Climate change and ecosystems dynamics over the last 6000 years in the Middle Atlas, Morocco

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Abstract

The present study aims at reconstructing past climate changes and their environmental impacts on plant ecosystems during the last 6000 years in the Middle Atlas, Morocco. Mean January temperature (Tjan), annual precipitation (*P*ann), winter (Pw) and summer (Ps) precipitation and a seasonal index (SI) have all been quantified from a fossil pollen record. Several bio and geo-chemical elements have also been analyzed to evaluate the links between past climate, landscape and ecosystem changes.

Over the last 6000 years, climate has changed within a low temperature and precipitation range with a trend of aridity and warming towards the present. Tjan has varied within a ca. 2°C range and *P*ann within less than 100 $\mathrm{mmyr^{-1}}$. The long-term changes reconstructed in our record between 6ka cal BP and today are consistent with the aridity trend observed in the Mediterranean basin. Despite the overall limited range of climate fluctuation, we observe major changes in the ecosystem composition, the carbon isotopic contents of organic matter (δ^{13}C), the total organic carbon and nitrogen amount, and the carbon to nitrogen ratio (C/N) after ca. 3750 cal BP. The main ecosystem changes correspond to a noticeable transition in the conifer forest between the Atlas cedar, which expanded after 3750 cal BP, and the pine forest. These vegetation changes impacted the sedimentation type and its composition in the lake.

Between 5500 and 5000 cal BP, we observe an abrupt change in all proxies which is coherent with a decrease in Tjan without a significant change in the overall amount of precipitation.

1 **Introduction**

The amplitude of climate change during the Holocene (11,700 cal BP to the present) is known to be globally less extreme than during the post-glacial period (Bianchi and McCave, 1999; Bond et al., 2001; Debret et al., 2007). However, several studies have shown that there were climate fluctuations (Alley et al., 1997; Wanner et al., 2008) related to the internal variability of the climate system, solar activity, albedo (Ruddiman, 2003; Eddy, 1982; Stuiver *et al*., 1991), volcanic eruptions (Kelly ~~&~~ and Sear, 1984; Sear et al., 1987; Bryson, 1989; Mann et al., 2005), ocean circulation (Manabe ~~&~~ and Stouffer, 1988; Dansgaard et al., 1989; Lascaratos et al., 1999; Rohling et al., 2002), etc. which all have a direct impact on the terrestrial ecosystems (Davis, 1963; Emmanuel *et al*., 1985). Although climate changes were less pronounced during the Holocene (Andersen et al., 2004; Mayewski et al., 2004; Witt and Schumann, 2005; Frigola et al., 2007; Cheddadi ~~&~~ and Bar-Hen, 2009) than during the last post-glacial period, they have still been noticeable enough to be recorded by different proxies (Dorale et al., 1992; Williams et al., 2002; Geiss et al., 2003, 2004). At the global scale, the Holocene climate stability allowed a sustainable vegetation dynamics with long-term ecosystems changes, plant species expansions and migrations, and an increase of species diversity over all latitudes (Rohde, 1992). However, the Holocene period has also recorded some abrupt and cold events such as the one at 8.2 ka cal BP (e.g. Alley and Agustsdottir, 2005) which recorded a depletion of about 4°C in winter temperature in the Eastern Mediterranean (Weninger et al., 2009).

In Morocco, climate changes during the Holocene have also been quantified and they show significant fluctuations (Cheddadi et al., 1998). As a matter of fact, the climate variability of the Holocene is less known than that of the post-glacial (Mayewski et al., 2004) because it has a lower amplitude and is less abrupt. This statement is even more acute in the Mediterranean region where high resolution and chronologically well-constrained Holocene records are much less numerous than in Europe or North America. The Mediterranean area is currently a hotspot of biodiversity (Myers et al., 2000) and it is one of the largest regions in the world that undergo long-lasting and pronounced droughts during the summer season (Roberts et al., 2004; Milano et al., 2013). The southern rim of the Mediterranean region is even more arid than the northern one because of the influence of the Azores high and the Saharan winds which increase the impact of the drought effect during the summer season. Most of the winter precipitation (Pw) originates from the trade winds which carry moisture from the Mediterranean Sea (Martin, 1981). The amount of Pw has a strong impact on the persistence of water bodies and on the lake levels in the Mediterranean area. Strong lake level fluctuations during the Holocene were observed in Lake Van, Turkey (Lemcke and Sturm, 1997), Lago Dell'Accesa and Lago di Mezzano, Italy (Magny et al., 2006), lake Kinneret, (Hazan et al., 2005) and the Dead Sea, Israel (Migowski et al., 2006), lake Siles, Spain (Carrión~~Carrion~~, 2002), and lakes Sidi Ali and Tigalmamine in Morocco (Lamb and Van der kaars, 1995; Märsche-Souli~~e~~é et al., 2008).

The analysis of marine and continental records from the central part of the Mediterranean shows that the lake levels were high between 10,300 and 4500 cal BP due to an enhanced moisture availability during both summer and winter (Magny et al., 2013). After 5000 cal BP, pollen data from southwestern Europe show that drought increased and led to a sustained reduction of the forest cover (Roberts et al., 2001; Jalut et al., 2009; Jiménez-Moreno et al., 2015). These environmental changes show that within the long-term climate trend there were humid-arid episodes that are related to internal forcings of the climate system such as, in the case of these westernmost Mediterranean ecosystems, the centennial changes in the North Atlantic Oscillation modes (Jiménez-Moreno et al., 2015), the enhancement/weakening of the trade winds, or the increase in the coastal upwelling off northwestern Africa (McGregor et al., 2007). Climate reconstructions from marine pollen records suggest that the Mediterranean environments may react with a reduced time lag to rapid climate changes (Fletcher et al., 2010). The response of the western Mediterranean ecosystems has even been synchronous with the North Atlantic variability during the post-glacial period and the Holocene (Combourieu-Nebout ~~Combourieu Nebout~~ et al., 2009). Changes in the pollen assemblages of a marine record from the Alboran Sea also show very synchronous fluctuations between the surrounding land ecosystems changes and the sea surface temperature fluctuations (Fletcher and Sánchez Goñi, 2008; Combourieu-Nebout ~~Combourieu Nebout~~ et al., 2009). Pollen records from the Middle Atlas (Reille, 1976; Lamb and Van der kaars, 1995; Cheddadi et al., 2009; Rhoujjati et al., 2010; Nour el Bait et al., 2014; Tabel et al., 2016) and the Rif mountains (Cheddadi et al., 2016) show that the Holocene climate change had a major impact on the ecosystems composition with a clear succession of different species sensitive to winter frost, strong rainfall seasonality and/or the total amount of annual rainfall throughout the year.

The aim of the present study is to evaluate the impacts of the climate changes on the ecosystems and the landscape of the Middle Atlas during the last six millennia. Our approach is multidisciplinary and based on the analysis of pollen grains, elemental and isotopic geochemistry and grain size from a fossil record collected in Lake Hachlaf, Middle Atlas. Temperature and precipitation variables have been quantified. They show a moderate change which is superimposed by an aridity trend that is combined with an increase in winter temperature over the past 6000 years. We also observed some noticeable ecosystem and landscape changes with one rapid and quite abrupt climate fluctuation between 5500 and 5000 detectable in all the proxies used.

2 **Study area**

The Middle Atlas Mountains, lying in northwestern Morocco, consist of two geological sets called Pleated and Tabular Middle Atlas (Fig. 1a). The latter is formed by a Paleozoic basement covered by a Mesozoic thick layer and Cenozoic and Quaternary volcanic flows (Texier et al., 1985; Herbig, 1988; Harmand and Moukadiri, 1986). The Liasic limestone and dolostone are shaped by karstic mechanisms (Martin, 1981; Baali, 1998; Hinaje and Ait Brahim, 2002; Chillasse and Dakki, 2004). In this geomorphological and structural composition, there exist nowadays about twenty permanent or semi-permanent natural lakes (Chillasse and Dakki, 2004) among which we can find the studied site, Dayet (lake) Hachlaf (33°33’20” N; 5°0’0” W; 1700m a.s.l.). This small water body is located about ten kilometers North-East of Ifrane national park (Fig. 1b). Available meteorological data (HCEFLCD, 2004) at Dayet Hachlaf show an average annual rainfall of ca. 600 mm with Pw and Ps ca. 150 and ca. 70 mm, respectively. The mean January temperature is ca 4 °C with ca. 90 rainy days per year, and ca. 70 frosty days among which ca. 17 with snow precipitation. The surface area and depth of the lake change throughout the year reaching up to respectively 14 ha and 4 m during late spring. The lake is fed by rainwater, snow, surface runoff and groundwater and has no river inflow.

