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Nazzareno Diodato, Fredrik Charpentier Ljungqvist, Gianni Bellocchi. Monthly storminess over the Po River Basin during the past millennium (800–2018 CE). *Environmental Research Communications*, 2020, 2 (3), pp.031004. 10.1088/2515-7620/ab7ee9 . hal-03082597

**HAL Id: hal-03082597**

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Submitted on 18 Dec 2020

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## Environmental Research Communications



## LETTER

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## OPEN ACCESS

## RECEIVED

26 November 2019

## REVISED

1 March 2020

## ACCEPTED FOR PUBLICATION

11 March 2020

## PUBLISHED

24 March 2020

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**Abstract**

Reconstructing the occurrence of diluvial storms over centennial to millennial time-scales allows for placing the emergence of modern damaging hydrological events in a longer perspective to facilitate a better understanding of their rate of return in the absence of significant anthropogenic climatic forcing. These extremes have implications for the risk of flooding in sub-regional river basins during both colder and warmer climate states. Here, we present the first homogeneous millennium-long (800–2018 CE) time-series of diluvial storms for the Po River Basin, northern Italy, which is also the longest such time-series of monthly data for the entire Europe. The monthly reconstruction of damaging hydrological events derives from several types of historical documentary sources and reveals 387 such events, allowing the construction of storm severity indices by transforming the information into a monthly, quantitative, record. A period of reduced diluvial storms occurred in the ninth and tenth centuries, followed by a stormier period culminating in the eleventh and thirteenth centuries. More complex patterns emerge in the fourteenth to sixteenth centuries, with generally wetter and stormier conditions than during other centuries. From the seventeenth century onwards the number of damaging hydrological events decreases, with a return in recent decades to conditions similar to those prior to the thirteenth century. The flood frequency tended to increase for all seasons during periods of low solar irradiance, suggesting the presence of solar-induced circulation changes resembling the negative phases of the Atlantic Multidecadal Variability as a controlling atmospheric mechanism.

**Introduction**

There has been increasing interest in the hydroclimatic response to large-scale environmental changes such as ongoing global warming (e.g., Luo *et al* 2018, Orth and Destouni 2018, Ljungqvist *et al* 2016, 2019) and large-scale urbanization (e.g., Debbage and Shepherd 2018, Paul *et al* 2018), including active construction sites (e.g., Ricks *et al* 2020). Water is not only a valuable natural resource and societal asset, but has also the potential to inflict damage on human society and the environment, causing large disasters and financial losses (Hoeppe 2016, Brown *et al* 2018). However, the millennium-long evolution of the regional distribution, and timing, of damaging hydrological events (DHEs) are yet poorly known (Benito *et al* 2015). At present, we have, at best, an incomplete picture of past hydroclimatic extremes as a backdrop to the frequency and severity of present-day extremes (Glur *et al* 2013, Stamatopoulos *et al* 2018). Identifying temporal and spatial changes and trends in precipitation—especially of extreme hydrological events—is difficult and poses a major challenge both

for past climate assessment and for future climate predictions. A twelve-century long (800–2017 CE) reconstruction of extreme hydrological events, with annual resolution, for Italy was published by Diodato *et al* (2019), proposing that the Atlantic Multidecadal Variability (AMV; Wang *et al* 2017) influenced the frequency of storms and floods in the central Mediterranean region. Based on terrestrial proxy records from the circum-North Atlantic region, the AMV reconstruction by Wang *et al* (2017) exhibits pronounced variability on multi-decadal time-scales, a behaviour commonly referred to as the Atlantic Multidecadal Oscillation (AMO; Kerr 2000, Enfield *et al* 2001), i.e. the internally generated component of AMV. This multi-decadal climate mode originates dynamically in the North Atlantic Ocean and propagates throughout the Northern Hemisphere via a suite of atmospheric and oceanic processes (Wyatt *et al* 2012, Wang *et al* 2018). Few diluvial events occurred during the Medieval Warm Period (MWP, see Lüning *et al* 2019 for the Mediterranean region; here, 800–1249 CE), dominated by a positive mode of the AMV, whereas more intense hydrological events occurred during the Little Ice Age (here, 1250–1849 CE), dominated by a generally negative mode of the AMV.

The current study presents the first monthly resolved reconstruction of extreme hydrological events over the past twelve centuries (800–2018 CE) in the Po River Basin of northern Italy. The Po River is one of the largest rivers draining the Alps, flowing eastwards into the Adriatic Sea. Already the German geographer and historian Philipp Clüver (1580–1622) reported that the waters of the Po River had flooded with disastrous consequences since ancient times (Bottoni 1872). Squatriti (2010) noted unusually high regional precipitation, causing especially severe floods, between the end of the sixth century and the beginning of the seventh century. Eighteenth century local historians Camillo Silvestri and Carlo Silvestri (a father-and-son team) refer to an episode of massive flooding in the autumn of 589 CE that even remodelled the lower course of the Po River (Squatriti 2010).

The compilation of continuous time-series of past hydrological extremes (e.g., storms and floods), is challenging as these phenomena change in response to seasonally variable environmental conditions across complex spatial patterns (Zhang *et al* 2017). Reliable reconstructions of the occurrence of DHEs are nonetheless important for the understanding of the effects of changing climatic patterns (including those potentially related to recent global warming) affecting the spatial and temporal variability of heavy rainfall events, flood episodes, and landslide events (Diodato *et al* 2019). Hydrological reconstructions—regardless of temporal scale—also facilitate an assessment of their impacts on ecosystem functioning and economic security at a regional to local level (Bakker *et al* 2017, Harris *et al* 2018). Historical accounts suggest that DHEs may have had considerable regional impacts even during periods of relatively small climate changes on a global scale (Knox 1993). However, considerable research remains to be undertaken on the mechanisms that lead to the occurrence of extreme hydroclimatic events, and on which the bases are for assessing their predictability and enable their prediction with reasonable accuracy (Sillmann *et al* 2017). Thus, various types of historical data are needed to place recent and expected future DHE changes into a long-term perspective. Reconstructions from palaeoclimate data, either derived from natural proxy archives or from historical documentary data, play a vital role in assessing the skill of climate model simulations on which future climate projections are based, and comparisons with reconstructions help identify important processes not yet fully incorporated into such models (Ljungqvist *et al* 2019). However, few studies have assessed the millennium-long evolution of hydrological extreme events in southern Europe (e.g., Diodato *et al* 2019, Benito *et al* 2003, Glaser and Stangl (2004), Finsinger *et al* 2010, Calò *et al* 2013). In Italy, based on a sedimentology study, Magny *et al* (2012) established a lake-level record for the Holocene at Lake Ledro (north-eastern Italy), and Taricco *et al* (2015) used foraminiferal  $\delta^{18}\text{O}$  data from a sediment core in the Ionian Sea for a millennium-long reconstruction of hydrological variability in northern Italy.

