LETTER

Monthly storminess over the Po River Basin during the past millennium (800–2018 CE)

Nazzareno Diodato1, Fredrik Charpentier Ljungqvist2,3,4 and Gianni Bellocchi1,5

1 Met European Research Observatory—International Affiliates Program of the University Corporation for Atmospheric Research, Via Monte Pino snc, 82100, Benevento, Italy
2 Department of History, Stockholm University, 106 91, Stockholm, Sweden
3 Bolin Centre for Climate Research, Stockholm University, 106 91, Stockholm, Sweden
4 Swedish Collegium for Advanced Study, Linneanum, Thunbergsvägen 2, 752 38 Uppsala, Sweden
5 UCA, INRAE, VetAgro Sup, UREP, 63000, Clermont-Ferrand, France

E-mail: fredrik.c.l@historia.su.se

Keywords: climate variability, climate reconstructions, storminess, Po River Basin, past millennium, documentary data

Supplementary material for this article is available online

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 palaeoclimatic 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. 2015). 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 $\delta^{18}O$ data from a sediment core in the Ionian Sea for a millennium-long reconstruction of hydrological variability in northern Italy.

Long reconstructions of hydroclimatic 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). Camufo 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.
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 ~74,000 km², situated almost entirely in Italy, with a present total population of ~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 (Pfi ster 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, inundazione, 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). A procedure, called weather hindcasting (Pfi ster 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
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 ≤ MSSI ≤ 4, as follows (10):

\[
\log_{10}(\text{CEN}_{i,j}) = a + b \cdot \text{MSSI}_{i,j} \quad \text{with} \quad i = 1, \ldots, 4 \text{ and } j = 1, \ldots, 4
\] (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)). 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 \(2 \leq SSI \leq 4\), are described in qualitative terms as very, great and extraordinary storms. The remaining 83 events with 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 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 \((0 \leq \text{ASSIS} < 9)\) 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 floods. 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 98th 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., Mazzarella 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

\[ \text{Figure 4. Overview of hydrological- and climate patterns over the period } 800-2018 \text{ CE (the Little Ice Age is identified as a light blue area across the graphs): (a) evolution of the smoothed } 11\text{-year Gaussian low-pass filter of annual storm severity index sum—ASSIS (GF)—across the Po River Basin (blue curve), with denoted values of ASSIS(GF) = 98th percentile (dashed blue line) and the peak values (red arrows) of each climatic phase, (b) Atlantic Multidecadal Variability (AMV, green curve; Wang et al 2017); and (c) Wavelet power spectrum for the reconstructed DHEs using a Morley wavelet with 10 cycles (Hammer et al 2001). Colours identify the 0.10 significance level areas. The bell-shaped, black contour marks the limit between the reliable region and the region above the contour where the edge effects occur.} \]
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 16th century, at the climax of the LIA), while the autumn events follow a distinct distribution (Kolmogorov-Smirnov pair-wise $p$-values < 0.05) with important peaks of activity (figure 5), which makes 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

| 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   | 0   | 4   | 16  | 16  | 4   | 12          |
| 4                      | 1   | 1   | 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
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

---

**Figure 5.** Seasonal distribution of DHEs across centuries (winter: December–January–February; spring: March–April–May; summer: June–July–August; autumn: September–October–November).

**Figure 6.** Comparison of frequency of damaging hydrological events and mean self-calibrated Palmer Drought Severity Index (scPDSI): Frequency per year of DHEs in any month for the Po River Basin for (a) Medieval Warm Period (800–1249 CE), (b) Little Ice Age (1250–1849 CE), and (c) Modern Period (1850–2018) from the tree-ring based Old World Drought Atlas by Cook et al (2015), showing respective maps of reconstructed scPDSI across Italy (d–f), with the Po River Basin outlined (red box).
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 (JFMAMJJASOND) together with the annual sum (ASSIS).

| Year | J | F | M | A | M | J | A | S | O | N | D | ASSIS | Source |
|------|---|---|---|---|---|---|---|---|---|---|---|------|--------|
| 1094 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 | Pignagnoli W. 1957. Diciamo male del Po (inondazioni e rivine nel suo bimillenario cammino). Milano, p. 28. |
| 1544 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 0 | 4 | Mantovani G. 1886. Il territorio Seminester e limitrofe marche archeologiche storiche ed etnografiche. Stab Fratelli Cattaneo. Bergamo, p. 150. |
| 1545 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 3 | Bertil A. 1812. Notizie storico-patri di Casamaggiore. Stamperia Imperiale, Parma, p. 50. |
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).