The forest cover around the site (Fig. 1c) is composed of holm oak (*Q. ilex* subsp. *rotundifolia)* which is evergreen and zeen oak (*Q. canariensis*) which is deciduous, and Atlas cedar (*Cedrus atlantica*) with occurrences of *Pinus halepensis*. Nowadays, there are some degraded populations of *Cedrus atlantica* with cultivated lands around the lake. At higher altitude (1700 to 2500 m, Fig. 1c) an herbaceous/shrubby vegetation (*Artemisia herba-alba* and Poaceae) dominates the landscape.

3 Materials and methods

In April 2008, a 2.5m core (33°33’2.49” N, 4°59’41.57” W) was collected using a Russian corer. Each section of the core was then sub-sampled for the analysis of pollen content (30 samples), grain size (39 samples), organic matter (43 samples) and its isotopic composition ($\delta^{13}C_{(org)}$; 46 samples), and total nitrogen and carbonates (43 samples).

Pollen grains were extracted using a standard laboratory procedure: HCl (20 %), KOH (10 %), $ZnCl_2$, acetolysis (CH_3CO_2O and H_2SO_4), KOH (10 %), ethanol and glycerine. The identification and counting of pollen grains were performed with an optical microscope (Leica

DM750) using a ×40 magnification (×63 for accurate identifications). The pollen percentages were calculated on the total sum of pollen grains originating from vascular terrestrial plants. The total pollen grains counted varies between ca. 200 and 1300. Aquatic plants percentages (including Cyperaceae and Juncaceae) were excluded from the total pollen sum. Cyperaceae were considered as aquatic plants since there are *Juncus* and *Cyperus* genera growing around the lake today.

The particle size analysis was carried out at the "*Laboratoire Marocain d'Agriculture* (LABOMAG)" and was only performed on the sediment fraction < 2 mm. The proportions of five fractions were identified as follows: coarse sand (2000–200 μm), fine sand (200–50 μm), coarse silt (50–20 μm), fine silt (20–2 μm) and clay (below 2 μm).

Organic matter amount (OM) was estimated based on the content of the organic carbon in lacustrine sediments (OC), elaborated by spectrometry (NF ISO 14235). Sediment OC was oxidized in a sulfochromic environment with an excess of potassium dichromate at 135 °C. Subsequently, the determination of chromate ions Cr^{3+} formed was analysed by spectrometry.

For total nitrogen (TN), the method used was based on the Kjeldahl mineralization (ISO 11464: 1994), but the catalyst used was the titanium dioxide (TiO_2). The technique consists in assaying the total nitrogen content in the sediment as ammonium, nitrate, nitrite and organic form.

Carbonates were measured by adding HCl to the bulk sediment to decompose all carbonates (NF ISO 10693: Juin, 1995). The volume of the carbonic gas produced was measured using a Scheibler apparatus.

Stable isotope ratios measurements of carbon were performed on a Thermo Fischer Flash 2000 Elemental Analyzer in line with a VG Isoprime Mass Spectrometer at the University of Bordeaux. All samples were pretreated with 1N HCl to remove inorganic carbon. The analytical precision of 0.15‰ was estimated from several calibrated laboratory standards analyzed along the samples. Stable isotopic ratios were reported as: $\delta^{13}C = [(^{13}C/^{12}C_{sample} / ^{13}C/^{12}C_{std}) - 1] * 1{,}000$, where the standard used is Vienna Pee Dee Belemnita (PDB)

Besides the multi-proxy analysis, four organic samples were dated. All this dates have been done on bulk sediment. We used the BACON software (Blaauw and Christen, 2011) to compute the age/depth model (Fig. 2). The default ^{14}C calibration curve used by BACON for terrestrial northern hemisphere samples is IntCal13. The AMS ^{14}C dates were also calibrated using the "CALIB 7.1" program (Stuiver and Reimer, 1986; table 1). The fossil record continuously encompassed the last 6000 years.

Annual precipitation (*P*ann), mean January temperature (Tjan) and precipitation seasonal index (SI) assessment (Fig. 3) were based on pollen data as follows:

$$PSI_{(s)} = (\sum P_w - \sum P_s)/\sqrt{P_{ann}}$$

Where PSI(s) is the seasonal index quantified for sample s; Pw is the sum of December, January and February precipitation; Ps is the sum of June, July and August precipitation; Pann is the total annual precipitation.

The monthly mean precipitation and Tjan were obtained using the probability density function of modern plant species (pdf-method). This method is described in Chevalier et al. (2014). In order to apply it to a fossil pollen record collected in the Mediterranean area it required a modern database of Mediterranean plant species distributions and their corresponding modern climate variables. We used a database of plant species that have been georeferenced from *Flora Europaea* (Jalas et al. 1972, 1973, 1976, 1979, 1980, 1983, 1986, 1989, 1991, 1994) and Hulten and Fries (1986). Additional geographical distributions were obtained from GBIF (2012) and personal field observations using GPS in Morocco. In order to use plant species distributions for the pollen-based climate reconstruction we assigned pollen taxa to the most probable plant species in our plant database (table 2). The modern climate variables were extracted from the WORLDCLIM database (Hijmans et al., 2005) and interpolated onto the species occurrences for inferring their pdfs.

4 **Results**

During the last 6000 years, the main change in the forest cover is marked by a decline of the pine populations, the expansion of Atlas cedars after 3750 cal BP and the persistence of the evergreen oaks. Although the latter dominate today the landscape around Lake Hachlaf, the microscope identification of the fossil pollen grains that originate from deciduous or evergreen plants may often be dubious and therefore, may not be reproducible by another pollen analyst. We have assigned all oak pollen grains to the evergreen *Quercus ilex* in the climate reconstruction. All other taxa, including trees, shrubs and herbs, also show some changes but within a much lower range than that of the two conifer taxa, Atlas cedar and pine (Fig. 4). We have applied a constrained cluster analysis to depict the main changes in the pollen fossil record. There are four main clusters summarizing the main changes in the ecosystem composition around Lake Hachlaf over the last 6000 years (table 3).

The grain size analysis revealed the presence of three fractions (Fig. 3) with the following proportions: clay (22.87%), silt (60.46% with 41.9% of fine silt) and sand (16.67 %). The dominant silty fraction tends to increase from the bottom to the top of the core after a brief decline between ca. 5600 and 5200 cal BP. The sandy fraction follows the same pattern. Clay shows an opposite trend to both the sandy and silty fractions.

Carbonates ($CaCO_3$) content is high throughout the record except around 5200 cal BP (Fig. 3). They are positively correlated with silt and sand. The total organic carbon (TOC) content is also high and varies significantly between 4 and 27.4% (Fig. 3). The total nitrogen (TN) remains low throughout the record. The carbon to nitrogen ratio (C/N) varies between 9 and 17.4, and the δ^{13}Corg between –21 and –27‰ (Fig. 3). Two origins of the organic matter are thus identified, with lake algae characterized by C/N < 11 and very depleted δ^{13}Corg and terrestrial plants characterized by C/N > 11 and less depleted δ^{13}Corg (Fig. 5). δ^{13}Corg and C/N are positively correlated (Fig. 3). TOC and TN are highly correlated (0.99, Figs. 3 and 6) as well.

In order to interpret the different bio and geo-chemical proxies within a climatic frame, a pairwise correlation was performed between the three climate variables and δ^{13}C, C/N, TN and TOC (Fig. 6). Although there could be no causal relationship, SI and Tjan are well correlated together. They are both correlated negatively with δ^{13}C and C/N and positively with TN and TOC (Fig. 6).

5 Discussion

The Holocene climate around the Mediterranean Sea was suitable for the expansion of human populations and their organization towards true civilizations (Kaniewski et al., 2012). The persistence and longevity of many Mediterranean populations may be linked to the relative suitability and also to an overall stability of the Holocene climate. However, climatic events have been recorded within the Holocene (e.g. Rohling and Pälike, 2005) and a causal relationship has been made between some abrupt climatic events and societal changes in the Mediterranean (Berger and Guilaine, 2009; Kaniewski et al., 2008).

