Clim. Past Discuss., 11, 4097–4121, 2015
www.clim-past-discuss.net/11/4097/2015/
doi:10.5194/cpd-11-4097-2015

Climate of the Past
Discussions
Open Access

Climate changes since the mid-Holocene in the Middle Atlas, Morocco

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Received: 25 July 2015 – Accepted: 28 July 2015 – Published: 1 September 2015

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The Holocene climate is known to be rather stable although with few abrupt changes that lasted few decades. The present study is related the climate changes and their environmental impacts during the last 6000 years from a fossil record collected in the Middle Atlas, Morocco. Reconstruction of three climate variables (January temperature (Tjan), annual precipitation (P_{ann}) and a precipitation seasonal index (SI)) was based on pollen data and analyzed various bio and geo-chemical elements. Then we evaluated the relationships between all the environmental variables.

Climate over the last 6000 years was rather stable with a smooth trend of aridity towards the present. Tjan has varied within about 2 °C range and P_{ann} within less than 100 mm yr^{-1}. Despite such overall climate stability, after ca. 3750 cal BP some important changes were observe in the ecosystem composition, the carbon isotopic contents of organic matter in lake sediments (δ^{13}C), the total organic carbon and nitrogen amount and the carbon to nitrogen ratio (C / N). These environmental changes are related to the transition in the conifer forest between the Atlas cedar, which expanded after 3750 cal BP, and the pine forest. These vegetation changes have impacted the sedimentation type and composition into the lake.

Between 5500 and 5000 cal BP an abrupt change is recorded in all bio and geochemical indicators as well as in the pollen data. The multi-proxy analysis, taking into account the climate variables, tends to indicate that it was mainly a decrease in temperature without a significant change in the overall amount of precipitation.

In summary, the present study confirms the overall climate stability over the last 6000 years and highlights the presence of short and abrupt climate events.

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 although within a range which was not as wide as that of the last post-glacial period but marked enough to be recorded by different proxies (Dorale et al., 1992; Williams et al., 2002; Geiss et al., 2003, 2004). As stated by Mayewski et al. (2004), little is know about climate variability during the Holocene. 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 for instance.

The Mediterranean area is currently one of the largest regions in the world, which undergoes long-lasting and pronounced droughts during the summer season (Robert et al., 2004; Milano et al., 2013). The southern rim of the Mediterranean region undergoes the Saharan summer winds which increase the impact of the drought effect and the winter north-eastern winds which bring moisture (Martin, 1981).

Although stable, the Holocene climate has sustained major ecosystems changes, plant species expansions, and an increase of species diversity over all latitudes (Masson et al., 2000; Andersen et al., 2004; Mayewski et al., 2004; Witt and Schumann, 2005; Frigola et al., 2007). These ecosystems changes may be observed in many fossil records in the Mediterranean as well. A pollen record from southwestern Spain suggests an increasing drought after ca. 5000 cal yr BP during which the forest cover reduces (Jiménez-Moreno et al., 2015). The authors suggest that within the long-term trend there were humid-arid cycles potentially related to multi-centennial changes in the North Atlantic Oscillation modes (Jiménez-Moreno et al., 2015).

Other studies based on lake level changes have also investigated the Holocene climate variability. In France, sedimentological investigations (Magny, 2004) have identified alternation of high and low lake levels which have been assigned to cool/wet and arid periods. These lake fluctuations are also recorded in several lakes around the Mediterranean such as in: Lake Van in Turkey (Lemcke and Sturm, 1997), Lago Dell'Accesa and Lago di Mezzano in Italy (Magny et al., 2006), lake Kinneret in Israel (Hazan et al., 2005), Dead Sea (Migowski et al., 2006) and in the western Mediterranean in the south of Spain in lake Siles (Carrion, 2002). In Morocco, climate changes have been investigated mainly in the Middle Atlas (Reille, 1976; Lamb and Van der kaars, 1995; Cheddadi et al., 1998, 2009; Märsche-Soulie et al., 2008; Rhoujjati et al., 2010, 2012; Nour el Bait et al., 2014).