References

Alfani G 2010 Climate, population and famine in Northern Italy: General tendencies and Malthusian crisis, ca. 1450–1800 Annales de Démographie Historique 120 23–53
Bakker P, Clark P U, Golledge N R, Schmittner A and Weber M E 2017 Centennial-scale Holocene climate variations amplified by Antarctic Ice Sheet discharge Nature 541 72–6
Baldini E and Bedeschi A 2018 Il Fango, la Fame, la Peste: Clima, Carestie e Epidemie in Romagna nel Medioevo e in Età Moderna (Cesena: Società Editrice Il Ponte Vecchio)
Borsato A et al. 2003 Ricostruzione climatica degli ultimi 17.000 anni da una stalagmite della Grotta Savi (Trieste, Italia) Studi Trentini di Scienze Naturali—Memorie Historiche 80 111–25 (in Italian)
Benito G, Díez-Herrero A and de Villalta M F 2003 Magnitude and frequency of flooding in the Tagus basin (central Spain) over the last millennium Clim. Change 58 171–92
Benito G, Macklin M G, Panin A, Rossato S, Fontana A, Jones A F, Machado M J, Matlakhova E, Mozzi P and Ziellohofer C 2015 Recurring flood distribution patterns related to short-term Holocene climatic variability Sci. Rep. 5 16398
Bottoni A 1872 Appunti storici delle Rotte del Basso Po dai Tempi Romani a Tutto il 1939 (Ferrara: Tipografia Sociale) (in Italian)
Brandolini F and Cremaschi M 2018 The impact of Late Holocene ice sheet discharge on the spatiotemporal characteristics of runoff and precipitation during the 2009 flood management on the Central Po Plain (Northern Italy) Sustainability 10 3968
Brown P, Daigneault A J, Tjernström E and Zou W 2018 Natural disasters, social protection, and risk perceptions World Dev. 104 310–25
Brázdil R et al. 1999 Flood events of selected European rivers in the sixteenth century Clim. Change 43 239–85
Calò C, Henne P D, Eugster P, van Leeuwen J, Gilli A, Hamann Y, La Mantia T, Pasta S, Vescovi E and Tinner W 2013 1200 years of decadal-scale variability of Mediterranean vegetation and climate at Pantelleria Island, Italy Holocene 23 1477–86
Camuffo D and Enzi S 1996 The analysis of two bi-millennial series: Tiber and Po river floods Climatic Variations and Forcing Mechanisms of the Last 2000 Years ed P D Jones, R S Bradley and J Jouzel (Berlin and Heidelberg: Springer) pp 433–50
Cantarrelli C 1882 Cronaca di Pisa Salmibene Parmigico: dell’Ordine dei Meniori Vol. II (Parma: Luigi Battie Editore) (in Italian)
Cazzola F 2010 Il Po. Le Calamità Ambientali nel Tardo Medioevo Europeo: Realità, percezioni, reazioni ed M Matheus et al. (Florence: Firenze University Press) pp 197–227
Cook E R et al. 2015 Old World megadroughts and pluvials during the Common Era Sci. Adv. 1 1–9
Debagne N and Shepherd J M 2018 Urban influences on the spatiotemporal characteristics of runoff and precipitation during the 2009 Atlanta flood J. Hydrometeorol. 20 3–21
Diodato N, Ljungqvist F C and Belloccchi G 2019 A millenium-long reconstruction of damaging hydrological events across Italy Sci. Rep. 9 9963
Diodato N and Mariani L 2007 Testing a climate erosive forcing model in the Po River Basin Clim. Res. 33 195–205
Eddy J A 1976 The Maunier Minimum Science 192 1149–202
Enfield D B, Mestas-Nuñez A and Trimble P J 2001 The Atlantic Multidecadal oscillation and its relation to rainfall and river flows in the continental U. S. Geophys. Res. Lett. 28 277–80
Finsinger W, Colomboari D, de Beaulieu J-L, Valsecchi V, Vannière B, Vescovi E, Chapron E, Lotter A F, Magny M and Tinner W 2010 Early to mid-Holocene climate change at Lago dell’Accesa (central Italy): climate signal or anthropogenic bias? J. Quaternary Sci. 25 1239–47
Glaser R and Stangl H 2004 Climate and floods in Central Europe since AD 1000: data, methods, results and consequences *Surv. Geophys* **25** 485–510

Glur L, Wirth S B, Büntgen U, Gilli A, Haug G H, Schar C, Beer J and Anselmetti F S 2013 Frequent floods in the European Alps coincide with cooler periods of the past 2500 years *Sci. Rep.* **3** 2770

