Point process methods for the diagnosis of extreme events in palaeoclimate records: Norwegian mega-floods in the Holocene

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Abstract

This study demonstrates the use of statistical marked point process techniques for interpreting irregular events recorded in palaeoclimate records by high-impact extreme phenomena such as floods. The methods are illustrated using a series of 114 flood events recorded during the Holocene (7264 BC to AD 1915) in a sediment core taken from lake Butjønna in east-central southern Norway. A non-parametric kernel density method is used to infer the rate of the process from the ^{14}C-dated ages of the events. The rate of all flood events has increased by around 1.90%/century up to one event every 39.5 years in AD 1950. A similar trend is also found for the rate of "mega-flood" events based on the subset of 26 events that have the largest magnitudes. There is no significant change in the magnitude of the flood events throughout the recorded period. Local maxima in rate are found at 4218 BC, 1390 BC, and at the present-day end of the record, yet these clusters could easily be due to chance sampling of the process. There is no strong evidence of dependence between successive flood events. The approach demonstrated here could be useful for interpreting many other types of palaeoclimatic records that consist of irregular magnitudes occurring at irregular dates.

Keywords: Palaeo-extreme, Holocene, river flood, statistical method, marked point process, clustering, kernel density estimation.

1. Introduction

Weather-related hazards such as floods are a major source of risk for society that needs to be better understood. Although generally rare at any particular location, extreme environmental conditions related to weather systems can take place very quickly (e.g. the severe Alpine floods on 23-25 August 2005). Such extreme events lead to severe damages both to man-made infrastructure and to the environment and ecosystems. Because of their rarity, short instrumental records do not always sample sufficient numbers of extreme events for definitive conclusions to be inferred. For example, for 50-year return period events (ones with probability of 0.02 of occurring each year) one expects an average of only four such events in 200 years of historical

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climate records. With such small sample sizes, it is not possible to make reliable inferences despite the fact that such events can (and do!) happen in our lifetimes and lead to catastrophic impacts Fortunately, longer records of such extreme events can be obtained from various palaeoclimatic records. Because of their very severity, extreme weather-related events often leave permanent records in the physical environment. For example, floods can transport large amounts of soil and rock that can be observed in lake sediment records and in geomorphological features (Knox, 1993; Brown et al., 2000; Bøe et al., in press). As noted by Shorthouse and Arnell (1999), such records provide a valuable additional source of information on past hydrological events to that provided by either documentary records (Mudelsee et al., 2003) or tree ring records (St. George and Nielsen, 2003).

Palaeoclimatic studies of past flooding have for the most part been qualitative, but some more quantitative studies have been carried out (e.g. Ely et al., 1996; Jain and Lall, 2001; Mudelsee et al., 2003). Using documentary records going back several centuries, Mudelsee et al. (2003) found no strong evidence for increasing trends in the occurrence of extreme floods in the rivers Oder and Elbe in central Europe. In contrast, Bøe et al., (in press) found an increasing trend in river flood activity toward the end of the Holocene in a 10 000 year flood record based on sediments trapped in a small lake in the upper Glomma catchment in east-central southern Norway. Flood layers of past floods, predominantly inorganic sediment, were found to be considerably thicker than many of the sediment layers deposited during the past 300 years suggesting that extreme mega-floods have occurred, albeit rarely, in southeastern Norway. A few such mega-flood events have been registered in historical records and on flood markers back to the 17th century and have been known to cause devastating impacts (e.g. the Stor-Ofsen flood of AD 1789).

This paper presents a general point process approach for interpreting extreme events recorded in palaeoclimatic data. It will illustrate the approach by application to the lake sediment record from east-central southern Norway in Bøe et al. (in press). Section 1 describes the palaeoclimatic data and puts it in context with a discussion of recent floods that have occurred in the region. Section 2 then describes the point process methodology. An important scientific aim is to determine the trends in frequency of events, especially for mega-flood events. Section 3 presents results obtained using the point process methodology and finally Section 4 concludes the paper with a brief summary of key findings and wider implications.

2. Data

2.1. Study area and methods

Glomma, Norway’s largest river catchment at 41.000 km^2, drains a wide range of altitudes, from sea level in the south up to elevations above 2000 m in the northwest. This implies a spring flood dominated discharge regime and all large floods happen during the snow-melting season in May-June. The mean annual precipitation and temperature is 364 mm and 0.7 °C, respectively, at the investigated local catchment basin (DNMI, 1993). Approximately one third of the annual precipitation falls as snow even in the lower lying areas, in the mountainous parts substantially more. To achieve floods recognizable in historical records (approximately > 2000 m^3 s^{-1} at Elverum gauging station), an extensive winter snow cover melting late in the spring season is a premise, often with a sudden summer rain speeding up the melting process. Lake Butjønna is located at a flat sandy terrace from the deglaciation of the last continental ice sheet