The aim of the present study is to evaluate the impacts of the climate change years on the ecosystems and the landscape in the Middle Atlas, Morocco during the last six millennia. Our approach is multi-disciplinary based on pollen, elemental geochemistry and grain size analysis of a fossil record. Although with some aridity and warming trends towards the present, the overall climate change is rather moderate. Within such rather stable climate, we observe some important ecosystem and landscape changes with one rapid and abrupt climate fluctuation between 5500 and 5000 which has affected the landscape and its vegetation but the ecosystems seems to have been resilient.

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 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 the 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 the studied site, Dayet (lake) Hachlaf (33°33′20″ N; 5°0′0″ W; 1700 m a.s.l.). This small water body is located at about ten kilometers to the North-East of Ifrane national park (Fig. 1b). Available meteorological data (1980–2008) at Ifrane station shows an average annual rainfall ca. 885 mm, a mean maximum temperature of 18 °C and a mean minimum temperature about to 6.3 °C with ca. 90 rainy days per year, ca. 70 frosty days among which ca. 17 with snow precipitation. Surface area and depth of the lake change throughout the year reaching up 14 ha and 4 m, respectively. The lake is fed by rainwater, snow, surface runoff and groundwater.

Forest cover around the site (Fig. 1c) is composed of holm oak (*Q. rotundifolia)*, zeen oak (*Q. canariensis*) and Atlas cedar (*Cedrus atlantica*), which develop from low to high altitudes. Nowadays, there are few degraded populations of *Cedrus atlantica* around the site.

3 Materials and methods

In April 2008, a 2.5 m 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 with 5 cm resolution. These samples were used for the analysis of the pollen content, stable isotopes of δ^{13}C, organic matter, carbonates and grain size.

Pollens 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 was performed with an optical microscope (Leica DM750) using a ×40 magnification (×63 for accurate identifications). The pollen percentages are calculated on the total sum of pollen grains originating from vascular terrestrial plants. Aquatic plants percentages (including Cyperaceae and Juncaceae) were excluded from the total pollen sum.

The particle size analysis was carried out at the "*Laboratoire Marocain d'AGriculture* (LABOMAG)" and was performed, only, on the fine grains (< 2 mm) of the sediment.

The proportions of five fractions were identified: 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 (OM) amount was estimated based on the sediment content of the organic carbon (OC) by spectrometry (NF ISO 14235). Sediment OC was oxidize in a sulfochromic environmental with an excess of potassium dichromate at 135 °C. Subsequently the determination of chromate ions Cr^{3+} formed is analysed by spectrometry.

For total nitrogen (TN), the method used is based on the Kjeldahl mineralization (ISO 11464: 1994), but the catalyst used is 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 for decomposing all carbonates (NF ISO 10693: Juin, 1995). The volume of the carbonic gas produced is measured using a Scheibler apparatus.

$\delta^{13}C$ contents were analysed in the "*Environnements et Paléoenvironnements Océaniques et Continentaux* (EPOC)" laboratory, Bordeaux 1 university.

Besides the mutli-proxy analysis, four organic samples were dated. The obtained AMS dates (Table 1) were then calibrated using "CALIB 6.0" program (Stuiver and Reimer, 1986). The age model (depth vs. calibrated dates) was performed using a third degree polynomial equation (Fig. 2). The fossil record encompasses the last 6000 years continuously.

Annual amount of precipitation (P_{ann}), mean January temperature (Tjan) and precipitation seasonal index assessment (Fig. 3) were based on pollen data as follows:

$$\mathrm{PSI}(s) = \left(\sum P_{\mathrm{w}} - \sum P_{\mathrm{s}}\right) / \sqrt{P_{\mathrm{ann}}}$$

Where PSI(s) is the seasonal index quantified for sample s; P_{w} is the sum of December, January and February precipitation; P_{s} is the sum of June, July and August precipitation; P_{ann} is the total annual amount of precipitation.

