PRELIMINARY COMPARISON OF GEOLOGICAL CLIMATE PROXIES WITH GCM PALAEOCLIMATE SIMULATIONS FOR SELECTED LOCATIONS IN NORTH AFRICA

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By

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I hereby declare that the master thesis submitted was in all parts exclusively prepared on my own and that other resources or other means (including electronic media and online sources), than those explicitly referred to, have not been utilized. All implemented fragments of text, employed in a literal and/or analogous manner, have been marked as such.

Ehimen Ebhohimen Williams

2014

ABSTRACT

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Thesis supervised by Prof. Dr. Yaping Shao

Our knowledge of palaeoclimate history is mainly based on climate proxies, which can infer past climatic conditions. In North Africa, sediment proxies such as palygorskite and the kaolinite-to-chlorite ratio are usually transported as dust components. Their relative increase or decrease is indicative of an arid or humid condition respectively.

Another way to understand palaeoclimate conditions is by the use of coupled atmospheric models within the Paleoclimate Modelling Intercomparison Project Phase III (PMIP3). In PMIP3, Global Climate Models (GCM), such as MPI-ESM (Max-Planck-Institute Earth System Model), simulate past climate conditions.

This thesis provides a preliminary comparison of the sediment proxies with the MPI-ESM simulations of precipitation and temperature for the LGM (last glacial maximum) and mid-Holocene in North Africa. By comparing proxy and model data, a positive correlation between proxies and model results can be assigned as the result of this thesis.

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1: INTRODUCTION

1.1 North Africa

North Africa is a region of Africa, which is geographically separated from the rest of Africa by the Sahara Desert. Geopolitically, this region (see figure 1.1) is comprised of seven countries and a territory, namely Morocco, Algeria, Tunisia, Libya, Egypt, and Sudan (recently divided into two countries, namely, Sudan and South Sudan) and Western Sahara.

Fig. 1.1 Regional map of North Africa (www.mapsofworld.com/africa/regions/northern-africa-map.html; copied on the 23/03/2014 at 8.56 AM)

In addition, the North African region can be further subdivided into two smaller regions; the north-western region and the north-eastern region. The north-western region, which is situated along the Atlas Mountains, is commonly referred to as the Maghreb, consisting of Western

Sahara, Morocco, Algeria, Tunisia, and Libya. The north-eastern region, is commonly referred to as the Nile Valley (or Sahara), comprising Egypt, Sudan, and South Sudan. All other countries, which are situated beneath this region of Africa, are collectively referred to as Sub-Saharan Africa.

Furthermore, as observed from figure 1.1, the western, northern, and eastern borders of most countries of North Africa (except south Sudan) are surrounded by the North Atlantic Ocean (to the West), the Mediterranean and Ionian Sea (to the North), and the Red Sea (to the East).

1.2 Climate of North Africa

The North Africa climate falls within the umbrella called "Mediterranean," which characterizes a temperate climatic belt. On the one hand, North Africa is influenced by the Mediterranean climate of prolonged and intense summer drought and rainfall distribution mainly in autumn and winter, while temperature distribution depends on factors such as latitude, altitude and also continentality (e.g. Magri et al., 2004). On the other hand, the distribution of winter rainfall (as observed presently) is limited to the coastal areas and the adjacent plateau and mountainous hinterland areas of Morocco, Algeria and Tunisia (Nash, and Meadows, 2012).

Hoelzmann et al. (2004) add that precipitation in North Africa shows a broadly zonal pattern as well as a varying seasonal distribution. In the northern parts of the Sahara, and especially during winter, precipitation results from a southward displacement of the mid-latitude Westerlies. While in areas south of the Sahara, and during summer, precipitation results from the seasonal northward movement of the Intertropical Convergence Zone (ITCZ). Additionally, the expansion and contraction phases experienced in the Sahara desert were also due to considerable changes in local precipitation.

Furthermore, Hoelzmann et al. (2004) argue that during the periods characterizing the humid phases (e.g. the Eemian and the Holocene), North Africa must have received precipitation from wet Atlantic air masses which cross the Northern Sahara from West to East. They built their argument on the basis of observed progressive depletion of ^{18}O (heavy oxygen) and D (heavy hydrogen) from West to East in Saharan fossil waters. They also ascribe precipitation in the Sahel to be of tropical convective origin.

Magri et al. (2004) attribute the variability of the North African climate to atmospheric forcing emanating outside the Mediterranean such as (i) changes in solar irradiance; changes in surface reflection (ii) cyclonic and anti-cyclonic systems originating over the Mediterranean and (iii) atmospheric perturbation due to local orographic features like mountain ranges that are common in many Mediterranean countries.

Thus, the aforementioned features have the capability to modify both the Mediterranean and the North African climate system. It is expected that these different climatic factors will interact and interfere in different ways in space and time, either adding to or contrasting with each other, resulting in the expression of varied seasonal patterns (e.g. Magri et al., 2004).

In addition, it is suggested that in reconstructing changes in palaeoenvironment, consideration should be given to the balance between extra-regional or global climatic factor influencing the Mediterranean and those emanating from regional or even local phenomena (Magri et al., 2004).

1.3 Importance of North Africa to this Thesis

North Africa is of interest for this thesis because it is situated within the sphere of the climate dynamics characterizing the mid-latitude regions. According to Nash, and Meadows, (2012) North Africa's climatology is controlled by tropical circulation within Africa on the one hand and by mid-latitude cyclogenesis in the North Atlantic on the other hand. Records show that precessional forcing and insolation which are induced by variations in the earth's orbital motion about the sun were influential parameters that defined the North African palaeoclimate during glacial-interglacial times. As such, this thesis might also contribute to the project SFB806 "Our way to Europe" (www.sfb806.uni-koeln.de) which attempts to reconstruct environmental conditions such as climate change leading to the movement of homosapiens from Africa to Europe.

Palaeoclimate models have been simulated by many specialized meteorological institutes, agencies and projects under the umbrella PMIP3. One of the members of the PMIP3 is the MPI-ESM. The MPI-ESM simulated models of past climate conditions in different parts of the world, including North Africa. The results of the MPI-ESM simulations during the periods of the LGM and mid-Holocene for North Africa will be investigated and compared with sediment proxies that are of Northern African origin and from the selected periods of consideration. The objective is to ascertain if the results of the model would be confirmed by the sediment proxies.

Therefore, this thesis is organized as follows: (i) review of palaeoclimate changes in North Africa over the past 200 kyr (thousand years), (ii) analyses of published geological proxy data from two selected time periods, the LGM ~ 21 kyr BP (before present) and the mid-Holocene ~ 6 kyr BP, (iii) analyses of a selected member of the PMIP3 ensemble (i.e. MPI-ESM-P) with focus on the LGM and mid-Holocene, (iv) comparison of the proxy data with the model simulations.

2: REVIEWS ON NORTH AFRICAN PALEOCLIMATE SINCE 200 KYR BP

2.1 Palaeoclimate

Paleoclimatic studies in North Africa have been advanced through analysis of different proxies. According to Nash, and Meadows, (2012), these proxies include: paleolake shorelines and sediments, paleodrainage patterns, terrestrial and near-shore fluvial deposits, fossil groundwater systems and speleothems, pollen, macrofossil, phytolith accumulations on sedimentary facies and also aeolian activity. These proxies have contributed an immense variety of information to understand as well as corroborate the reconstruction of the paleoclimate in Africa.

Even though evidence from terrestrial palaeohistory is not as thorough and continuous as evidence generated from sediment cores in adjacent marine domains, records from palaeolakes and pollen have shed more light on the paleoclimate in continental North Africa. Nonetheless, marine records provide more continuous and complete paleoclimatic information for unravelling the climatic regime in North Africa (e.g. Hoelzmann et al., 2004 Petit-Marie et al., 1991; Nash, and Meadows, (2012)).

2.2 Periods Prior to the Last Glacial Maximum (LGM)

Since the last 200 kyr BP, records show that the climate of North Africa has undergone a series of glacial-interglacial periods, resulting in a dry or wet palaeoclimatic condition respectively. The periods spanning approximately 30, 45, 65-90 and 120-150 kyr BP in the Northern Sahara are described by Hoelzmann et al. (2004) as the most recent humid phases prior to the Holocene. The authors' submission was based on U/Th (Uranium-Thorium) dating of molluscs from the N.W. Sahara, as well as authigenic carbonates from southern Tunisia and eastern Sahara.

Changes in vegetation deduced from pollen records also support the assumption of humid phases. According to Hoelzmann et al. (2004), there was northward extension of Sudanian savannas (see figure 2.1) at about 130-74 kyr BP, coinciding with MIS 5 (marine isotope stages). They also said that the larger northward movement occurred between 130 and 120 kyr BP, and the smaller ones between 110-100 kyr and 90-80 kyr BP. Furthermore, they argue that between 125 to 115 kyr BP, the boundary of the Saharan-Sahelian shifted from 23°N to 15°N. This is indeed a sign of aridity and expansion of the desert. The characteristic back and forth migration of the Sahara-Sahelian boundary is a reflection of the prevailing palaeoclimate (see figure 2.1).

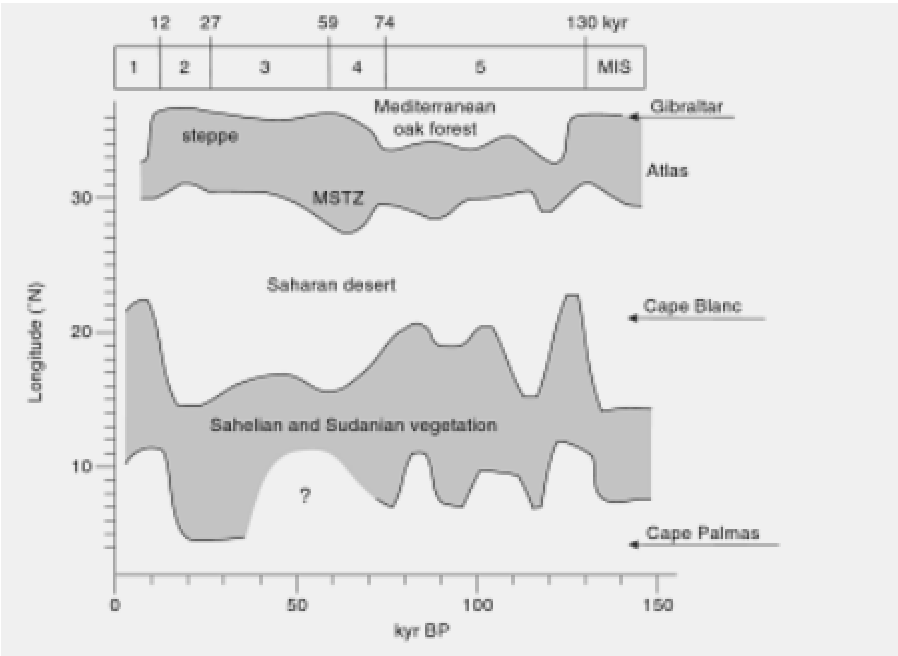

Fig. 2.1 Schematic representation of latitudinal shifts of vegetation zones in NW Africa during the last Glacial-Interglacial climate cycle. MIS: Marine Isotope Stage; MSTZ: Mediterranean Saharan Transitional vegetation Zone. Taken from Hoelzmann et al., 2004.