Guidoboni E 1998 Human factor, extreme events and floods in the lower Po Plain (Northern Italy) in the 16th century *Environ. Hist.* **4** 279–308

Hammer O, Harper D A T and Ryan P D 2001 Past: Paleontological Statistics Software Package for Education and Data Analysis *Palaeontologia Electronica* **4** 1

Harries R M B et al 2018 Biological responses to the press and pulse of climate trends and extreme events *Nat. Clim. Change* **8** 579–87

Hoepp P 2016 Trends in weather related disasters—Consequences for insurers and society *Weather and Climate Extremes* **11** 70–9

Kaplan J O, Krumhardt K M, Ellis E C, Ruddiman W F, Lemmen C and Goldewijk K K 2010 Holocene carbon emissions as a result of anthropogenic land cover change *Holocene* **21** 775–91

Kaplan J O, Krumhardt K M and Zimmermann N 2009 The prehistoric and preindustrial deforestation of Europe *Quat. Sci. Rev.* **27-28** 3014–34

Kerr R A 2000 A North Atlantic climate pacemaker for the centuries *Science* **288** 1984–6

Kirby M E 2016 Water’s past revisited to predict its future *Nature* **532** 44–5

Knox J C 1993 Large increases in flood magnitude in response to modest changes in climate *Nature* **361** 430–32

Lionello P, Bhend J, Buzzi A, Della-Marta P M, Kirchhak S O, Jansa A, Maheras P, Sanna A, Trigo I F and Trigo R 2006 Cyclones in the Mediterranean region: climatology and effects on the environment *Climate Mediterranean Climate Variability ed P Lionello, P Malanotte-Rizzoli and R Roscolo (Amsterdam: Elsevier) pp 325–72

Ljungqvist F C, Krusic P J, Sundqvist H S, Zorita E, Brattström G and Frank D 2016 Northern Hemisphere hydroclimatic variability over the past twelve centuries *Nature* **532** 94–8

Luino F 2013 Le inondazioni storiche del Fiume Po in particolare dal 1861 a oggi *Clim. Res.* **111** 382–92

Magny M, Joannim S, Galop D, Vanniere B, Haas J N, Bassetti M, Bellintani P, Scandolari R and Desmet M 2012 Holocene paleohydrological changes in the northern Mediterranean borderlands as reflected by the lake-level record of Lake Ledro, northeastern Italy *Quaternary Res.* **77** 382–96

Mazzarella A and Scafetta N 2012 Evidences for a quasi 60-year North Atlantic Oscillation since 1700 and its meaning for global climate change *Theor. Appl. Climatol.* **107** 599–609

Miyahara H, Masuda K, Muraki Y, Kitagawa H and Nakamura T 2006 Variation of solar cyclicity during the Spoerer Minimum *J. Geophys. Res.* **111** A03103

Nikolopoulois E I, Anagnostou E N and Borga M 2013 Using high-resolution satellite rainfall products to simulate a major flood event in Northern Italy *J. Hydrometeorol.* **14** 171–85

Ojala A E K, Launonen I, Holmström L and Tiljander M 2015 Effects of solar forcing and North Atlantic oscillation on the climate of continental Scandinavia during the Holocene *Clim. Dyn.* **45** 1543–57

Parajka J et al 2010 Seasonal characteristics of flood regimes across the Alpine–Carpathian range *J. Hydrol.* **394** 78–89

Paul S, Ghosh S, Mathew M, Devanand A, Karmakar S and Niyyogi D 2018 Increased spatial variability and intensification of extreme monsoon rainfall due to urbanization *Sci. Rep.* **8** 3918

Pavesi M P, Baronzio V, Colacino M, Gregori G P and Pasqua M 1994 Three historical data series on floods and anomalous climatic events in Italy *Clim. Res.* **8** 1509–10

Pfister C, Camenisch C and Lobkovsky P 2018 Analysis and interpretation: temperature and precipitation indices *The Palgrave Handbook of Climate History ed S White, C Pfister and F Mauelshagen (London: Palgrave Macmillan) pp 115–29

Prein A F and Pendergrass A G 2017 Can we constrain uncertainty in hydrologic cycle projections? *Geophys. Res. Lett.* **44** 3911–6

Raible C C, Messmer M, Lehner F, Stocker T F and Blender R 2018 Extratropical cyclone statistics during the last millennium and the 21st century *Clim. Past* **14** 1499–514

Ricks M D, Wilson W T, Zech W C, Fang X and Donald W N 2020 Evaluation of hydromulches as an erosion control measure using laboratory-scale experiments *Water* **12** 515

Rubel F, Bruggen K, Haslinger K and Auer J 2017 The climate of the European Alps: Shift of very high resolution Köppen–Geiger climate zones 1800–2100 *Meteorol. Z.* **26** 115–25