P_{ann} and Tjan were obtained using the probability density function of modern plant species (pdf-method). The method is described in Chevalier et al. (2014) and it requires a modern database of plant species distributions and their corresponding modern climate variables. We have a georeferenced database of plant species. The modern climate variables were extracted from the WORLDCLIM database (Hijmans et al., 2005).

4 Results

During the last 6000, the main change in the forest cover is marked by a decline of the pine populations and the expansion of Atlas cedar around 3750 cal BP. All other taxa, including trees, shrubs and herbs, show also some changes but within a much lower range than that of these two conifer species.

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 dominating 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 with 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 quite high and varies 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. The δ^{13}C varies between −21 and −27 ‰ (Fig. 3). Two origins of the organic matter are identified, from lake algae ($C/N < 11$) and from terrestrial plants ($C/N > 11$) (Fig. 5). Both TN and δ^{13}C are, respectively, highly correlated with TOC and C/N (Fig. 3).

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, their persistence and evolution towards true civilizations (Kaniewski et al., 2012). The persistence and longevity of many Mediterranean populations may be linked to the relative stability of the Holocene climate. However, several climatic events have been recorded within this overall stable climate (Rohling and Pälike, 2005). For instance, a causal relationship has been made between two short climate events centered around 8200 and 5200 cal BP and some societal changes in the Mediterranean (Berger and Guilaine, 2008; Kaniewski et al., 2008, respectively). Thus, Holocene climate stability in the Mediterranean is relative.

In the present study, we have focused on the environmental and climate changes during the last 6000 millennia in the northern part of the Middle Atlas mountains, Morocco. We evaluated the vegetation dynamics using the palynological content of a fossil sequence and analyzed its bio and geo-chemical content for reconstructing the overall landscape changes. Using the pollen content we quantified three climatic variables: mean January temperature (Tjan), annual precipitation (P_{ann}) and a seasonality index (SI) (Fig. 3). Our aim is to investigate the past environmental changes in Morocco using different and independent proxies from the same record.

The reconstructed climate variables show that climate during the last 6000 years was rather stable with a relatively low amplitude change of both precipitation (less than 100 mm) and temperature (about 2 °C). Besides the low range, both P_{ann} and Tjan show consistent trends. P_{ann} decreases progressively since 6000 cal BP which is in line with the aridity trend that has been observed in other records from the Mediterranean borderlands (Risacher and Fritz, 1992; Brooks, 2006; Hastenrath, 1991; Anderson and Leng, 2004; Umbanhowar et al., 2006). The Mediterranean climate is known for its seasonality, particularly in the annual amount of precipitation. Summers are fairly dry and most of the annual amount occurs during the cold months (end of autumn and beginning of winter). We have evaluated this rainfall seasonality using a simple index (SI).

Currently, 75 % of the Moroccan territory with a grassy or wooded vegetation (thus excluding the desert) records between 500 and 800 mm 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 100 mm with a random distribution as is the case in the South of Morocco, and 15 in areas where the annual rainfall is quite high (more 800 mm) and occurs mainly in the winter as in the Rif mountains today (Fig. 7). SI is higher in mountainous areas. Nowadays, in the areas surrounding lake Hachlaf (located at ca. 1600 m elevation) SI is around 5. Such SI has changed over the past thousand years.

The fossil record shows that there is a fairly significant change in the SI (Fig. 3) between 6000 cal BP and today. The amplitude between winter and summer precipitation has increased 2 to 3 times towards today. Since the annual rainfall has a decreasing trend, the opposite increased seasonality is necessarily related to a significant reduction in the amount of rainfall during the months of June, July and August. This strengthening of the contrast between winter and summer rainfall had a rather limited impact on the main species because they can withstand the summer drought and the overall amount of winter precipitation remained sufficient to their persistence. However, a change in the amplitude of SI has probably favoured those species best adapted to the length of the dry season, for instance the evergreen more than the deciduous oaks.