Long reconstructions of hydroclimate extremes with seasonal, let alone monthly, resolution are still virtually non-existing in southern Europe, as available proxy data typically do not provide this type of temporal resolution. However, many historical documentary data have very precise temporal resolution which potentially allows for a reconstruction down to monthly resolution at the same time as this type of source can help analyse the diverse effects of climate variability on society as embodied in narratives (Wilhelm *et al* 2018). Unfortunately, European documentary data back in medieval times are for the most part fragmented in space and time. However, data concerning the Po River Basin may be an exception to this. Shorter reconstructions of historical floods in the various sections of the Po River valley have already successfully been conducted based on documentary data, including analyses of historical floods in the high Po valley (north of the river) for the period 1500–1650 CE (Pavese *et al* 1994), and for the lower Po valley (south of the river) during the 16th century (Guidoboni 1998). Camuffo and Enzi (1996) published the first continuous, bi-millennial series of Po River (and Tiber River) floods, based on annually resolved data, but acknowledged the limitations of their analysis arising from the non-homogeneous flood series used.

Based on historical documentary data, this research extends the time-series of extreme hydrological events that occurred through the broad plains of the entire course of the Po River. We provide a continuous series of the monthly flood-causing storms, which affected riparian cities and villages (figure 1) over the period 800–2018 CE.



**Figure 1.** Perspective view from east of Po River landscape damaged by an approaching storm: the winding curve (in dark blue) is the Po River, which is associated with riparian vegetation (in green) and cities and villages. On the horizon are the reliefs of the Alps (arranged through OpenStreetMap, <https://demo.f4map.com/#camera.theta=0.9>).

A *Monthly Storm Severity Index* (MSSI) was developed to verify the scale-invariance in the relationship between the number of events larger than the storm strength events and the same strength events, i.e., to verify the completeness of the ‘catalogue’ of extremes both for the entire data set over 800–2018 CE and for three sub-periods (800–1249, 1250–1849, and 1850–2018 CE), resulting in an *Annual Storm Severity Index Sum* (ASSIS), i.e., the yearly sum of MSSI values.

#### Data

The Po River Basin contains the longest river in Italy (652 km), the Po River, flowing eastward across northern Italy in the administrative regions Aosta Valley, Piedmont, Lombardy, Emilia-Romagna, and Veneto (figures 2(a)–(b)). The Po River Basin has an area of  $\sim 74,000 \text{ km}^2$ , situated almost entirely in Italy, with at present a total population of  $\sim 16$  million. The Po Delta Regional Park in the Emilia-Romagna region was designated in 1999 as a World Heritage Site by UNESCO. The Po River Basin is also where the most disastrous floods in the Italian history are recorded (Luino 2013).

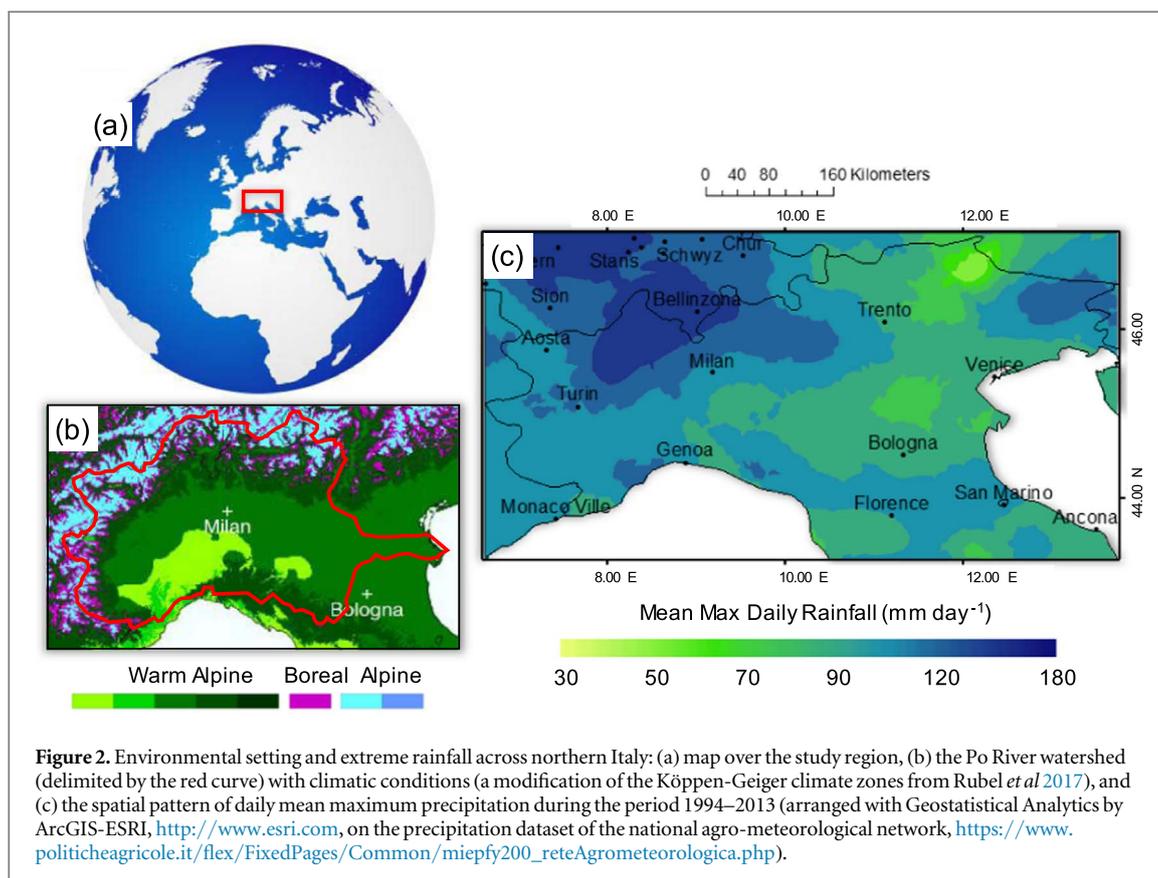
The Po River Basin climate is rather complex and differentiated, given the geographical position that the basin occupies, together with the different morphology of the sectors that compose it (figure 2(b)). In this way, the climate of the Po River Basin is situated in the transition zone between the sub-continental climate of Central Europe (Alpine and Boreal) and a Mediterranean climate (Warm Temperate). (See also Köppen’s classification in Strahler and Strahler (2000).

