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Holocene flooding and climate change in the Mediterranean

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A B S T R A C T

Mediterranean fluvial hydrology is characterised by decadal-to-multi-centennial length wet and dry episodes with abrupt transitions related to changes in atmospheric circulation. Since the mid-1990s site-based flood chronologies from slackwater deposits in bedrock rivers and regionally aggregated flood histories from alluvial deposits have developed increasingly higher resolution chronological frameworks, although regional coverage is still uneven. This paper analyses the spatial and temporal distribution of extreme Holocene hydrological events recorded in fluvial stratigraphy in the Iberian Peninsula (Spain and Portugal), southern France, southern Italy, Northern Africa (Morocco and Tunisia) and eastern Mediterranean (Greece, Crete, Turkey, Cyprus and Israel). This study constitutes the most comprehensive investigation of Holocene river flooding ever undertaken in the Mediterranean and is based on the analysis of 515 ^{14}C and 53 OSL dates. It reveals that flood periods in different regions cluster into distinct time intervals, although region-wide flooding episodes can be identified at 7400–7150, 4800–4600, 4100–3700, 3300–3200, 2850–2750, 2300–2100, 1700–1600, 1500–1400, 950–800, ca. 300, 200–100 cal. BP. Periods with more frequent floods in the western Iberian region coincide with transitions to cool and wetter conditions and persistent negative NAO mode. In Northern Africa increased flood frequency coincides with periods of generally drier climate, while in the eastern Mediterranean there is a higher incidence of extreme flood events under wetter conditions. Our meta-data analysis identifies an out-of-phase pattern of extreme events across the Mediterranean over multi-centennial timescales, which is particularly evident between the western Iberian and eastern Mediterranean regions. This centennial-to-multi-centennial see-saw pattern in flooding indicates that bipolar hydroclimatic conditions existed in the Mediterranean during the Holocene.

1. Introduction

Mediterranean river hydrology is strongly influenced by the seasonal distribution of the precipitation (Thornes et al., 2009). River flow regime in the region is characterised by maximum discharge during the autumn and winter months, minimum discharge in summer, as well as by extreme seasonal and annual discharge variability with peak discharges frequently more than 50 times average flows (Pardé, 1950). Past hydrological records from instrumental, documentary and fluvial sedimentary archive sources also show significant hydroclimatic variability with multi-decadal to multi-centennial length alternation of wet and dry episodes with abrupt transitions related to changes in atmospheric circulation (Benito, 2003; Fletcher and Zielhofer, 2013; Macklin and Woodward, 2009; Macklin et al., 1995; Zielhofer et al., 2010). As a result, extreme hydrological events are an inherent component of past and present Mediterranean hydrology whose controlling climatic mechanisms are difficult to predict and model.

Societal response to this high hydrological variability on water resources in the region is reflected in the early construction of reservoirs and irrigation schemes beginning in Roman times that became ubiquitous during the Middle Ages, although construction of large scale arch dams did not occur until the late 18th century (Butzer et al., 1983, 1985). Written records of hydrological events, mostly related to the impacts of severe floods and droughts, started as early as the 13th century (Barriendos Vallve and Martín-Vide, 1998; Brázdil et al., 2012). Centennial to millennial-length records have also been retrieved from sedimentary records which can be combined with historical documentary evidence (e.g. Benito et al., 2010). Both, sedimentary and documentary archives record an alternation of flood-rich and flood-poor periods over the Holocene (Macklin and Woodward, 2009; Thorndycraft and Benito, 2006b). Hence, a pan-Mediterranean analysis of the timing of those periods may provide further information concerning the driving mechanisms (climate and/or environmental changes related to human impact) enhancing or reducing the occurrence of extreme events.