The SI derived from the Hachlaf sequence was below 5 before 3750 cal BP despite an amount of precipitation between 600 and 700 mm yr^{-1}. This suggests that between 6000 and 3750 cal BP, the amount of rainfall occurring during winter was lower than today and that the summer months were probably less arid. In such case, water persisted in the lake during the summer season which allowed the presence of aquatic plants (which flower during late spring and summer) and algae that are identified in both the pollen data and by low values of δ^{13}C and the C/N ratio that is greater than 11 (Figs. 3 and 5). In fact, the relationship between δ^{13}C and the C/N ratio indicates that there are two types of organic matter which have different origins (Figs. 3 and 5).

A local one, rich in nitrogen (C/N < 10), which originates mainly from algae with a C3 metabolism ($-29\,‰ < \delta^{13}C < -27\,‰$) and an allochtonous one (C/N > 10) which corresponds to a terrestrial input. Fresh organic matter from lake algae, are protein-rich and cellulose-poor. The molar C/N values are 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). However, a C/N ratio higher than 11 may correspond to a mixture of both local and terrestrial organic matter (Fig. 5).

After 3750 cal BP, Atlas cedar spread noticeably around the site while the pine forest strongly regressed. During this ecosystem transition we do not observe any major change in the reconstructed amount of annual rainfall or in winter temperature. This is due to the fact that the two taxa have similar climatic requirements. Now a more careful analysis of the seasonal distribution of rainfall throughout the year shows a stronger contrast after 3750 cal BP. SI became as high as today. Although, we can not state any obvious causal relationship between SI and the sustained ecosystem dynamics it seems reasonable to consider that cedar forests are better adapted to strong SI than pines at the altitude of our site. Competition is another parameter that might be worth to be considered. After 3750 cal BP, the C/N ratio is below 11 and the $\delta^{13}C$ remains below $-26\,‰$ which suggests that the primary productivity of the lake was. 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 species (Kaushal et al., 1989). Thus, the expansion of Atlas cedar population around the site may explain the high input of OM into the lake.

During the last six millennia, super-imposed 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. 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 $\delta^{13}C$, TN, TOC and $CaCO_3$ (Fig. 3). Carbonates, considered as a “paleo-thermometer” (Meyers, 1994, 2003), decrease also abruptly around 5200 cal BP

(Fig. 3). The latter may be linked to a low evaporation of the lake which has been favoured by the Tjan lowering.

The finer sediment fraction increased in the record as a consequence of low seasonal precipitation contrast and a continuous sediment input to the lake. Such sustained input of clay along with the decreasing carbonate content indicate a higher lake level between 5500 and 5000 cal BP (Fig. 3). The finer sediment fraction increased as a consequence of low seasonal precipitation contrast and/or a continuous sediment input to the lake. Such sustained input of clay and a decreasing carbonate content indicate 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. In both cases this is coherent with the increased amount of clay as well as the low carbonates content which tend to precipitate less due to a higher amount of available water. At the same time, the sand to silt ratio is very low which confirms a low energy during the sedimentation process and a high level lake. The major change in the ecosystem composition around the lake is the rapid collapse of the pine forest which has inevitably released an increased amount of terrestrial biomass that has been transported to the lake.

6 Conclusions

This study provides valuable climate and environmental reconstructions, which are aimed at contributing to a better knowledge of the past changes in mountainous areas in North Africa. 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 varied within a range of 100 mm and 2 to 3 °C, respectively. However, one may observe both a trend towards lesser annual precipitation and warmer climate today and a higher contrast between winter and summer precipitation as well. The precipitation seasonality became as contrasted as today after 3750 cal BP. This seasonality pattern suggests that the aridity increasing trend over the last 6000 years concerns mainly the summer season since the amount of annual rainfall did not change substantially while the winter-summer contrast became 2 to 3 times higher.