A large spectrum of environmental variables and phenomena is associated with cyclones in this region (Lionello *et al* 2006). In particular, northern Italy is affected by Atlantic storm tracks, which otherwise more directly affect western and northern Europe. The influence of Atlantic storm tracks in northern Italy quite frequently subjects the region to sudden events of extreme and adverse weather conditions, frequently causing considerable societal and economic impacts. The western-most part of this region is particularly stormy (Nikolopoulos *et al* 2013), though DHEs are common in some of the eastern regions of northern Italy too. Maximum daily rainfall is still capable of inflicting significant damages even in the less stormy eastern hydroclimatic areas (figure 2(c)).

The main Po River tributaries (Ticino, Adda, Oglio, and Mincio) provide the maximum water supply at the time of the thawing of alpine snow and ice (May–June), while numerous other tributaries descending from valleys of the Apennine contribute with meltwater and rain especially in spring and autumn, assuming in summer and winter a torrential character with low flow rates. The Po River Basin region can thus be viewed as the culmination of a complex hydrographic system (Guidoboni 1998). This regime of river hydrography includes rare waves of flooding of the Po’s tributaries on both its right and left banks. When this occurs, the danger of disastrous and extensive floods is very high (Brandolini and Cremaschi 2018).

#### Documentary sources

The amount of surviving documentary sources in the Mediterranean region is sufficient back into medieval times to construct quantitative or quasi-quantitative climatic indices (see Pfister *et al* 2018). These sources also

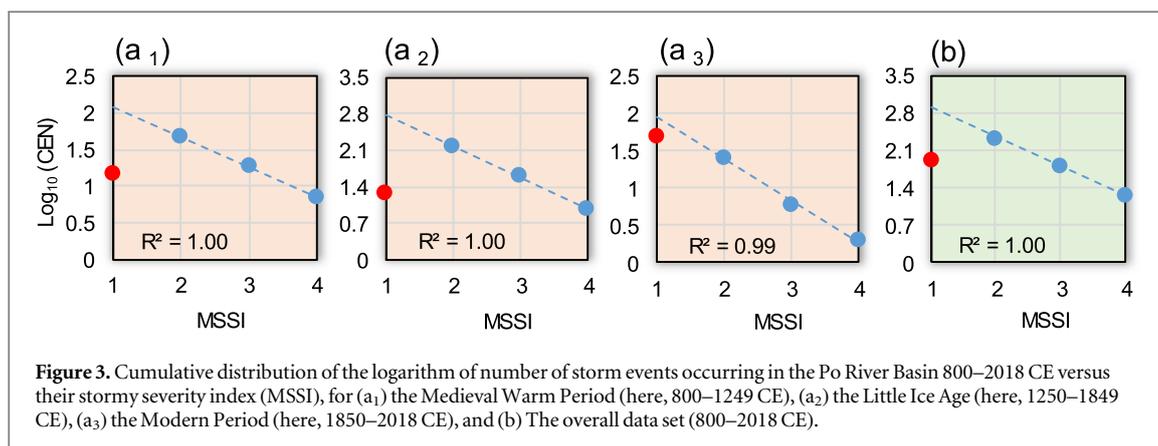


provide information about social vulnerability and impacts of climate extremes that allow for direct comparison with contemporary climatology (Wilhelm *et al* 2018). The study of the most famous fluvial floods affecting urban settings in the Middle Ages offers a conceptual reference to overcome too rigid a distinction between natural disasters and disasters produced by human agency. For many ancient sources, or sources referring to now lost original documents, information is available in Latin, and there are several words for the term *storm* and its damaging hydrological events (DHEs): *diluvium*, *inundatio*, *excrescentia*, *fluminum* and related composite locutions such as *magnae pluviae*, *aqua maxima*, *tanta aquorum*, *inundation abundavit*, *impetu & aquarum multitudine*.

Most historical climatology research in Europe focuses on the Early Modern Period (c. 1500–1800). It is research for this period that established the methods and procedures that have become standard in the discipline of historical climatology (Pfister *et al* 2018). In northern Italy, Milanese and Parmensi documents (Cantarelli 1882), and a variety of sources from the Po River Basin (Bottoni 1872, Cazzola 2010, Baldini and Bedeschi 2018) are qualified for reconstructing time-series of extreme events over the past millennium or more.