In the present study, we have focused on the environmental and climate changes that occurred during the last 6 millennia in the northern part of the Moroccan Middle Atlas Mountains. We have evaluated the vegetation dynamics using the palynological content of a fossil sequence and analyzed its bio- and geo-chemical content to reconstruct the overall landscape changes.

The reconstructed Tjan and Pann show a relatively low amplitude of change over the last 6000 years (Fig. 3). *P*ann decreases progressively by ca. 100mm which is in line with the aridity trend that has been observed in other fossil records (Risacher and Fritz, 1992; Brooks, 2006; Hastenrath, 1991; Anderson and Leng, 2004; Umbanhowar et al., 2006) and particularly in the Mediterranean area (Pons and Reille, 1988; Julià et al., 2001; Burjachs et al., 1997; Yll et al., 1997; Roberts et al., 2001; Valino et al., 2002, Jalut et al., 2009) and northern Africa (Ritchie, 1984; Ballouche~~ et al.~~, 1986; Lamb et al., 1989). At a more regional scale, reconstructed Pann is coherent with that obtained from Lake Tigalmamine (Cheddadi et al., 1998) which shows a decreasing trend over the last ca. 5000 cal BP. The arid trend observed after ca. 5ka cal BP is marked by a spread of Poaceae and a progressive replacement of pines by Atlas cedars which better stand the high seasonal contrast of precipitation at the altitude of Hachlaf Lake. SI increases from 3 to 7 times over the last 6000 years (Fig. 3). A study of drought thresholds influencing the growth and photosynthesis was performed on different cedar stands and species (*C. atlantica*, *C. libani*, *C. brevifolia* and ~~&~~ *C. deodora*) of different origins (Aussenac and ~~&~~ Finkelstein, 1983). This study showed that among many conifers, cedar trees may keep a sustained photosynthesis activity even when drought is very high. Thus, a strong precipitation contrast between Ps and Pw (Fig. 3) may not affect the Atlas cedar overall growth as long as the total amount of rainfall is sufficient (higher than 600 mm/year) and the winter temperature is low enough (below 6°C) for the vegetative cycle (Aussenac et al., 1981). The Mediterranean climate is known for its strong seasonal distribution of precipitation throughout the year. Summers are fairly dry and most of the annual precipitation occurs during the cold months (end of autumn and beginning of winter).

Currently, 75% of the Moroccan territory with a grassy or wooded vegetation (thus excluding the desert) records between 500 and 800mm of annual rainfall with an SI between 5 and 8 (Fig. 7). The whole range of SI in Morocco is between –1 in areas where *P*ann is less than 100mm with a random distribution as for instance in the South of Morocco, and 15 in areas where the annual rainfall is quite high (over 800 mm) and occurs mainly in the winter season such as in the Rif mountains today (Fig. 7). SI is higher in mountainous areas. Nowadays, in the areas surrounding Hachlaf lake (located at ca. 1600m elevation) SI is around 5. Such SI has changed over the past thousand years as confirmed, at least between 6000 cal BP and today, by the studied fossil archive (Fig. 3). The amplitude between Pw and Ps precipitation has increased 2 to 3 times towards the present (Fig. 3). Since *P*ann has a decreasing trend, the opposite increased seasonality is related to a significant reduction in the amount of rainfall during the months of June, July and August (Fig. 3). This strengthening of the contrast between Pw and Ps had a rather limited impact on the dominating taxa because they can withstand the summer drought and the overall amount of Pw remained sufficient for their persistence. However, a change in the amplitude of SI has probably favoured those species best adapted to the length of the dry season, as for instance evergreen oaks rather than deciduous. Pollen-based climate reconstructions from records collected in the Alboran Sea (Combourieu-Nebout et al., 2009) and Italy (Magny et al., 2013; Peyron et al., 2013) suggest a rather steady and low seasonal contrast between Pw and Ps (about two times) over the past 6000 years cal BP. Such discrepancy between the reconstructed SI from Hachlaf and the marine record may potentially be related to the fact that marine records collect pollen grains from a much wider geographical source area than continental (mountainous) records which probably tends to smooth the local/regional changes. The reconstructed seasonality from the Italian records (Magny et al., 2013; Peyron et al., 2013) is buffered by the less abrupt precipitation seasonal contrast at the European temperate latitude than at the arid Mediterranean one.

SI was lower than 5 before 3750 cal BP despite an amount of precipitation between 600 and 700 $\mathrm{mm\,yr^{-1}}$ (Fig. 3). During that period, water probably persisted in the lake all throughout the year which allowed the presence of aquatic plants (Fig. 4) flowering during late spring and summer, and algae identified in the pollen data, through the low values of δ^{13}Corg and the C/N ratio being greater than 11 (Figs. 3 and 5). The proportion of aquatic plants cannot be directly related to a high lake level and may not be used to state the lake level changes but only the presence of water in the site. The δ^{13}Corg and C/N (Fig. 5) provide information concerning the origin of the organic matter (*in situ* production versus input from the catchment area) but not on the lake level changes. Thus, high δ^{13}Corg and C/N ratios (Fig. 3) with low presence of aquatic plants (Fig. 4) may not be inconsistent in cases where there is a low terrestrial input (low Sand/Silt, Fig. 3) during a period when the lake level is high.

The relationship between δ^{13}Corg and the C/N ratio indicates the occurrence of two main types of organic matter mainly originating from a C3 metabolism. Lacustrine algae can be considered as dominantly autochthonous; in the lower part of the record, the organic matter, with higher C/N ratios and less depleted δ^{13}Corg corresponds to a terrestrial input. Indeed, Fresh organic matter from lake algae is known to be protein-rich and cellulose-poor with molar C/N values commonly between 4 and 10, whereas vascular land plants, are protein-poor and cellulose-rich, creating organic matter usually with C/N ratios of 20 and greater (Meyers, 1994, 2003). However, a C/N ratio > 11 may correspond to a mixture of both local and terrestrial organic matter (Fig. 5).

After 3750 cal BP, Atlas cedars noticeably spread around the site while the pine populations strongly regress. A series of fossil pollen records in the Middle Atlas show that Atlas cedar populations expanded after ca. 6 ka cal BP. The sustained expansion of Atlas cedar after ca. 3750 cal BP around Hachlaf Lake expresses its late occurrence at higher altitude. Around lake Tigalmamine (Lamb et al., 1995), the Ras El Ma marsh (Nour El Bait et al., 2014) and the Ait Ichou marsh (Tabel et al., 2016) which are all located at about 100 to 200 meters altitude below

Hachlaf lake (ca. 1700m asl), Atlas cedar occurs much earlier. The expansion of Atlas cedar around the lake is probably related to both an upslope spread and a south-north migration.

During this ecosystem transition we observe a major change in both Pann and Tjan. The increase of SI after 3750 cal BP is due to a combined increase of Pw and decrease of Ps (Fig. 3). The expansion of cedar forests in the studied area may be related to their better adaptation to strong SI than pines at higher altitude.

Competition is another parameter that might be worth considering. After 3750 cal BP, the C/N ratio is below 11 and the δ^{13}C remains below –26‰ which suggest the important primary productivity of the lake associated with low input of land plant derived organic matter. Atlas cedar forests have a more important growth in both height and diameter than pines which leads to a higher biomass production. This is linked to the genetic model of growth that is very distinct between the two taxa (Kaushal et al., 1989). Thus, the expansion of Atlas cedar population around the site may explain the high input of OM into the lake.