Sigg M et al 2015 Timing and climate forcing of volcanic eruptions for the past 2,500 years *Nature* **523** 543–9

Stimm J, Thorarinssottir T, Keesiyde N, Schaller N, Alexander L V, Hegerl G, Seneviratne S I, Vautard R, Zhang X and Zwiers F W 2017 Understanding, modeling and predicting weather and climate extremes: challenges and opportunities *Weather and Climate Extremes* **18** 65–74

Squartriti P 2010 The floods of 589 and climate change at the beginning of the Middle Ages: An Italian microhistory *Speculum* **85** 799–812

Stamatioupolos L, Alevizos G and Evelpidou N 2018 Geomorphological evolution and fluvial system development during the Holocene: The case of Variaekos River evolution in Kalavrita Plain, Northern Peloponnese, Greece *J. Geoscience and Environment Protection* **6** 37–15

Steinhilber F, Beer J and Frohlich C 2009 Total solar irradiance during the Holocene *Geophys. Res. Lett.* **36** L19704

Strahler A and Strahler A N 2000 *Introducing Physical Geography* (Chichester: Wiley)

Tareco C, Alessio S, Rubinietti S, Zanchettin D, Cossoli S, Cacici M, Mancuso S and Rubino A 2015 Marine sediment remotely unveils long-term climatic variability over Northern Italy *Sci. Rep.* **5** 12111

Trenberth K E 2011 Changes in precipitation with climate change *Clim. Res.* **47** 123–38

Trenberth K E, Dai A, van der Schrier G, Jones P D, Barichivich J, Briffa K R and Sheffield J 2014 Global warming and changes in drought *Nat. Clim. Change* **4** 17–22
Veggiani A 1986 Clima, uomo e ambiente in Romagna nel corso dei tempi storici *Romagna, vicende e protagonisti* ed C Marabini and W Della Monica (Bologna: Edison) pp 3–19 (in Italian)

Wagner S and Zorita E 2005 The influence of volcanic, solar and CO₂ forcing on the temperatures in the Dalton minimum 1790–1830: a model study *Clim. Dyn.* 25 205–18

Wang J, Yang B, Ljungqvist F C, Luterbacher J, Osborn T J, Briffa K R and Zorita E 2017 Internal and external forcing of multidecadal Atlantic climate variability over the past 1,200 years *Nat. Geosci.* 10 512–7

Wang J, Yang B, Osborn T J, Ljungqvist F C, Zhang H and Luterbacher J 2018 Causes of East Asian temperature multidecadal variability since AD 850 *Geophys. Res. Lett.* 45 13485–94

Wetter O, Pfister C, Weingartner R, Luterbacher J, Reist T and Trösch J 2011 The largest floods in the High Rhine basin since 1268 assessed from documentary and instrumental evidence *Hydrolog. Sci. J.* 56 733–58

Wilhelm B et al 2012 1400 years of extreme precipitation patterns over the Mediterranean French Alps and possible forcing mechanisms *Quaternary Res.* 78 1–12

Wilhelm B et al 2018 Wetter, Interpreting historical, botanical, and geological evidence to aid preparations for future floods *WIREs Water* e1318

Wilson R et al 2016 Last millennium northern hemisphere summer temperatures from tree rings: Part I: The long term context *Quat. Sci. Rev.* 134 1–18

Wirth S B, Gilli A, Simonneau A, Ariztegui D, Vannière B, Glur L, Chapron E, Magry M and Anselmetti F S 2013 A 2000 year long seasonal record of floods in the southern European Alps *Geophys. Res. Lett.* 40 4025–9

Wolf R 1852 Neue Untersuchungen über die Periode der Sonnenflecken und ihre Bedeutung *Mittheilungen der Naturforschenden Gesellschaft in Bern* 255 249–70 (in German)

Wolf R 1853 Über den Zusammenhang magnetischer Erscheinungen mit dem Zustande der Sonne *Astron. Nachr.* 35 59–60 (in German)

Wyatt M G, Kravtsov S and Tsonis A A 2012 Atlantic Multidecadal Oscillation and Northern Hemisphere’s climate variability *Clim. Dyn.* 38 929–49

Zhang X, Zwiers F W, Li G, Wan H and Cannon A J 2017 Complexity in estimating past and future extreme short-duration rainfall *Nat. Geosci.* 10 255–9

Zanchettin D, Rubino A, Traverso P and Tomasino M 2008 Impact of variations in solar activity on hydrological decadal patterns in northern Italy *J. Geophys. Res.* 113 D12