential features of a time series can be detected by smoothing the series in order to eliminate some of the variability not attributable to the physical signal (i.e., cut-off white noise), thus revealing the desired signal (i.e., trends, harmonic components, or synergistic contributions of major fluctuations). The most commonly used method of smoothing data is the method of using running averages, usually the unweighted running mean, i.e., a rectangular filter in which all the data falling within a fixed interval of time (i.e., the window width W) are averaged and centered at the midpoint of each interval corresponding to the actual position of the window. All the data outside the window are eliminated. Moving this window by regular steps, a series composed of these running averages is obtained. However, although in a number of cases this method is apparently satisfactory for practical purposes, a critical analysis has demonstrated that the unweighted running mean is both inefficient and potentially misleading (Harnett and Murphy, 1980; Burroughs, 1992) for the following reasons.

(i) Every data point inside the window has the same weight, so that an anomalous point which departs very much from the average will enter the running mean

TABLE II

Major sea storms in the Adriatic Sea which cased shipwreaks or other major damages (period 787–1820)

840; 864; 885; 900; 963; 1004; 1020; 1105; 1154; 1162; 1210; 1228; 1240; 1283; 1321; 1322; 1343; 1380; 1410; 1413; 1418; 1430; 1455; 1471; 1473; 1500; 1504; 1514; 1521; 1525; 1526; 1530; 1531; 1550; 1600; 1656; 1660; 1695; 1742; 1755; 1768; 1771; 1773; 1779; 1783; 1784; 1790; 1792; 1794; 1795; 1797; 1798; 1802; 1820.

TABLE III

Major sea storms in the Western Mediterranean sea off Barcelona (period 1346–1848)

1346; 1376; 1396; 1404; 1420; 1426; 1439; 1447 (2); 1448; 1451; 1479; 1480; 1482; 1483; 1484; 1489; 1495; 1581; 1594 (2); 1595; 1596; 1597; 1598; 1599; 1603; 1604; 1605; 1617; 1620; 1623; 1625; 1629; 1630 (2); 1631; 1632; 1633; 1634; 1636; 1640; 1643; 1645; 1684; 1685; 1711; 1715; 1770; 1777; 1782; 1787; 1790; 1793; 1827; 1839; 1840 (3); 1843; 1844; 1845; 1848.

The figure in parentheses indicates the number of occurrences during one year.

with a sudden jump and will exit in the same way. Therefore, an anomalous fluctuation will be transformed into a rectangle having a time duration which is twice the window width. This isolated datum will fully characterize this long period.

(ii) The cyclic components having a period equal to the window width W are eliminated, as are all the higher harmonics which are an exact multiple of W^{-1}. If the window width equals half a period of a cyclic harmonic, the amplitude will also be approximately halved. On the other hand, if the window width is an odd multiple of half a cycle of the original series, the original harmonic is lost and this new spurious frequency is introduced. Thus, instead of removing cycles, this method can introduce non-existing cycles and a spurious signal completely out of phase with the original harmonic in the unsmoothed series. In general, the filtered series have cyclical components reduced compared with the original values. Also, the overall variation is reduced.

These problems can be solved, or minimized, with weighted running means which act as a relatively efficient low-pass filter to remove the high frequencies without introducing phase or amplitude distortions. Many types of such filters have been suggested. The main feature is that they have a more or less bell shape, e.g., half a sinusoid at the first (Hamming–Tukey filter) or second (Ormsby filter) power, a Gaussian, a triangle. They have a selective narrow band which corresponds to the top area of the bell, and a smoothing weight proportional to the increasing (or decreasing) values corresponding to the ordinate of each point of the bell sides. This allows for a gradual transition of the weight from zero (external to the bell) to one at its center, so that any isolated extreme value will emerge as a bell, appearing and disappearing gradually. Trends, harmonics, and phases are not attenuated, dis-