The study of Ehrmann et al., 2013 on a late Quaternary sediment core from the central Aegean Sea, also agrees with the general trend of humid climate in North Africa. However, they suggested that there were three conspicuous humid phases between sapropel layers S4, S3 and S1 formation. They narrow the time of occurrence of these humid phases in North Africa to greater than 105 to 95 kyr, 83.5 to 72 kyr and 14 to 2 kyr. They described the first two phases as being characterized by relatively abrupt lower and upper boundaries, and they agree that it depicts “a non-linear response of vegetation to precipitation, with critical hydrological thresholds”. On the other hand, the last humid phases were described by a more gradual onset and termination.

In addition, humid conditions during the Eemian (about 130 kyr BP) have been stated to be comparable to the conditions of the established “African Humid Period” which occurred in the Holocene. The Eemian humid periods occurred during the last interglacial cycles of the Pleistocene, corresponding to MIS5a, MIS5c and MIS5e (e.g. Tjallingii et al., 2008; Claussen, M. 2009). Opposed to that, MIS4 and MIS2 depict continuous arid condition that occurred during the maximum glacial episodes, while MIS3 is characterized by abrupt millennial-scale alternations of arid and humid events (e.g. Tjallingii et al., 2008). Additional information on the suggested starting dates of MIS can be seen on the link below (http://archaeology.about.com/od/mameterms/a/Marine-Isotope-Stages.htm).

In addition, analyses of Petit-Maire et al. (1991) on the atmospheric methane concentration and environmental changes in the Sahara and Sahel showed that methane concentration doubled during interglacial phases relative to glacial phases (figure 2.2). As observed from the Mediterranean core, at about 130 kyr BP, coinciding with the MIS5, the atmospheric concentration of methane was recorded to be at about 700 ppbv (part per billion by volume), being the highest recorded during the climatic cycle. At that period, eastern Mediterranean sediment cores contain layers of sapropel with the highest organic carbon content. Petit-Maire et al. (1991), argue that the presence of sapropel indicates the stagnation of deep and intermediate waters, due to a significant release of fresh waters from the Nile (note that: sapropel formation is a sign of increased humidity, fresh water availability and stratification that prevents thermohaline convection). The exceptionally low values of delta-18-Oxygen or heavy oxygen ($\delta^{18}O$) corroborate these claims.

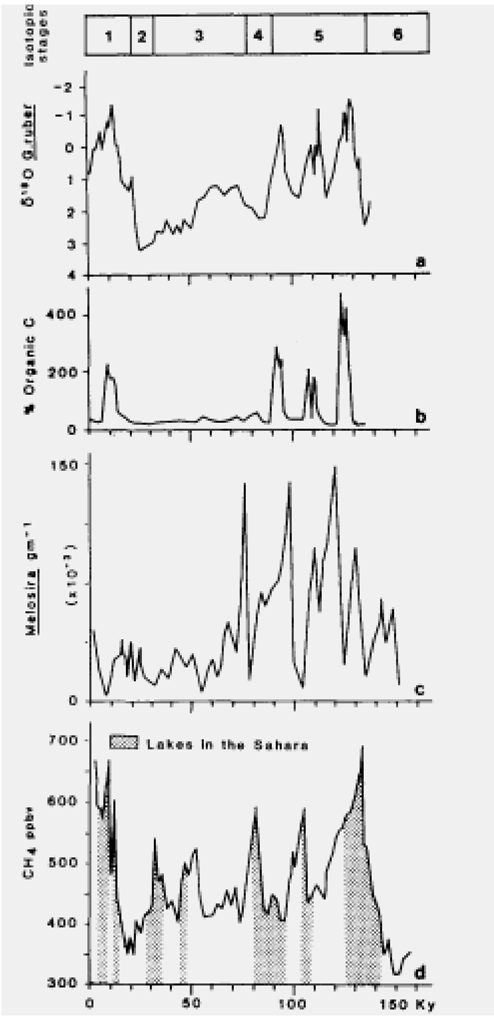

Fig. 2.2 Proxy results from Petit-Maire et al., 1991 – (a) Isotopic composition of G. ruber planktonic foraminifera in core 84641. (b) Organic carbon % from sapropel in core MD 84641 off the Nile delta. (c) Melosira sp. fresh water diatom in V 30-40. (d) Atmospheric CH4 changes in the last 150 kyr. At top: isotopic oceanic stages. Core MD 84641 (33°02''N/32°38'E, 1375 m) stratigraphy was based on sapropel identification, radiocarbon dating, oxygen isotopes and palaeomagnetism.

Cheddadi, 1988 (in Petit-Maire et al., 1991), stated that pollen analysis of sediment cores from the Nile river supports the increased humidity around the Mediterranean basin. The aeolian input of Melosira sp. (i.e. fresh water diatom) in the east Atlantic sediment is negligible. Records derived from pollen off the Sahara indicate a weakening of the trade-winds, thereby allowing the sub-tropical depression to reach the central Sahara (see Petit-Maire et al., 1991).

A similarly high concentration level of methane of 600 ppbv was recorded during MIS5c at about 106-96 kyr BP, as well as during MIS5a at about 82 kyr BP. Other recorded methane peaks were at about 52 kyr BP, where the value was 525 ppbv, and a conspicuous absence of Melosira sp. from the eolian records was noted. There was another peak at about 32 kyr BP, which was said to be the last interstadial methane peak at 550 ppbv.

Barrows et al. (2014) argue that the presence of a White Nile megalake during the last interglacial period adds to an emerging picture that the Sahara was an oasis-studded savannah. The high lake phase was given a probable age of about 100-110 kyr BP for Lake Megafazzan in the Libyan Desert, and about 95 kyr BP has been suggested to represent a humid phase in the western Sahara Desert based on uranium dating of lake sediments. Deep-sea cores taken off the west coast of Africa also inferred that during the last interglacial period the climate in North Africa was more humid because there were low inputs from dust and there was high river flow.

Analysis of a 50 kyr sediment core from the western Mediterranean by different proxies (such as clay mineral composition in dust, pollen, marine microfaunal and other properties) showed that there was frequent change of North African climate. This is a representation of stadial-interstadial cycles where conditions of greater atmospheric stability coincided with North Atlantic cooling (Nash, and Meadows, 2012). Such events lead to higher percentages of Artemisia pollen (a sign of aridity) that originates from the uplands of Morocco and increases Saharan dust transport.

The reasons given for this climatic pattern are ascribed to the influence and dominance of the north Atlantic on the late Quaternary and to precessional forcing as the most important climatic influence during this period (e.g. Nash and Meadows, 2012). Other authors such as Rossignol-Strick, 1985; Hilgen 1991; Lourens et al., 1996; Krom et al., 2002; Zabel et al., 2001;Tjallinghi et al., 2008 agree with this opinion that precessional influence is a viable factor that could have influenced the climate at that time.

It is noted that boreal insolation maxima (associated with precession index minima) produced an intensified African monsoon, and consequently wetter conditions that may in turn reduce the aridity in the North African climate. However, during precession maxima, there is increased evidence for regional aridity and dust supply from the Sahara (e.g. Tzedakis, 2007).

2.3 The LGM

Records from the LGM in North Africa are somehow ambiguous (e.g. Nicholson, and Flohn, (1980)). This is evident in the information from marine core sediments of the Mediterranean Sea, which infers a drier and obviously cooler LGM. However, this climatic inference differs with some terrestrial climate indicators in the areas around the Mediterranean (Nash, and Meadows, 2012). For example, in the analysis of 35 sites in the Maghreb by Rognon's (1987) on the basis of palaeosols, palaeolakes, alluvian or aeolian deposits and pollen, indicated a cooler and wetter period between 40 and 20 kyr BP. Further evidence from lake levels sourced from the eastern and northern Mediterranean sequences around this time indicates greater availability of moisture. Records from Lake Ifrah (Morocco) also conform to the evidence of greater moisture availability. Thus, the term Mediterranean 'pluvials' was given to describe the observed wet climatic scenario, believed to be "under the influence of a southward shift in the position of the mid-latitude Westerlies" (Butzer 1957. In: Nash, and Meadows, (2012)).

However, palaeovegetation evidence from the region does not support the pluvial scenario observed in the northern and eastern parts of the North African Mediterranean. Steppe that is usually associated with semi-desert conditions is dominant in pollen originating around the coastal region of the Mediterranean during this period of maximum glacial extent (Elenga et al., 2000. In: Nash, and Meadows, 2012).

In addition, a variety of pollen from the basal Tigalmamine core (Tigalmamine is a lake in the Middle Atlas of Morocco) also showed an abundance of grasses, chenopods and Artemisia, which are indicators of cold and arid climatic conditions. It is believed that from about 29 kyr BP onwards, the palaeoclimate appeared to be relatively colder and generally drier than today, with the most pronounced aridity at around 19.5 to 12 kyr BP (e.g. Rhoujjati et al., 2010. In: Nash, and Meadows, 2012).

Furthermore, detailed research on the basis of palaeolakes records in the late Pleistocene (prior to the Holocene) showed that the palaeoclimate prevailing in much of sub-tropical and tropical Africa, which is described as relatively arid, is at variance with that of broader North Africa (e.g. Nicholson, and Flohn, 1980).

Even though palaeoclimatic evidence from northern Africa during the late Pleistocene (c. 20 kyr to 12 kyr BP) is described by Nicholson, and Flohn, (1980) as “less conclusive and somewhat contradictory”, the general trend in research shows that relatively wet conditions prevailed in most areas of northern Africa from about 20 kyr to 14 kyr BP, except for northern Egypt.