## Methods

In addition to extensive primary archival research and research in Italian historical libraries, literary sources were accessed by web-engine search (<https://books.google.com>), generating ~100,000 bibliographic records. From this first massive bibliographic search, only ~1,000 records met the criteria of including the keywords *abundant rainfall*, *storm*, *downpour*, *diluvial*, *flood* and *alluvial* (*piogge abbondanti*, *tempesta*, *nubifragio*, *diluvio*, *inondazione*, *alluvione*), in addition to some Latin locutions (e.g., *magnae pluviae*, *aqua maxima*, *diluvium*, *excrescentia fluminum*, *inundatio*), which were chosen for careful reading. Useful data from the documentary sources were retrieved by transforming the information contained in narrative accounts into numbers on an index scale (see Appendix and Scoring system with monthly data [MSSI] in supplementary information is available online at [stacks.iop.org/ERC/2/031004/mmedia](https://stacks.iop.org/ERC/2/031004/mmedia)). A procedure, called *weather hindcasting* (Pfister *et al* 2018), was applied to become familiar with well-documented anomalies within the instrumental period prior to analysing analogous cases in the pre-instrumental past. In this way, a scoring system was applied to grade the MSSI, equal to 0 (normal), 1 (stormy), 2 (stormy with a few floods), 3 (stormy with large floods) and 4 (extraordinarily stormy with very large floods) (following Wetter *et al* 2011). In this way, a scoring system was



**Figure 3.** Cumulative distribution of the logarithm of number of storm events occurring in the Po River Basin 800–2018 CE versus their stormy severity index (MSSI), for (a<sub>1</sub>) the Medieval Warm Period (here, 800–1249 CE), (a<sub>2</sub>) the Little Ice Age (here, 1250–1849 CE), (a<sub>3</sub>) the Modern Period (here, 1850–2018 CE), and (b) The overall data set (800–2018 CE).

used to grade a MSSI (which is defined as the period of the year between December and November), equal to 0 (normal), 1 (stormy event), 2 (very stormy event), 3 (great stormy event) and 4 (extraordinary stormy event):

**Normal** means average or storm passed unobserved, without comments about its severity or its impacts on society and economy.

**Stormy** means an event is considered stormy if intense rainfall occurred with only limited damage, and no floods, recorded.

**Very stormy** was classified when intense rainfall occurred with some floods.

**Great stormy** refers to an extreme diluvial event, with severe and large floods and agricultural works are suspended, and urban communications are interrupted.

**Extraordinary stormy** is characterized by sporadic very extreme events, with a low centennial recurrence rate. These extreme diluvial events affect, at the same time, several river basins, killing people, animals and felling trees.

This kind of understanding is exemplified in the form of table (appendix A), incorporating monthly and annual values and the relative sources for exemplary years. The creation of an annual index was so designed to summarise the sum of MSSI of each month, as the Annual Storm Severity Index Sum (ASSIS). The study was based on the systematic and critical analysis of data about the above-mentioned phenomena offered by Italian documentary sources for a period covering 800–2018 CE. For most of the information, it was possible to make an ‘event check’ by considering more than one documentary source to the same event. It was also possible to contextualise the storm events with other types of historical events (e.g., social, agricultural, religious). In this way, the reliability of information can be assessed by trying to shed some light on the issue of climate relations and extreme events, looking beyond the quantitative data, and seeking alternative information from diaries, chronicles, and local stories.

### Completeness and robustness of the reconstructed extreme hydrological events

In the documentary data, we have revealed the presence of 387 extreme hydrological events occurring in northern Italy from 800 to 2018 CE, of which 14% have an unknown date. Sorting these events by class of severity results in 83 *stormy events*, 219 *very stormy events*, 65 *great stormy events*, and 20 *extraordinary stormy events*. However, our historical hydrological database relies on several types of heterogeneous sources, including accounts which might be an exaggeration of what it was, uncritical reference to previous sources, misprints in documentation and natural records of environmental parameters (proxy data), all that can be different factors of uncertainty in ‘cataloguing’ storm records (Pavese *et al* 1994). It is well established, for example, that there is a tendency to underestimate smaller events with isolated storms, especially from remote places or during summer, when more localized storms can be common. To resolve some of these uncertainties in our database, we established a reasonable criterion with respect to the recorded MSSI events. This was done by defining a partition of the time-series in three climatic sub-periods—the Medieval Warm Period (MWP; here 800–1249), Little Ice Age (LIA; here 1250–1849) and Modern Period (MP; here 1850–2018 following Diodato *et al* 2019)—and verifying for each climatic sub-period (figure 3(a)), and for the entire dataset (figure 3(b)), the scale-invariance in the relationship between the number of events larger than the storm strength events and the same strength events. The complete analysis was formalized with the relationship between the cumulative number of events (CEN) and MSSI values within the range  $1 \leq \text{MSSI} \leq 4$ , as follows (10):

$$\log_{10}(\text{CEN}_{i,j}) = a + b \cdot \text{MSSI}_{i,j} \text{ with } i = 1, \dots, 4 \text{ and } j = 1, \dots, 4 \quad (1)$$

where MSSI is the monthly storm severity index by severity class ( $i$ ) and sub-period ( $j$ ). The negative slopes in all the climatic sub-periods, and for the entire dataset, reflect the principle of a progression towards less frequency as storm events become larger. A Pearson's correlation coefficient  $r = 1$  is expected, with probability to reject  $r = 0$  equal to  $p < 0.01$ .

The 'catalogue' concerning the Modern Period 1850–2018 represents an exception. For this period, a distinct set of more complete information is evident (figure 3(a<sub>3</sub>)). In this way, the storm events in the period 800–2018 CE can be assumed significantly scale-invariant and therefore complete only for the 304 events that, within the range  $2 \leq \text{SSI} \leq 4$ , are described in qualitative terms as *very*, *great* and *extraordinary* storms. The remaining 83 events with  $\text{MSSI} = 1$  (red points in the scatterplots) are not fitted by the regression lines drawn in figure (3). Their number is much smaller than required by equation (1), probably because many of these low-energy events escaped detection in the past. Events with  $\text{MSSI} = 1$ , classified simply as stormy events only, have been discarded from our temporal analysis because they are not representative of the entire 'catalogue' within the investigated time-period. The methodology adopted not only ensures a great homogeneity, and a reduced uncertainty in the whole time-series 800–2018, but also in each climate sub-period (the Medieval Warm Period, the Little Ice Age, and the Modern Period).