Over the last six millennia, superimposed to the overall climate trend, we observe one relatively abrupt event between 5500 and 5000 cal BP during which Tjan declined by about 2°C compared to its average over 6000 years. A climatic transition between 6 and 5 ka cal BP at the end of the Holocene thermal maximum has been globally identified (Steig, 1999; Mayewski et al., 2004; Wanner et al., 2008; Brooks, 2012). This transition has been recorded by a wide range of climate proxies (e.g. Kaufman et al., 2004; Jansen et al., 2009; Seppä et al., 2009; Bartlein et al., 2011) and has been related to different biosphere feedbacks and potentially to a decay of the remaining Laurentide ice sheet (Renssen et al., 2009). All proxies from the Hachlaf sequence as well as the reconstructed climate variables have recorded marked changes during that period of time. SI has the lowest value of the record and a succession of abrupt changes are recorded in the C/N ratio, the grain size fractions, the δ^{13}C, TN, TOC and $CaCO_3$ (Fig. 3). Carbonates, considered as a "paleo-thermometer" (Meyers, 1994, 2003), also decrease abruptly around 5200 cal BP (Fig. 3). The latter may be linked to a low evaporation of the lake which may have been favored by low winter temperature around 5200 cal BP. The fine grain size sediment also increased as a consequence of low seasonal precipitation contrast and/or a continuous sediment input to the lake. Such sustained input of clay and decreasing carbonate content suggest a higher lake level between 5500 and 5000 cal BP (Fig. 3). Thus, the Tjan and SI decrease may have contributed to the higher lake level or at least to the presence of water throughout the year (Fig. 3). At the same time, the sand to silt ratio is very low which confirms a low energy during the sedimentation process. The major change in the ecosystem composition around the lake is the rapid collapse of the pine forest which has inevitably released an important amount of terrestrial carbon (biomass) into the lake (positive peaks in $\delta^{13}C$ and C/N, Fig. 3).

6 **Conclusions**

This study marks a new contribution to the knowledge of past climates and environmental history in North Africa mountainous areas. The range of climate change in the Middle Atlas, Morocco, was rather minor between 6000 cal BP and the present. Annual precipitation and January mean temperature have respectively varied within a range of 100 mm and 2 to 3°C. However, they both show a trend towards a more arid and warmer climate as well as a higher rainfall seasonality. Pann became as contrasted as today after 3750 cal BP. The aridity trend observed in Hachlaf over the last 6000 years is consistent with other climate reconstructions available from other Mediterranean fossil records. Besides these overall climatic trends, we also observe an abrupt cold event between 5500 and 5000 cal BP which is well marked in all environmental proxies from our studied fossil record. The $\delta^{13}C$ and C/N ratios, which are well correlated together, suggest an increase in the organic matter input from the catchment area. Concomitantly, the pollen record indicates a decline of the pine forest which may have contributed to the organic matter input into the lake too. The marked change in both the carbonates content and clay composition of the record were probably related to a perennial presence of water throughout the year. Synchronously, seasonality index and January mean temperature were the lowest of the record which has contributed to a reduction of the evaporation.

The increase in rainfall seasonality has probably favored the expansion of Atlas cedars around the studied site at the expense of the pine forest.

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References

Alley, R. B., Mayewski, P. A., Sowers, T., Stuiver, M., Taylor, K. C., and Clark, P. U.: Holocene climatic instability: a prominent, widespread event 8200 yr ago, Geology, 25, 483–486, 1997.

Alley, R.B., Agustsdottir, A.M.: The 8k event: cause and consequences of a major Holocene abrupt climate change, Quat. Sci. Rev., 24, 1123–1149, 2005.

Andersen, C., Koç, N., Jennings, A., and Andrews, J. T.: Non uniform response of the major surface currents in the Nordic Sea to insolation forcing: implications for the Holocene climate variability, Paleoceanography, 19, PA2003, doi:10.1029/2002PA000873, 2004.

Anderson, N. J. and Leng, M. J.: Increased aridity during the early Holocene in West Greenland inferred from stable isotopes in laminated-lake sediments, Quat. Sci. Rev., 23, 841–849, 2004.

Aussenac, G. and Finkelstein, D.: Influence de la sécheresse sur la croissance et la photosynthèse du cèdre, Ann. Sci. for., 40, 67–77, 1983.

Aussenac, G., Granier, A., and Gross, P.: Etude de la croissance en hauteur du Cèdre (Cedrus atlantica Manetti) Utilisation d'un appareillage de mesure automatique, Ann. Sci. for., 38, 301–316, 1981.

Baali, A.: Genèse et évolution au Plio-Quaternaire de deux bassins intramontagneux en domaine carbonaté méditerranéen. Les bassins versants des dayets Afourgagh et Agoulmam (Moyen Atlas, Maroc), PhD thesis, University of Rabat, 326 pp., 1998.

Ballouche, A. : Paléoenvironnements de l'homme fossile holocène au Maroc. Apports de la palynologie, PhD thesis, University of bordeaux, 134 pp., 1986.

Bartlein, P.J., Harrison, S.P., Brewer, S., Connor, S., Davis, B.A.S., Gajewski, K., Guiot, J., Harrison-Prentice, T.I., Henderson, A., Peyron, O., Prentice, I.C., Scholze, M., Seppä, H., Shuman, B., Sugita, S., Thompson, R.S., Viau, a. E., Williams, J., Wu, H.: Pollen-based continental climate reconstructions at 6 and 21 ka: a global synthesis. Clim. Dyn., 37, 775–802, 2011.

Berger, J. F. and Guilaine, J.: The 8200 cal BP abrupt environmental change and the Neolithic-transition: a Mediterranean perspective, Quat. Int., 200, 31–49, 2009.

Bianchi, G. G. and McCave, N.: Holocene periodicity in North Atlantic climate and deep-ocean flow south of Iceland, Nature, 397, 515–517, 1999.

Blaauw, M. and Christen, J.A.: Flexible Paleoclimate Age-Depth Models Using an Autoregressive Gamma Process, Bayesian Analysis, 6, 457–474, 2011.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G.: Persistent solar influence on North Atlantic climate during the Holocene, Science, 294, 2130–2136, 2001.

Brooks, N.: Beyond collapse: climate change and causality during the Middle Holocene Climatic Transition, 6400–5000 years before present, Geogr. Tidsskr. Geogr., 112, 93–104, doi:10.1080/00167223.2012.741881, 2012.

Brooks, N.: Cultural responses to aridity in the middle Holocene and increased social complexity, Quat. Int., 151, 29–49, 2006.

Bryson, R.A.: Late Quaternary volcanic modulation of Milankovitch climate forcing. Theor. Appl. Climatol., 39, 115–125, 1989.

Burjachs, F., Giralt, S., Roca, J.R., Seret, G., and Julia, R.: Palinologia holocenica y desertizacion en el Mediterraneo occidental. El Paisaje Mediterraneo a Traves del Espacio y del Tiempo. Implicaciones en la Desertificacion (eds J.J. Ibanez, B.L. Valero and~~&~~ C. Machado), 379–394. Geoforma Editores, Logrono, Spain, 1997.

Carrión~~Carrion~~, J. S.: Patterns and processes of Late Quaternary environmental change in a montane region of Southwestern Europe, Quat. Sci. Rev., 21, 2130–2136, 2002.

Cheddadi, R., Lamb, H.F., Guiot, J., and van der Kaars, S.: Holocene climatic change in Morocco: a quantitative reconstruction from pollen data. 14, 883–890, 1998.

Cheddadi, R. and Bar-Hen, A.: Spatial gradient of temperature and potential vegetation feedback across Europe during the late Quaternary, Clim. Din., 32, 371–379, 2009.

Cheddadi, R., Bouaissa, O., Rhoujjati, A. and Dezileau, L.: Holocene Environmental changes in the Rif Mountains, Morocco. Quat., 27, 15–25, 2016, in press.

Cheddadi, R., Fady, B., François, L., Hajar, L., Suc, J. P., Huang, K., Demarteau, M., Vendramin, G. G., and Ortu, E.: Putative glacial refugia of Cedrus atlantica from Quaternary pollen records and modern genetic diversity, J. Biogeogr., 36, 1361–1371, 2009.

Chevalier, M., Cheddadi, R. and Chase, B. M.: CREST (Climate REconstruction SofTware): a probability density function (PDF)-based quantitative climate reconstruction method, Clim. Past, 10, 2081–2098, doi:10.5194/cp-10-2081-2014, 2014.

Chillasse, L. and Dakki, M.: Potentialités et statuts de conservation des zones humides du Moyen-Atlas (Maroc), avec référence aux influences de la sécheresse, Sécheresse, 15, 337–45, 2004.

Combourieu-Nebout~~Combourieu Nebout~~, N., Peyron, O., Dormoy, I., Desprat, S., Beaudouin, C., Kotthoff, U., and Marret, F.: Rapid climatic variability in the west Mediterranean during the last 25 000 years from high resolution pollen data, Clim. Past, 5, 503–521, doi:10.5194/cp-5-503-2009, 2009.

Dansgaard, W., White, J.W.C., and Johnsen, S.J.: The abrupt termination of the Younger Dryas climatic event, Nature, 339, 532–534, 1989.

