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Assessment of the impact of climate and anthropogenic factors on Holocene Mediterranean vegetation in Europe on the basis of palaeohydrological records

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Abstract

Correlations between lake-level and river-activity records from the western Mediterranean and palaeohydrological records from northern Africa and central Europe suggest a distinction, in the western Mediterranean region, between an early Holocene period characterised by cooler and moister conditions than at present, favourable to temperate deciduous trees, and, after 5000 yr BP, a later Holocene period with a warmer and drier climate. The second phase was favourable to the extension of evergreen sclerophyllous trees possibly reinforced by human activities. These two successive Holocene periods reflect orbitally induced changes in summer insolation. Furthermore, superimposed on this general climatic trend, century-scale climatic oscillations punctuated the whole Holocene period. Decreases in river activity in the western Mediterranean region occurred at ca. 11 500, 10 500, 9000, 7000, 4000, 3000, 2000 and 800 cal yr BP. These decreases coincided with lake-level lowering in Jura, eastern France, and glacier retreat in the northern Alps and could be associated with a temporary expansion of sclerophyllous trees. This general pattern could have resulted from an alternatingly southward/northward displacement of the Atlantic Westerly Jet.

Keywords: lake level; river activity; climatic change; human impact; Holocene vegetation; western Mediterranean

1. Introduction

Over the last few decades, many authors have debated the climatic and/or antropogenic origin of the present vegetation in the northwestern Mediterranean area. Some authors have pointed to climatic change and considered that the dominance of temperate forests during the first half of the Holocene reflected cooler and moister conditions than at present (Huntley and Prentice, 1988; Jalut et al., 1997). However, others have also observed that several sites present palaeoenvironmental records questioning this general pattern. As an example, Davis et al. (2001), using a method based on modern pollen analogues, have quantified the climatic parameters from the sites of Laguna di Medina and San Rafael in Spain, Dry Lake II in

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Bulgaria and Lake Van in Turkey, and reconstructed contrary shifts in the climatic conditions during the mid-Holocene, i.e. increasing drought stress at Laguna di Medina and Lake Van, and decreasing drought stress at San Rafael and Dry Lake II. As discussed by these authors, these results could suggest problems inherent with the modern analogue approach (potential lack of analogues due to human impact). They could also indicate either that some sites are not indicative of general shifts in the regional climate, or that a complex rather than a simple pattern of climatic change prevailed across the circum-Mediterranean region over the Holocene period (Roberts et al., 2001a). In any case, many recent pollen investigations have given results which show rather substantial differences between the early and late Holocene, suggesting a general evolution from wetter to drier climatic conditions (Denèfle et al., 2000; Roberts et al., 2001b; Sadori and Narcisi, 2001).

Using the pollen ratio between deciduous broad-leaf and evergreen sclerophyllous taxa and a comparison between modern and fossil pollen spectra, Jalut et al. (2000) have recently provided a reinterpretation of Holocene palynological data distributed from southeastern Spain to southeastern France. They concluded that in the western Mediterranean, north of 40°N, the period of 4500–4000 yr BP coincided with changes in the vegetation cover reflecting an evolution towards Mediterranean climatic conditions. According to these authors, these changes induced by the climate have been enhanced by human activity, but the Mediterranean climate clearly prevailed before 10 000 yr BP in southeast Spain at 36–39°N and thereafter expanded to southeast France at 41–44°N where it was established at ca. 2800 yr BP. Moreover, Jalut et al. (2000) identified 6 aridification phases at about 9500–9000 yr BP (10 900–9700 cal yr BP), 7500–7000 yr BP (8400–7600 cal yr BP), 4500–4000 yr BP (5300–4200 cal yr BP), 3700–3300 yr BP (4300–3400 cal yr BP), 2600–1900 yr BP (2850–1730 cal yr BP), and 1300–1000 yr BP (1300–750 cal yr BP). These phases are assumed to be synchronous with positive ^{14}C anomalies and cooling phases in eastern France and central Europe marked by rising lake levels and glacier advances, respectively. Based on geomorphological evidence for hydrological variations in the middle Rhône valley, i.e. at the northern border of the Mediterranean area, another recent study (Berger, 2000) suggests correlating positive ^{14}C anomalies and cooling phases in eastern France and central Europe not with phases of aridification, but with phases of increasing fluvial activity and erosion in the northwestern Mediterranean.