Evidence of wet periods (also known as pluvials) shows that a terrace was formed in the Saouara (SW Algeria) as a result of increased flow from the Atlas Mountains at about 24 kyr to 14 kyr BP or later (e.g. Nicholson, and Flohn, (1980)). They also infer that the Soltanian terrace in Morocco could have formed within this time frame and the lowlands of Ahnet (Algeria) were covered with water at about 34 kyr to 18 kyr BP. In the Touat and erg Chech regions of Algeria, the occurrence of lacustrine development began after about 22 kyr BP. However, the Great Western Erg and the erg Chech were inactive during that period until about 10 kyr BP or later (e.g. Nicholson, and Flohn, 1980).

There was increased aquifer recharge in Algeria as well as Tunisia from 21 kyr to 15 kyr BP, and signs of aridity did not appear until 16 kyr BP or later in Algeria and Tunisia. In south-eastern Egypt, intense wadi activity occurred at about 17 kyr to 13 kyr BP, induced by wetter conditions and advancing winter extra-tropical rains towards more southern latitudes. However, in the Western Desert of Egypt, there was a major arid interval and the presence of an important Nile terrace during the same period. Nicholson, and Flohn, (1980) assumed that more powerful and more sporadic floods as an alternative to wetter conditions in the source regions of the Nile may be responsible for the occurrence.

Another period of brief aridity occurred in some regions of North Africa (e.g. near Touat, the Great Western Erg, the erg Chech, in southern Egypt and the Nile Valley, northern Cyrenaica i.e. the eastern coastal region of Libya, near Algiers and along the southern piedmont of the Atlas) during the peak of the higher latitude glaciers (about 18 kyr BP), leading to the formation of Dunes. But the exact timing of Dune formation in the region was not uniform. In the case of the Great Western Erg, dune formation was relatively long (began at about 19.8 to 17.5 kyr BP). Thus Nicholson, and Flohn, (1980) concluded that until about 12 kyr BP, the late Pleistocene palaeoclimate conditions in North Africa were predominantly wet, except for an arid interval at about 18 kyr BP that led to one or two arid millennia.

2.4 Early and Mid-Holocene

The work of Marret and Turon, (1993) on pollen and dinoflagellate cyst of a deep-sea core (mainly of clay sediment) extracted off the coast of Morocco, has also been used to ascertain the palaeoclimatic conditions in Northwest Africa (also known as the Maghreb) during LGM and the Holocene. Dinoflagellate as an organism is highly sensitive to temperature, salinity as well as nutrients.

Thus, assemblages of dinoflagellate cyst and pollen are good palaeoclimate indicators. In addition, the presence and distribution of pollen in the marine domain reflects the regional vegetation of the adjacent continent and can also infer the pattern of atmospheric circulation, which in this case, was driven by the north-eastern trade winds (e.g. Marret and Turon, 1993).

Furthermore, Marret and Turon, (1993) argue that the abrupt abundance of certain dinoflagellate cyst assemblages, such as Trinovantedinium capitatum, towards the end of Termination IA (it is a defined period prior to the Bølling-Allerød interstadial) and the Younger Dryas time slice suggest respectively cooler conditions of surface water masses and more arid conditions on the continent than present. This is also supported by the corresponding increase of pollen spectra from coniferous trees such as Pinus, Cedrus, and steppe elements such as Chenopodiaceae/Amaranthaceae, and Artemisia. This high abundance of Pinus pollen corresponds to the two periods when the atmospheric circulation gained strength at about 15 kyr BP (Termination 1A) and between 11 kyr BP and 10 kyr BP (Younger Dryas).

On the other hand, the high abundance of the dinoflagellate cyst assemblages, such as Lingulodinium machaerophorum, Operculodinium centrocarpum, Impagidinium, as well as the abundance of moist pollen elements such as Cyperaceae, Isoetes, and a corresponding decrease of steppe elements and Pinus during the Bølling-Allerød (about 14.1-12.9 kyr BP) and Termination IB, suggest a high abundance of humid components and enhanced freshwater water runoff due to a climatic shift towards more humid conditions.

According to Nicholson, and Flohn, (1980) analysis of inland palaeolakes in North Africa has advanced the understanding of the palaeoclimate conditions during the Holocene. During the early Holocene (about 12 kyr BP), north-eastern Africa was inundated with lacustrine episodes that attain a maximum at about 10 to 8 kyr BP. Radiometric dates from lacustrine deposits in the Sudan show that lakes were at their maximum between 11.3 and 8.3 kyr BP, and between 8.4 and 6.9 kyr BP near Kosti and Jebel Aulia respectively. These lakes were not fed by runoff from the White Nile, but rather from annual rainfall that was possibly three times higher than present (e.g. Nicholson, and Flohn, 1980).

The White Nile is said to have been less seasonal at about 12 kyr BP because of the overflow from adjacent rivers, such as Lakes Victoria and Albert. At about 8 kyr BP, it is assumed that the White Nile was higher and broader than present. The Blue Nile is described to have ceased aggrading its bed, changed to a meandering course, and begun depositing finer alluvial material which is indicative of a wetter climate regime than its prior deposition of sand and gravel before 12 kyr BP. The increased rainfall in the Ethiopian highland may have contributed to these changes (e.g. Nicholson, and Flohn, 1980).

The same lacustrine episode was observed in the Sahara highlands of Hoggar (Algeria), where Lake and marsh deposits near Tamanrasset were dated to about 11.5 and 8.3 kyr BP. Activation of the wadi system in Upper Egypt from about 11.5 to 9.5 kyr BP is a further sign of the southward shifting of the winter rainfall in North Africa in early Holocene times.

Evidence from other regions of North Africa (e.g. Northwest) showed increased aridity during this tropical lacustrine phase, while the eastern parts of Algeria, Tunisia, and possibly areas further east were relatively humid. The exact nature of the dry palaeoclimate as observed in the more western part of North Africa conforms to the end of the Younger Dryas of Marret, and Turon, (1993). However, Nicholson, and Flohn, (1980) were not certain if the dryness was relative to the present or if it is simply drier than the late Pleistocene humid phase.

Nicholson, and Flohn, (1980) describe the palaeoclimate in Northwest Africa as follows: At about 14 kyr BP, the Saoura (Algeria) began down cutting its floodplain, as a result of a dry phase that lasted until about 6 kyr BP. After about 10 kyr BP, the Great Western Erg and the Erg Chech (Algeria and Libya) became inactive. At about 12 to 8 kyr BP, aeolian sand was deposited at Laghouat (Algeria), while at Ouarghla (Algeria), evaporites developed and dunes were active from 9.5 kyr BP to sometime after 7.9 kyr BP.

Evidence from vegetation changes indicates a dry episode in the Algerian Maghreb from 14 to 9 kyr BP. The Chotts and Atlas region of Tunisia were relatively arid between 16 kyr BP and 8 kyr BP. However, within this arid period, brief humid phases occurred in the Maghreb at the peak of the tropical lake episode (e.g. between 9 to 7.5 kyr BP in the Tunisian piedmont north of Aurès while in the Algerian Maghreb, between 8.5 to 7.5 kyr BP). In the southern Libyan Desert an arid interval ended at about 9.5 kyr BP, while from 8.5 to about 6 kyr BP numerous playa lakes existed that are partly sustained by runoff from Tibesti (Chad). After 10 kyr BP several wetter phases occurred also in the Western Desert of Egypt as well as in the Nubia (a region between northern Sudan and southern Egypt).

2.5 Second Holocene Wet Phase

According to Nicholson and Flohn, (1980), a brief arid period was recorded at about 7 kyr BP in most tropical and sub-tropical areas of Africa. Afterwards, a second lacustrine episode began, in which deposits from stream flow suggest a semi-arid, more seasonal and more torrential rainfall regime. This period, according to the authors, also saw that the Blue Nile ceased aggrading and began down cutting, leading to lower level of 2 to 3 m.

The second lacustrine phase of the Holocene was characterized by increased rainfall in the semi-arid subtropics south of the Sahara and in the tropics further south, while north-western Africa and the northern fringes of the Sahara, were characterized by arid conditions. At about 6.5 to 4.5 kyr BP, wetter conditions than present characterized both the temperate and tropical margins of the Sahara, which led to a considerable shrinking of the desert belt (Nicholson and Flohn, 1980).

In both the Sudan and the Nile Valley, there was increased Nile flood after 7 kyr BP, and the levels of the floods were at least 5 m higher than present. A low flood stage was reached only after about 4 kyr BP, when wadi activity that indicates winter rainfall regimes, reduced to a minimum in Upper Egypt. The same pattern was observed in the Blue Nile, where floods of about 5 m higher than present were recorded. The river was still a sinuous and suspended-load channel that indicates a less arid rainfall regime, until 4 kyr BP. In other parts of North Africa, the period 6.5 to 4.5 kyr BP was wetter than present. For example, runoff from the northern part of Tibesti (Chad) continued to feed playa lakes in the Libyan Desert around this period (e.g. Nicholson and Flohn, 1980).

Further evidence detailing the second humid period in the North African Mediterranean region, as given by Nicholson and Flohn, (1980) are the following: After a humid period of 7.6-5.8 kyr BP, in which Mediterranean vegetation prevailed in the Tassili (south-east Algeria) near Ghat (Ghat lies in the Fezzan region of south-western Libya), a semi-arid vegetation developed between 5.5 and 4.5 kyr BP, to be succeeded by deposits of aeolian sand, which mark the present desert. Tassili near Djanet was also less arid from 8-4 kyr BP, and Mediterranean vegetation existed in the Hoggar (southern Algeria) until about 5.5 kyr BP. At about 6 kyr BP, dry episodes which earlier prevailed in southern Tunisia and near Laghouat (central Algeria) and Ouarghla (southern Algeria), the region of Saoura in south-western Algeria and in southern Morocco ended.

Wetter conditions prevailed in the region of the Saoura (south-western Algeria), and its terrace was covered with vegetation, from about 6.5 to 4.5 kyr BP, while lakes existed in the Erg Chech (south-western Algeria and northern Mali) from 6 to 3 kyr BP. The Touat (a natural region of desert in central Algeria) also became wetter while the dunes of southern Morocco became inactive toward 6 kyr BP. There is vegetation evidence of increased precipitation in the Maghreb from about 8.5 to 4 kyr BP. During the core of this humid period at about 6.5 to 4 kyr BP, rainfall may have been 300 to 600 mm greater than present (Nicholson, and Flohn, 1980).

Silts containing freshwater mollusca near Biskra (Algeria) indicate a humid episode at about 5.4 kyr BP. A calcareous deposit and palaeosols suggest similar conditions in the Monts d'Ougarta (Algeria) between 5 to 4 kyr BP. At Tihodaine (Algeria), marsh deposits that are radiometrically dated to 4.9 kyr BP, also correlate with this evidence. On the basis of fauna, flora and archaeology, the reconstruction of Libyan and Egyptian climate also indicated a humid period north of the Sahara (Nicholson, and Flohn, 1980).