Davis, M.B.: On the theory of pollen analysis. Am. J. Sci., 261, 899–912, 1963.

Debret, M., Bout-Roumazeilles, V., Grousset, F., Desmet, M., McManus, J. F., Massei, N., Sebag, D., Petit, J.-R., Copard, Y., and Trentesaux, A.: The origin of the 1500-year climate cycles in Holocene North-Atlantic records, Clim. Past, 3, 569–575, doi:10.5194/cp-3-569-2007, 2007.

Dorale, J. A., Gonzalez, L. A., Reagan, M. K., Pickett, D. A., Murrell, M. T., and Baker, R. G.: A high resolution record of Holocene climate change in speleothem calcite from Cold Water Cave, northeast Iowa, Science, 258, 1626–1630, 1992.

Eddy, J.A.,: The solar constant and surface temperature. AIP Conf. Proc, La Jolla, CA, USA, 9-11 March 1981, 82, 247, 1982.

Emmanuel, W.R., Shugart, H.H. and Stevenson, M.P.: Climate change and the broad-scale distribution of terrestrial ecosystem complexes. Clim. Chang., 7, 29–43, 1985.

Fletcher, W., J., Sánchez Goñi, M., F., Allen, J. R. M., Cheddadi, R., Combourieu-Nebout, N., ~~and~~ Huntley, B., Lawson, I., Londeix, L., Magri, D., Margari, V., Müller, U. C., Naughton, F., Novenko, E., Roucoux, K. and Tzedakis, P.C.: Millennial-scale variability during the last glacial in vegetation records from Europe. Quat. Sci. Rev., 29, 2839–2864, 2010.

Fletcher, W.J. and Sánchez Goñi, M.F.: Orbital- and sub-orbital-scale climate impacts on vegetation of the western Mediterranean basin over the last 48,000 yr, Quat. Res., 70, 451–464, 2008.

Frigola, J., Moreno, A., Cacho, I., Canals, M., Sierro, F. J., Flores, J. A., Grimalt, O., Hodell, D., and Curtis, J. H.: Holocene climate variability in the western Mediterranean region from a deepwater sediment record, Paleoceanography, 22, PA2209, doi:10.1029/2006PA001307, 2007.

GBIF: Recommended practices for citation of the data published through the GBIF Network. Version 1.0 (Authored by Vishwas Chavan), Copenhagen: Global Biodiversity Information Facility, 12, ISBN: 87-92020-36-4. http://links.gbif.org/gbif_best_practice_data_citation_en_v, 2012.

Geiss, C. E., Banerjee, S. K., Camill, P., and Umbanhowar, J. C. E.: Sediment-magnetic signature of land-use and drought as recorded in lake sediment from south-central Minnesota, USA, Quat. Res., 62, 117–125, 2004.

Geiss, C. E., Umbanhowar, C. E. J., Camill, P., and Banerjee, S. K.: Sediment magnetic properties reveal Holocene climate change along the Minnesota prairie-forest ecotone, Paleolimnol., 30, 151–166, 2003.

Harmand, C. and Moukadiri, A.: Synchronisme entre tectonique compressive et volcanisme alcalin: exemple de la province quaternaire du Moyen Atlas (Maroc), B. Soc. Geol. Fr., 8, 595–603, 1986.

Hastenrath, S.: Climate Dynamics of the Tropics, Kluwer Academic Publishers, 1383-8601, Springer Netherlands, 463–488 pp., 1991.

Hazan, N., Stein, M., Agnon, A., Marco, S., Nadel, D., Negendank, J. F. W., Schwab, M., and Neev, D.: The late Pleistocene–Holocene limnological history of Lake Kinneret (Sea of Galilee), Israel, Quat. Res., 63, 60–77, 2005.

HCEFLCD : Haut-Commissariat aux Eaux et Forêts et Lutte Contre la Désertification. Bilan annuel, Santé des Forêts au Maroc. Etudes d'aménagement concerté des forêts et des parcours collectifs de la province d'Ifrane. Composante III : études forestières. Rapports 9 et 10, 2004.

Herbig, H. G.: Synsedimentary tectonics in the Northern Middle Atlas (Morocco) during the Late Cretaceous and Tertiary, in: The Atlas System of Morocco, edited by: Jacobshagen, V., Springer-Verlag, Berlin, 321–337, 1988.

Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G., and Jarvis, A.: Very high resolution interpolated climate surfaces for global land areas, Int. J. Climatol., 25, 1965–1978, 2005.

Hinaje, S. and Ait Brahim, L.: Les Bassins Lacustres du Moyen Atlas (Maroc): un exemple d'Activité Tectonique Polyphasée Associée à des Structures d'Effondrement, Com. Instituto Geológico e Mineiro, 89, 283–294, 2002.

Hulten, E. and Fries, M.: Atlas of North European vascular plants: north of the Tropic of Cancer I-III. Koeltz Scientific Books, Konigstein, DE, 1986.

ISO 11464: 1994. Qualité du sol-Prétraitement des échantillons pour analyses physico-chimiques. Norme révisée par ISO 11464 : 2006, 11, 2006.

Jalas, J. and Suominen, J.: (eds) Atlas florae Europaeae. Distribution of vascular plants in Europe. The Committee for Mapping the Flora of Europe and Societas Biologica Fennica Vanamo, Helsinki, vols 1–10, 1972, 1973, 1976, 1979, 1980, 1983, 1986, 1989, 1991, 1994.

Jalut, G., Dedoubat, J. J., Fontugne, M. and Otto, T. : Holocene circum-Mediterranean vegetation changes: Climate forcing and human impact. Quat. Int., 200, 4–18, 2009.

Jansen, E., Andersson, C., Moros, M., Nisancioglu, K. H., Nyland, B. F. and Telford, R. J.: The Early to Mid-Holocene Thermal Optimum in the North Atlantic, in Natural Climate Variability and Global Warming: A Holocene Perspective (eds R. W. Battarbee and H. A. Binney), Wiley Blackwell, Oxford, UK. doi: 10.1002/9781444300932.ch5, ~~2008~~2009.

Jiménez-Moreno, G., Rodríguez-Ramírez, A., Pérez-Asensio, J. N., Carrión, J. S., López-Sáez, J. A., Villarías-Robles, J. J. R., Celestino-Pérez, S., Cerrillo-Cuenca, E., León, A., and Contreras, C.: Impact of late-Holocene aridification trend, climate variability and geodynamic control on the environment from a coastal area in SW Spain, Holocene, 25, 607–627, doi:10.1177/0959683614565955, 2015.

Julià, R., Riera, S., and Wansard, G.: Advances in Mediterranean lacustrine studies and future prospects: the Southern European group of ELDP project (1999– 2001) contribution, Terra Nostra, 3, 43–51, 2001.

Kaniewski, D., Paulissen, E., Van Campo, E., Al-Maqdissi, M., Bretschneider, J., and Van Lerberghe, K.: Middle East coastal ecosystem response to middle-to-late Holocene abrupt climate changes, Proc. Natl. Acad. Sci. U.S.A., 16, 13941–13946, doi:10.1073/pnas.0803533105, 2008.

Kaniewski, D., Van Campo, E., and Weiss, H.: Drought is a recurring challenge in the Middle East, Proc. Natl. Acad. Sci. U.S.A., 109, 3862–3867, 2012.

Kaufman, D. S., Ager, T. A., Anderson, N. J., Anderson, P. M., Andrews, J. T., Bartlein, P. J., Brubaker, L. B., Coats, L.L., Cwynar, L. C., Duvall, M. L., Dyke, a. S., Edwards, M.E., Eisner, W.R., Gajewski, K., Geirsdóttir, a., Hu, F.S., Jennings, A.E., Kaplan, M.R., Kerwin, M.W., Lozhkin, a. V., MacDonald, G.M., Miller, G.H., Mock, C.J., Oswald, W.W., Otto- Bliesner, B.L., Porinchu, D.F., Rühland, K., Smol, J.P., Steig, E.J., and Wolfe, B.B.: Holocene thermal maximum in the western Arctic (0–180°W), Quat. Sci. Rev., 23, 529–560, doi:10.1016/j.quascirev.2003.09.007, 2004.

Kaushal, P., Guehl, J. M., and Aussenac, G.: Differential growth response to atmospheric carbon dioxide enrichment in seedlings of *Cedrus atlantica* and *Pinus nigra* ssp. *Laricio* var. *Corsicana*, Can. J. For. Res., 19, 1351–1358, 1989.