However, some authors have proposed an opposite interpretation and concluded that the replacement of the early Holocene deciduous forests by the late Holocene xerophytic vegetation resulted from the human activity initiated by Neolithic forest clearing (Vernet, 1997; Heinz and Thiébault, 1998). Pons and Quézel (1998) have questioned the use of the deciduous/sclerophyllous pollen ratio to reconstruct the installation of a Mediterranean climate: this ratio could reflect the human impact on the vegetation rather than the natural evolution of the Holocene climate. Indeed, these authors observed that human impact could have favoured the expansion of sclerophyllous taxa to the detriment of deciduous species. They noted that, over the last 50 yr, deciduous oaks have shown a constant expansion in the areas abandoned by human activities.

Using palaeohydrological records from northern Africa and from southern and middle Europe, this paper aims at reexamining (1) the possible climatic origin of the replacement of early Holocene temperate deciduous forests by the present northwestern Mediterranean vegetation and (2) the possible correlations among century-scale climatic oscillations from southern and middle Europe, their implications for atmospheric general circulation patterns and their possible impact on vegetation in the northwestern Mediterranean area.

2. Palaeohydrological records

2.1. Changes in lake levels

To avoid any problem of data interpretation resulting from a possible combination of climatic and anthropogenic factors, lake-level records can be used to outline the general pattern of climatic evolution over the whole Holocene period as demonstrated by Harrison and Digerfeldt (1993) and Harrison et al. (1993, 1996). However, lake-level changes can also be caused by various local non-climatic factors and, among others, anthropogenic factors. Forest clearing could have affected the runoff/evapotranspiration balance within a lake catchment area and hence the amount of water supply (Vassiljev, 1997). But, as noted by Harrison and Digerfeldt (1993), local (anthropogenic) factors are most unlikely to cause synchronous changes in all the lakes within a region and even more unlikely over several regions from the Sahara in northern Africa to the northwestern Mediterranean, and from the western to the eastern Mediterranean region. Thus, regionally synchronous changes in lake levels can be thought to be governed by the climate. Authors have also pointed out that a marked human impact on the environment generally appears to have occurred rather late in the last part of the Holocene (Carrion et al., 2001; Sadori and Narcisi, 2001; Roberts et al., 2001b). Finally, keeping in mind the possibility of human disturbances most often limited in time and space during the early and mid-Holocene, the following discussion focuses on the general evolution of lake levels over the whole Holocene rather than on short-lived successive lake-level fluctuations.

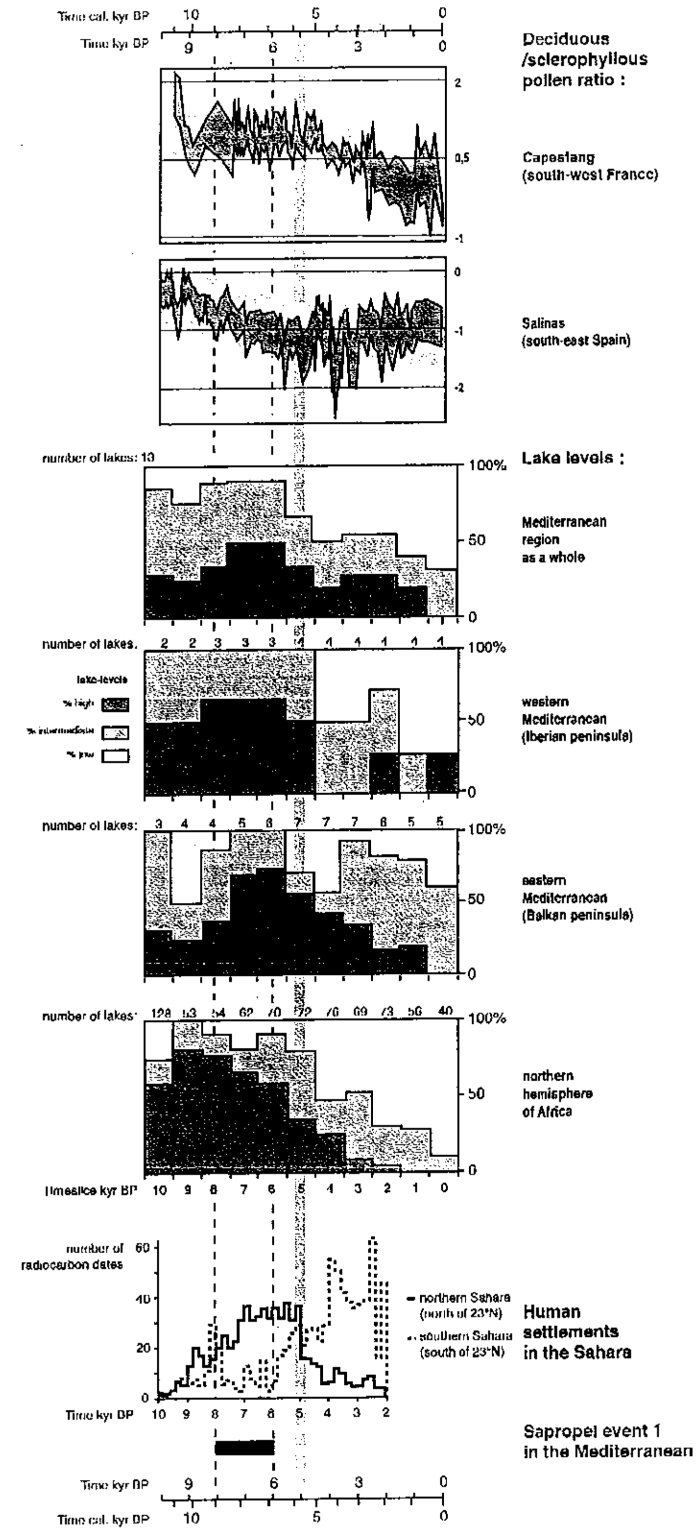
Fig. 1 presents the Holocene lake-level variations reconstructed in the Mediterranean region and the northern portion of Africa. The Mediterranean records were established by Harrison and Digerfeldt (1993) and Harrison et al. (1993, 1996) using a compilation of various proxy data from the literature. The method enables lake status (high, intermediate, low) to be reconstructed at 1000-yr intervals (e.g. time slice $10\,000 \pm 500$ yr BP).