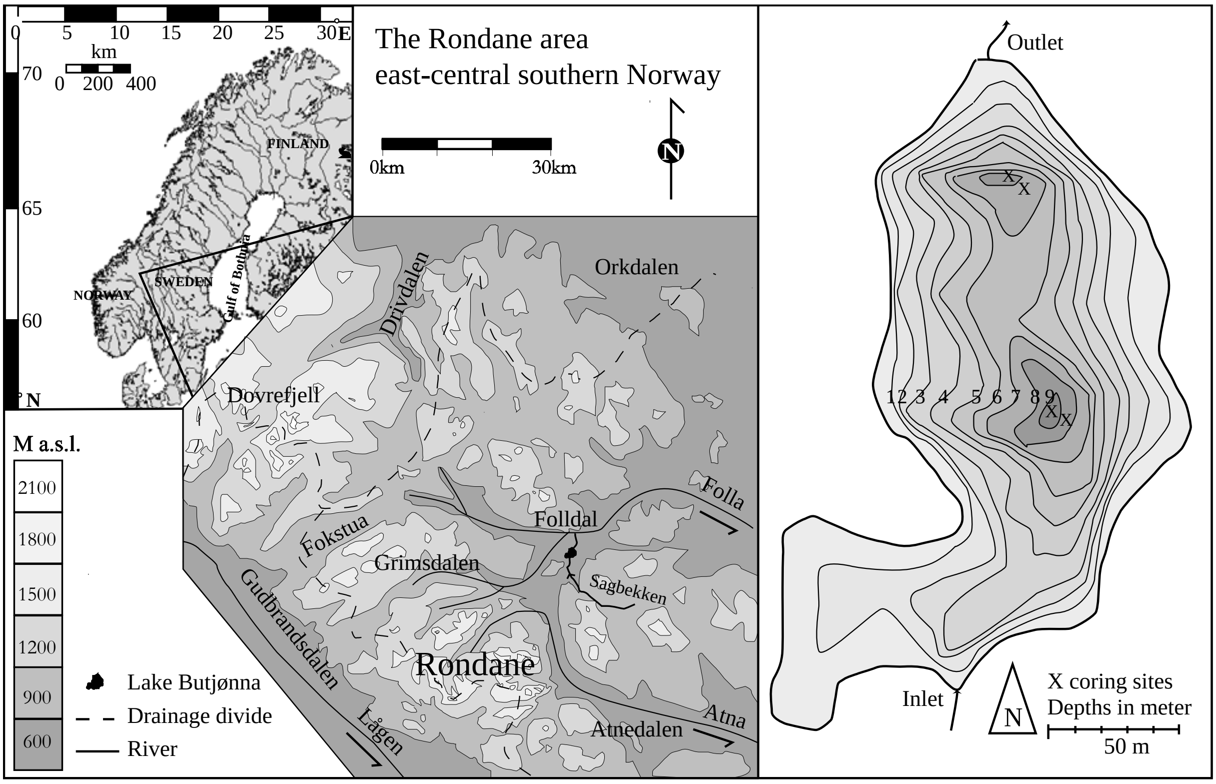

Fig. 1. Location map of lake Butjønna, 667 m a.s.l. 62˚08` N 10˚10` E, in the upper Glomma catchment, east-central southern Norway. Right: The bathymetric map of lake Butjønna with 1 m contour lines. The two deepest troughs were preferred coring sites.

(Gjessing, 1960; Berthling and Sollid, 1999) and receives water and sediments as continuous runoff from the small river Sagbekken, parallel to the larger river Grimsa in the upper Glomma catchment (Figure 1). Delivery of such soil, rock and sandy material has been associated with surface soil erosion during individual flooding events (Thorndycraft et al., 1998; Brown et al., 2000). The existing criteria for detection of Holocene river floods in lake sediments led to the conclusion that deposition of the recognized layers are large Holocene river floods (Bøe et al., in press). The advantage in choosing east-central Norway and lake Butjønna is that this lake only receives sufficiently sediments from greater than 50-year floods, according to calibration to modern discharge measurements and number of floods recorded throughout the Holocene. The sand layers deposited in lake Butjønna are then used as a proxy for spring flooding, with enhanced runoff from more than average winter precipitation as a function of layer thickness. A thin sandy layer from the most recent observed flooding in AD 1995 is found in the disturbed top sediments. There are several proxies useful for reconstruction of temperature (e.g. chironomids, pollen, tree rings, ice cores), but flooding and glacier variations are among the few natural processes vulnerable to precipitation changes. Few flood records are in addition easily correlated to known precipitation patterns, which makes these spring floods in eastern Norway worth studying. A Holocene flood record of 114 dated flood units (palaeofloods) is presented from coring of this natural sediment trap.

A bathymetric survey was carried out with an echo sounder to reveal the deepest areas to obtain as long records as possible (Figure 1). Four cores from the two throughs were retrieved (c. 9-10 m water depth) with a manually equipped raft with a piston corer with diameter 110mm (Nesje, 1992), holding 5.1-5.3 m of sediment.