Kelly, P.M. and Sear, C.B.: Climatic impact of explosive volcanic eruptions. Nature, 311, 740–743, 1984.

Lamb, C.J., Lawton, M.A., Dron, M., and Dixont, R.A.: Signals and Transduction Mechanisms for Activation of Plant Defenses against Microbial Attack, Cell, 56, 215–224, 1989.

Lamb, H. F. and Van der Kaars, S.: Vegetational response to Holocene climatic change: pollen and palaeolimnological data from the Middle Atlas, Holocene, 5, 400–408, 1995.

Lamb, H.F., Gasse, F., Benkaddour, A., El Hamouti, N., van der Kaars, S., Perkins, W. T., Pearce, N. J., and Roberts, C. N.: Relation between century-scale Holocene arid intervals in tropical and temperate zones, Nature, 373, 134–137, doi:10.1038/373134a0, 1995.

Lascaratos, A., Roether, W., Nittis, K., and Klein, B.: Recent changes in deep water formation and spreading in the eastern Mediterranean Sea: a review, Prog. Oceanography, 44, 5–36, 1999.

Lecompte, M.: La végétation du moyen atlas central. Esquisse phyto-écologique et carte des séries de végétation au 1/200 000, Rev. geogr. Maroc., 16, 1–31, 1969.

Lemcke, G. and Sturm, M.: ^{18}O and trace element measurements as proxy for the reconstruction of climate changes at Lake Van (Turkey): preliminary results, in: Third Millenium BC Climate Change and Old World Collapse (Proceedings of the NATO Advanced Research Workshop on Third Millenium BC Abrupt Climate Change and Old World Social Collapse, held at Kemer, Turkey, 19–24 September 1994), edited by: Nüzhet Dalfes, H., Kukla, G., and Weiss, H., Springer, Berlin, Heidelberg, New York, 653–678, 1997.

Magny, M., Combourieu-Nebout~~Combourieu Nebout~~, N., de Beaulieu, J. L., Bout-Roumazeilles, V., Colombaroli, D., Desprat, S., Francke, A., Joannin, S., Peyron, O., Revel, M., Sadori, L., Siani, G., Sicre, M. A., Samartin, S., Simonneau, A., Tinner, W., Vanni`ere, B., Wagner, B., Zanchetta, G., Anselmetti, F., Brugiapaglia, E., Chapron, E., Debret, M., Desmet, M., Didier, J., Essallami, L., Galop, D., Gilli, A., Haas, J. N., Kallel, N., Millet, L., Stock, A., Turon, J. L., and Wirth, S.: North–south palaeohydrological contrasts in the central Mediterranean during the Holocene: tentative synthesis and working hypotheses, Clim. Past., 9, 1901–1967, doi:10.5194/cpd-9-1901-2013, 2013.

Magny, M., De Beaulieu, J. L., Drescher-Schneider, R., Vanniere, B., Waltersimonnet, A. V., Millet, L., Bossuet, G., and Peyron, O.: Climatic oscillations in central Italy during the Last Glacial–Holocene transition: the record from Lake Accesa, J. Quat. Sci., 21, 311–320, 2006.

Manabe, S. and Stouffer, R. J.: Two stable equilibria of a coupled ocean-atmosphere model. J. Clim., 1, 841–866, 1988.

Mann, M. E., Cane, M. A., Zebiak, S. E. and Clement, A.: Volcanic and solar forcing of the tropical Pacific over the past 1000 years. J. Clim., 18, 447–456, 2005.

Märsche-Soulié, I., Benkaddour, A., Elkhiati, N., Gemayel, P., and Ramdani, M.: Charophytes, indicateurs de paléo-bathymétrie du lac Tigalmamine (Moyen Atlas, Maroc), Geobios, 41, 435–444, 2008.

Martin, J.: Carte géomorphologique du Moyen Atlas central au 1/100.000, Notes ~~&~~ et Mém. Serv. géol. Maroc, 258 bis, 445 pp., 1973.

Martin, J.: Le Moyen Atlas central étude géomorphologique, Notes et Mémoires du service Géologique N^{o} 258 bis Rabat Maroc, 447 pp, 1981.

Mayewski, P. A., Rohling, E., Stager, C., Karlén, K., Maasch, K., Meeker, L. D., Meyerson, E., Gasse, F., Van kreveld, S., Holmgren, K., Lee–thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R., and Steig, E. J.: Holocene climate variability, Quat. Res., 62, 243–255, 2004.

McGregor, H. V, Dima, M., Fischer, H. W., and Mulitza, S.: Rapid 20th-century increase in coastal upwelling off northwest Africa. Science, 315, 637–9, 2007.

Meyers, P. A.: Preservation of elemental and isotopic source identification of sedimentary organic matter, Chem. Geol., 144, 289–302, 1994.

Meyers, P. A.: Applications of organic geochemistry to paleolimnological reconstructions: a summary of examples from the Laurentian Great Lakes, Org. Geochem., 34, 261–289, 2003.

Meyers, P. A.: Preservation of elemental and isotopic source identification of sedimentary organic matter, Chem. Geol., 144, 289–302, 1994.

Migowski, C., Stein, M., Prasad, S., Negendank, J. F. W., and Agnonc, A.: Holocene climate variability and cultural evolution in the Near East from the Dead Sea sedimentary record, Quat. Res., 66, 421–431, 2006.

Milano, M., Ruelland, D., Fernandez, S., Dezetter, A., Fabre, J. Servat, E., Fritsch, J. M., Ardoin–Bardin, S., and Thivet, G.: Current state of Mediterranean water resources and future trends under global changes, Hydrolog. Sci. J., 58, 498–518, doi: 10.1080/02626667.2013.774458, 2013.

Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A. B., and Kent, J.: Biodiversity hotspots for conservation priorities, Nature, 403, 853–858, 2000.

NF ISO 10693: Juin, 1995. Qualité du sol-Détermination de la teneur en carbonate - Méthode volumétrique, 7, 1995.

NF ISO 14235. Qualité du sol–Dosage du carbone organique par oxydation sulfochimique, 11, 1998.

Nour El Bait, M., Rhoujjati, A., Eynaud, F., Benkaddour, A., Dezileau, L., Wainer, K., Goslar, T., Khater, C., Tabel, J., and Cheddadi, R.: An 18,000 year pollen and sedimentary record from the cedar forests of the Middle Atlas, Morocco, J. Quat. Sci., 29, 423–432, 2014.

Peyron, O., Magny, M., Goring, S., Joannin, S., de Beaulieu, J.-L., Brugiapaglia, E., Sadori, L., Garfi, G., Kouli, K., Ioakim, C., and Combourieu-Nebout, N.: Contrasting patterns of climatic changes during the Holocene across the Italian Peninsula reconstructed from pollen data. Clim. Past, 9, 1233-1252, doi:10.5194/cp-9-1233-2013, 2013.

Pons, A. and Reille, M.: The holocene- and upper pleistocene pollen record from Padul (Granada, Spain): A new study, Palaeogeogr. Palaeoclimatol. Palaeoecol., 66, 255–249–263, 1988

Reille, M.: Analyse pollinique de sédiments postglaciaires dans le Moyen Atlas et le Haut Atlas marocains: premiers résultats, Ecol. Mediterr., 2, 153–170, 1976.

Renssen, H., Seppä, H., Heiri, O., Roche, D.M., Goosse, H., and Fichefet, T.: The spatial and temporal complexity of the Holocene thermal maximum. Nat. Geosci., 2, 411–414, 2009.

Rhoujjati, A., Ortu, E., Baali, A., Taïeb, M., and Cheddadi, R.: Environmental changes over the past 29,000 years in the Middle Atlas (Morocco): a record from Lake Ifrah, J. Arid Environ., 74, 737–745, 2010.

Risacher, F. and Fritz, B.: Mise en évidence d’une phase climatique holocène extrèmement aride dans l’Altiplano central, par la présence de la polyhalite dans le salar de Uyuni (Bolivie), Paleoclimatology, CR. Acad. Sci. Paris, 314, 1371–1377, 1992.

Ritchie, M. : Analyses polliniques de sédiments holocènes supérieurs des Hauts-Plateaux du Maghreb oriental, Pollen Spores, Paris, 16, 489–496, 1984.