Taken as a whole, the Holocene appears to be characterised by a general trend towards a fall in lake levels following a first lake-level optimum. However, a more pronounced lowering at ca. 5000–4000 yr BP leads to a distinction between two successive periods in the Holocene, i.e. the first more humid than the second. The distinction is more obvious in the western rather than the eastern Mediterranean where a humidity optimum appeared at ca. 7000–6000 yr BP; this followed a drier phase in the early Holocene and was followed by a more progressive lowering (Harrison and Digerfeldt, 1993). The Holocene lake-level record reconstructed by Digerfeldt et al. (1997) at Lake Saint-Leger, southeast France, also displays a higher water table before 7500 yr BP.

Recent lake-level investigations in southwestern Spain (Reed et al., 2001) and Sicily (Sadori and Narcisi, 2001) support the idea of a general trend to climatic aridification over the second half of the Holocene after 5830 yr BP in southwestern Spain where it was reinforced after 5000 yr BP, and as early as 7200 yr BP in Sicily. However, the Spanish record shows a wet mid-Holocene stage at 6000–5830 yr BP not only followed but also preceded by drier conditions, i.e. a pattern which is not so different from the one prevailing in the Balkan peninsula.

The lake-level pattern of the northern part of Africa has been established by Damnati (2000) using an approach similar to that of Harrison and Digerfeldt (1993). The north African pattern presents similarities with that reconstructed in the Mediterranean region. The first half of the Holocene was more humid than the second (Fig. 1). The Holocene humidity optimum is centred at 9000 yr BP and a more pronounced fall occurred at ca. 5500–4500 yr BP. This coincides with a strong development of human settlement in the Sahel after 6000 yr BP and a rapid abandonment of the Sahara after 5000 yr BP (Fig. 1) as suggested by the decreasing number of radiocarbon dates obtained from archaeological sites (Vernet and Faure, 2000). The maps of lake status reconstructed by Damnati (2000) observe that after a generally high stand at 7000 yr BP, intermediate and then low lake levels developed earlier in eastern than western Africa.

Fig. 2 presents Holocene lake-level changes in the Jura mountains, the French northern Pre-Alps and the Swiss Plateau. They were reconstructed using a specific sedimentological method based on multiple lines of evidence, including changes in the lithology, the sediment texture and the relative frequency of different carbonate concretion



Time cal. kyr BP
Time kyr BP
Deciduous /sclerophyllous pollen ratio :
Capestang (south-west France)
Salinas (south-east Spain)
number of lakes
Lake levels :
Mediterranean region as a whole
lake-levels
% high
% intermediate
% low
western Mediterranean (Iberian peninsula)
eastern Mediterranean (Balkan peninsula)
northern hemisphere of Africa
timeslice kyr BP
number of radiocarbon dates
northern Sahara (north of 23°N)
southern Sahara (south of 23°N)
Human settlements in the Sahara
Sapropel event 1 in the Mediterranean

morphotypes in the lake marl. A contiguous high-resolution subsampling of sediment sequences made the identification of short-lived palaeohydrological events possible. The curve displays a synthesis of results obtained from 26 sites. The chronology is based on 180 radiocarbon and tree-ring dates (Magny, 1998, in press). This mid-European lake-level record indicates that the whole Holocene was characterised by an alternation of higher and lower lake-level phases. An overall synchroneity of these lake-level fluctuations with variations in altitude of the tree-limit and in the extent of the glaciers in the Austrian and Swiss Alps (Patzelt, 1977; Zoller, 1977; Burga and Perret, 1997; Magny, 1993, 1995) suggests that they reflect climatic changes.