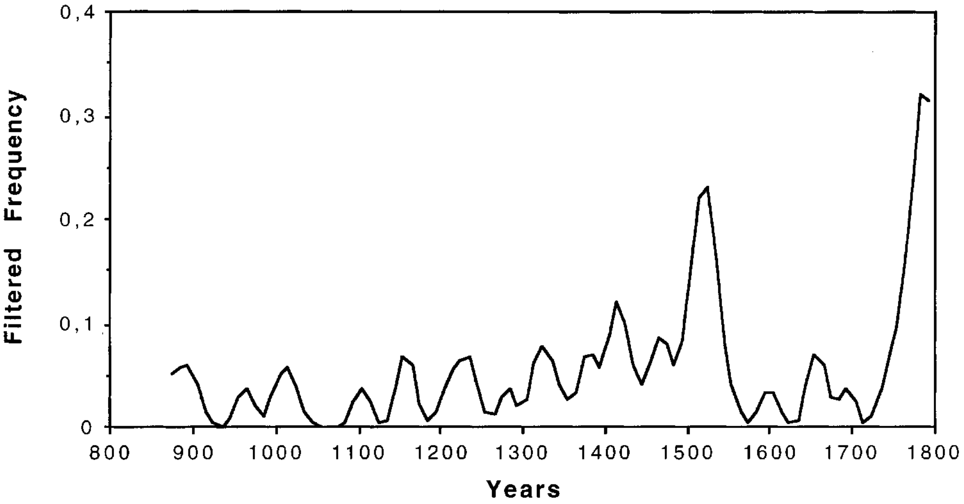

Figure 1. Frequency of sea surges in the Adriatic Sea, filtered with the Hamming–Tukey filter.

torted, or shifted. The Fourier transforms of these modified functions (especially for a half cosine filter) give a very satisfactory estimate of the smoothed values of the true energy spectrum.

The changing frequency of sea storms during past centuries has been highlighted by applying the Hamming–Tukey filter to cut off the fluctuations and point out the epoch when the storms were more frequent. The Hamming–Tukey filter $D(t)$ is a cosine type filter, defined as follows:

$$D(t) = 0.54 + 0.46\cos(\pi t/W)$$

where the time variable t is within the window $W = 50$ years and $D(t) = 0$ externally (Vinnicehenko et al., 1980; Wei, 1990). The window has been moved in 10-year steps.

The filtered plot of the sea storms in the Adriatic Sea (Figure 1) shows two main peaks in the first half of the 1500s, and in the second half of 1700s. A third peak was found in the most recent period, as already noted for Venice for the *Acqua Alta* surges (Camuffo, 1993). As data from Venice contribute so much to the general record of storms in the Adriatic Sea, this is the expected result.

The filtered plot of the sea storms at Barcelona (Figure 2) shows a more perturbed sea state in the 1400s (during the Spörer Minimum), at the end of the 1500s and the first half of the 1600s (which is the peak period), and at the end of the 1700s. As in the previous case, nothing appears during the Maunder Minimum, and the secondary maximum at the end of the 1700s is still present. The main difference is the major peak which started at the end of the 1500s and finished after the first half of the 1600s.

Sea storm generation is determined by two main factors: the air-sea temperature difference and the wind speed and direction. Air colder than sea water means a