## Results and discussion

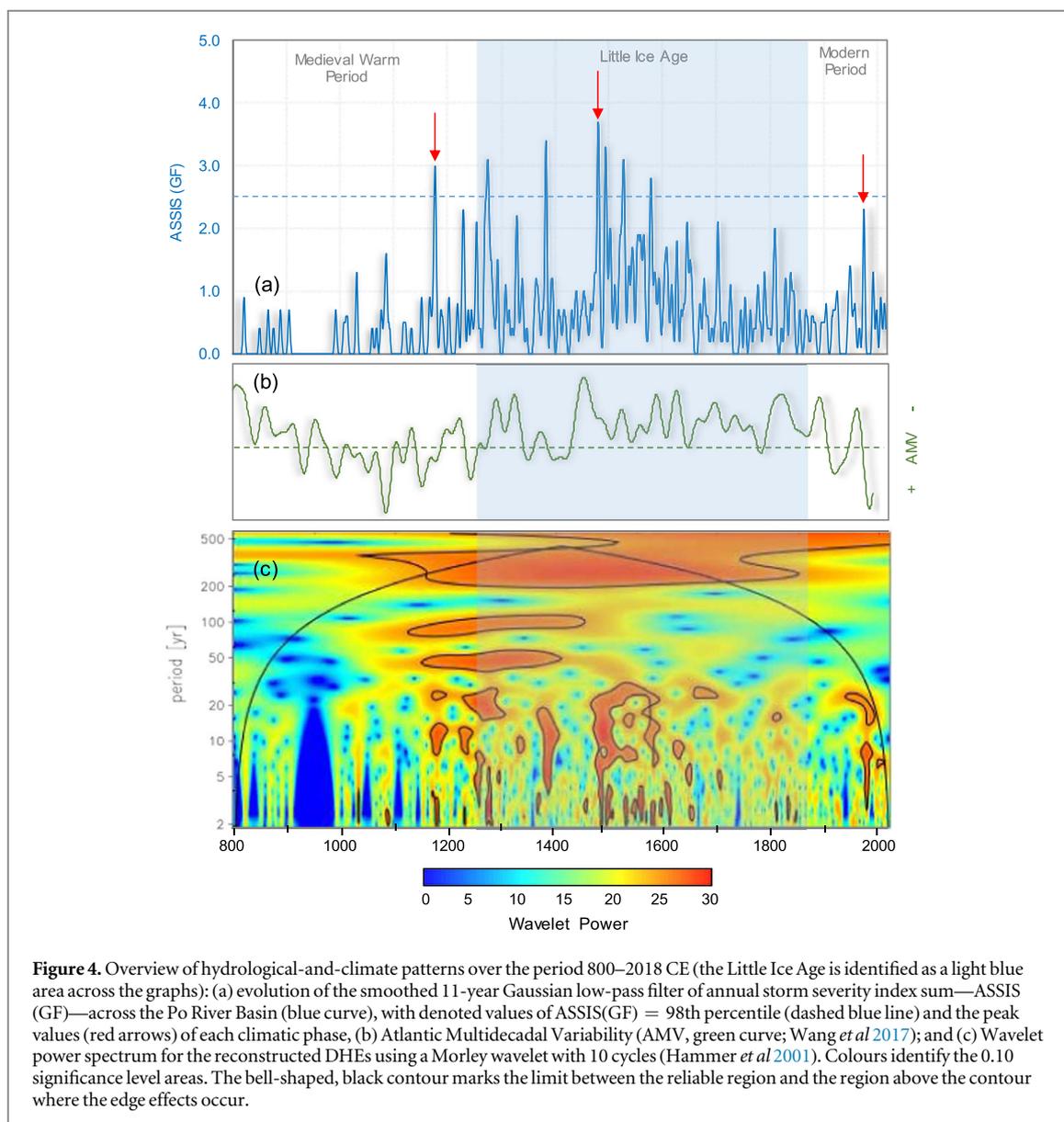
### Po River Basin-wide reconstruction of extreme hydrological events

The influence of large-scale climate variability on the occurrence of DHEs in the Po River Basin since 800 CE, i.e., at the beginning of the MWP, through the Little Ice Age, until the warming phase of the Modern Period (MP), is summarised in the graphical representation of figure 4. Changes in DHEs can be visualised and explained by repeated occurrences of an annual storm severity index sum (ASSIS). In order to identify possible trends and oscillations, the reconstructed time-series was filtered using a 11-year low-pass Gaussian filter to compute a continuous time-series of ASSIS(GF), which is meant to remove the high-frequency noise in the reconstructed discontinuous data (figure 4(a), blue curve). Filtering reduced the range of ASSIS values ( $0 \leq \text{ASSIS} \leq 9$ ) to between 0 and 3.7.

Until the middle of the thirteenth century, few and sporadic—sometimes moderate—DHEs affected the Po River Basin. From the ninth to twelfth centuries, catastrophic floods appear to have been rather exceptional, with only seasonal floods not considered as events worth considering. The presence of still rather extensive woodlands may have prevented rain-water from arriving downstream quickly in the form of dangerous flood waves. This is distinctly visible in figure 4(a), which shows that ASSIS(GF) is only little accentuated in this drier period in the ninth and tenth centuries. Between *c.* 750 and 1250 CE, southern Europe, including northern Italy, tended to receive relatively low amounts of precipitation, at least in summer, whereas the temperature, on average, was higher (Luterbacher *et al* 2016, Ljungqvist *et al* 2019).

With the rapid disappearance of the woodland coverage (e.g., Kaplan *et al* 2009, 2010), culminating in the twelfth and thirteenth centuries (owing to increased agricultural activities), the time required for river waters to flow from the most remote point of a watershed to the watershed outlet decreased, together with a reduced absorption of rainfall in the soil through vegetation cover (Cazzola 2010). During the twelfth to fourteenth century pulsing storms were observed with greater frequency and intensity, with the ASSIS(GF) index oscillating upwards from the thirteenth century. Human activities may have contributed to the impacts of rainfall events on land degradation when frequent floods occurred in this period (Brandolini and Cremaschi 2018). However, the regional storminess, which increased systematically at the beginning of the LIA, can be considered the main cause of the hydrological change occurring in this period (Baldini and Bedeschi 2018). The exception is one brief phase (1176–1178 CE) when (accompanied by a temporary lowering of temperatures; Borsato *et al* 2003, Luterbacher *et al* 2016, Wilson *et al* 2016) the first major floods are recorded—with the ASSIS(GF) greater than 98<sup>th</sup> percentile (that is when it is stormy with great and extraordinarily stormy floods occurring in the same year)—and hydrographic changes in the Po River Valley, with damages also on agricultural crops (Veggiani 1986).