2.6 Summary

By consideration of the foregoing descriptions, the climate of North Africa for the last 200 kyr BP is characterized by dry climate conditions that extended into the early parts of 200 kyr ago (which is an extension of MIS 6) and is then progressively replaced by warmer climates from about 150 kyr BP onwards (beginning of MIS 5). These periods were marked by increases in precipitation across Africa north of the Sahara. The interludes or relapses into cold and dry climates during the periods 150 to 30 kyr BP are good indicators of climate change. What was however conspicuous in North Africa, was the significant shift or movement of greener vegetation covering a vast area of the Sahara during wet climates to a drier or desert-like ecosystem during colder climates. Thus the latitudinal boundary between wetter and drier climate stages was constantly in transition over North Africa with respect to the prevailing climatic condition.

The LGM and the Holocene epoch in North Africa was even more interesting because studies have shown that cold and drier conditions associated with the LGM and Younger Driers were not uniform across the region. Palaeosol and Palaeolake studies showed that eastern and northern parts of North Africa as well as the Maghreb were still inundated by wet climates even during the LGM. However, on the basis of palaeovegetation, the western parts of North Africa exhibit evidence of desert-like conditions (e.g. presence of Steppe and Artemisia pollen) that are associated with the LGM.

The onset of the Holocene in North Africa was marked with conspicuous changes. There was a marked shortening of the extent of the Sahara desert and an expansion of greener vegetation from southern part of the Sahara (Sahel region) northwards. This phenomenon of intense humidity and water availability was widespread over North Africa. However, during the later part of the early Holocene (ca. 7 kyr BP), there was a partial return to a cold and drier climate in North Africa.

Immediately after this partial break of the cold period, a wetter period in the mid Holocene returns (ca. 6.5 to 6 kyr BP) where the hydrology was once again inundated with water although not comparable to the early Holocene period. Conditions reminiscent of today started at about 4 kyr BP. This period once again rejuvenated the expansion of the Sahara southward and restricted precipitation to a seasonal phenomenon, and an attendant increase in temperature.

Climatologically, the whole process of climate change is adduced to many factors, of which the most important were precessional forcing (rotation of the earth around its axis as a result of an external force e.g. gravitational attraction between the Sun and Moon, and between Planets), boreal insolation maxima, and associated boundary conditions (such as Polar front, North Atlantic Oscillation, Orography, etc).

3: PUBLISHED GEOLOGICAL PROXY DATA FOR THE LGM AND MID-HOLOCENE

3.1 Introduction

This part of the thesis presents two main geological (sediment) proxies: palygorskite and the kaolinite/chlorite (k/cl) ratio. These proxies will be the basis for comparing the LGM and mid-Holocene periods with PMIP3 model simulations of the same periods and for selected areas in North Africa. The proxies are based on Bout-Roumazeilles et al. (2007) and Ehrmann et al. (2013) respectively.

The proxy palygorskite, as examined in Bout-Roumazeilles et al. (2007), is found in the north-western part of North Africa. It is based on the mineralogy of clay derived from core extraction in the Alboran Sea. The proxy k/cl ratio, as examined in Ehrmann et al. (2013), is found in the north-eastern part of North Africa. It is also based on the mineralogy of clay sediments derived from core extraction in the Aegean Sea. Both proxies serve as good indicators of geographic origin and for palaeoenvironmental reconstruction. They will be used for this thesis to infer the palaeoclimate as well as to compare the PMIP3 simulation models for both the Maghreb and Nile Valley region of North Africa respectively.

3.2 The published paper of Bout-Roumazeilles et al., 2007

The first geological proxy adopted for this thesis is deduced from the paper of Bout-Roumazeilles. The proxy palygorskite is a clay mineral that is (among other clay minerals) analyzed by the authors based on a clay sediment core extracted from ODP site 976 (see figure 3.1) in the Alboran Sea. The focus of the clay mineralogical analyses was on the interpretation of the upper 25 m depth of the core extraction, which covers the time period of 50 kyr ago.

The average clay composition contained 33% illite, 31% smectite, 16% kaolinite, 15% chlorite and 5% palygorskite. The authors observed that all the clay minerals found in this site show several oscillations during the LGM. However, in the Holocene, there was little variation in their abundances. Furthermore, pollen analysis was employed to indicate the presence of Argania pollen, which was also used to localize Morocco as the main source location of palygorskite to the Alboran Sea sedimentation.

3.2.1 The Alboran Sea

The Alboran Sea is a semi enclosed basin at the westernmost part of the Mediterranean. It is described to be positioned in a transitional window between the Atlantic Ocean and the Mediterranean Sea (see figure 3.1).

3.2.2 Sedimentation in the Alboran Sea via the Mediterranean Sea

Sedimentation in the Alboran Sea on the basis of grain sizes and elemental compositions is dominated by aeolian deposition, especially during the North Atlantic cold events. Sediments reaching the Alboran Sea usually originate either from discharges into the Mediterranean Sea or wind-borne from landmasses around the Mediterranean areas.

Sedimentation in the Mediterranean Sea is described by the authors as being mainly terrigenous due to its closeness to continental landmasses. There exists a network of rivers discharging into the Mediterranean as well as huge sources of aeolian deposits. In recent times, part of the huge clay detrital that is deposited in the Mediterranean Sea was channelled through river sources. For example, the Nile River is the biggest channel through which detrital deposits flow into the eastern Mediterranean while the Rhone River is the largest source in the north-western Mediterranean Sea.

However, the huge contribution of aeolian sediments has also been widely acknowledged, especially the fine-grained fraction, which has the tendency to travel as far as aerosols. Desert dust rises as a pool of massive plumes with the support of strong winds, and is transported to the Atlantic Ocean as well as the Mediterranean. Throughout the years, studies carried out in the Mediterranean, have determined that aeolian sedimentation contributes significantly to the western Mediterranean Sea and the Alboran Sea compared to riverine sedimentations.

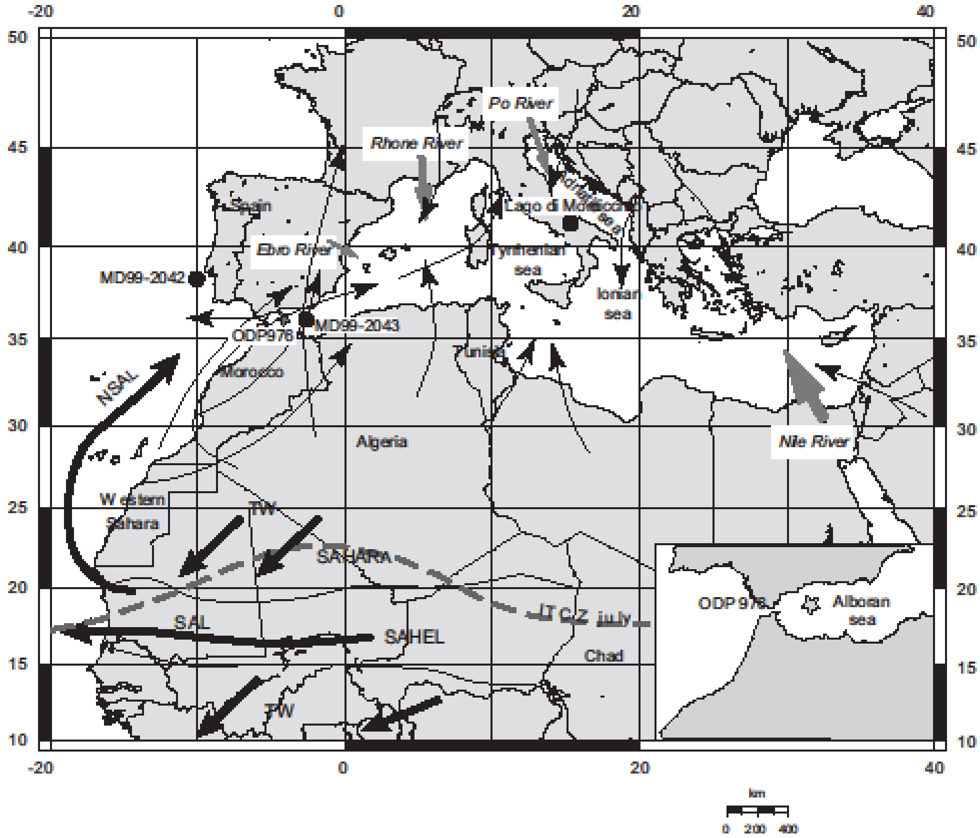

Fig. 3.1 Main wind trajectories (black arrow) and rivers supply (gray arrow) in the Mediterranean area, ODP site 976. The geographical boundary between Sahara and Sahel is noted. SAL: Saharan air layer, TW: northeast trade winds, NSAL: northern branch of the SAL, ITCZ July: position of the Inter-Tropical Convergence Zone in July. Taken from Bout-Roumazeilles et al., 2007. (For a description of the wind system, refer to section 2.3. of Bout-Roumazeilles et al., 2007).

3.2.3 Sources of dust to the Alboran Sea via the Mediterranean Sea

The main sources of dust influx into the Atlantic Ocean and the Mediterranean Sea, comes from arid regions in the Sahara as well as semi arid regions of northern North Africa and the Sahel. The authors differentiated source areas by grain sizes and transport mechanisms.

Dust particles with the coarsest grain fraction are said to have originated from remobilized Saharan dunes while finer grained fractions are from palaeosols and little formations that have been consolidated around the southern and northern borders of the desert. Coarse grained particles are typical of dust storms and are restricted to continental and adjacent marine locations. They are usually transported by trade winds at high altitude (e.g. Torres-Padrón et al., 2002. In: Bout-Roumazeilles et al., 2007). On the other hand, finer grained particles (usually less than 2 µm) travel at higher altitude over longer distances (e.g. Schütz, 1980. In: Bout-Roumazeilles et al., 2007).

3.2.4 Mineralogy of the investigated sediment core of ODP site 976

The clay minerals in the ODP site 976 are typical of mineral deposits in the western Mediterranean. A detailed account of the clay mineralogy and the distribution of sediments in the western Mediterranean Sea is given by the authors (see figure 3.2). The purpose is to understand and visualize the different composition of the clay sediments in the Alboran Sea.

The average sediment from the Western Mediterranean is predominantly composed of 50% illite and 25% kaolinite, smectite 15% and chlorite 10%, while palygorskite (fibrous clay) occurs in trace amounts.