Besides these overall climatic trends we observe an abrupt cold event between 5500 and 5000 cal BP. This climatic event is well marked in all environmental proxies obtained from the fossil record. The δ^{13}C and C/N, which are well correlated together, suggest an increase in the organic matter from the catchment area. Concomitantly, the pollen record translate a decline of the pine forest which may have contributed to the organic matter input into the lake. The marked change in both the carbonates content and clay composition of the record are related to a presence of water throughout the year. During this period span, SI and Tjan are the lowest of the record which has contributed to, if not to an increase in the water input into the lake, at least to a reduction of the evaporation.

Acknowledgements. This work was supported by the Volubilis Program (Programme mixte Interuniversitaire Franco-marocain, MA/11/251), 2011, by CNRS-CNRST Convention, 2009 (ScVie07/09) and by the French national program EC2CO-Biohefect, “Variabilité paléoclimatique et impact sur les forêts de conifères au Maroc depuis la période glaciaire”.

This is an ISEM contribution n° xx-xxxx

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Table 1. Radiocarbon ages for the Hach-I core. Calibrations were performed using Calib 7.0 (Stuiver and Reimer, 1993).

Samples	Core depth (cm)	Thickness (cm)	Midpoint	^{14}C age	SD1	Calibrated age (cal BP)	SD2
Hac-60	60	2	61	2535 ± 30	2609	2624,5	2640
Hac-120	120	2	121	3220 ± 35	3368	3427	3486
Hac-170	170	2	171	4390 ± 35	4859	5035	5211
Hac-240	240	2	241	5200 ± 40	5897	5959	6021

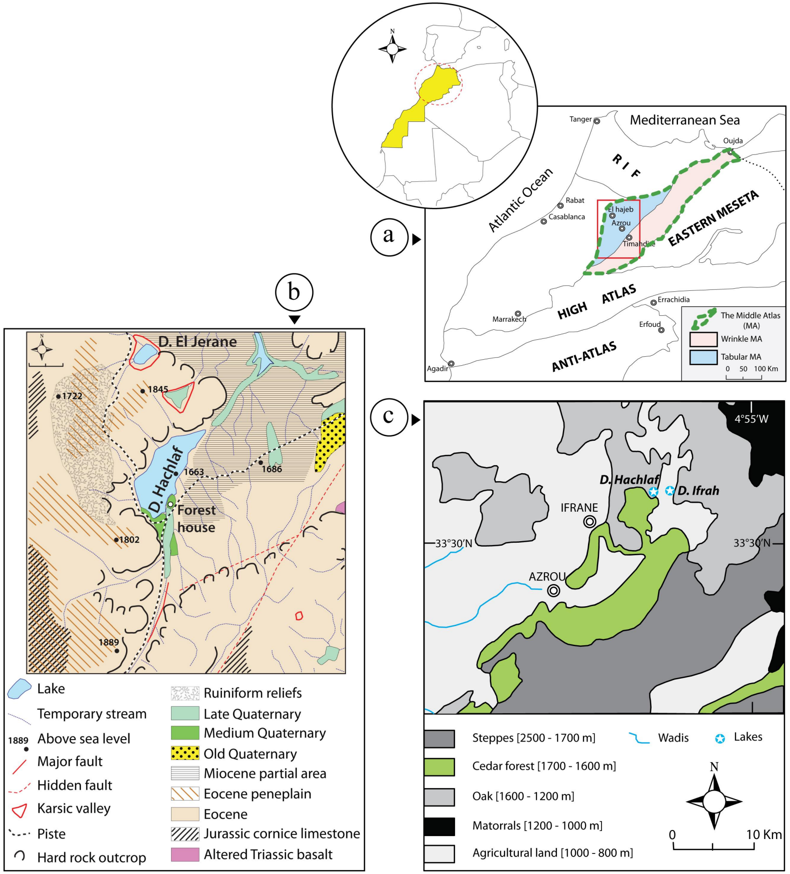

Figure 1. Location maps of the study area. **(a)** Geographical location of the tabular and pleated Middle Atlas (MA); **(b)** geological and geomorphological location of the studied area of Hachlaf (from Martin, 1973); **(c)** phytoecological map showing the location of Hachlaf Lake (Dayet Hachlaf)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