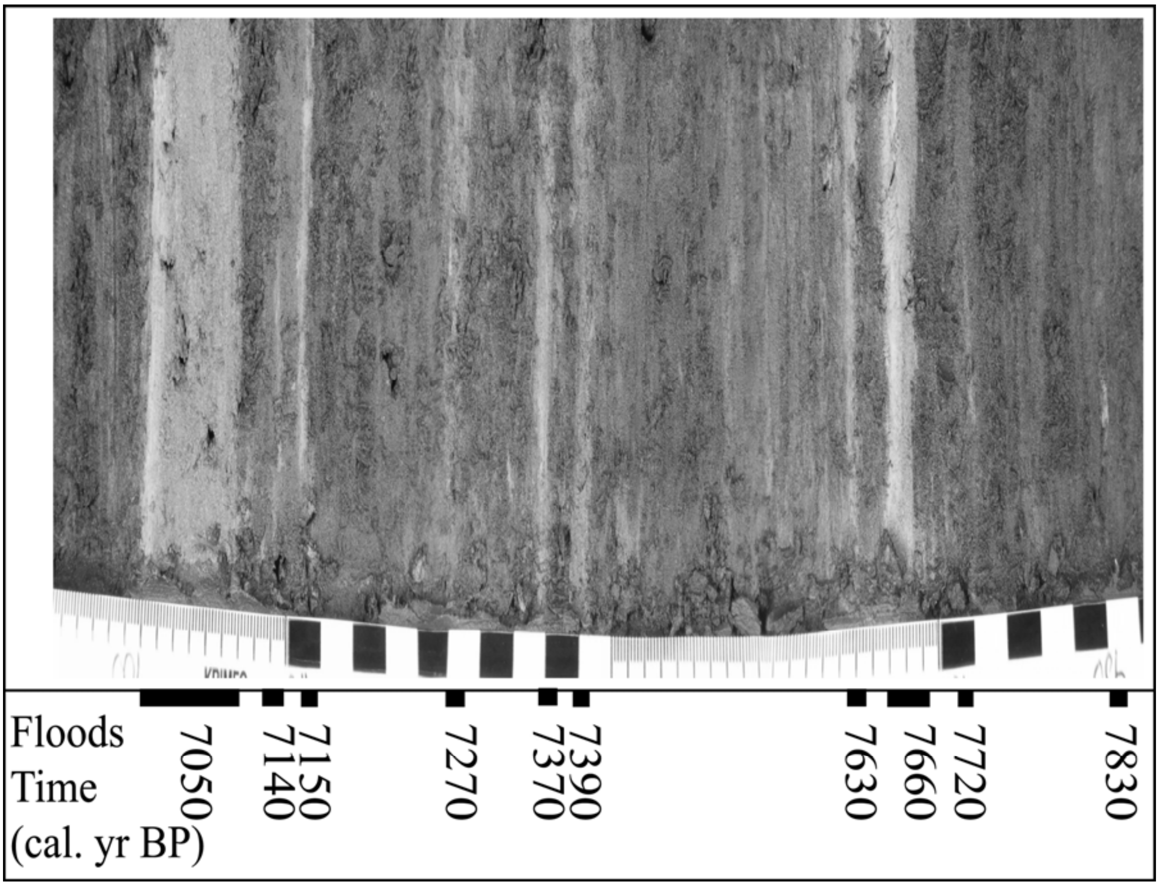

Fig. 2. Photography of section of core showing succession of light minerogenic (flood layers) and dark organic horizons. Ages are given for the flood layers present in this interval from 5880 - 5100 BC.

A lateral consistency in the sediments is found within the four cores. Ahead of and after opened in half lengthwise, the cores have been stored at +4^{o}C.

A variety of analytical techniques were used to investigate the sediments, particularly the sandy layers punctuating the otherwise organic-rich sediments. After visual logging and photographs, each core was analyzed for magnetic susceptibility, organic content, wet and dry bulk density, gamma- and X-ray radiograph density. Two cores were dated after extracting and identifying macrofossils for accelerator mass spectrometry ^{14}C-dating. Lithological grain-size analyses were carried out on a Micromeritics Sedigraph 5100 Particle Size Analyses System (Udden, 1914). A total of 12 macrofossil samples were prepared at Poznan Radiocarbon Laboratory in Poland to establish a reliable age-depth control.

2.2. Stratigraphy

These 114 discrete palaeoflood layers are 1 – 620 mm thick, and exhibit sharp, but non-erosional contacts with both underlying and overlying organic material. The flood layers consist of sand, silt and clay and are in most cases fining upwards. Two main lithostratigraphic units (organic and minerogenic, Figure 2) are recognized in all cores. The organic type consists of brown or black coloured organic material. Organic units are believed to be associated with hydrologically stable periods characterized by no or low-magnitude flood activity. Associated accumulation of brown or black coloured organic material comes from both the lake catchment and produced within the lake it self (Bogen, 1983). The flood units are irregularly distributed, representing episodes or periods of higher sedimentation energy.

The ^{14}C dates were calibrated by *Calib (Intcal98)* (Stuiver et al., 1998), and the age-depth model created in Bøe et al. (in press) is applied. This deposition model supports instantaneous layer deposition. The layers do not represent significant time within the chronology, but do represent significant thickness and need to be removed.

Based on layer thickness, the minerogenic layers are divided into eight classes: 37 of 1 mm, 36 of 5 mm, 31 of 10 mm, 5 of 30 mm, 2 of 45 mm, 1 of 55 mm, 1 of 115 mm and 1 of 620 mm. Based on the average of all samples (1-cm contiguous intervals) of minerogenic units, the mean grain-size value increases with sediment layer thickness, and spans from 16.9 to 19.1 μm. The sorting shows an equivalent trend (standard deviation 2.3 - 2.9), and the two values demonstrate a negative correlation, r = -0.7 (Bøe et al., in press). The flood units are accompanied by a high mean grain-size and better sorting, which in turn is associated with increased runoff, higher competence and higher sediment influx.

2.3. Recent historical floods

From historical records and written documentation, the twenty biggest floods, ranged from largest to smallest in the Glomma catchment at Elverum happened in AD 1789, 1995, 1675, 1773, 1717, 1724, 1749, 1850, 1934, 1916, 1827, 1666, 1846, 1967, 1760, 1852, 1887, 1890, 1867 and 1897. Discharge data commenced by the Norwegian Water and Energy Directorate in 1871 confirms that these are spring floods. The only exception is the largest event, “Stor-Ofsen” in 1789, which happened during three weeks of intensive July summer rain on top of delayed snow melt and deep frozen ground. This flood resulted in a sandy layer in lake Butjønna with an altered mineralogical composition, found from magnetic analyses. This extreme mega river flood shows the possible import of particles from a broader source area. Hence, the nearby regional river Grimsa may have interfered with the drainage from the local river Sagbekken with a mixed sediment transport as a probable consequence (Bøe et al., in press). The floods found in lake Butjønna are *mega-floods* rather than just normal floods according to the fact that only the largest damaging floods at Elverum are represented in lake Butjønna’s flood archive.