2.2. Changes in river discharge

Over the last 20 years, systematic investigations have been carried out in the French southern Alps valleys to reconstruct morphogenic processes associated with regional palaeohydrological changes (Jorda, 1985; Gautier, 1992; Rosique, 1996; Miramont, 1998; Miramont et al., 1999, 2000). The synthesis presented in Fig. 2 is based on (1) a compilation of data from 25 sites in the middle Durance valley and its tributaries and (2) more than 90 dates from radiocarbon dating and archaeological materials (Miramont et al., 2000; Jorda et al., in press). Most of data are from second-order tributaries of the middle Durance, located in the so-called 'Terres Noires', i.e. a Jurassic marl highly sensitive to erosion. In such catchments phases of decrease in water discharge and sediment load correspond to soil formation, forest expansion in valleys floors, and floodplain incision.

The period from 12 000 to 6500 yr BP corresponds to higher river discharge marked by a major sediment accumulation in valley floors, i.e. the so-called 'Principal Postglacial Infilling' (PPI; Jorda, 1985). The second half of the Holocene, after 6500 yr BP, is characterised by a relative decrease in sediment deposition and by a general trend towards floodplain incision.

Superimposed on this general trend, detritic crises marked by coarser deposits appear to punctuate the whole Holocene period, in particular during the period from 12 000 to 6500 yr BP. Moreover, interbedded in the massive alluvial and colluvial infillings accumulated in the valleys during the early to mid-Holocene period, layers including many subfossil tree trunks (*Pinus silvestris* sp.) were found and dated by radiocarbon. The good preservation of the trunks and their often in-life position indicate that they were rather quickly buried. Their growth patterns, reconstructed from tree-ring observations, suggest successive rapid environmental changes: an increase in the flooding frequency resulting in an increase in sediment accumulation over the growth sites of the *Pinus* trees and their death after less than a century.

2.3. Changes in glacier extent

The Holocene maxima of Alpine glacier advances presented in Fig. 2 have been reconstructed by Rothlisberger (1986) from radiocarbon dating of many subfossil tree trunks found in glacier forefields. Periods of glacier retreat are thought to be favourable to the colonisation by trees in areas formerly occupied by glacier tongues, whereas glacier advances are responsible for overriding trees and burying them in moraine deposits. Taken as a whole, Rothlisberger's record shows a similar pattern of climatic changes as those reconstructed by Patzelt (1977), Zoller (1977) and Burga and Perret (1997) in the Swiss and the Austrian

Fig. 1. Long-term comparison over the Holocene period between (1) vegetation changes in the northwestern Mediterranean region as reconstructed by Jalut et al. (2000) from the deciduous/sclerophyllous pollen ratio at Salinas, southeast Spain, and Capestang, southwestern France, and (2) palaeohydrological changes in north Africa and the Mediterranean as reflected by lake-level variations in the Mediterranean region compiled by Harrison and Digerfeldt (1993) and Harrison et al. (1996) and in the northern hemisphere of Africa compiled by Damnati (2000), and (3) variations in the distribution of human settlements in the Sahara (Vernet and Faure, 2000). Values less than 0.5 in the pollen ratio are assumed by Jalut et al. (2000) to correspond to a Mediterranean climate. The date of the Sapropel 1 deposition in the Mediterranean has been taken from Ariztegui et al. (2000).