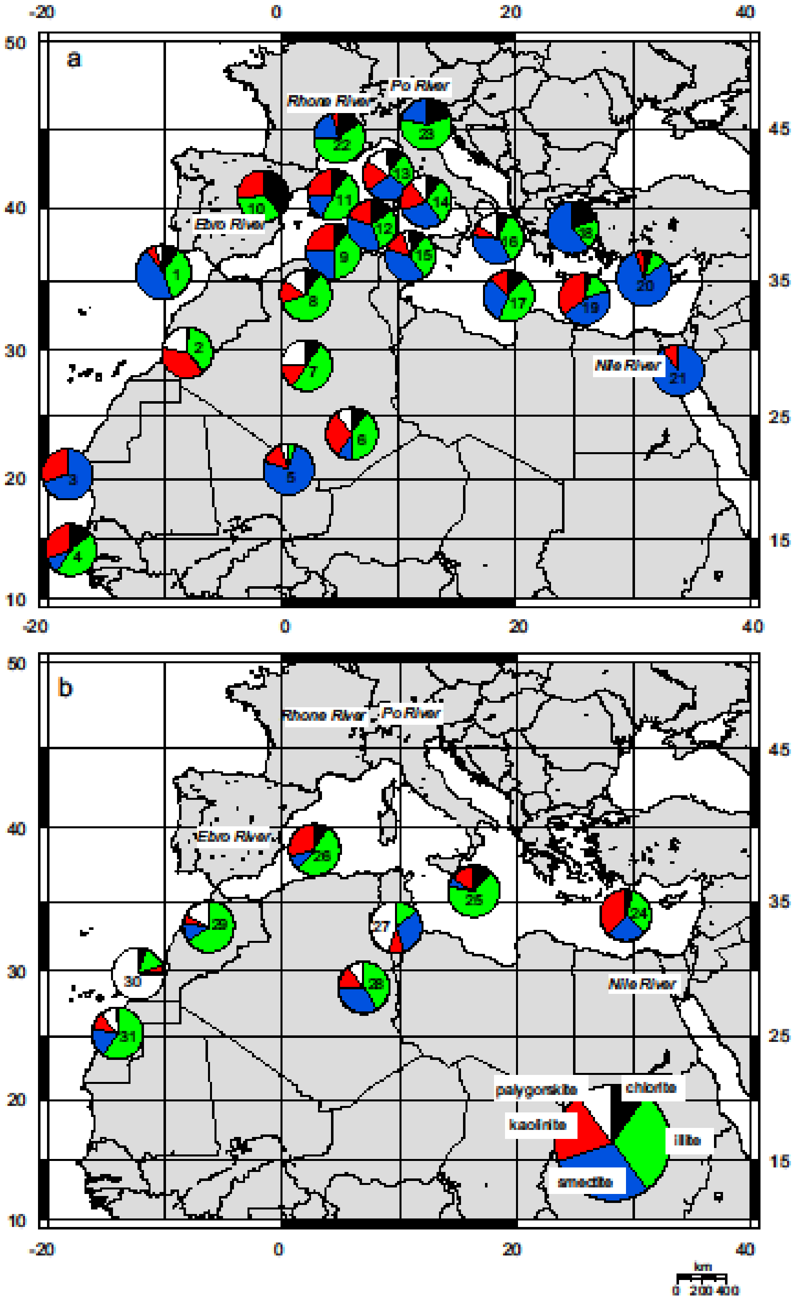

Fig. 3.2 Clay mineralogy and distribution (a) peri-Mediterranean river particles and sediments (in %) and (b) dust and aerosols (Pastouret et al., 1978; Coude´-Gaussen, 1982; Paquet et al., 1984; Robert et al., 1984; Chamley, 1989; Alonso and Maldonado, 1990; Grousset et al., 1992; Avila et al., 1997; Guerzoni et al., 1999; El Mouden et al., 2005). 1: Gibraltar, 2: Morocco; 3: Cape blanc, 4: Cape Verde, 5: Tanezrouft, 6: Tamanrasset, 7: In Salah, 8: northern Algeria, 9: Algerian shelf, 10: Ebro river, 11: western Mediterranean sediments, 12: Sardinia, 13: Corsica, 14: Tyrrhenian sea, 15: Malta, 16: Ionian sea, 17: central Mediterranean sediments, 18: eastern Mediterranean sediments, 19: Aegean sea, 20: Florence rise, 21: Nile river, 22: Rhone river, 23: Po river, 24 eastern Mediterranean aerosols, 25: central Mediterranean aerosols, 26: western Mediterranean aerosols, 27: Tunisian loess, 28: dust from central Algeria, 29: dust from Moroccan Atlas, 30: Moroccan dust, 31: dust from central Sahara. The above information is taken from Bout-Roumazeilles et al., 2007.

Illite is described as a product of physical weathering, which is resistive to degradation and to transport. The main source of illite into the northern Mediterranean Sea is from the Alps. The Rhone and Po rivers are the major channels of illite into the northern Mediterranean Sea.

In North Africa, illite concentration decreases from north to south. It accounts for 60% of the clay mineral constituent in northern Algeria, 50% in central Sahara and less than 30% in the Sahelian region.

Chlorite is usually associated with illite. It is however, less resistant to weathering and transport, and often a reflection of the composition of adjacent source environment. The main source of chlorite to the north-western part of the Mediterranean basin is the Ebro sedimentary system.

Kaolinite, derived from the processes of hydrolysis, is typical of a highly weathered environment such as well-drained lateritic soils that define the equatorial sectors. It is rare (about 10%) and usually originates from reworked ancient formations, e.g. in the Rhone and Nile rivers sediment, the Ebro River and not present in the Po River.

The distribution of kaolinite in North Africa, however, depends on the latitude. For example, in the northern and westernmost part of North Africa, it is found in trace amounts, whereas it is common in central and South Sahara, Sahelian and equatorial regions. On the basis of aeolian transportation, kaolinite is described to be more abundant in eastern Sahara dust than in western Sahara dust.

Smectite is not a mineral found in abundance on the western part of the Mediterranean because of its increasing distance from the Nile River, which is described as the main contributor of smectite in the Mediterranean Sea. In the North African sector, smectite is said to be rare in northern Sahara, however, in southern Sahara and the Sahel, smectite abundance could represent about 70%. Smectite is associated with kaolinite derived from ancient lateritic bodies.

3.2.5 Geological Proxy 1 – Palygorskite

Palygorskite, which is the main parameter in this section of the thesis for reconstructing the change in palaeoclimate in the north-western part of North Africa, is described by the authors to be representative of the sub-arid belt of the northern hemisphere. Palygorskite prefers to form in environments that favour chemically restricted conditions, such as the anti-Atlas where poorly drained carbonate rocks evaporate and concentrate chemically, setting the condition for palygorskite formation. Palygorskite is of relatively minor importance in other areas of the peri-Mediterranean region, because it occurs only in trace amount and because it is easily destroyed while transported by rivers.

3.2.6 Palygorskite Mode of Transportation and Sources

Several studies off North Africa (e.g. Chamley, 1989; Coudé-Gaussen et al., 1982; Molinaroli, 1996; Coudé-Gaussen and Blanc, 1985; Avila et al., 1997) have built up a consensus proving palygorskite to be predominantly of aeolian transport. In addition, to palygorskite travelling in dust particles over long distances, the potential source areas of palygorskite are western Morocco, northern Algeria, central Algeria, southern Sahara and reworked Neogene deposits of North African.

3.2.7 Composition of Palygorskite

The composition of palygorskite varies with the location of the source areas. For example, in northern Algeria, the clay mineral fraction contains between 10 and 15% palygorskite, in central Algeria, the clay mineral fraction contains between 10 and 25% palygorskite, and less than 10% palygorskite in southern Sahara. In the case of the dust fractions, central Algeria contains 10% palygorskite, western Sahara contains 10% palygorskite, Morocco Atlas contains 17% palygorskite, while dust originating from northern Morocco contains 75% palygorskite

3.2.8 Importance of palygorskite to the Thesis

Palygorskite is important as a palaeoclimate indicator because it characterizes arid and semi-arid climate. Its area of provenance and mode of deposition can be additionally constrained by the illite/kaolinite (I/K) ratio. Palygorskite in association with the pollen Argania defines north-western Africa (especially southern Morocco) as its origin. Palygorskite can be used to determine the Saharan origin of dust.

Finally, the other clay minerals (e.g. illite, kaolinite, smectite and chlorite) can be transported to the Alboran Sea through various options (e.g. oceans, rivers and dust). Thus their variations are not unique and less informative in terms of global atmospheric configurations. However, palygorskite is mainly transported aeolian to the Alboran Sea. This makes palygorskite an important palaeoclimate indicator.

3.2.9 The Illite/Kaolinite (I/K) ratio for determining palygorskite provenance

The I/K ratio is an additional tool for determining the probable origin of palygorskite in dust transported particles. This ratio is reliable because it stays unchanged after long-term transport. By evaluating this ratio, it is possible to determine whether the source is aeolian or riverine. It can also infer the regional origin of Sahara dust. Dust from North and West Sahara is described to be enriched in illite if the ratio of I/K is 2. However, if the ratio is 0.1, the kaolinite content is enriched and therefore, the dust has a Sahelian origin. Dust from south and central Sahara is characterized by intermediate I/K of 0.4.

3.2.10 Interpreting palygorskite as a palaeoclimate indicator

The percentage of palygorskite in the clay minerals fraction from the ODP site 976 is interpreted to be between 3 and 11%. Several significant peaks characterize the palygorskite record as observed in figure 3.3. The peaks are associated with cold climatic events such as the Younger Dryas (YD) and the Heinrich Events (HE). Apart from these peaks, the record is best described as smooth and showing very marginal variations. However, the Holocene record shows decreased amount of palygorskite (see figure 3.3).

The increase of palygorskite during the glacial events is remarkable in comparison to other analyzed clay minerals. This is because other analyzed clay minerals show multiple peaks that are oscillating and at best incongruous records. However this characteristic behaviour of other minerals was absent in the palygorskite record and therefore makes it a better palaeoclimate indicator.

The authors found that the I/K ratio in the analyzed data ranged from 1.35 to 3 with an average value of 2.1. They stated that this range of values did not alter significantly in the periods of the cold events, implying that aeolian contribution may have been dominant in the Alboran Sea. The argument supporting this point of view is deduced from the rather low I/K ratio of 1.38 derived for proximal riverine sources. In the case of the core extract within the studied area, the I/K ratio ranges from 1.3 to 2.6. This range of values confirms that the sources of dust are from the North and West Sahara. This result rules out any contribution from Sahel with an I/K ratio of less than 0.25 or South and central Sahara with I/K ratio of 0.4 to 0.7.