3. Point process methodology

Figure 3 summarises the 114 flood events in the sediment record that have occurred throughout the Holocene until present (7264 BC to AD 1915). The magnitude is calculated as the logarithm (base 10) of the flood layer thickness. Figure 4 shows in more detail the events that have occurred since AD 1000, a period dominated by the “*Stor-Ofsen*” mega-flood event of AD 1789. Several other large events with magnitude of one or greater have also occurred in the period and will be referred to as *mega-floods*. The threshold for the definition of mega-floods is rather arbitrary. The magnitude of one represents a good compromise for obtaining enough events that are sufficiently intense – there are 70 events in the record having magnitude of one or more, and only 26 events having magnitude of two or more.

Similar to many other palaeoclimatic records, the events have been recorded at irregular dates (*points*) in the past and have randomly varying magnitudes (*marks*). Such series are not amenable to the usual methods of regular time series analysis developed for a sequence of randomly varying values sampled at regular time intervals. However, such records can be considered to be a realisation of a different type of stochastic process known as a *marked point process* – a process with

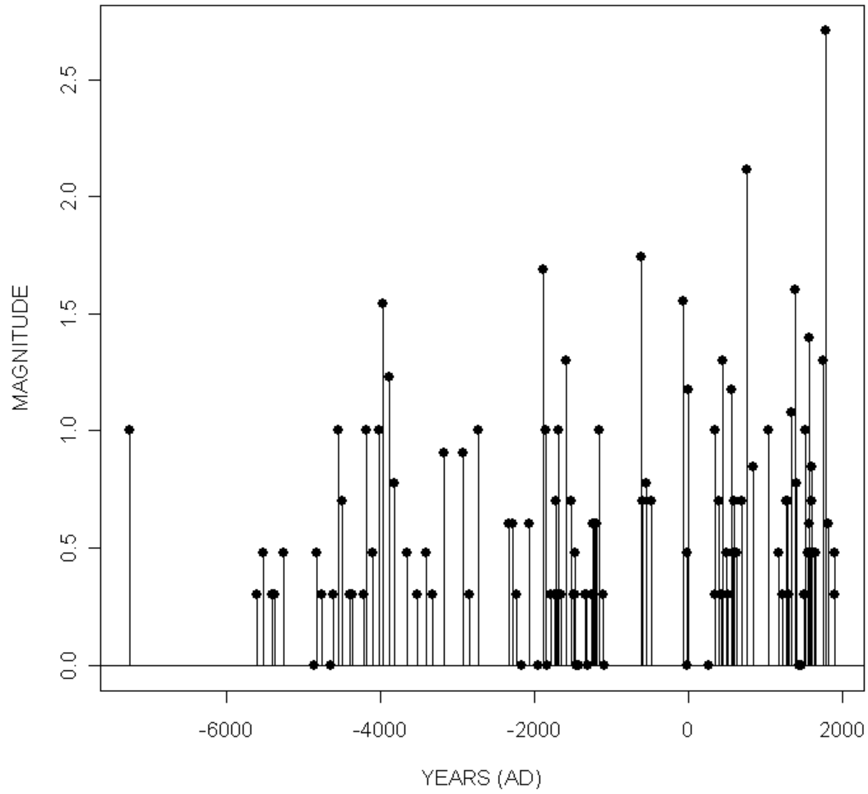

Fig. 3. Time plot of all 114 events showing the age of the events (the points) and the magnitude (log10 of the recorded amplitude) of the events (the marks).

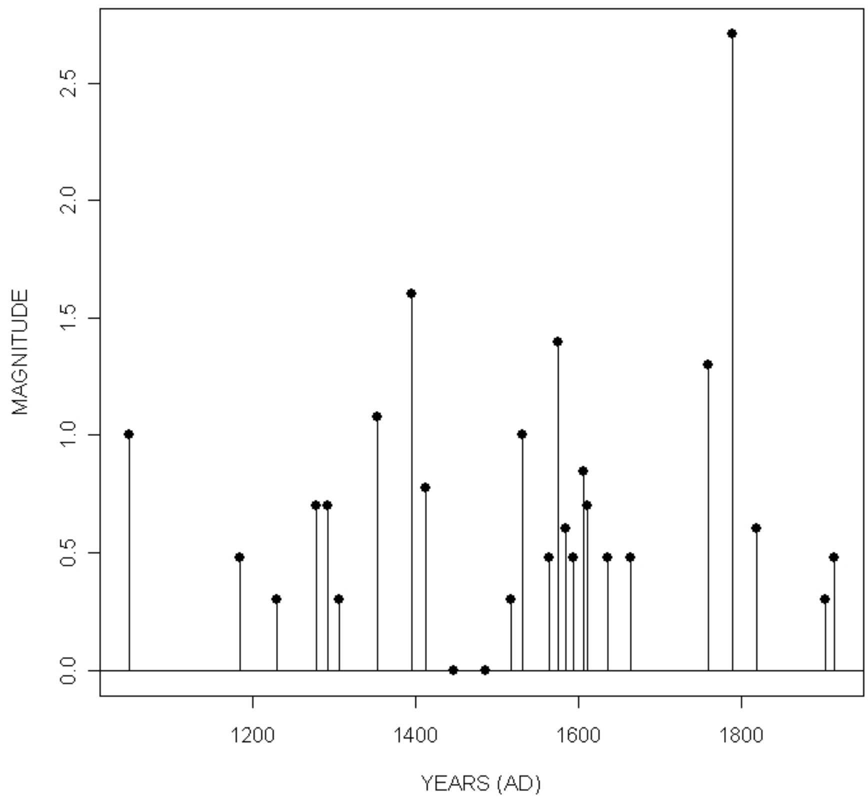

Fig. 4. Time plot of the events that occurred after AD 1000. Note the extreme Storofsen event of AD 1789.