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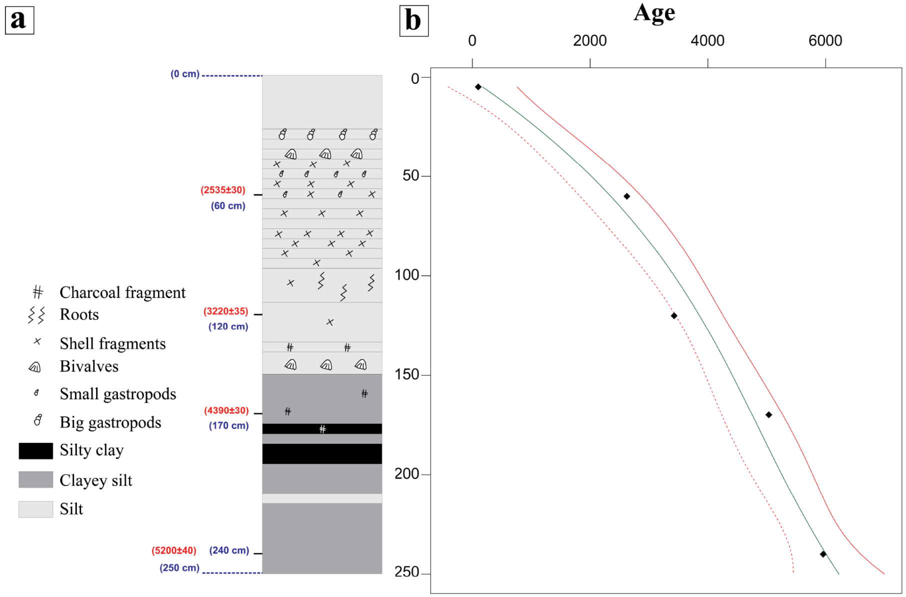

Figure 2. **(a)** Lithology of the core Hach-I and radiocarbon ^{14}C projection; **(b)** age/depth curve for Hach-I core and its linear regression: $y = 15.417x + 1562.2$ with $R^2 = 0.97$.

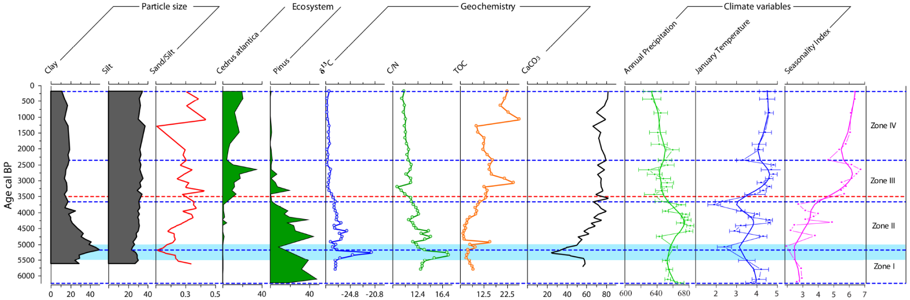

Figure 3. Diagramme showing the sediment fractions (clay, silt and Sand/Silt ratio), the pollen percentages of *Cedrus atlantica* and *Pinus*, geochemical elements (delta 13 C [δ^{13}C ‰], nitrogen to carbon ratio [C/N], total nitrogen [TN], total organic carbon [TOC]) and carbonates concentrations ($CaCO_3$), January temperature (Tjan), Annual precipitation (P_{ann}) and precipitation seasonality index (SI).