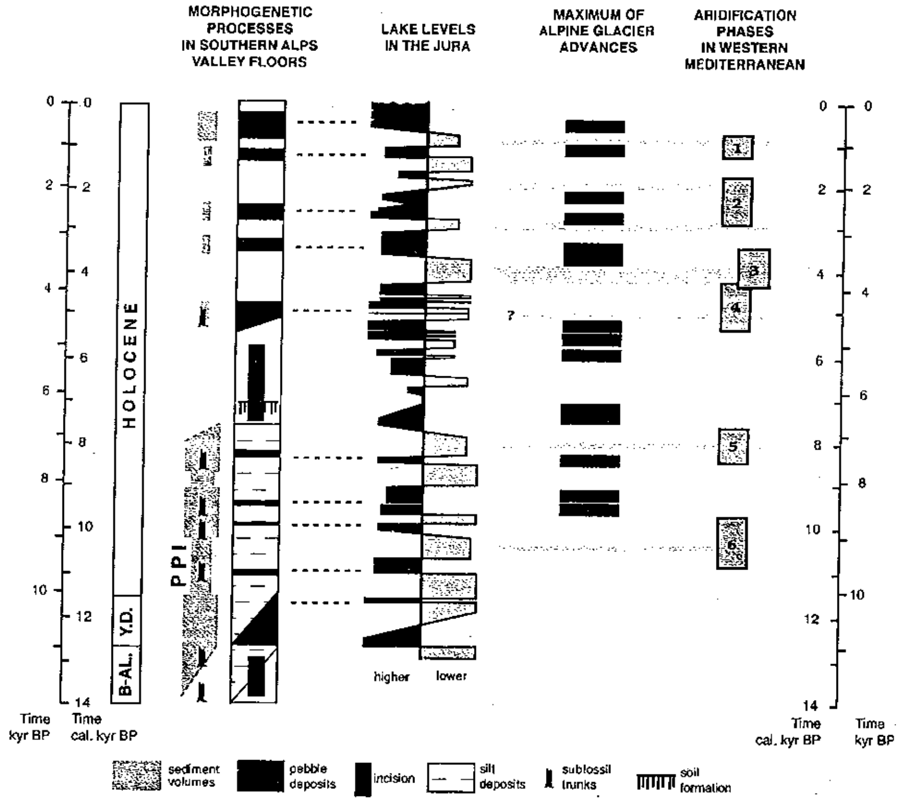


Fig. 2. Comparison between Holocene century-scale climate oscillations in central Europe and the northwestern Mediterranean region, as reflected by variations in (1) the fluvial activity in the southern Alps (Miramont et al., 1999, 2000), (2) the aridification phases identified by Jalut et al. (2000) in the northwestern Mediterranean region, (3) the lake-level variations in the Jura mountains, the northern French Pre-Alps and the Swiss Plateau (Magny, 1999), and (4) the glacier advances in the Alps (Rothlisberger, 1986). Abbreviations: Y.D., Younger Dryas; B-AL., Bølling–Allerød; PPI, Principal Postglacial Infilling.

Alps. Observations and experiments have shown that the declining tree-limits, occurring synchronously with the glacier advances, were caused not by severe winters, but chiefly by a lowering by ca. 1.5°C of mean temperature, and a consequent shortening of the growing season (Bortenschlager, 1977).

Unfortunately, the Holocene history of the glaciers in the Pyrenées is still poorly documented. In the central Pyrenées, Gellatly et al. (1992) have reconstructed a glacier advance synchronous with the Little Ice Age and older ones developing before 5190 ± 90 yr BP and between 4955 ± 90 and 4650 ± 60 yr BP, i.e. possibly synchronous with the Rotmoos 1 and 2 phases of glacier advances reconstructed in the Alps and centred at ca. 5200 and 4700 yr BP, respectively (Patzelt, 1977).

3. Discussion

The following discussion deals with two successive points: firstly, on a long timescale, the possible climatic cause of the replacement of early Holocene temperate deciduous forests by a late Holocene xerophytic vegetation; secondly, on shorter timescales, the possible correlations between century-scale climatic oscillations in south and mid-Europe will be considered.

3.1. A bipartite Holocene

The palaeohydrological records from the Mediterranean region and the northern half of Africa presented in Fig. 1 suggest a clear bipartition of the Holocene period. Taken as a whole, lake levels show a coherent pattern of changes from Africa to the north Mediterranean region and distinguish two halves in the Holocene, i.e. the first characterised by relatively wet conditions in comparison with the second marked by a progressive desiccation. The eastern Mediterranean records as well as some sites in the western Mediterranean (Reed et al., 2001) show a more complex picture with a wet mid-Holocene stage preceded and followed by drier conditions. In any case, according to all the regional palaeohydrological patterns presented here, the period 5500–4500 yr BP appears to be a crucial transition from wetter to drier climatic conditions. The human settlements in the Sahara show an abrupt change in the distribution at the same moment.

This bipartition of the Holocene from the north African and western Mediterranean lake-level records has also an equivalent in the southern Alps river-activity record (Fig. 2) where the PPI corresponds to a large sediment accumulation due to rather humid climatic conditions before ca. 6500 yr BP. However, it is noteworthy that the general pattern of glacier variations reconstructed by Holzhauser (1987) in the northern Alps shows another illustration of regional differentiation in the bipartite Holocene of central Europe. The distribution of radiocarbon dates documenting the glacier fluctuations over the entire Holocene period suggests that glacier advances and retreats developed at higher altitudes during the period 10 000–6000 yr BP than after 6000 yr BP. The lower location of the glacier tongues in the northern Alps during the second part of the Holocene marks cooler and moister conditions than during the first part. It could also explain the lack of data giving evidence for major glacier advances during the early Holocene in the Rothlisberger's curve (Fig. 2).