A possible climate mechanism governing the frequency of DHEs in northern Italy is the AMV. During a positive phase of the AMV the number of DHE are significantly lower whereas during a negative phase of the AMV the number of DHE are significantly higher (figures 4(a)–(b)). Moreover, the colder phases of the LIA were associated with the intensification of extreme precipitation in the region and correspond to periods of reduced solar activity (Steinhilber *et al* 2009) and/or increased volcanic forcing (Sigl *et al* 2015). Time-lagged cross-correlations between ASSIS(GF) and the AMV time-series reveal significant negative correlations at zero and positive lag-time values (appendix B). Significant correlation values stably around  $-0.3$  as of about +60-year lag suggest a multi-decadal cycle. North Atlantic sea surface temperatures experience variability with a similar periodicity (e.g., Mazarella and Scafetta 2012).



A more continuous increase in DHEs occurred at the beginning of the last quarter of the fourteenth century and extended throughout the last decades of the fifteenth century (figure 4(a)). This is in line with the results of Brázdil *et al* (1999), which show a concentration of floods in all the investigated rivers of northern and central Italy at the same time. Such heavy and persistent rainfall was likely the trigger of the great floods of 1528–1530, 1554 and 1557 (around the Spörer minimum of solar activity, ~1490–1550; Miyahara *et al* 2006), which are a recurring theme in the narratives of different sources due to their devastating magnitude and societal consequences (Baldini and Bedeschi 2018). Frequent storms also occurred during the 1620s and 1640s, concurrent with when severe food shortage as well as plague outbreaks prevailed in northern Italy (Alfani 2010). However, around the Maunder Minimum in solar activity (*c.* 1645–1715 CE; Eddy 1976), there was a temporary decrease of in the number of storm events, with catastrophic floods becoming less frequent, according to results from Wilhelm *et al* (2012) for the Mediterranean French Alps. During the eighteenth century, the number of storms decreased corresponding with an increase in solar activity. Only in 1807, 1810, 1812 (concurrent with the Dalton minimum of solar activity, ~1790–1830; Wagner and Zorita 2005), and especially in 1976 and 1977 (marking the end of since the 1940s globally stable, and in Europe decreasing, temperatures; Diodato and Mariani 2007), floods became more powerful with disastrous damage. Extraordinary storms were very isolated in the nineteenth and twentieth centuries in the Po River Basin (e.g., the catastrophic floods in 1839, 1951, and 1994): ASSIS(GF) < 1 makes this period very similar to the ninth and tenth centuries.

The wavelet coherence spectrum (figure 4(c)) displays both high- (~11 years) and low-frequency (~300-years) periodicities during the LIA. The ~11-year sunspot cycle is a main feature of solar activity

**Table 1.** Number of storm severity index classes for each month (MSSI).

Severity classes (MSSI)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Unknown date
2	14	6	6	14	19	24	13	8	20	29	24	6	42
3	5	1	0	3	1	0	0	0	4	16	16	4	12
4	1	1	0	0	0	0	0	0	1	4	6	3	2
$\sum_{SC=2}^4$ MSSI	20	8	6	17	20	24	13	8	25	49	46	13	55

variability (Wolf 1852, 1853), while the ~300-year cycle may reflect a quasi-periodic feature of sunspot variability, which is likely related to precipitation changes in the North Atlantic region (as determined by Ojala *et al* (2015) from sediment records of lakes Nautajärvi and Korttajärvi in Finland). Whereas significant periodicities less than ~11 years occasionally occur without any relation with climatic periods, the periodicity of ~300 years extends over the entire LIA. Other low-frequency periodicities (>300 years) are also significant but they fall above the reliable area formed by the time axis and the bell-shaped contour. On the one hand, this suggests that recurrences of storminess become less statistically predictable outside the LIA. This may demonstrate that dynamic atmospheric processes are present in generating cyclone-related precipitation extremes throughout the LIA (Raible *et al* 2018), departing from the Clausius–Clapeyron thermodynamic expectations of an increase in precipitation intensity associated with atmospheric warming (Pall *et al* 2007, Trenberth 2011, Trenberth *et al* 2014, Kirby 2016, Prein and Pendergrass 2019). Our study thus shows the same tendency as revealed by Ljungqvist *et al* (2019) for a negative low-frequency temperature–hydroclimatic coupling (i.e., warm and dry) in southern Europe. Likewise, solar-type periodicities suggest that the Sun may be one of the precursors of hydrological processes in northern Italy (Zanchettin *et al* 2008).