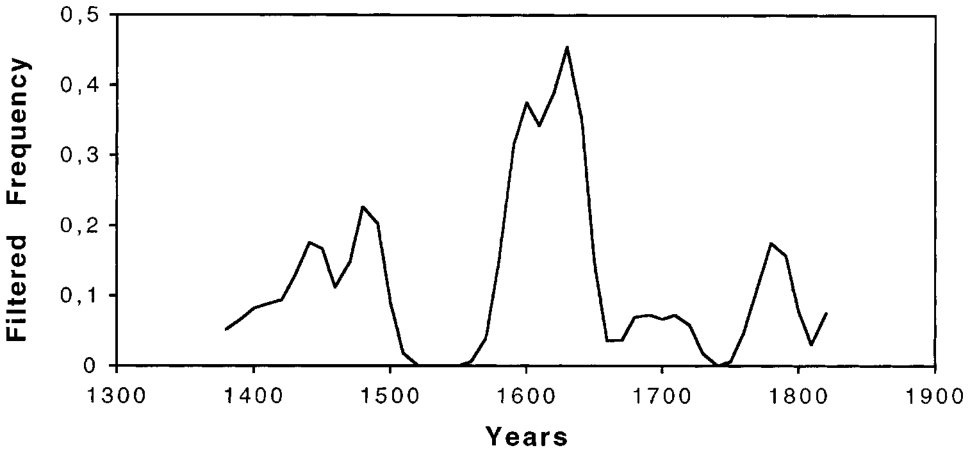

Figure 2. Frequency of sea surges in the Western Mediterranean, filtered with the Hamming–Tukey filter.

transfer of heat and moisture from the sea to the atmosphere, with the generation of instability, the formation of clouds, and an increase of the wind speed. This occurs especially in autumn and winter. Fresh to gale winds flowing for a relatively long time over the sea may generate waves and make the sea rough. Winds perpendicular to the coast are most important: the Sirocco at Venice, for example. The synoptic pattern that generates the forcing wind has a seasonal character and the Sirocco storms are most frequent in autumn and winter. A change in the seasonal storm frequency is an index of a climatic anomaly, e.g., unusual air-sea temperature difference, frequency of the forcing wind, or a combination of the two.

For the Adriatic storms, the events occurring in the two periods 1500–1550 and 1755–1802 were grouped according to the Italian hydrological seasons, i.e., winter comprises December, January, and February; spring: March, April, and May; summer: June, July, and August; and autumn: September, October, November. The results are shown in Figure 3. The two periods show different distributions. In the 1500s, the highest frequency was in autumn, immediately followed by summer and winter; spring was without storms. In the 1700s, the highest frequency occurred in winter, followed by spring and autumn; summer was without storms.

The seasonal distribution in the Western Mediterranean (Figure 4) also changed across the centuries. In the period 1400–1500, the highest frequency was in spring, equally followed by autumn and winter; in the period 1550–1650, the highest frequency was in winter, followed by autumn and spring; in the period 1750–1800, the storms were equally divided between autumn and winter. In practice, the cold season was always affected, with an enhanced variability in spring. In the summertime, storms were totally absent or rare. These changes in sea storm frequency were also associated with changes in catastrophic floods of rivers in the Spanish Mediterranean coastal area, which can be put in three anomalous periods,

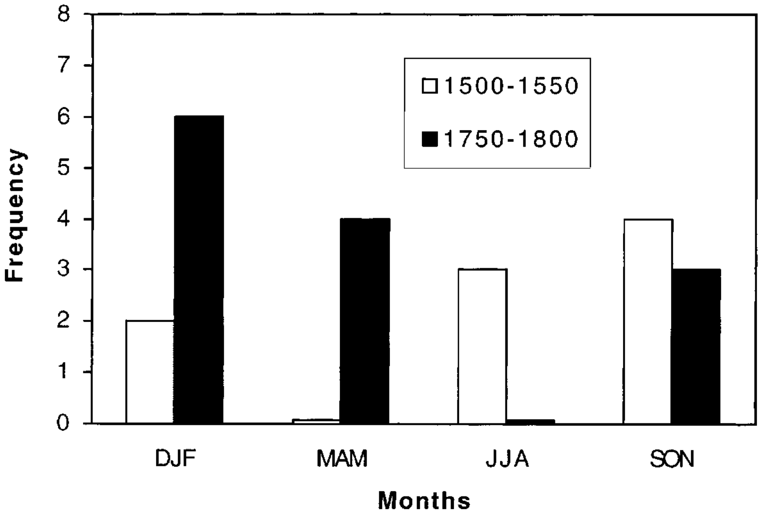

Figure 3. Seasonal distribution of sea storms in the Adriatic sea during the periods 1500–1550 and 1750–1800.