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Extensive use of radiometric dating in the study of Holocene fluvial archives has much improved the records of extreme hydrological events worldwide, and presents the opportunity to compare the occurrence of extreme hydrological events at regional and inter-regional scales (Macklin et al., 2006; Macklin et al., 2012). An extreme hydrological event is here defined, following Gregory et al. (2006), as any past process or phenomenon related to the hydrological cycle (e.g. rainfall, runoff, snowmelt, flood, water recharge) with a magnitude significantly higher or lower than the mean and very often associated with crossing a geomorphic threshold. A hydrological event may relate to periods ranging from minutes to months (e.g. floods), or up to several years in the case of droughts. Clustering of extreme hydrological events has been related to climate variability (Ely, 1997; Knox, 2000; Redmond et al., 2002; Rumsby and Macklin, 1994), although land use changes have affected runoff generation at the catchment scale, particularly during the Middle Ages and the 19th Century (Benito et al., 2010; Greenbaum et al., 2006).

Recent fluvial research in the Mediterranean has focused on trying to extend flood series primarily as a means of identifying changes in the frequency and magnitude of floods and relating these to atmospheric circulation patterns modulated by climate variability (Fletcher and Zielhofer, 2013; Luterbacher et al., 2012; Macklin et al., 2006, 2010; Thorndycraft and Benito, 2006a). Both site-based flood chronologies (Benito et al., 2003a; Benvenuti et al., 2006; Greenbaum et al., 2006) and regionally aggregated flood histories (Arnaud-Fassetta et al., 2010; Zielhofer and Faust, 2008) have developed increasingly higher resolution chronological frameworks based on meta-analysis of large radiocarbon-dated fluvial databases. Following the approach developed by Macklin and Lewin (2003), systematic and probability-based analysis of radiocarbon dated fluvial units from a growing number of Mediterranean regions has recently been undertaken, facilitated through the analysis of different sub-sets of radiocarbon dates classified by depositional environment and catchment physiography (Benito et al., 2008; Macklin et al., 2006; Thorndycraft and Benito, 2006a,b; Zielhofer and Faust, 2008). This paper aims to evaluate large databases of ^{14}C- and OSL-dated Holocene fluvial units in different regions across the Mediterranean in order to identify past extreme hydrological events, their temporal and geographical distribution, and possible relationships with climate variability and land-use change.

2. Hydroclimatology of the Mediterranean region

The Mediterranean region lies between 30–47°N and 10°W and 35°E (Fig. 1), and is a zone of transition between the continental influences of Europe, Asia, and the north-African desert, and the maritime effects of the Atlantic Ocean and Mediterranean Sea (Harding et al., 2009). The seasonal and interannual climate of the northern and western parts of the region is linked to the mid-latitude atmospheric patterns characterised by the NAO (North Atlantic Oscillation) and other mid-latitude teleconnection patterns such as the Arctic Oscillation (Lionello and Galati, 2008; Xoplaki et al., 2004). The southeast Mediterranean region is under the subtropical influence of the descending branch of the Hadley cell for a large part of the year and is exposed to the Asian monsoon in summer and to the western Russian/Siberian High Pressure System in winter (Corte-Real et al., 1995; Lionello et al., 2006; Xoplaki et al., 2004). The climate of the Mediterranean exhibits strong contrasts between different areas due to its complex orography and its location within the boundary between subtropical and mid-latitude atmospheric patterns (Lionello et al., 2006; Trigo et al., 2006). Temperature and precipitation contrasts are significant, with permanent glaciers in the