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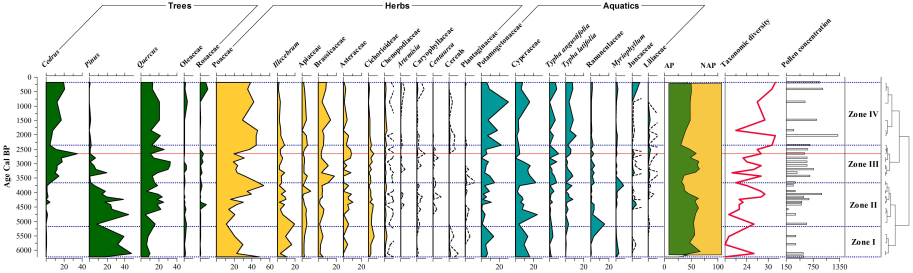

Figure 4. Diagram showing the percentages of the main pollen taxa identified in the Hach-I core. Cyperaceae and Juncaceae were grouped within aquatic taxa. The dashed black curves shows an exaggeration (×7) of the percentages of some taxa.

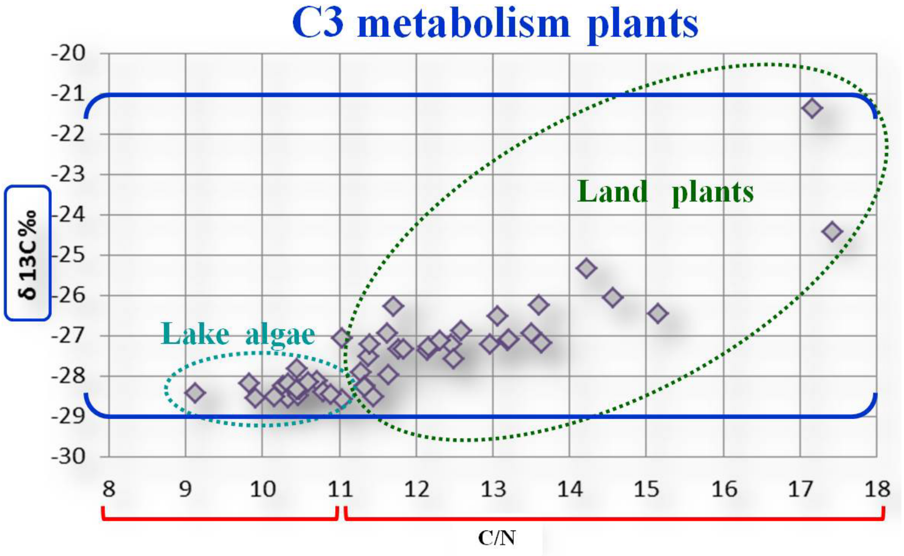

Figure 5. δ^{13}C and C/N bi-plot (from Meyers, 1994).