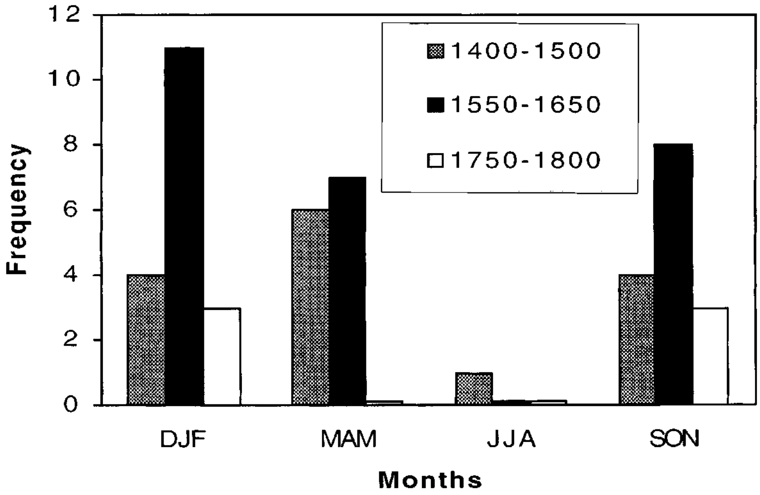

Figure 4. Seasonal distribution of sea storms offshore of Barcelona during the periods 1400–1500, 1550–1650, and 1750–1800.

i.e., 1570–1630, 1760–1800, and 1830–1870 (Barriendos Vallvé and Martin-Vide, 1998).

5. Connections with Climate Changes

It is possible to look for a coupling of the oceanic-atmospheric system and search for teleconnections with the El Niño Southern Oscillation (ENSO), which occurs in the central Pacific and generates hurricanes and storms, and a number of climatic anomalies (e.g., torrential rains in Ecuador and severe droughts in Bolivia), and possible teleconnections in other parts of the world (Jordàn, 1991). ENSO recurs at irregular intervals; each century two or three very strong events are found, six to ten strong events, and 15 to 18 moderate ones. A critical list of the historical records of El Niño events in the last 500 years has been published by Quinn and Neal (1992) and Quinn (1993). Once an ENSO event is triggered, the cycle of climate change operates over a minimum of two years; a four-year perturbation was recorded in 1911–1915 (Bryant, 1997).

In the Adriatic Sea and the Western Mediterranean, no teleconnection was found between storminess and ENSO. A number of *Acqua Alta* surges flooding Venice occurred in 1625 (ENSO, 1624, strong), 1651 (ENSO, 1652, strong), 1727, 1728, 1729 (ENSO, 1728, very strong), 1746, 1747 (ENSO, 1747, strong), 1792, 1794 (ENSO, 1791, very strong), 1805 (ENSO, 1803/4, strong), 1813, 1816, 1817 (ENSO, 1814, strong), 1827 (ENSO, 1828 very strong), 1879 (ENSO, 1877/78, very strong), 1927, 1928 (ENSO, 1925/26, very strong), and finally the long series of yearly events from 1965 to 1987 culminating in 1979 with six city floodings (ENSO, 1982/83, very strong). These occurrences, however, have no statistical value.

In fact, a correlation performed between ENSO and *Acqua Alta* that occurred in the same year (zero delay), after one year, after two years, and after three years shows, respectively, the correlation coefficients $r(0) = 0.21$, $r(1) = 0.13$, $r(2) = -0.24$, and $r(3) = 0.03$, i.e., nearly complete independence. For Barcelona, the correlation coefficient is still extremely low, i.e., $r = -0.06$ and shows substantial independence between ENSO and Western Mediterranean storms.