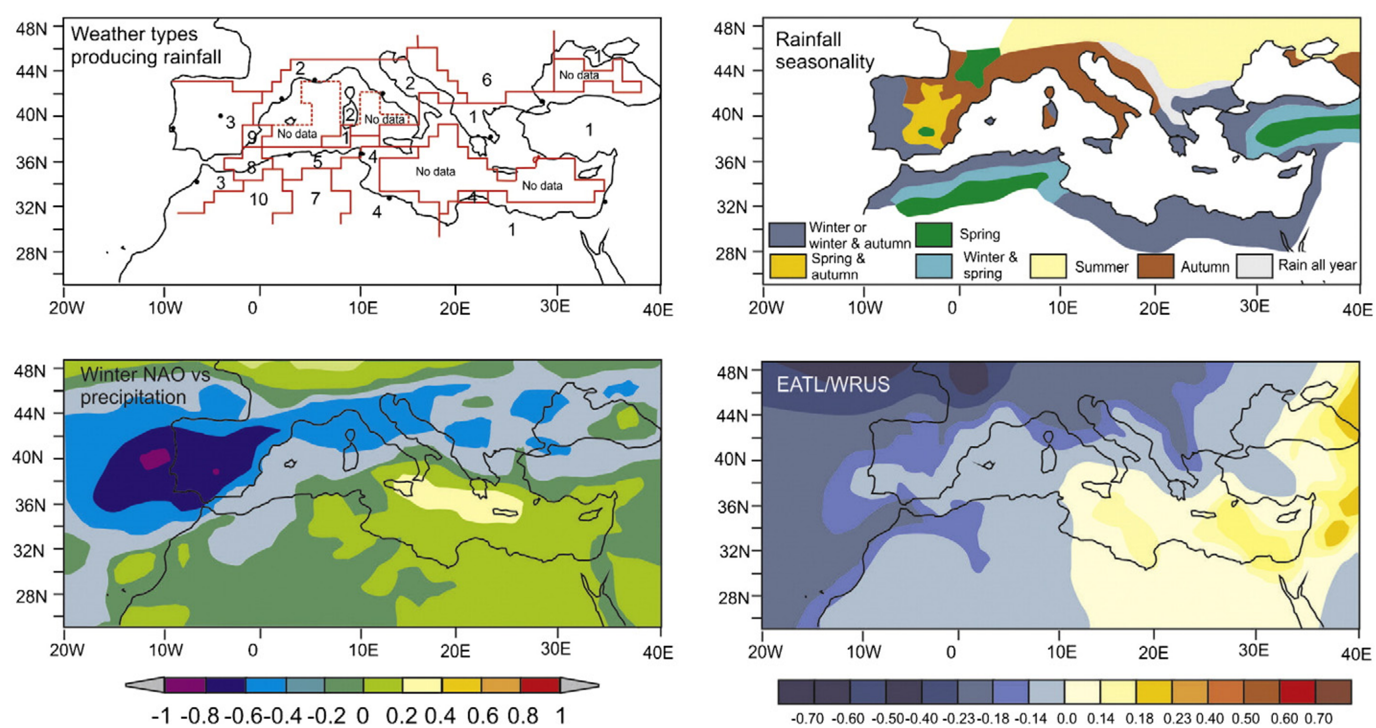

Fig. 1. A: Mediterranean rainfall regions based on PCA analysis of weather types from daily occurrences of surface pressure centres at 500 hPa (1992–1996) (Littmann, 2000). Numbers explained below. B: Rainfall regimes in the Mediterranean with indication of seasonal rainfall maxima (after Thornes et al., 2009). C: Correlation between NAO index and Mediterranean precipitation in the cold season (December-February), derived from the CRU NAO index and the NCEP reanalysis (Zorita et al., 2004). C: Spatial Spearman correlation between the East Atlantic/Western Russia patterns (EA/WRUS; Xoplaki et al., 2004) and winter (NDJF) Mediterranean precipitation for the period 1950–1999 (Xoplaki, 2002). Legend for weather types (A): 1. November (max rainfall) to March. Linked to deflection of cyclonic tracks and Tyrrhenian cut-off flow towards Greece and Cyprus after the establishment of Siberian Anticyclone. 2. September (maximum rainfall) until April with summer rainfall. Atlantic frontal systems explains 54% of rainfall from September to November. 3.- October to January related to Atlantic frontal systems. Second rainfall maximum in May. 4. Drier than 3 with maximum rainfall occurring in October, December and February. 5. Rainfall pattern similar to 2 but rainy season is shorter. 6. Rainfall in all seasons but high amounts in winter (November, December) and summer (May, June). 7. Short rainy season with rainfall above average in March and September. 8. Moulouya basin. Rainfall from November to March and Maxima in February and March. 9. Rainfall pattern similar to 2, but with a shorter season. 10. Rainfall pattern similar to 2 but rainy season is shorter.