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Annually-resolved lake record of extreme hydro-meteorological events since AD 1347 in NE Iberian Peninsula

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ABSTRACT

We present an annual reconstruction of extreme rainfall events interpreted from detrital layers and turbidites interbedded within a varved sediment record since the 14th century in Montcortés Lake (NE Spain, 1027 m a.s.l.). Clastic microfacies intercalated within the biochemical calcite varves were characterized and their depositional dynamics interpreted using high-resolution geochemical and sedimentological analyses. Annual number of detrital layers was compared against instrumental records of extreme daily rainfalls providing minimum rainfall thresholds and return periods associated to the identified types of clastic microfacies. Non-continuous detrital layers were deposited during rainfall events higher than 80 mm (>2-year return period) while graded detrital layers and turbidites were associated with higher magnitude rainfall events (>90 mm and >4-year return period). The frequency distribution of extreme hydro-meteorological events is not stationary and its pattern coincides with historical floods from the nearby Segre River. High frequency of heavy rainfalls occurred during the periods AD 1347–1400 and AD 1844–1894. A lower frequency of heavy rainfall was found during the periods AD 1441–1508, 1547–1592, 1656–1712, 1765–1822 and 1917–2012. The 20th century stands out as the longest interval within the studied period of very low number of extreme rainfall events. Variability in extreme rainfall events prior to the 20th century is in phase with solar activity, suggesting a mechanistic link in mid-latitude atmospheric circulation patterns that ceased during the 20th century.

1. Introduction

Floods and storms are the most devastating natural disasters in terms of casualties and economic losses due to infrastructures damage (Kundzewicz et al., 2014). In the context of current global warming, there is a high uncertainty on the observed trends and projected changes in heavy rainfall and floods at a global scale (Seneviratne et al., 2012). For example, in Europe, there are regions recording a statistically significant increase in heavy precipitation events during the last decades, e.g. central Europe (Zolina et al., 2008; Kyselý, 2009) while others show significant decreases in winter precipitation extremes – e.g. Mediterranean coastal sites (Toreti et al., 2010), and even within these regions there are strong sub-regional or local variations. Uncertainties are overall larger in southern Europe and the Mediterranean, where confidence in secular trends is low (Hartmann et al., 2013).

Understanding the spatial and temporal scale at which changes on hydrological extremes occur in response to climatic variability is essential to anticipate climate change impacts and to implement adaptation and mitigation measures in relation to natural hazards. Another important issue in climate change science is the detection and attribution of human influence on the heavy precipitation trends and, therefore, in the hydrological cycle (Min et al., 2011). Detection of temporal changes on extreme events requires long-term records to overcome the problems derived from their high inter-annual and inter-decadal rainfall variability, particularly in Mediterranean climates (Machado et al., 2011). Moreover, attribution entails a profound knowledge of the natural variability of the water cycle at fine enough resolution, identifying all potential drivers of hydrological change (Hattermann et al., 2012).

Paleohydrological studies play here an important role as they enable us to investigate the dynamics of extreme events under natural climate variability beyond the instrumental period, as well as to evaluate the main forcings controlling the hydrological cycle. Numerous studies have been carried out during the last decades to quantify the magnitude and recurrence periods of extreme rainfall

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events and subsequent flooding episodes, e.g. (Knox, 1985; Noren et al., 2002; Czymzik et al., 2013). Among natural archives, fluvial and lake records are most adequate to carry out reconstructions of hydrological extremes. Palaeoflood studies in bedrock rivers are typically based on stratigraphic descriptions of slack-water flood sediments deposited during high flood stage at high elevation zones from which robust discharge estimates can be obtained based on hydraulic modeling (Baker, 2008; Benito and ÓConnor, 2013). In these fluvial environments, only the largest floods exceeding the elevation of previous flood deposition thresholds are recorded (Thorndycraft et al., 2008).

Lake sediments have proven to be a valuable archive of recurrence rates and intensities of past floods as they constitute the natural sink for sediments transported by rainfall-induced run-off (Czymzik et al., 2013; Gilli et al., 2013). The advantage of lake sequences for palaeoflood reconstructions is their high preservation potential and their capability to record a wider range of runoff events from medium to high magnitude flows. During the last decade, numerous records in European lakes have improved our knowledge of the hydrological fluctuations during the Late Holocene (Gilli et al., 2003; Moreno et al., 2008; Bussmann and Anselmetti, 2010; Debret et al., 2010; Giguet-Covex et al., 2012; Swierczynski et al., 2012; Wilhelm et al., 2012; Czymzik et al., 2013; Swierczynski et al., 2013; Vanniere et al., 2013). Among them, flood deposits intercalated in varve sequences provide the most accurate chronologies, with annual to seasonal resolution (Czymzik et al., 2010; Swierczynski et al., 2012; Czymzik et al., 2013; Swierczynski et al., 2013; Vanniere et al., 2013). Recent studies in European varve sequences have linked Late Holocene variations in solar irradiation with North Atlantic atmospheric circulation shifts, e.g. (Martin-Puertas et al., 2012), and with frequency of heavy summer rainfall leading to higher flooding frequency during solar minima in the Alps (Czymzik et al., 2013; Wirth et al., 2013a). So far, varve sediment-based flood reconstructions are restricted to the alpine region and not available, for example, for the Mediterranean area. Lake Montcortès is an exceptional site to reconstruct past flood events as the sedimentary record preserves different types of flood-related detrital layers with annual to seasonal resolution over the last 3500 years (Corella et al., 2011). Sedimentological analyses in two well-preserved gravity cores have been performed to achieve the following objectives: i) to interpret the depositional dynamics of the different detrital micro-facies; ii) to evaluate the sensitivity of the record to rainfall variability by comparison with instrumental time series; iii) to carry out an annually-resolved palaeohydrological reconstruction of extreme rainfall since the 14th century and; iv) to compare the lake record with other sources of information such as historical floods reported from documentary archives in the nearby rivers, leading to an improved and comprehensive view on the hydrological variability in the NE Iberian Peninsula during the last millennia.