In contrast, from 1500 to 1990, there were 148 ENSO events with an average frequency of 30.2% and 142 years affected by *Acqua Alta* at Venice with an average frequency of 29.0%. Under the null hypothesis, i.e., that the sea storms and the ENSO events are independent, the probability of occurrence of one year with a sea storm and, at the same time, an ENSO event is $30.2 \times 29.0 = 8.7\%$. However, only 38 years were found with simultaneous ENSO and *Acqua Alta*, with a frequency 5.6%, slightly less than the probability found. Similarly, the Adriatic Sea had 29 major storms with a frequency 5.9%; only 9 (frequency 1.8%) were found during an ENSO. The combined expected probability is $30.2 \times 5.9 = 1.8\%$, identical to the frequency actually found. In the period 1581 to 1850, Barcelona had 41 storms (15.2% average frequency) and 70 ENSO events (25.9% average frequency). Under the null hypothesis, the probability of occurrence of one year with a sea storm and, at the same time, an ENSO event is $15.2 \times 25.9 = 3.9\%$. This value is not very different from the observed frequency, 16 cases over 270 years, i.e., 5.9%. In conclusion, no teleconnection is evident.

A comparison of the occurrence of the *Acqua Alta* in association with, or with some delay with reference to, the North Atlantic Oscillation (NAO) for the period 1950–1990 (data source: NOAA Climate Prediction Center) has given the following correlation coefficients $r(0) = -0.1$, $r(1) = -0.07$, $r(2) = 0.13$, and $r(3) = 0.06$. These values show a substantial independence between the two phenomena.

6. Conclusions

Sea storms in the Adriatic Sea and the Western Mediterranean originate under different meteorological situations, apparently independent of each other. Data analysis, however, showed that sea storms became more frequent in both areas in two periods of the Little Ice Age: during the first half of the 1500s and at the end of the 1700s.

One application of this study was to test the hypothesis of solar forcing advanced by Eddy (1977), who suggested that meteorological anomalies were connected with periods of low solar activity. In the second millennium, solar activity had four important Minima, i.e., the Oort Minimum (1010–1090), the Wolf Minimum (1282–1342), the Spörer Minimum (1416–1534), and the Maunder Minimum (1645–1715). The present data analysis of the Adriatic Sea shows that during the first two solar Minima, the signal did not rise above the noise. In Italy, as already found for several other phenomena (Camuffo and Enzi, 1994, 1995a), the period of the Spörer Minimum was perturbed, with a peak of storminess. In contrast, as usually found in northern and central Italy, the Maunder Minimum was a period of low storminess. In Italy, extreme events were rare during the Maunder Minimum, and in some cases a peak frequency preceded the solar forcing (e.g., the Tiber River floodings; Camuffo and Enzi, 1995a, b). In addition, the dominant peak of the Adriatic storm frequency fell well outside these two key periods of solar activity. A similar feature was found for the Western Mediterranean, with a peak immediately preceding the Maunder Minimum.

As no anomalies were found during the Maunder Minimum or the other periods (Oort and Wolf) of minimum solar activity, it is likely that the anomaly during the Spörer Minimum was coincidental and not indicative of a teleconnection between low solar activity and sea storminess. This may mean that: (i) any teleconnection between solar forcing and Mediterranean storminess remains unproven; (ii) during the Maunder Minimum, the forcing was not so strong to overcome other factors; or (iii) in the Mediterranean Basin, solar forcing is masked by other local factors. As a teleconnection was evident during the Spörer Minimum, one, or a combination, of the last two hypotheses seems more convincing.

This study has demonstrated that the seasonal distribution of the sea storms was dissimilar through the course of centuries, showing that the beginning and the ending period of the Little Ice Age were different, at least in the seasonal distribution of sea storms. In both the Adriatic Sea and the Western Mediterranean, the cold season was particularly affected by storms, with an enhanced variability in spring. In the summertime, storms were absent or rare, except during the first half of the 1500s in the Adriatic, where the frequency of the summer storms was relatively high.

No teleconnection between ENSO and sea storms was found showing that these two parts of the Mediterranean basin (at least as far as surges are concerned) are not conditioned by the ENSO. Similarly, the Adriatic storms are independent of NAO forcing.

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