random magnitude that occurs at random points in time (see (Diggle, 1983; Cox and Isham, 2000). Point process methods have been widely used in various areas of science, for example, in providing a framework for earthquake risk assessment and prediction in seismology (Daley and Vere-Jones, 2002). Point process methods can be used to explore and summarise such records and are invaluable for making inference about the underlying process that gave rise to the record. Broadly speaking, this is performed by considering statistical properties of the points such as how many events occur per unit time interval (the *rate/intensity of the process*), statistical properties of the marks (e.g. how the magnitude of the marks has changed over time), and joint properties such as how the marks depend on the position and spacing of the points, the magnitude of preceeding events, etc. Section 3 of this study will illustrate the use of such methods by applying them to the Norwegian flood palaeoclimate series.

4. Results

4.1. Rate of flood events

There are two main types of approach for estimating the rate of a point process: the *counting specification* based on counting the number of points in fixed time intervals, and the *interval specification* based on estimating the mean time interval between successive points (see p.11 of Cox and Isham (2000). The simplest counting specification involves dividing the time axis into a set of non-overlapping equally spaced bins (e.g. a set of 100 year intervals) and then counting the number of points that fall into each bin. This approach gives rather noisy results due to the sharp bin edges. More efficient and smoother rate estimates can be obtained using smooth local weighting based on a smooth kernel function rather than a sharp-edged bin (Diggle, 1985).

Figure 5 shows the rate estimate obtained using the kernel approach described by Diggle (1985). The kernel half-width was chosen subjectively to be 2000 years as this gave a good compromise between resolving features such as the clustering around AD 4000 and 2000 yet still included enough points so as to avoid overly noisy rate estimates. The cross bar in the figure shows the width of the kernel (horizontal line) and the 95% confidence interval on the rate estimate (vertical line) obtained by Monte Carlo simulation by randomly placing 114 points in any year from 7300 BC to AD 1950. There is a trade-off between kernel width and uncertainty in the rate estimate: wider kernels give more accurate rate estimates having smaller confidence intervals because they use information from more points yet they are less able to resolve faster time variations in rate. The most apparent feature in Figure 5 is that the rate has shown an increasing trend over the whole period from close to zero at 7300 BC up to 0.025 events per year (one event every 39.5 years) in AD 1950. A linear fit to the kernel rate estimate gives a rate trend of 1.90%/century. It is possible, but not likely, that the trend in rate is an artefact of how the cores are processed. The lower sandy layers will experience compaction as a function of deposition of new sand and organic material. This makes it hard to detect all flood layers. All variables, however, show a consistent picture of the flood layers from visual inspection, mineral magnetic measurements and X-ray photos. Therefore, it is most likely that this trend is a result of changes in the climate system. The detailed mechanisms are as yet unknown but it is likely due to increasing trends in winter/spring temperature and/or precipitation.

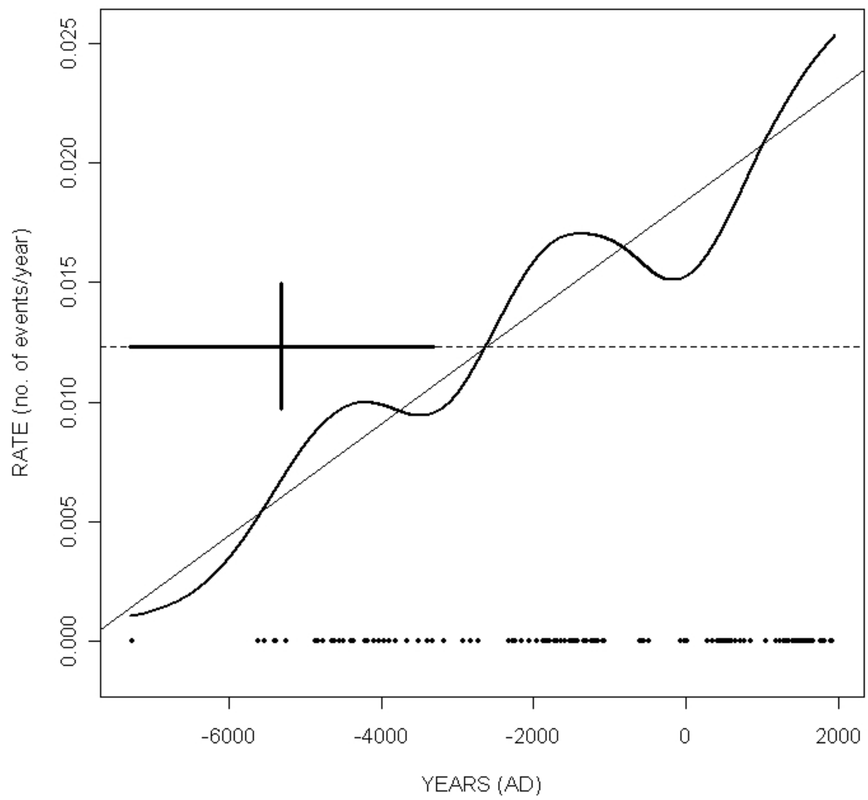

Fig. 5. Kernel estimate (thick line) of the rate of all events together with a least squares linear trend fit to this estimate (thin line). The horizontal cross-bar shows the kernel width (4000 years) and the vertical cross-bar gives the 95% confidence interval expected for a homogeneous point process having the same mean rate. Dots denote the events used to estimate the rate.