Other palaeoenvironmental records document a change from wetter to drier conditions over the Holocene in the Mediterranean region. Variations in the carbon isotope composition of grain cereals from Spanish archaeological sites suggest an increase in aridity along the western Mediterranean basin over the last seven millennia and a more rapid increase in aridity in recent times (Araus et al., 1997). Sea-surface temperature estimates reconstructed by Kallel et al. (1997) from foraminiferal fauna variations in the Mediterranean Sea show a cooling by about 1.5°C in the Alboran Sea and 2.5°C in the Tyrrhenian Sea during (the last) sapropel event 1. This event, dated at around 9000–6800 yr cal BP, i.e. ca. 8050–6000 yr BP, is assumed to have been initiated by increasing discharge of freshwater into the Mediterranean due to wetter climatic conditions (Ariztegui et al., 2000). As pointed out by Kallel et al. (1997) and Ariztegui et al. (2000), the formation of sapropel 1 in the Mediterranean Sea between 9000 and 6800 cal yr BP coincided with a lake-level Holocene optimum in northern Africa and the western Mediterranean region. The end of its formation at about 6800 cal yr BP can be compared with a rapid development of human settlement in the southern Sahara region from 6800 cal yr BP (announcing the abandonment of the north Sahara settlements), a lake-level lowering at ca. 6200–5750 cal yr BP in northern Africa and at ca. 5750–4500 cal yr BP in the western Mediterranean. The beginning of the trend towards incision in southern Alps valleys after 7600–7000 cal yr BP could be synchronous with the cessation of the sapropel 1 deposition.

These results from lake-level, carbon-isotope and foraminifera-faunal studies are consistent with the reconstruction of cooler and moister summers in the Mediterranean at 6000 yr BP based on the modern pollen analogue technique constrained or unconstrained with lake-level data (Huntley and Prentice, 1988; Guiot et al., 1993; Yu and Harrison, 1996; Cheddadi et al., 1997) and AGCM simulations (Jolly et al., 1998; Masson et al., 1999).

According to Huntley and Prentice (1988), Harrison and Digerfeldt (1993), Harrison et al. (1996), Cheddadi et al. (1997), Jolly et al. (1998) and Broström et al. (1998), GCM experiments and proxy data from northern Africa and the Mediterranean suggest an orbitally-induced enhancement of land–sea contrast during the first half of the Holocene resulting in a reinforcement of the African monsoon and an associated northward displacement of the Intertropical Convergence Zone (ITCZ) in summer. Moreover, this ITCZ migration is associated with a northward displacement of the subtropical anticyclone (STA) over the North Atlantic ocean. This position of the STA further north during the early to mid-Holocene would block less the westerly flow over southern Europe in summer in comparison with the present-day conditions. The winter and summer temperature could have been 2°C less than at present and the difference between precipitation and evapotranspiration could have been 50–200 mm greater than at present in the western Mediterranean region (Cheddadi et al., 1997). The Holocene pattern of variations in river discharge in the southern Alps and glacier tongue locations in the northern Alps fully agrees with the reconstruction of cooler and moister conditions in the western Mediterranean and warmer and drier conditions in the northern Alps during the first part of the Holocene (Huntley and Prentice, 1988; Cheddadi et al., 1997).

The palaeoclimatic significance of the proxy data presented here supports the hypothesis by Jalut et al. of a climate-driven substitution of evergreen sclerophyllous trees at the expense of deciduous trees. This climatic hypothesis defines a general climatic context, but does not exclude the possibility that natural processes could have been reinforced by anthropogenic factors: various pollen records from southwestern France have recently shown the precocity of human impact on the vegetation even if limited due to the weak density of the Neolithic settlements (Richard, 2000). Interdisciplinary investigations by Brochier et al. (1998) in the forelands of the eastern Pyrenées (France) suggest that the Neolithic activities were not continuous and thus did not have an enduring influence on the natural environment, but the more continuous and diversified exploitation associated with Bronze Age cultures favoured the development and maintenance of garrigues. In any case, several Mediterranean records clearly show that changes in vegetation preceded human impact on the forest by several millennia (Sadori and Narcisi, 2001; Roberts et al., 2001b).

Fig. 1 shows a comparison of the Mediterranean and African lake-level records with the deciduous/sclerophyllous pollen ratio reconstructed by Jalut et al. (2000) at Salinas (southeast Spain, ca. 38°N) and Capestang (southwestern France, ca. 43°N), i.e. close to the southern and northern boundaries of the zone considered by Jalut et al. The Salinas record matches more the lake-level pattern of northern Africa, whereas the Capestang record fits more the western Mediterranean pattern rather than that of northern Africa. The expansion of sclerophyllous taxa after 5000 yr BP at Capestang is close to the marked lowering of the western Mediterranean lake levels at ca. 5000–4000 yr BP and the lake levels of northern Africa at ca. 5500–4500 yr BP. This difference between the Capestang and the Salinas records could reflect the effects of latitude, in agreement with the changes in the general circulation pattern mentioned above.