Roberts, N., Reed, J. M., Leng, M. J., Kuzucuoglu, C., Fontugne, M., Bertaux, J., Woldring, H., Bottema~~j~~, S., Black S., Hunt, E., and Karabiyikoglu, M.: The tempo of Holocene climatic change in the eastern Mediterranean region: new high-resolution crater-lake sediment data from central Turkey, Holocene, 11, 721–736, 2001.

Roberts, N., Stevenson, T., Davis, B., Cheddadi, R., Brewer, S., and Rosen, A.: Holocene climate, environment and cultural change in the circum Mediterranean region, in: Past Climate Variability through Europe and Africa, edited by: Battarbee, R. W., Gasse, F., and Stickley, C. E., Kluwer Academic Press, Dordrecht, 343–362, 2004.

Rohde, K.: Latitudinal gradients in species diversity: The search for the primary cause, Oikos, 65, 514–527, 1992.

Rohling, E. J. and Pälike, H.: Centennial-scale climate cooling with a sudden cold event around 8,200 years ago, Nature, 434, 975–979, doi:10.1038, 2005.

Rohling, E., Mayewski, P., Abu-Zied, R., Casford, J., and Hayes, A.: Holocene atmosphere-ocean interactions: records from Greenland and the Aegean Sea, Clim. Dyn., 18, 587–593, 2002.

Ruddiman, W. F.: Orbital insolation, ice volume, and greenhouse gases, Quat. Sci. Rev., 22, 1597–1629, 2003.

Sear, C.B., Kelly, P.M., Jones, P.D. and Goodess, C. M.: Global surface-temperature responses to major volcanic eruptions, Nature, 330, 365–367, 1987.

Seppä, H., Bjune, A.E., Telford, R.J., Birks, H.J.B., and Veski, S.: Last nine-thousand years of temperature variability in Northern Europe, Clim. Past., 5, 523–535, 2009.

Steig, E.J.: Mid-Holocene climate change. Science, 286, 6–8, 1999.

Stuiver, M. and Reimer, P. J.: Extended ^{14}C data base and revised calib 3.0 ^{14}C age calibration program, Radiocarbon, 35, 215–230, 1986.

Stuiver, M., Braziunas, T. F., Becker, B. and Kromer, B.:~~,.~~ Climatic, solar, oceanic and geomagnetic influences on late-glacial and Holocene atmosphere ^{14}C/^{12}C change, Quat. Res., 35, 1–24, 1991.

Tabel, J., Khater, K., Rhoujjati, A., Dezileau, L., Bouimetarhan, I., Carré, C., Vidal., L., Benkaddour, A., Nour El Bait, M., and Cheddadi, R. : Environmental changes over the past

25,000 years in the southern Middle Atlas, Morocco, J. Quat. Sci., in press, DOI: 10.1002/jqs.2841, 2016.

Texier, J. P., Raynal, J. P., and Lefevre, D.: Nouvelles positions pour un cadre chronologiques raisonné du Quaternaire marocain, CR. Acad. Sc. Paris, 301, 183–188, 1985.

Umbanhowar, C. E. J., Camill, P., Geiss, C. E., and Teed, R.: Asymmetric vegetation responses to mid-Holocene aridity at the prairie-forest ecotone in south-central Minnesota, Quat. Res., 66, 53–66, 2006.

Valino, M.D., Rodr!ıguez, A.V., Zapata, M.B.R., Garcia, M.J.G., and Gutiérrez, I.B.: Climatic changes since the Late-glacial/Holocene transition in La Mancha Plain (South-central Iberian Peninsula, Spain) and their incidence on Las Tablas de Daimiel marshlands, Quat. Int., 73–84, 2002.

Wanner, H., Beer, J., Bütikofer, J., Crowley, T. J., Cubasch, U., Flückiger, J., Goosse, H., Grosjean, M., Joos, F., Kaplan, J. O., Küttel, M., Müller, S. A., Prentice, I. C., Solomina, O., Stocker, T. F., Tarasov, P., Wagner, M., and Widmann, M.: Mid- to Late Holocene climate change: an overview, Quat. Sci. Rev., 27, 1791–1828, 2008.

Weninger B., Clare L., Rohling E. J., Bar-Yosef O., Böhner U., Budja M., Bundschuh M., Feurdean A., Gebel H.-G., Jöris O., Linstädter J., Mayewski P., Mühlenbruch T., Reingruber A., Rollefson G., Schyle D., Thissen L., Todorova H., and Zielhofer C.: The Impact of Rapid Climate Change on prehistoric societies during the Holocene in the Eastern Mediterranean, Documenta Praehistorica, 36, 7–59, 2009.

Williams, J. T., Post, D. M., Cwyner, L. C., Lotter, A. F., and Levesque, A. J.: Rapid and widespread vegetation responses to past climate change in the North Atlantic region, Geology, 11, 971–974, 2002.

Witt, A. and Schumann, A. Y.: Holocene climate variability on millennial scales recorded in Greenland ice cores, Nonlinear Process. Geophys., 12, 345–352, 2005.

Yll, E.I., Perez-Obiol, R., Pantaleon-Cano, J., and Roure, J.M.: Palynological Evidence for Climatic Change and Human Activity during the Holocene on Minorca (Balearic Islands), Quat. Res., 48, 339–347, 1997.

1

Depth (cm)	**Material dated**	**^{14}C age yr BP**	**95,4 % (2δ) cal age ranges (BP)**	**Relative area under probability distribution**	**Median probability cal BP**
60	Bulk	2535 ± 30	2494 – 2746	0,447	2624
120	Bulk	3220 ± 35	3371 – 3509	0,936	3436
170	Bulk	4390 ± 35	4859 – 5047	0,991	4949
240	Bulk	5200 ± 40	5897 – 6021	0,943	5958

2

Pollen taxa	**Plant species**
Alisma	*Alisma plantago-aquatica*
Alnus	*Alnus glutinosa*
Berberis	*Berberis hispanica*
Brassica	*Brassica*
Campanula	*Campanula afra*
Caryophyllaceae	Caryophyllaceae
Centaurea	*Centaurea cyanus*
Chenopodiaceae	Chenopodiaceae
Asteroideae	Compositae Subfam. Asteroideae
Cichorioideae	Compositae Subfam. Cichorioideae
Corylus	*Corylus avellana*
Cupressaceae	Cupressaceae
Ephedra	*Ephedra fragilis*
Euphorbia	*Euphorbia characias*
Geranium	*Geranium macrorrhizum*
Helianthemum	*Helianthemum canariense*
Ilex	*Ilex aquifolium*
Juglans	*Juglans regia*
Myriophyllum	*Myriophyllum aquaticum*
Plantago	*Plantago lanceolata*
Polygonaceae	Polygonaceae
Ranunculaceae	Ranunculaceae
Salix	*Salix pedicellata*
Saxifraga	*Saxifraga*
Taxus	*Taxus baccata*
Urtica	*Urtica dioica*
Papaveraceae	Papaveraceae
Pinus	*Pinus halepensis*
Olea	*Olea europaea*
Paronychia	*Paronychia argentea*
Erica	*Erica arborea*
Quercus	*Quercus ilex*
Cedrus	*Cedrus atlantica*
Artemisia	*Artemisia herba-alba*