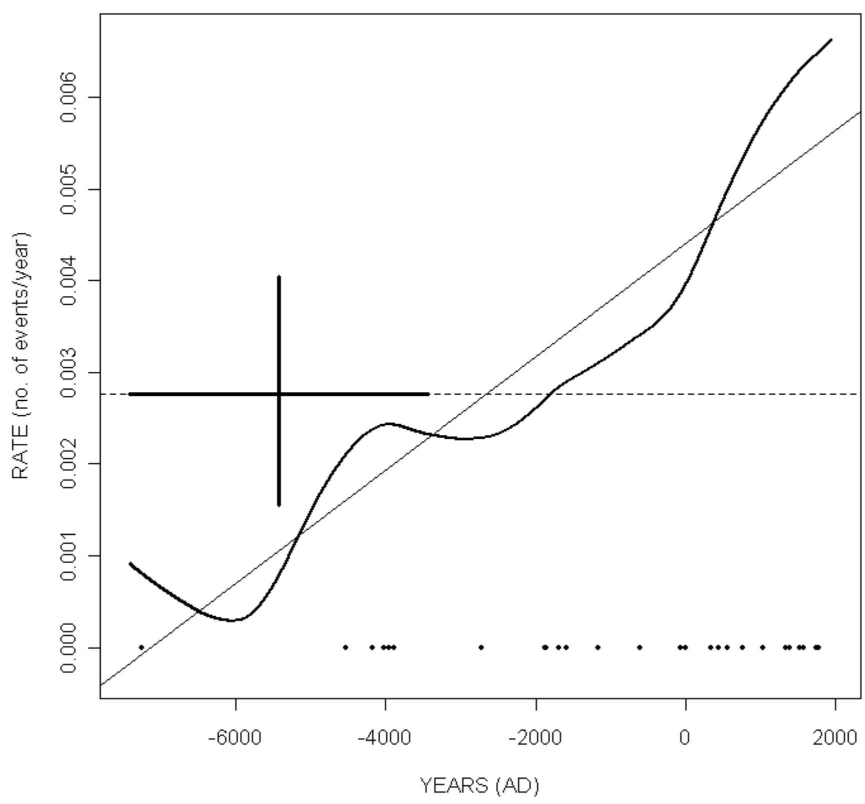

Fig. 6. Same as Figure 5 but for only the mega-flood events having magnitudes greater than or equal to one.

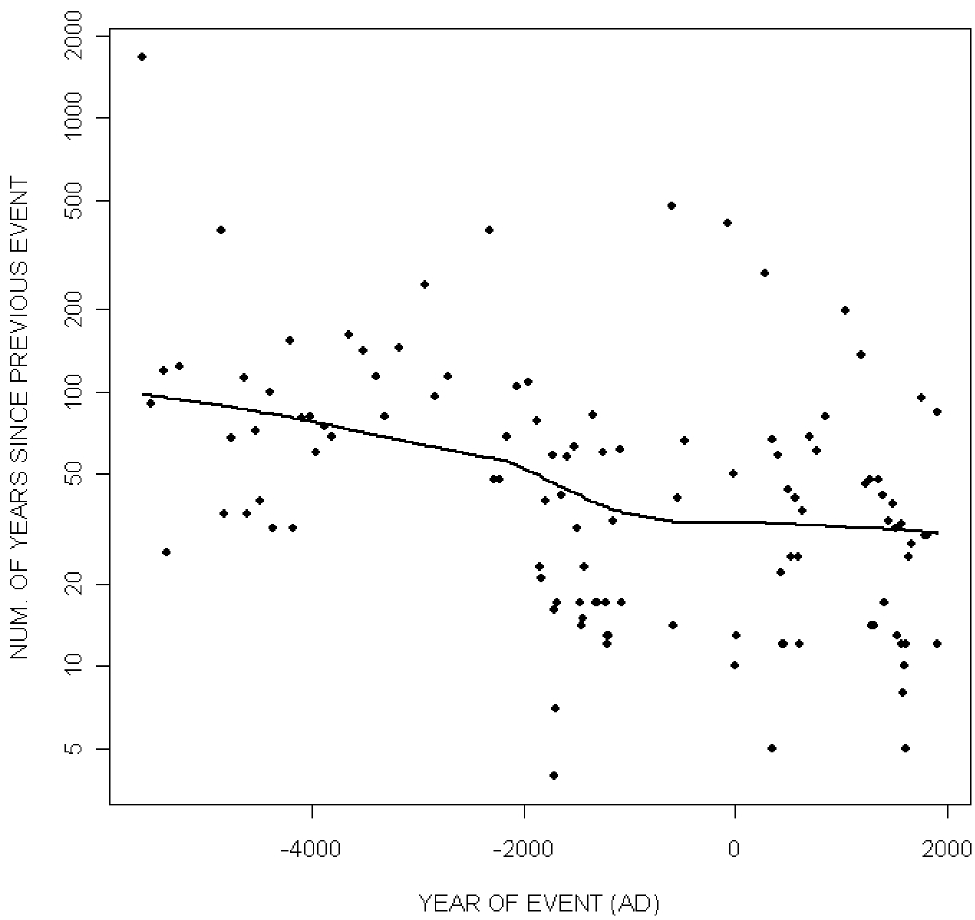

Fig. 7. Time difference between successive events, T(n)-T(n-1), versus the age of the event T(n). Solid line indicates a local robust non-linear trend estimate (lowess fit). Note that the y-axis is on a logarithmic scale.