On this basis, Bout-Roumazeilles et al. (2007) argue that during the North Atlantic cold events the I/K ratio remains unchanged (i.e. I/K = 2) while there is an increase in the palygorskite content. Their interpretation indicates a greater contribution of aeolian source that is characterized by a high content or deposition of palygorskite originating most probably from western Morocco.

3.2.11 Palygorskite Association with Argania Pollen

The presence of Argania pollen is described as typical of southern Morocco, and usually occurs in areas of low precipitation (200-400 mm) and positive temperatures. By appending Argania with positive temperatures, the authors reason that Argania is evidence of intense aeolian transportation from southern areas of the Mediterranean Sea during the HE. They added that Argania pollen were probably transported together with palygorskite from southern areas, which were not so cold but arid, to the Alboran Sea. The discovery of Argania pollen in close association with palygorskite during the HE (H1 to H4) supports a southern origin of the dust in the Alboran Sea sediments.

Finally, a modified figure (originally from Bout-Roumazeilles et al., 2007) of Nash, D.J, and Meadows, M.E, (2012) is presented in Figure 3.3. It serves as a basis for comparing palygorskite with palaeoclimate models (see chapter 4). The goal is to apply this data (i.e. figure 3.3) in the comparison of the reconstructed north-western Africa (i.e. Maghreb) models of climate changes during the LGM and the mid-Holocene.

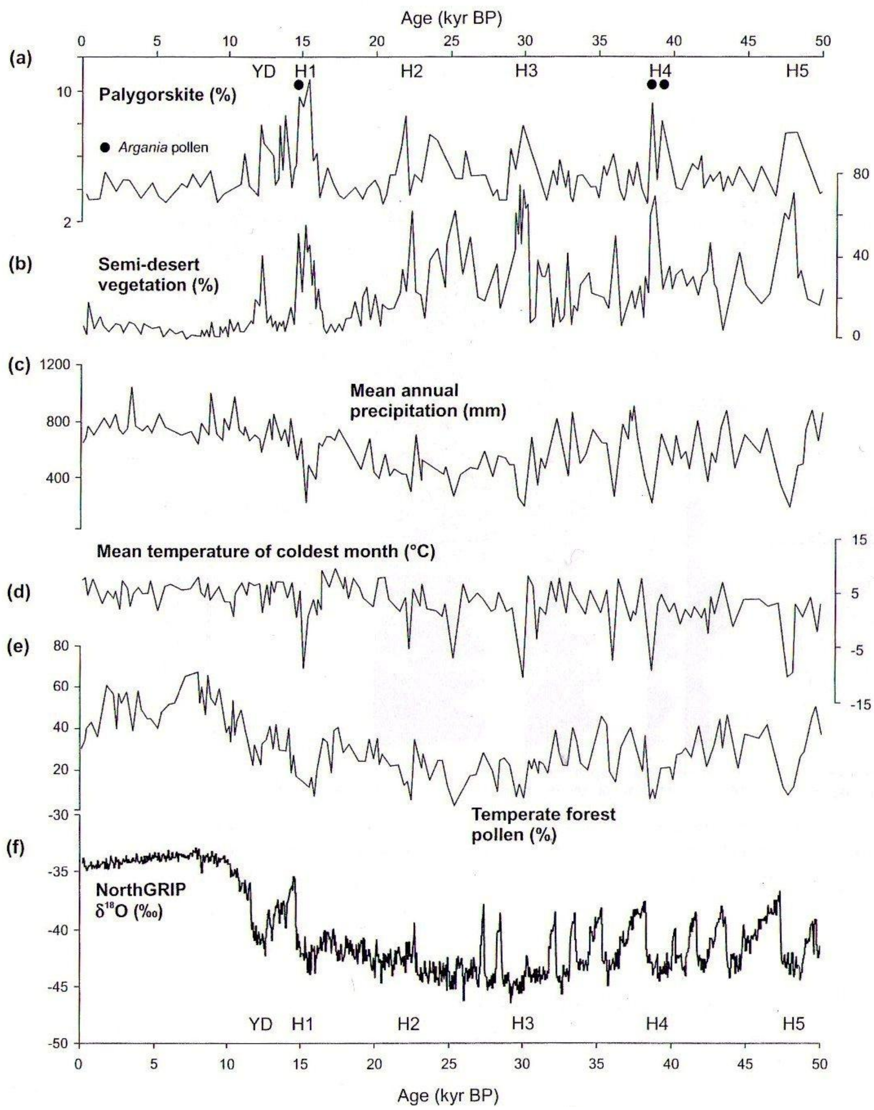

Fig. 3.3 Analysis of palygorskite – Data from core ODP 976 in the western Mediterranean Sea showing the relationship between (a) palygorskite content, (b) semi-desert vegetation abundance, (c) mean annual precipitation, (d) mean temperature of the coldest month, (e) temperature forest pollen and (f) oxygen isotope ratios at NorthGrip. The timing of the Younger Dryas (YD) and Heinrich Events (H1-H5) are also indicated. Palygorskite is regarded as a proxy for Saharan dust inputs to the Mediterranean basin at this site, while pollen from Argania is suggested to be of western Moroccan origin. Taken from Nash, and Meadow, (2012).

3.3 Published Article of Ehrmann et al., 2013

The published work of Ehrmann et al. (2013) on the extracted clay sediment core named “GeoTü SL143” of over 105 kyr BP, from the central Aegean Sea, is divided into sub topics below.

3.3.1 Climatology of the Eastern Mediterranean Sea

Ehrmann et al. (2013) describe today’s climate over the Eastern Mediterranean Sea as a climate that is influenced by the temperate European and the subtropical African climate systems. They argue that strong temperature gradients characterize the Eastern Mediterranean climate and that the large-scale atmospheric circulation is determined by the position and strength of the semi-permanent North Atlantic high (i.e. Azores) - and low (i.e. Icelandic) - pressure systems, which have a strong seasonal contrast.

During wintertime, the Mediterranean region is influenced by westerly air streams that combine with cold outburst of winds originating from the south European mountain areas. The result of this interaction is the development of cyclones over the western basin which then travel eastwards resulting in intensified winter precipitation. The Mediterranean region are generally dry and hot during summer due to the northward displacement of the westerly winds.

As a result of the above exemplified climatic condition, Ehrmann et al. (2013) stress that the Mediterranean region is separated from the zonal circulation. They state that the climate is rather controlled by internal dynamics, originating from differences in temperature between surface waters and surrounding borderlands. Closely following the stated internal dynamics is the Sirocco wind, a hot southerly desert wind that occurs during spring and early summer.

3.3.2 Morphology and flow regime of the Aegean Sea

The Aegean Sea is the northern part of the Eastern Mediterranean Sea. It is of interest to this thesis because of its marginal and semi-closed shape. As a result of this pattern, the Aegean Sea has the ability to react to, as well as to preserve long- and short-term climatic changes occurring on the adjacent landmasses.

The authors describe that a certain portion of the Mediterranean surface waters flow into the Aegean Sea. From there, water flows parallel to the eastern coast to the north, where it mixes with the colder Black Sea Water. Thereafter, the water flows west and then northwest in the direction of the northern Aegean Sea and then south and southwest parallel to the coast of Greece (see figure 3.4).

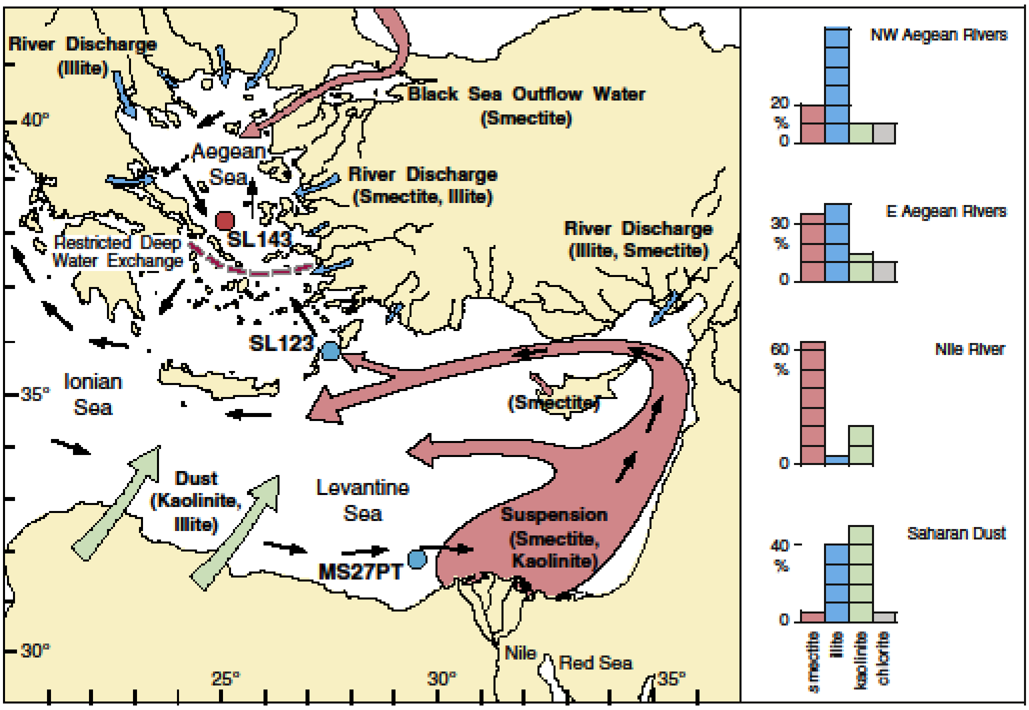

Fig.3.4 Location of the investigated sediment core GeoTü SL143 in the central Aegean Sea and the most important recent sediment source areas, transport processes and transport paths for the main clay mineral groups (after Ehrmann et al., 2007a, following Venkatarathnam and Ryan, 1971; Foucault and Mélières, 2000). Black arrows indicate the surface circulation (after Pickard and Emery, 1990; Aksu et al., 1995). The locations of cores MS27PT and GeoTü SL123 are also indicated. The histograms indicate the generalized clay mineral composition of sediments delivered by NW and E Aegean Rivers (after Ehrmann et al., 2007a), the Nile River (after Hamann et al., 2009) and of Saharan dust in the eastern Mediterranean (after Chester et al., 1977). The above information is taken from Ehrmann et al., 2013.