Zones	Depth (cm)	Age (cal BP)	Pollen data description		
Zone I	250 – 190	6227 – 5171	AP	27 – 60%	- Mainly *Quercus* and *Olea*. - Peak of *Pinus* (47%) at 6100 cal BP then decreasing. - Low percentages of *Cedrus atlantica* with initial spread around 5800 cal BP.
			NAP	39 – 72 %	- Herbs dominated by Poaceae (11 – 48 %), *Illecebrum* (3 – 19 %), Apiaceae (2 – 5 %), Brassicaceae (1 – 5 %), Asteraceae (0 – 5 %), Cichorioideae (1 – 6 %), Chenopodiaceae (0.5 – 2 %) and Cereals (0 – 1 %).
			DT	18 – 26	- Rapid fluctuations
Zone II	190 – 111	5171 – 3651	AP	28 – 56 %	- *Pinus* dominates the pollen record but regresses at 5500 cal BP (from 44 to less than 2 %). - *Cedrus atlantica* continues to expand (0 – 5 %). - We observe a peak of Rosaceae (6 %).
			NAP	43 – 72 %	- Herbs are dominated by Poaceae, *Illecebrum* and Asteraceae which reach their maximum (53, 20 and 10 %, respectively). - Cereals disappear.
			DT	19 – 29	- Moderate to high with two peaks.
Zone III	111 – 60	3651 – 2351	AP	23 – 58 %	- Strong expansion of *Cedrus atlantica* and *Quercus*. - An abrupt decline of *Cedrus atlantica* around 2653 cal BP is recorded. - *Pinus* regresses as well but shows a peak of 20% at 3300 cal BP.
			NAP	41 – 76 %	- Herbs dominate the pollen record. - Sharp decline in Poaceae, Asteraceae, Chenopodiaceae and Caryophyllaceae at 5600 cal BP. - Appearance of Cereals around 2653 cal BP.
			DT	20 – 31	- High.
Zone IV	60 – 5	2351 – 173	AP	23 – 43 %	- Abundance of *Cedrus atlantica*, *Quercus*, *Olea* and Rosaceae. - Sharp decline and disappearance of *Pinus*.
			NAP	56 – 76 %	- Herbs continue to dominate the pollen record with Poaceae, Cereals, Brassicaceae, Chenopodiaceae and Caryophyllaceae which are most abundant. - Asteraceae, *Illecebrum* and Apiaceae decline. - Centaurea and Cichorioideae disappear.
			DT	21 – 32	- High.

Table 1. Radiocarbon ages for the Hach-I core. Calibrations were performed using Calib 7.1 (Stuiver and Reimer, 1986).

Table 2. Pollen taxa assigned to the most probable plant species in our plant database.

Table 3. Pollen zones identified in the fossil record using a constrained cluster analysis. AP: arboreal pollen taxa, NAP: non-aroboreal pollen taxa, DT: taxa diversity.

Figure 1. The study area. **(a)** Geographical location of the tabular and pleated Middle Atlas (MA); **(b)** sketch of the geological and geomorphological characteristics of the Hachlaf area (from Martin, 1973); **(c)** phytoecological map showing the main ecosystems and the location of the Hachlaf Lake (Dayet Hachlaf) within an oak forest (from Lecompte, 1969).

Figure 2. (a) Lithology of the core Hach-I and radiocarbon ^{14}C dates; **(b)** age/depth model from BACON software (Blaauw and Christen, 2011).

Figure 3. Diagram showing the sediment fractions (clay, silt and Sand/Silt ratio), the pollen percentages of *Cedrus atlantica* and *Pinus*, geochemical elements (delta 13 C [δ^{13}C‰], nitrogen to carbon ratio [C/N], total organic carbon [TOC], Total Nitrogen [NT]) and carbonates concentrations (CaCO$_3$), January mean temperature (Tjan), Annual precipitation (*P*ann), winter and summer precipitations (Pw and Ps) and precipitation seasonality index (SI). The red rectangles are pointing the values of present-day Tjan, Pann, Pw and Ps (HCEFLCD, 2004), t~~. T~~he red line shows the limit 3.7 ka cal BP and the blue rectangle shows the time interval of the cold phase 5.2 cal PB.

Figure 4. Diagram showing the percentages of the main pollen taxa identified in the Hach-I core. Cyperaceae and Juncaceae are included within aquatic taxa. The dashed black curves shows an exaggeration (×7) of the percentages of some taxa. On the right, pollen zones with their boundaries are set up using a constrained hierarchical clustering (R Development Core Team, 2013). The taxonomic diversity is computed using a rarefaction analysis. The red line shows the limit 3.7 ka cal BP.

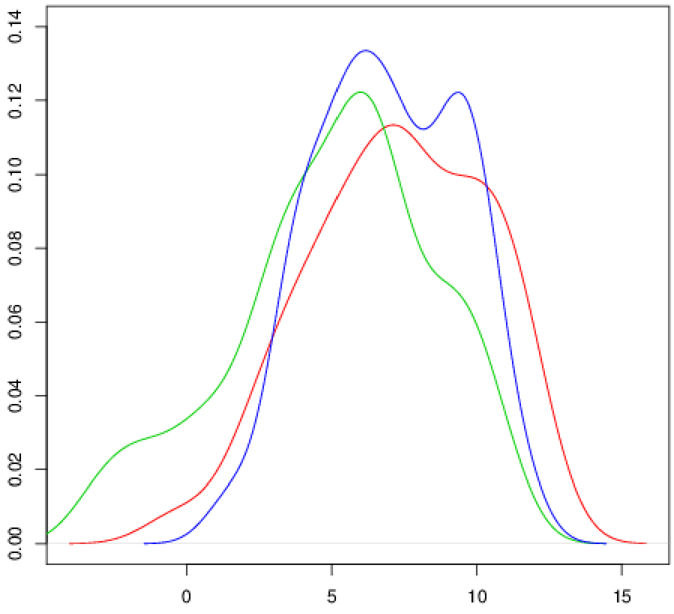
Figure 5. δ^{13}C and C/N bi-plot (from Meyers, 1994).

Figure 6. Pairwise correlation between the three climatic variables (Tjan, *P*ann and SI) and the chemical elements.

Figure 7. Modern SI (upper panel) and *P*ann (middle panel) from the gridded WorldClim dataset (Hijmans et al., 2005) over Morocco. The lower panel shows the distribution of *P*ann vs. SI: the lowest index occurs in southern Morocco where *P*ann is lower than 200 mm.y^{-1} and the highest index occurs in the high altitudinal areas (Middle Atlas and Rif mountains).

In the text:

1. You have added some indications on the present day vegetation and amended the method. Could you please add a short sentence on the Quercus saying why you have only taken into account Q. Ilex in the pollen based climate reconstructions although you have today two type of Quercus. In fact the two Quercus living in the studied area are probably adapted to Mediterranean conditions. Nevertheless may be the Q. Canariensis have been more developed in some part of the Holocene. As you have not been able to separate the two taxa, it will be interesting to consider the two in the reconstructions if they have not exactly the same requirements in terms of temperature and precipitations. For this reason I ask you to add this sentence to justify a little your choice.



In this figure we have plotted the three dominating oak species in Morocco (Q. ilex=green, Q. coccifera= red and Q. suber = blue). We have chosen Q. ilex (green curve) because it has the widest climatic. In our method for reconstructing the past climate values, the median values of the three species are very close (ca. 5°C in the case of Tjan) and therefore the choice of any of the three species will not constraint

2. Thank you to have added the table of the taxa chosen for the pollen-based reconstructions. This table is useful. Keep it in the last version.

Ok.

Concerning the figures and captions

1. Figure 2: in the figure, you have to add the ages in cal year, for the reader it will be better to have the two on the schema. Please add also the marks at 50, 100,150 and 200 cm on the stratigraphic column. Put the text on horizontal way on the profiles presented on the right.

Done

2. Figure 3 what is the blue rectangle? Please indicate what it is in the caption.

The blue rectangle shows the time interval of the cold phase 5.2 cal PB and therefore the response of the main proxies studied.

3. Figure 4. It is very difficult to see which pollen sum correspond to which sample.

Ok, resolved.

<u>Concerning the citations and references, there are some little verification to be done:</u>

1. First, could you please homogenize the”&” and the “and”. In my opinion, it will be better to have only “and” in citations and in reference list.

Done

2. Ballouche 1986 is named Ballouche et al. in the text. Please verify and change as necessary

Done

3. P15 l10 Brooks et al., 2012 directly follow Bond et al., 2001. Please separate the two references

Done

4. Please name Carrion as follows: Carrión

Done

5. Cheddadi at al., 2016: it has not been possible to find this reference. Is it already published? If it is in press, please note that as “in press”

Ok.

6. Fletcher et al., 2010: lot of authors are missing. Please complete the list of authors. And verify if there are no other names missing in the reference lists of authors.

Done

7. Jansen et al., 2008 is noted in 2009 in the text???

Done: Jansen et al., 2009.

8. Märsche-Soulié is noted Märsche-Soulie in the text p.4, l.5

Done

9. Bottema is written Bottemaj p.22 l.26

Done

10. The two references of Myers are not in the right order.

Done

11. Rohling et al., 2002 is noted Rohling, 2002 p.3 l.9

Done

12. The reference Stuiver et al, 1991 is not written with the Climate of the Past rules

Done

13. Could you please write my name Combourieu-Nebout in all you text and references. Thank you.

Naturally.

Marked-up manuscript version :