3.2. Century-scale climatic oscillations

Using the deciduous/sclerophyllous pollen ratio in western Mediterranean pollen sequences, Jalut et al. (2000) have identified six second-order aridification phases superimposed on the general Holocene trend towards a drying climate. However, as pointed out already, tentative correlations between these century-scale climatic variations in southern Europe with those defined in mid-Europe show a relative confusion (Jalut et al., 2000; Berger, 2000) and need reexamination.

The six successive aridification phases distinguished by Jalut et al. (2000) could be a regional response of Holocene climatic variability such as reconstructed from southern France (Miramont et al., 1999, 2000; Jorda, 1992; Jorda et al., in press; Provansal, 1992; Bruneton, 1999), central and northern Europe (Denton and Karlén, 1973; Patzelt, 1977; Zoller, 1977; Rothlisberger, 1986; Magny, 1999), the North Atlantic Ocean (Bond et al., 1997) or the Greenland ice sheet (Mayewski et al., 1997). Jalut et al. (2000) suggest correlating these aridification phases with positive ^{14}C anomalies and cooling phases in central Europe marked by rises in lake level and glacier advances, respectively.

However, this general scheme could be questioned in relation to both the method and the climatic implications. The chronology of Rothlisberger's curve of glacier advances and retreats in the northern Alps used by Jalut et al. (2000, figure 14) is expressed in uncalibrated ^{14}C dates (Rothlisberger, 1986) and cannot be directly compared with the records in calibrated radiocarbon years. A similar confusion can be found in the correlations proposed by Berger (2000, figure 21). Fig. 2 presents a calibrated version of Rothlisberger's curve (Stuiver et al., 1998). It is based on the calibration of the radiocarbon dates of the Holocene glacier-extent maxima reconstructed by Rothlisberger. Moreover, the overlap of aridification phases 3 and 4 reconstructed by Jalut et al. (2000) points to uncertainties in the chronology resulting from a synthesis of different records where events are sometimes not dated directly, but from interpolation between two horizons dated by radiocarbon. Keeping in mind these difficulties, the Holocene aridification phases distinguished by Jalut et al. (2000) in the western Mediterranean could be correlated not with the rises in lake level in the Jura and the glacier advances in the northern Alps, but with phases of low lake level and glacier retreat as illustrated by Fig. 2. In any case, these correlations support the hypothesis by Jalut et al. of century-scale climate-driven phases affecting the vegetation in the northwestern Mediterranean area over the whole Holocene.

Furthermore, the correlations proposed by Jalut et al. (2000) could be questioned from the point of view of their general climatic significance. The Little Ice Age period offers an illustration of the problem. The available proxy data clearly show that this cooling phase developing between AD 1300 and 1850 coincided with not only a glacier advance in the northern Alps and a rise in lake level in the Jura, but also with a higher frequency of frost events in the lower Rhône valley (Jorda and Roditis, 1993; Pichard, 1995, 1999) and an increase in fluvial activity in southern France (Miramont, 1998; Miramont et al., 1998; Provansal et al., 1999), i.e. with cooler and moister conditions. Various proxy data from southern France (Provansal, 1992; Jorda, 1992; Arnaud-Fassetta, 1998; Berger, 2000; Bruneton and Provansal, in press; Vigne, in press) as well as from northeastern Spain (Guttierez-Elorza and Pena-Monné, 1998) suggest that over the last three millennia, phases of increasing fluvial activity in the western Mediterranean region corresponded to cooling phases in central Europe evidenced from Alpine glacier advances (Patzelt, 1977; Zoller, 1977; Rothlisberger, 1986) and higher Jurassian lake levels (Magny, 1999). Moreover, the rare data relative to glacier variations in the Pyrenées presented above support this general pattern of correlations between southern and central European cooling phases. Gellatly et al. (1992) have also observed that the Little Ice Age advance had a smaller extension than that dated at 4955 ± 90/4654 ± 60 yr BP; in the same way, Gutierrez-Elorza and Pena-Monné (1998) note that the increase in fluvial activity during the Little Ice Age had a lower magnitude than that dated at 2700–2500 yr BP. These observations could provide further evidence for the general trend towards climate drying over the later Holocene reconstructed by Jalut et al. (2000) or illustrated by the lake-level records from northern Africa and the western Mediterranean.