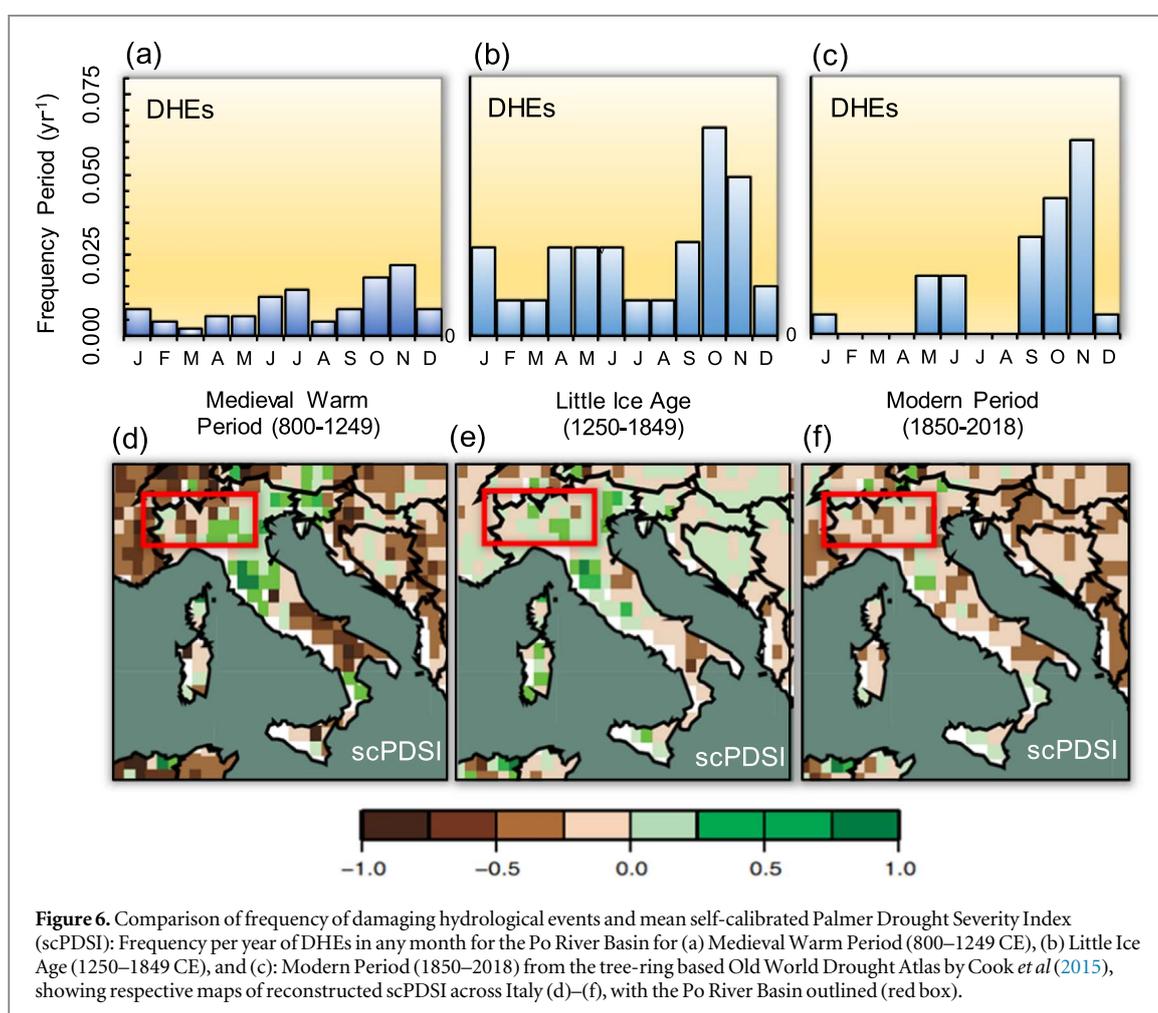
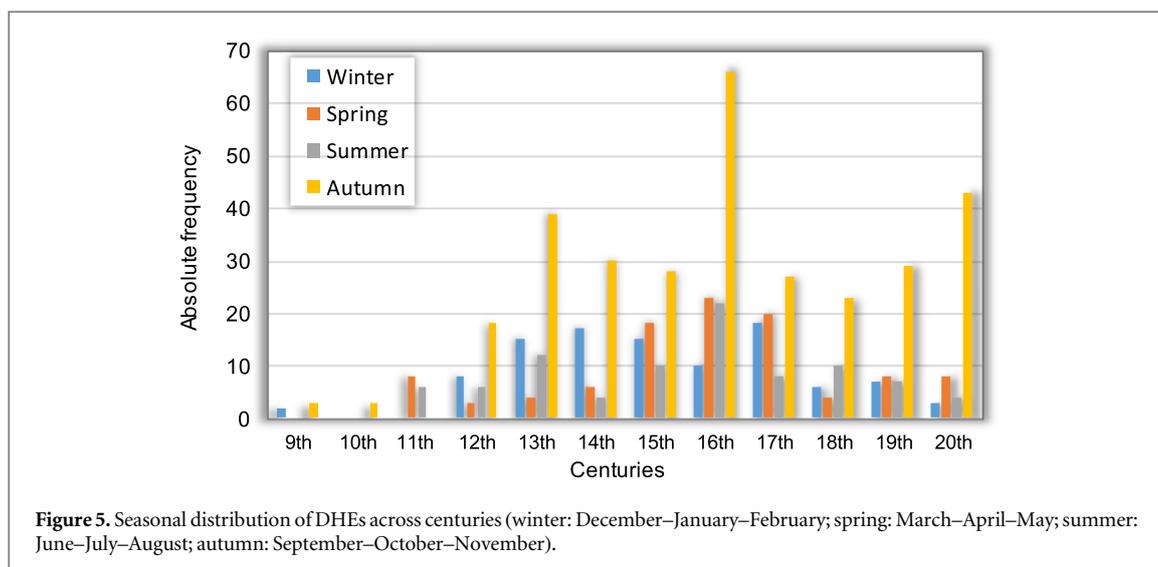
### Variability, frequency distribution and seasonal patterns of the storms

Knowledge of the monthly or seasonal variability of storms is important to obtain an insight into the water's destructive force. As it is a measure of how far monthly values deviate from their average value, it reflects the dangerousness of storms for land management (associated with land cover/use changes). We have presented a twelve century-long (800–2018 CE) perspective of storm regime patterns shown as the absolute frequency distribution of storm events (table 1).

The seasonal distribution of events, grouped on a seasonal basis, showed that autumn is unambiguously dominating with most frequent flooding (49%), while the remainder of the events is almost identically distributed over the other three seasons: summer (18%), spring (17%) and winter (16%). This distribution is in agreement with the assessment of reconstructed hydrological conditions of the Central Alps derived from Wirth *et al* (2013). We also consider the attribution of changes in DHEs at the monthly scale. These analyses provide more insight into flood-generating processes and enable the evaluation of the conclusions we reached using data on an annual scale. Grouped by century, the seasonal DHEs appear distributed according to similar distributions (Kolmogorov–Smirnov pair-wise  $p$ -values > 0.05) in winter, spring and summer (with a maximum during the 16<sup>th</sup> century, at the climax of the LIA), while the autumn events follow a distinct distribution (Kolmogorov–Smirnov pairwise  $p$ -values < 0.05) with important peaks of activity (figure 5), which make them unpredictable in any climatic period.

The yearly frequency of monthly DHEs across the three considered climatic periods: 800–1249 (MWP), 1250–1849 (LIA), and 1850–2018 (MP) is shown in figure 6. The respective histograms of frequency indicate that the three periods present distinct climatic regimes: quasi-multimodal (MWP); bimodal-continental (colder) with diluvial events roughly occurring in all seasons and strengthening in spring and autumn (LIA); and bimodal-Mediterranean (warmer) with concentration of extreme events in late spring and autumn only (MP). As shown in the maps of figure 6, these shifts of the peak positions align with the shifts in relative regional reconstructed drought (Palmer Drought Severity Index, scPDSI) in the tree-ring based Old World Drought Atlas (Cook *et al* 2015).