2. Study site

Lake Montcortès is located in the southern Central Pyrenees, in Catalonia region (NE Spain) (42°19.50′N, 0°59.41′E, 1027 m a.s.l.). The watershed (1.39 km^2 surface area) is emplaced between *Les Nogueres* and the *South Pyrenean* structural units, composed by Mesozoic and Tertiary sedimentary units tectonically thrusted southwards. The watershed lies on Oligocene conglomerates (36% of the total catchment area) and siliciclastic, carbonate and evaporitic Mesozoic rocks (Keuper and Muschelkalk facies, 24% of the total area), with some hypovolcanic ophite bodies also present in the southern areas of the watershed (8%). Quaternary sediments outcrop around the lakeshore (7%) (Fig. 1). The origin of the lake is attributed to interstratal dissolution and collapse of Keuper evaporites (Corella et al., 2012). The land use in the watershed mainly consist on cereal crops, meadows and pastures in the lowlands (60% of the total area) and deciduous and conifer forests in elevated areas (30%) (Fig. 1). Hygrophytic communities colonize the lakeshore. Lake Montcortès basin is almost circular, with a surface area of 0.14 km^2 (10% of the catchment area, Fig. 1) and very steep margins, with a maximum water depth of 30 m. There are two ephemeral streams that drain the southern area of the watershed providing water and sediments to the lake mainly during extreme rainfall events (Fig. 1). The maximum lake level is controlled by an outlet stream in the northern shore. No quantitative water balance is available for the lake, but groundwater is a significant input. The lake's water column has permanent annual stratification that allows the preservations of biogenic varves (Corella et al., 2012). The coldest and warmest months have average temperatures of 1.9 °C (January) and 20.3 °C (July). Mean annual rainfall in the area is 860 mm. Heavy rainfall (>100 mm) in the region occurs mainly in autumn (50%) and winter (22.1%) (Martin-Vide et al., 2008). Autumn and spring heavy rainfall events are associated with mesoscale convective systems fed by Mediterranean moisture and enhanced by the orography of the eastern pre-Pyrenean Mountains (Llasat and Puigcerver, 1994). Rainfall is also influenced, although on a lesser extent, by frontal Atlantic systems generating persistent rainfall during the autumn and winter months. Indeed, in this area the highest magnitude precipitation events are related to negative phases of North Atlantic Oscillation (NAO) (Vicente-Serrano et al., 2009).

3. Materials and methods

3.1. Sediment coring

Previous studies (Corella et al., 2011) have shown the occurrence of mass wasting deposits and gravitational slides in the distal areas of Montcortés Lake that could compromise the recovery of undisturbed sediment sequences at some locations. Therefore, several seismic profiles were acquired with a high-resolution, single channel Edge-Tech sub-bottom profiling systems to determine optimal core location for undisturbed sediments. Two UWITEC gravity cores (MON12-3A-1G, 78 cm length, and MON12-2A-1G, 106 cm length) were retrieved using the coring equipment from the Pyrenean Institute of Ecology (IPE-CSIC) at the deepest area (~30 m depth) of the lake, where the seismic profiles displayed parallel reflections indicating undisturbed sediments. Distance between coring sites is 30 m. Hammering was avoided during coring operations at site MON12-3A-1G to minimize sediment disturbance, but it was necessary to retrieve the longer core MON12-2A-1G. A composite sedimentary sequence 104-cm long was obtained by detailed varve correlation between both cores. The sediment cores were carefully transported to the lakeshore and stored there for 5 days to favor sediment consolidation before transport to the IPE cold-room.

3.2. Laboratory analyses

The sediment cores were split lengthwise. X-ray fluorescence element scanning was analyzed at the University of Barcelona using an AVAATECH XRF core scanner (2000 A, 10–30 kV and 20–50 s measuring time) every 0.2 mm. The resulting intensities for major elements – potassium (K), calcium (Ca) and zirconium (Zr) – are given as counts per second (cps), providing semiquantitative information of the elemental composition of the sediments. Core images were obtained by using the high resolution AVAATECH core scanner coupled camera. The upper 43 cm of the sedimentary