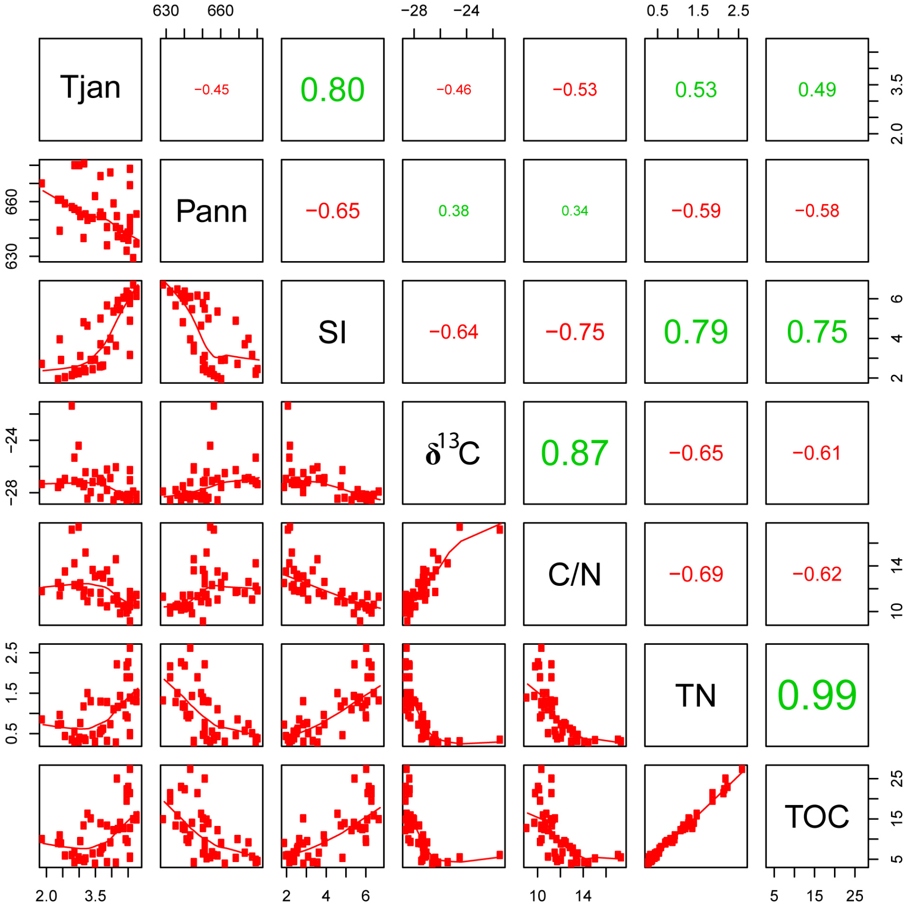

Figure 6. Pairwise correlation between the three climatic variables (Tjan, P_{ann} and SI) and the chemical elements.

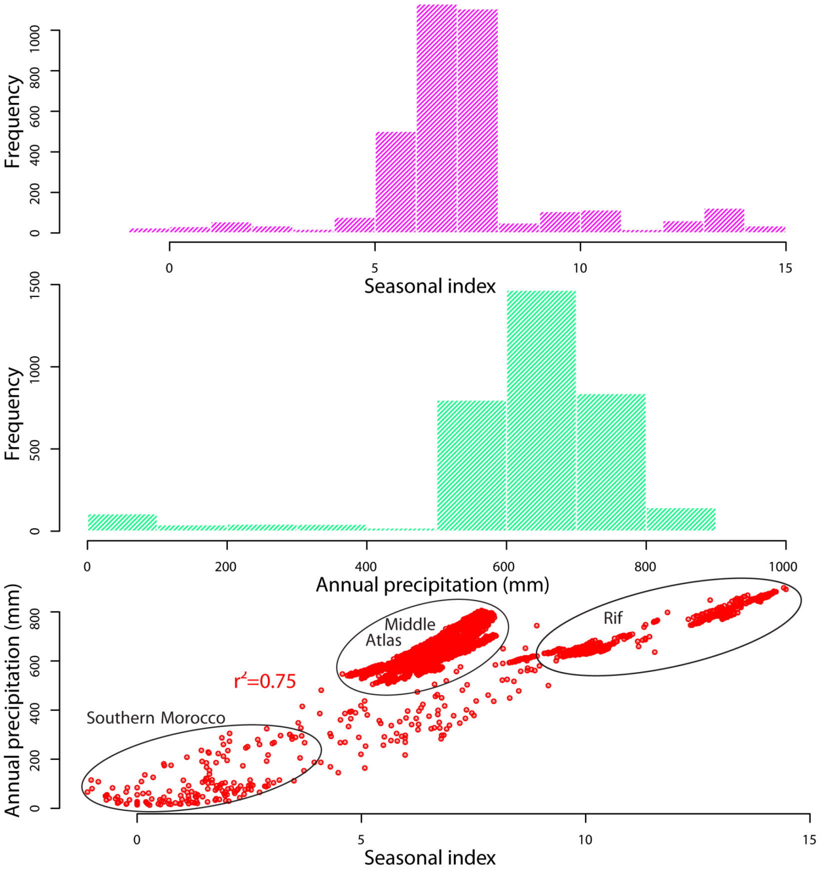

Figure 7. Modern SI (upper panel) and P_{ann} (middle panel) from the gridded WorldClim dataset over Morocco. The lower panel shows the distribution of P_{ann} vs. SI: the lowest index occurs in southern Morocco where P_{ann} is lower than 200 mm year^{-1} and the highest index occurs in the high altitudinal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