3.3.3 North African dust

Dust generation in North Africa, is one of the most effective sources in the world. It brings large quantities of wind-blown sediment to the Mediterranean Sea. The major source aiding the transport of dust in North Africa is the sirocco wind. Furthermore, Pye, (1992), Goudie and Middleton, (2001), Prospero et al. (2002), Engelstaedter et al. (2006), Stuut et al. (2009), Scheuvens et al. (2013) associated the Sirocco winds with large dust storms travelling over thousands of kilometres across northern Africa and the Mediterranean Sea towards Europe.

In contrast, wind transport within the hinterland of the northern and eastern Mediterranean, is described to be only of minor importance.

Furthermore, Pye, (1992) argues that dust deposition in the Aegean Sea, originating from North Africa mostly occurs during March and April. It is also connected with southerly and south-westerly winds (Sirocco). Other sources of dust in North Africa are the central and eastern desert of Libya, southern Algeria, central Sahara and specifically the Bodélé Depression in the Chad Basin (see Ehrmann et al., 2013).

According to the authors, the concentration and dispersal of aeolian dust is a function of the surface wind velocity and the availability of erodible wind-borne material. These also depend on the vegetation cover and precipitation, soil composition, moisture content and surface structure.

In addition, deMenocal et al. (2000), Drake et al. (2008) and Stuut et al. (2009) argue that a large portion of the North African dust comes from the erosion of lake sediments that were deposited during enhanced wet phases than today. Thus an increase in the deposits of dust and their dispersal may indicate a sudden rise in the proportion of erodible material due to sudden dryness of large playas and lakes and of their sediments. On the other hand, dust sources are mostly restricted to areas with an average wind velocity beginning from 8 m/s and less than 200-250 mm annual rainfall (see Ehrmann et al., 2013).

3.3.4 Mineralogy of the investigated sediment core GeoTü SL143

The analyzed clay sediments of the Eastern Mediterranean seafloor are similar to those discussed in the western Mediterranean Sea (except for palygorskite). However, they are described to be majorly made-up of detrital. They consist of smectite, illite, chlorite and kaolinite, and their concentrations show variability from the source areas (figure 3.4; e.g. Venkatarathnam and Ryan, 1971; Foucault and Méliéres, 2000; Ehrmann et al., 2007a; Hamann et al., 2009; Poulos, 2009).

The properties of these clay minerals have already been discussed in the Maghreb section above. Only additional attributes that make these minerals unique in the Nile Valley will be mentioned. However, the emphasis in this section is on the mineralogy of kaolinite and chlorite.

The Nile River discharges into the south-eastern Levantine Sea bringing smectite and other minerals (e.g. kaolinite). They are redistributed through the surface current along the coasts of Israel, Lebanon, Syria and Turkey towards the northern Levantine Sea and most likely to the southernmost Aegean Sea. However, Venkatarathnam and Ryan, (1971) and Weldeab et al. (2002) argue that the minerals do not reach the central Aegean Sea (see figure 3.4). Illite, on the other hand, flows mainly from the south European rivers as well as from the Turkish rivers into the Aegean Sea. In addition, component of illite is carried along with the aeolian dust that enters the Eastern Mediterranean Sea from North Africa.

3.3.5 Geological Proxy – 2: The kaolinite/chlorite ratio

In the Eastern Mediterranean region, it is common to find argillaceous sediments and low-grade chlorite-bearing metamorphic rocks. Thus, chlorite is common in the seafloor surface sediments throughout the Aegean Sea and it occurs in minor amounts of less than 12%. In addition, chlorite shows no dominant point source (Ehrmann et al., 2007a; Poulos, 2009), and shows only minor temporary changes in sediment cores. Because of the relatively negligible increases in the proportion of chlorite of the Aegean Sea cores, in comparison to the simultaneous decrease in the kaolinite content, the authors conclude that the k/cl ratio in the Aegean Sea is mainly controlled by the kaolinite content.

Kaolinite is said to be derived mostly from chemical weathering of basement rocks, requiring humid and warm conditions for its formation. High concentrations of kaolinite occur in regions with long lasting, intense hydrolysis and lateritic soil formation. Kaolinite can also be reworked from older sedimentary rocks and soil because it is very resistant.

In today's Aegean Sea region, there are only minor potential source areas from where kaolinite can be supplied. That explains the less than 15% kaolinite content in seafloor surface sediments of the Aegean Sea and the absence of a distinct source for kaolinite on both the nearby landmasses and the Aegean islands (see Ehrmann et al., 2013).

On the contrary, the African continent on the basis of the large quantities of kaolinite provided by the Nile River, has been designated a more likely source for kaolinite. The concentration of kaolinite reaches about 25% in the Nile delta as well as in the southern Levantine Sea. This is due to erosion of because kaolinite from Mesozoic, Palaeozoic and Eocene sediment deposits and lateritic soils which are common in Egypt. In addition, the clay fractions of these sediments in Egypt have up to 70% kaolinite concentrations (e.g. Stanley and Wingerath, 1996; Bolle et al., 2000). But, as mentioned above, kaolinite does not reach the central Aegean Sea through fluvial activities. Rather, kaolinite is deposited mainly through aeolian supply to the Aegean Sea and kaolinite is derived mainly from the North African desert.

3.3.6 Proof of kaolinite occurrences in North Africa

Kaolinite occurrences in North Africa have been attributed solely to the erosion of old kaolinite-bearing sediments (as discussed above) and in addition, the Cretaceous Nubian sandstone (north-east Africa). The authors diagnosed further that kaolinite concentrations originating from the North African dust of the south and central Saharan also contain a high concentration of about 50% kaolinite. The authors stated that the overall higher concentrations of kaolinite in sediment cores extracted from the southern basins as compared to those extracted from the northern basins of the Aegean Sea, prove their theory of an aeolian origin for kaolinite in the Aegean Sea.

Furthermore, satellite images, direct observation and sedimentological studies, according to the authors, have proven that the Aegean Sea regardless of its relative position in the Eastern Mediterranean Sea is a receptor of North African dust. Other researchers such as Roussakis et al. (2004); Nihlén and Olsson, (1995) and Pye, (1992) corroborated the authors' claim that North Africa is the aeolian origin of kaolinite and there is a dominance of kaolinite in the Aegean Sea clay fraction.

3.3.7 Importance of kaolinite/chlorite ratio to palaeoclimate reconstruction

The importance of using the k/cl ratio as a parameter for reconstructing palaeoenvironment is that it can be used to infer wind activity, aridity and vegetation cover in the source area. Kaolinite being present mainly in the fine fraction of the dust can quickly indicate subtle changes in the climate system compared to other windblown mineral proxies. For example, the use of the concentration of the terrigenous sediment fraction as defined by deMenocal et al. (2000) or end-members of the silt fraction as defined by Hamann et al. (2008) and Tjallinghii et al. (2008), for environmental reconstruction, requires different approaches such as analyzing the coarseness of the dust fraction. To use these methods, different wind strength and intensity may be required. However this is not the case for kaolinite because its ease of deposition usually reflects aridity. Thus, the authors stated that, the presence of more dust indicates more aridity, whereas the presence of coarser grain sizes indicates stronger winds (after Rea, 1994).

3.3.8 Interpreting the kaolinite/chlorite ratio as an environmental indicator

The authors state that seasonality between wet and dry deposition regimes may affect the concentration of kaolinite in sediments of the central Aegean Sea. However, the most dominant controlling factor determining the concentration of kaolinite depends on the ability of the African wind systems to erode and transport sediment particles, which is directly related to the aridity of the source area (e.g., Rea, 1994; Foucault and Méliéres, 2000; Trauth et al., 2009).

On that basis, reconstructing a palaeoenvironment based on the ratio between kaolinite and chlorite (see figure 3.5c) shows that high kaolinite abundance indicates dry conditions in North Africa. This also shows that erosion was not inhibited by vegetation and that there was intense wind activity. On the other hand, low abundance of kaolinite is associated with humid conditions, probably combined with a vegetation cover that prevents wind erosion, and therefore restricts aeolian transport.

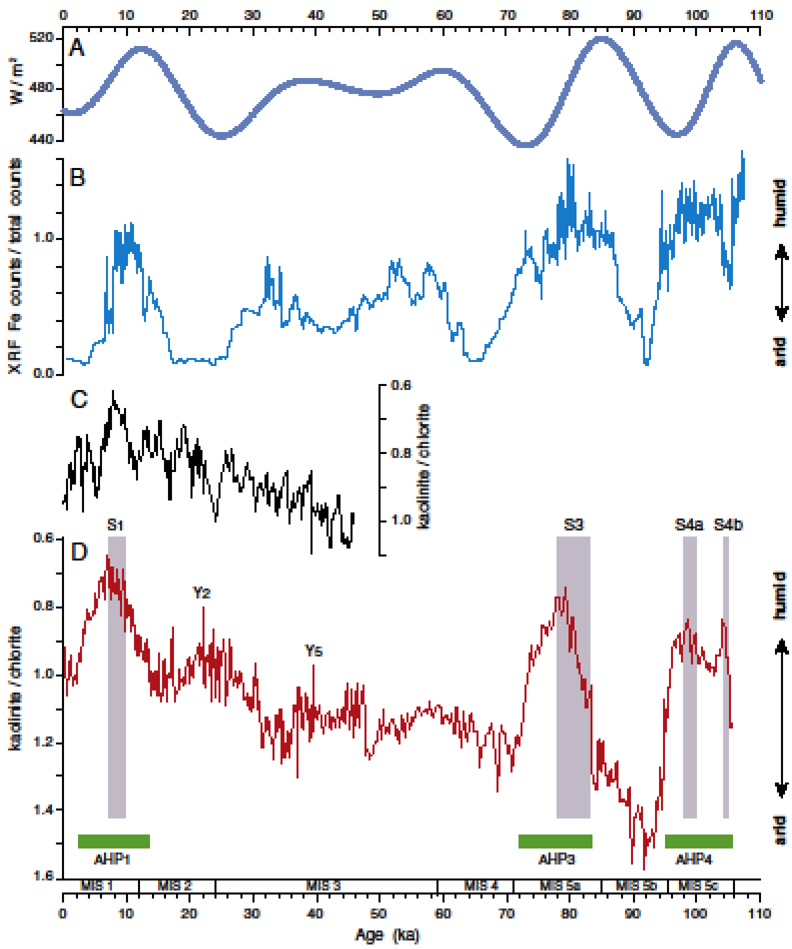

Fig. 3.5 Analysis of the kaolinite/chlorite ratio – Combination of (A) the June insolation at 65°N, (B) the Nile sediment discharge deduced from core MS27PT (Revel et al., 2010; Caley et al., 2011), (C) the kaolinite/chlorite record in sediment core GeoTü SL123 from the southernmost Aegean Sea (Ehrmann et al., 2007b), and (D) the kaolinite/chlorite record in sediment core GeoTü SL143 from the central Aegean Sea. AHP: African humid periods, S sapropels in SL143, Y tephra layers, MIS = Marine Isotope Stages. The above information is taken from Ehrmann et al., 2013.