The MWP (figure 6(a)) shows only a little prominence of multi-modality, while intra-seasonal character—i.e., when the seasonality in rainfall intensities was in phase with the seasonality of previous catchment wetness—appears to be small. In these months, with relatively wet antecedent conditions, small floods are occurring quite frequently, leading to a stable flood-frequency curve. Hence, meridional circulation conditions could have



affected the MWP inducing heavy convective storms throughout the year, which resulted in large variability, and thus little seasonality, of DHEs over northern Italy. This phase displays dry-to-very-dry western and northern margins of the Po River Basin (figure 6(d)), with an only marginally more humid area in the southeast.

In contrast, a strong bimodal component in spring and autumn is found during the LIA, with a relative peak of flood frequency in April–June and an absolute peak in October (figure 6(b)). This is an important finding, indicating that small and moderate flooding in spring–summer is related to the frequency of storms. However, there may be quite unusual and extreme DHEs occurring in the autumn, which are presumably related to

southerly circulation patterns when warm and moist air is advected from the Mediterranean Sea (e.g., Parajka *et al* 2010). During the MP (figure 6(c)), only autumn storminess remains active. In these months, with dry antecedent conditions and large rainfall intensities (e.g., in June–August), localized storms are more frequent with a number of larger floods occurring only in October–November. The map in figure 6(f) also shows dry conditions, with alternating dry and very dry anomalies.

### Conclusions

From the ninth century onwards, floods are reported more systematically than for earlier periods. Recurring storms are listed in documentary data, allowing a quantitative reconstruction of extreme hydrological events on a monthly level. It is clear that the past twelve centuries (800–2018 CE) have been marked by alternating phases of higher and lower frequency of storms and floods providing a backdrop for how to manage natural resources to protect new generations. Periods with increasing flood frequency are found to align with solar minima. Though the physical meaning of this finding merits further investigation, we tentatively suggest that solar activity likely helps to induce large-scale circulation changes resembling negative phases of the AMV acting as a controlling atmospheric mechanism of DHEs. Then, despite the presence of increasing anthropogenic climatic forcing, an expected decrease in solar activity during coming decades could possibly re-intensify the risk of frequent flooding in southern Europe. The rapidly developing sub-mesoscale convective systems tend to be responsible for the heaviest and most locally destructive storm events in the Mediterranean region as they are affecting small catchments with the most vulnerable systems to storm-driven flash floods and soil erosion hazards.

### Acknowledgments

We thank the two anonymous reviewers whose useful comments helped improve this article. F.C.L. was supported by the Swedish Research Council (Vetenskapsrådet, grant no. 2018-01272), and conducted the work with this article as a Pro Futura Scientia XIII Fellow funded by the Swedish Collegium for Advanced Study through Riksbankens Jubileumsfond. The publication cost was covered by Stockholm University.

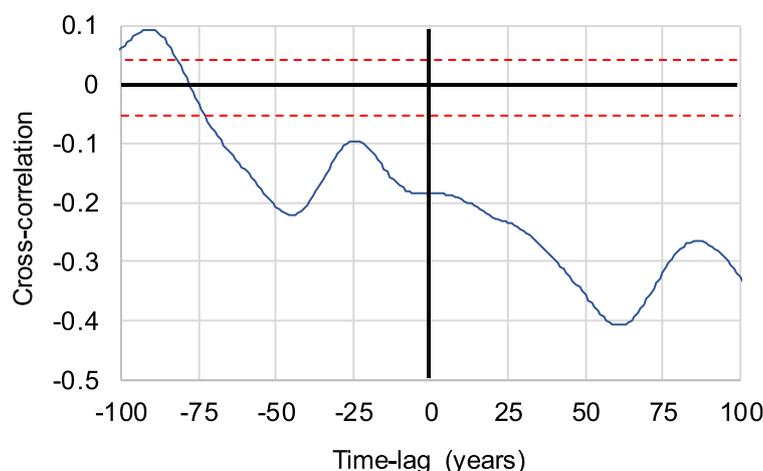
### Appendix A

Coded storm events from the written sources for exemplary years (with English translation from italicized original). With blue numbers, monthly indices (MSSI) are reported for all the months of the year (JFMAMJJJASOND) together with the annual sum (ASSIS).

Year	J	F	M	A	M	J	J	A	S	O	N	D	ASSIS	Source
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
									<i>Rotta a Coronella: l'acqua ha inondato Ferrara.</i> Flood at Coronella: the water flooded Ferrara					Pignagnoli W. 1952. Diciamo male del Po (inondazioni e rovine nel suo bimillenario cammino). Milano, p. 28.
1394	0	0	0	0	0	0	0	0	2	0	0	0	2	
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
									<i>Rotta a carbonara e Serminese.</i> Rotta a Berra e Scortega . Flood at Carbonara and Serminese					Mantovani G. 1886. Il territorio Sermidese e limitrofe ricerche archeologiche storiche ed idrografiche. Stab Fratelli Cattaneo. Bergamo, p. 150.
1544	0	0	0	0	0	0	0	0	0	2	2	0	4	
									<i>Grande alluvione del Po con rottura degli argini nei pressi di Ficarolo. Gravi danni alla campagna.</i> Great flood of the Po' with breakage of the embankment near Ficarolo. Serious damage to the countryside.					Barili A 1812. Notizie storico-patrie di Casalmaggiore. Stamperia Imperiale, Parma, p. 50.
1545	0	0	0	0	0	0	0	0	0	3	0	0	3	
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

## Appendix B

Lagged cross-correlations between ASSIS(GF) and Atlantic Multidecadal Variability (blue curve). Hatched red lines define the 95% confidence interval. The ASSIS(GF) was filtered using a 30-year low-pass Gaussian filter to conform to the 30-year low-pass filtered AMV reconstruction (Wang *et al* 2017).



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