Figure 6 shows the kernel rate estimate for the mega-floods (i.e. only the events having magnitude greater than or equal to one). The rate for such events is smaller than that for all events but it also shows an increasing trend through the record up to a present day value of 0.0066 events per year (one event every 150.7 years). A linear fit to the rate estimate gives a rate trend of 2.23%/year similar to that found for all events. In other words, despite the recent increase in the number of mega-flood events apparent in Figure 1, the rate of such events has increased at a similar rate to that of all events.

The increasing trend in rate of events leads to a decreasing time interval between successive events. Figure 7 shows the time interval between each event and its preceding event versus the age for all the events. The mean time interval between events has dropped from around 100 years in 7500 BC to around 40 years in recent times.

4.2. Magnitude of flood events

The events in Figure 3 appear more intense in recent times not because the magnitude of the events has increased but because with increased numbers of events, there is more chance of observing ones with extreme magnitudes. The distribution of magnitudes shows no obvious changes in time as can be seen from the box plots in Figure 8 of events before and after 2000 BC. The medians of the magnitudes for events before and after 2000 BC are very similar suggesting no significant

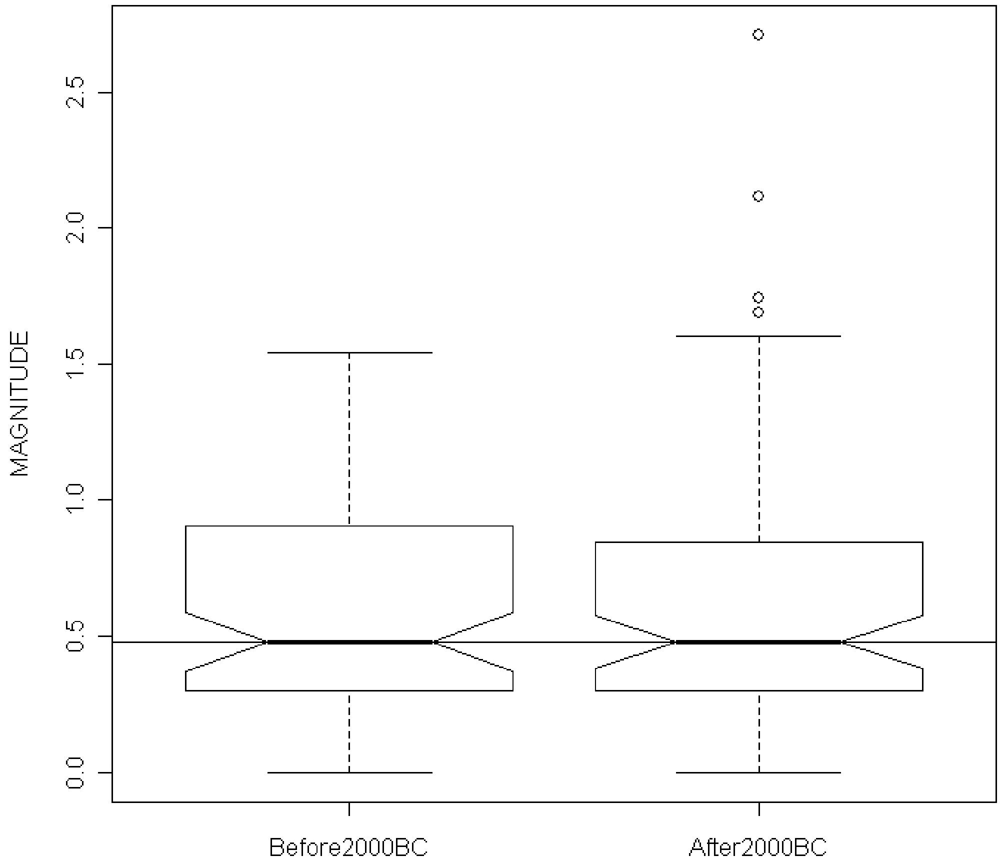

Fig. 8. Box-and-whisker plots (box plots) of the magnitudes for events before 2000 BC (left box) and after 2000 BC (right box). The box denotes the central location of the data by a mid-line at the median value, and the scale (spread) of the data by hinge lines at the lower and upper quartiles – half the sample values lie within the box. The notches on the box extend to $\pm 1.58 IQR / \sqrt{n}$ and give an asymptotic 95% confidence interval for the difference in two medians. The whiskers extend to the most extreme data values not more than 1.5 times the inter-quartile range from the respective hinges. Dots outside the whiskers denote potentially suspicious outlier values. The horizontal reference line denotes the median amplitude of all the data.

increase in the magnitude in more recent times. For example, the relative frequency of mega-flood events with magnitude greater than or equal to one was 7/35=0.20 before 2000 BC, which is well within sampling uncertainty of the relative frequency of 19/79=0.24 obtained for mega-flood events after 2000 BC.

4.3. Clustering of flood events

In addition to the increasing trend in rate (Figure 5), local maxima in rate can be noted at around 4218 BC, 1390 BC, and at the present-day end of the record. These maxima are due to local clusters of events that can be seen in the dot plots in Figure 5.