Fig. 2 presents tentative correlations over the Younger Dryas and Holocene periods between southern and central Europe using the fluvial activity record reconstructed by Miramont et al. (1999, 2000) in the southern Alps and the lake-level record established in the Jura (Magny, 1998, 1999). Generally speaking, a synchronicity between rises in lake levels in the Jura and increases in fluvial activity in the southern Alps valleys marked by buried *Pinus silvestris* trees or gravel and pebble accumulations can be observed over the whole period except for the mid-Holocene. The chronology of this mid-Holocene phase of interruption of sediment accumulation has still to be detailed. The available radiocarbon dates place it after 6920 ± 190 yr BP, i.e. ca. 7750 cal yr BP, and before 5240 ± 190 yr BP, i.e. ca. 5600 cal yr BP (Rosique, 1996; Sivan, 1999). These correlations suggest that wetter conditions marked by high lake levels in central Europe corresponded to a higher frequency of stormy precipitation inducing floods, gravel deposits and buried trees in the northern Mediterranean area. Furthermore, it is noteworthy that the decreases in fluvial activity in the southern Alps recorded at 11 500, 9000 and 7000 cal yr BP do not have an equivalent in the aridification phases identified by Jalut et al. (2000) from the deciduous/sclerophyllous pollen ratio.

The general synchronicity observed between century-scale climatic oscillations marked by increasing river discharge in the southern Alps, rises in lake levels in the Jura and glacier advances in the Alps could have resulted from an alternatingly southward–northward displacement of the Atlantic Westerly Jet. These observations are in agreement with the general circulation patterns described by van Geel and Renssen (1998) and Magny (1993, 1999), Magny et al. (2001) with respect to the Holocene period or those outlined by Trigo et al. (2000) and Eshel and Farrell (2000) to explain the mechanisms of Mediterranean rainfall variability over the last century. An expansion of the polar cell and an associated constriction of the latitudinal extent of the Hadley cell could have induced a southward displacement of the main depression tracks at mid-latitudes, and the reverse.

4. Conclusions

Correlations between the palaeohydrological records from the western Mediterranean region and those from northern Africa and central Europe support working hypotheses as follows.

Variations in lake level and river discharge suggest a distinction between two steps in the Holocene period in the western Mediterranean region, a first one characterised by cooler and moister conditions than at present and the second by climate drying and warming. This bipartite Holocene resulted from an orbitally induced early Holocene summer insolation maximum. Generally speaking, this observation supports the hypothesis by Jalut et al. of a climate-driven substitution of the early Holocene temperate deciduous trees by sclerophyllous trees in the western Mediterranean. Several sites indicate that human impact occurred after the changes in lake levels and vegetation induced by the climate took place. However, the precocity of the installation of a Mediterranean climate in southeastern Spain such as can be assumed from the deciduous/sclerophyllous pollen ratio at Salinas appears to correspond to a lake-level optimum in northern Africa and the western Mediterranean.

Century-scale periods of decrease in the fluvial activity in the Mediterranean region were in phase not with cooling periods marked by rises in lake level and glacier advance in central Europe, but with a glacier retreat in the northern Alps and lake-level lowering in the Jura. They occurred at ca. 11 500, 10 500, 9000, 7000, 4000, 3000, 2000 and 800 cal yr BP. These second-order climatic oscillations could have resulted from an alternatingly southward/northward displacement of the Atlantic Westerly Jet. They could have affected the vegetation in the northwestern Mediterranean area throughout the Holocene and reinforced the effects of human impact. However, the 11 500, 9000 and 7000 cal yr BP phases could not be identified as the aridification phases by Jalut et al. (2000) from the deciduous/sclerophyllous pollen ratio.

The available proxy data suggest a discrepancy between southern and central Europe in the mid-Holocene period: lake-level and glacier records from central Europe show uninterrupted century-scale variations whereas valley floors in the southern Alps appear to be characterised by relatively continuous incision and/or soil-formation processes. A more precise chronology of this mid-Holocene phase in the western Mediterranean region has still to be established. The available radiocarbon dates indicate that it developed after 6920 yr BP (ca. 7750 cal yr BP) and before 5240 yr BP (ca. 5600 cal yr BP).

As pointed out by Kallel et al. (1997) and Ariztegui et al. (2000), the formation of sapropel 1 in the Mediterranean Sea between 9000 and 6800 cal yr BP coincided with a lake-level Holocene optimum in northern Africa and the western Mediterranean. The end of its formation at about 6800 cal yr BP can be compared with the rapid abandonment of the human settlements in the northern Sahara region from 6800 cal yr BP onwards, a lake-level lowering at ca. 6200–5750 cal yr BP in northern Africa and at ca. 5750–4500 cal yr BP in the western Mediterranean.

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