Clustering of events generated by a point process can arise due to any of the following mechanisms:

1. Chance sampling;
2. Time variations in the underlying rate of the process;
3. Interactions between successive events (*clustered process).*

The variations in rate in Figure 5 are smaller than the 95% confidence interval (the vertical line in the cross bar) from the linear increasing trend, which may have occurred as a result of chance sampling. However, this does not mean that they did arise from chance sampling and it is of interest to explore briefly the other mechanisms.

Mechanism 3 would occur, for example, if one flood event increased the chances of the following event. Alternatively, an extreme flood event may also decrease the chance of (inhibit) future flooding accessibility thereby leading to more regular time intervals between events. This is seen when a large flood erodes and transports available loose material, leaving less material for the next flood event to work on. To explore whether or not the process is truly clustered, one can investigate the auto- and cross-correlation structure of the time intervals between successive events. Figure 9a shows scatter plots of the time interval between successive events, T(n)-T(n-1), versus the preceding time interval, T(n-1)-T(n-2), and versus the magnitude of event n. There is a large amount of scatter in both plots and no strong evidence of association – the product moment correlation (a measure of linear association) is only 0.073 between successive intervals and is 0.005 between the time interval and magnitude. Therefore, there is little evidence of strong clustering occurring between these flood events – they may be considered to be locally independent of one another.

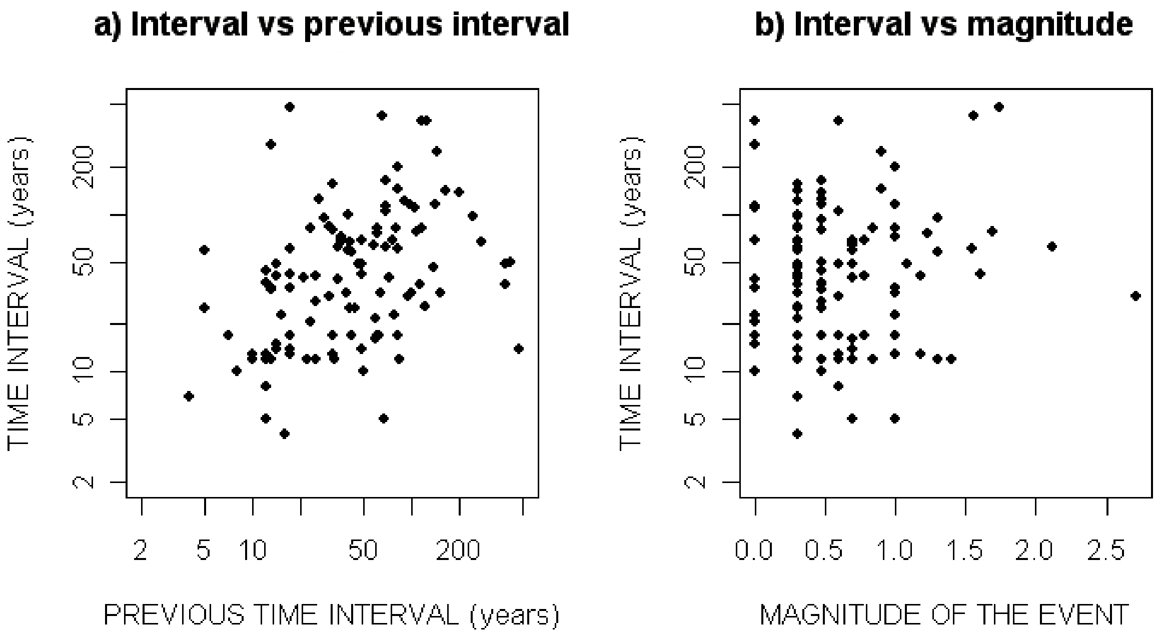

Fig. 9. Scatter plot of the time interval between successive events, T(n)-T(n-1) versus a) the preceding time interval, T(n-1)-T(n-2), and b) the magnitude of event n. Note that intervals are plotted on logarithmic axes.

5. Conclusions

This study has demonstrated how statistical point process methods can be used to infer properties of the underlying processes that lead to events recorded in palaeoclimatic records. The methods have been illustrated using an example of 114 flood events recorded in a sediment core taken from lake Butjønna in east-central southern Norway from the early Holocene until at present (7264 BC to AD 1915). The sample of random ages and magnitudes are treated as a realisation of a marked point process. The rate of all flood events has shown an approximately linear increasing trend over the whole period from close to zero at 7300 BC up to 0.025 events per year (one event every 39.5 years) in AD 1950. A linear fit to the kernel rate estimate gives a rate trend of 1.90%/century. A similar linear rate trend of 2.23%/century was also found to occur for the more extreme floods having magnitude exceeding one (the mega-floods). In contrast to the rate, the distribution of flood magnitudes was not found to show any statistically significant changes before and after 2000 BC. Local maxima in the rate of all events were found at around 4218 BC, 1390 BC, and at the most recent end of the record. However, these local variations in rate could easily be the result of chance clustering of events rather than reflect true variations in the rate of the underlying process. There is, however, no strong evidence for dependency between either rates or magnitudes of successive events.

The stochastic approach demonstrated in this study could be used for the interpretation of many other palaeoclimatic records that consist of a series of discrete events with varying magnitudes recorded at distinct ages. A key idea is to use fundamental point process concepts to infer properties such as rate of the underlying process from the sample of recorded events. Such estimates of the underlying process from multiple records could then be easily compared with one another and with time series from other types of more continuous records (such as ice cores) to help build a more comprehensive model of climate-driven processes in the past.

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