4: PMIP3 SIMULATION (MPI-ESM) AND RESULT ANALYSES

The analyses of sophisticated Earth system models (ESM) which simulate the processes within the atmosphere, land and ocean as carried out by the Max Planck Institute for Meteorology (MPI-M) are applied for this thesis and obtained from the PMIP3 simulations. The Max Planck Institute for Meteorology (MPI-M) as part of their contribution in advancing research in climatology developed the ECHAM6 which is the atmospheric part of the MPI-ESM.

For this thesis, simulations that have been run with MPI-ESM are selected to reproduce the palaeoclimate conditions in Africa, North Africa and specifically north-western Africa (Maghreb) and north-eastern Africa (Nile Valley) on the basis of precipitation and temperature. The model results as shown below, reflect a reconstructed climate for historical times (i.e. recent), mid-Holocene times as well as for the LGM.

However, it should be noted that only a time-slice of 100 years of simulation was carried out for each epoch, e.g. a 100 year simulation for the historical times, a 100 year simulation for the mid-Holocene times and also a 100 year simulation for the LGM. The result for each period is presented on the basis of mean precipitation and temperature. Furthermore, the mean difference between each epoch on the basis of precipitation and temperature was calculated. This is done by subtracting the model result of two different periods given the same climatic parameter (e.g. precipitation in millimetres per day or temperature in degree Celsius).

Precipitation in Africa (mm/day)

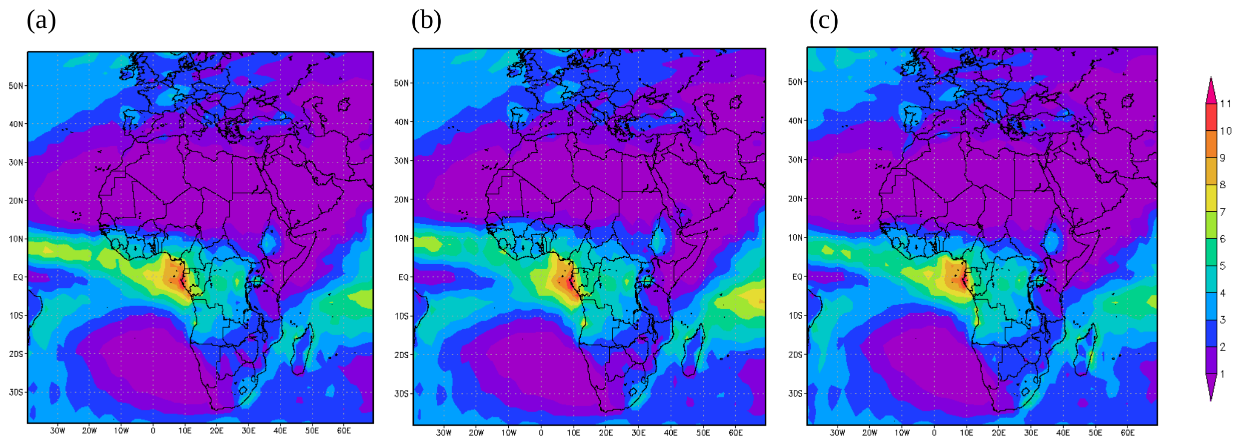

Fig. 4.1 Precipitation in Africa as deduced from (a) Historical data, (b) mid-Holocene and (c) LGM. The scale on the right depicts the mean precipitation in millimetres per day.

As observed from figure 4.1, the model shows only relatively minimal changes in the rates of precipitation during the Historical, mid-Holocene and LGM periods. However, at closer examination, there are subtle differences in the distribution and spread. It is observed that there is a gradual change in precipitation beginning from the Equator to areas around 15 degrees North and South of the Equator, and extending beyond longitude 30 degrees West to about 40 degrees East. This change in precipitation covers equatorial Africa, the Sahel and parts of the Ethiopian Highlands. Areas of higher latitude (e.g. between 18 and 32 °N) are observed to show no variation in precipitation. Further variations in precipitation have been observed from distant region such as the Indian Ocean to the East of Africa, fringes of south-eastern Africa, North Atlantic as well as the Mediterranean.

Therefore, this indicates that Equatorial areas show higher rates of precipitation in comparison to higher latitudinal areas of Africa (especially to the north of Sahara). The mean rate of precipitation around the Equatorial areas up to parts of the Sahel ranges from about 3 to 10 mm/day (see scale). Areas of higher latitude such as North Africa are shown to record about 1 mm/day or less. Except for the LGM, the rate of precipitation extends in the Historical and mid-Holocene periods in Africa to 14 and 16 °N while in the LGM, its highest northwards extension is between 12 and 13 °N. The marginal difference between the model results as observed within the Equatorial corridor could be related to the strong seasonal influence of the Intertropical Convergence Zone (ITCZ) moving northwards in the mid-Holocene times as compared to its relatively southward extension in the LGM.

Change in mean precipitation in Africa (mm/day)

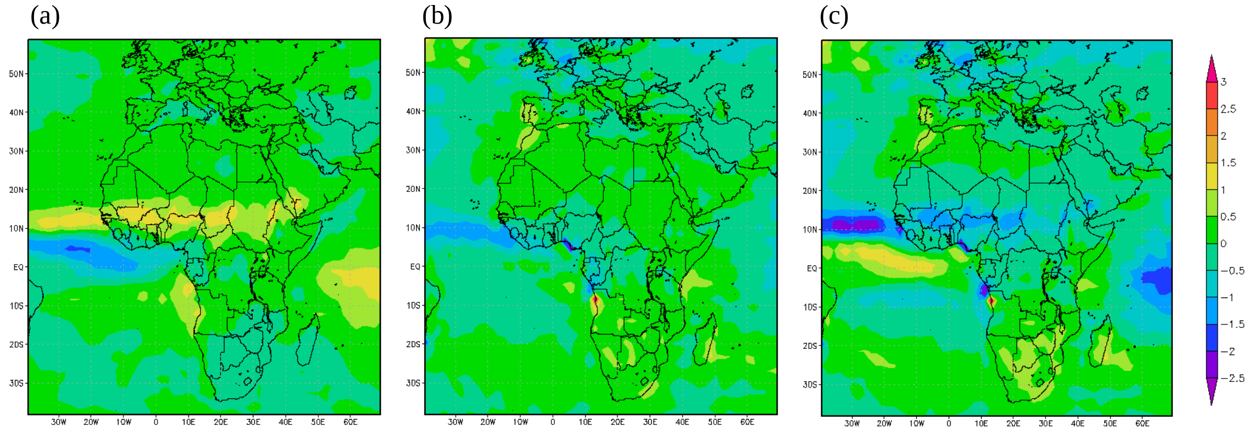

Fig. 4.2 Change in African mean precipitation between (a) the mid-Holocene and Historical periods, (b) the LGM and Historical periods, (c) the LGM and mid-Holocene periods. The scale on the right depicts the change in the rate of precipitation in millimetres per day.

As deduced from figure 4.2, the change in precipitation between the periods varies from positive to negative values. Each value whether positive or negative in this interpretation, represents a change that results from the subtraction of two time periods (e.g. LGM minus Historical or mid-Holocene minus Historical). Areas with characteristic negative values depict less precipitation while areas with positive values show more precipitation.

The difference in mean precipitation as observed between the mid-Holocene and Historical times in Africa ranges from about -0.1 to -0.5 mm/day in the southernmost parts of Africa and from about 0 to 0.5 mm/day in the northernmost parts of Africa respectively. This means that the southern parts Africa are relatively dryer in the mid-Holocene than the northern parts of Africa which are relatively wetter.

Furthermore, the observed increase in precipitation extends from about 10 to 18 °N, reaching more northern areas than those represented in figure 4.1, where the precipitation window begins at the Equator and extends to about 16 degrees north and south of the Equator. The wetness (0.5 to 1.5 mm/day) observed during this period also extends from West to East at latitudes from 10 to 18 °N. Among many other explanations this scenario presents a clear manifestation of the movement of the ITCZ northward during the mid-Holocene in comparison to recent times and a corresponding rise in the precipitation level compared to present times. How significant this increase is, is not within the framework of this thesis. There is also an observed slight increase in precipitation in areas around the boundary of south-western Africa (i.e. below the Equator to about 13 °S).

The change in mean precipitation between the LGM and Historical periods (see figure 4.2) as observed in the model shows a rather different trend when compared to the observed mean change in precipitation between the mid-Holocene and Historical periods. The model results indicating the mean difference in precipitation during the LGM and Historical periods vary generally between arid and semi-arid (0 to 0.5 mm/day) in northern Africa. Areas along the Atlas Mountains of North Africa, however, show a slight increase in humidity (0.5 and 1 mm/day). Areas around southern Algeria and southern Egypt were dryer (-1 to -0.5 mm/day). Areas along the Sahel and particularly in West Africa show a mean decrease in precipitation (-2 to -0.5 mm/day) and are therefore very dry. There is also a noticeable increase in mean precipitation of between 1 to 1.5 mm/day and about 2.5 mm/day at areas located on the coasts at about 10 °S of Africa. The net increase in precipitation at about 10 °S of Africa when compared to West Africa is considerable. Perhaps, the shift in ITCZ southwards during the LGM may provide the explanation for the sudden increase in precipitation. Other areas within southern Africa record low to moderate precipitation rates (about 0.5 to 1 mm/day), but in general, the mean change in precipitation (0 to 0.5 mm/day) in southern Africa is consistent with the dry conditions observed for northern Africa.

The model results for the difference in mean precipitation between the LGM and mid-Holocene periods (see figure 4.2c) reveal low mean change in precipitation for most parts of West Africa, East Africa, the Sahel, Sahara and parts of North Africa. However, most parts of southern Africa and the upper border areas of North Africa show high mean changes in precipitation. Thus, areas between 5 °S and 28 °N are relatively dryer while areas between 10 and 30 °S and 29 to 32 °N change between dry and wet conditions. Areas located on the borderline of south-western Africa are much wetter.

This thesis contends that the no-to-low mean changes in precipitation recorded in most regions north of the Equator may be associated with the southward displacement of the ITCZ, shifting the precipitation window away from these regions southward. On the other hand, the positive changes in mean precipitation in northern and southern Africa may be induced by mid-latitude cyclogenesis.

Temperature in Africa (°C)

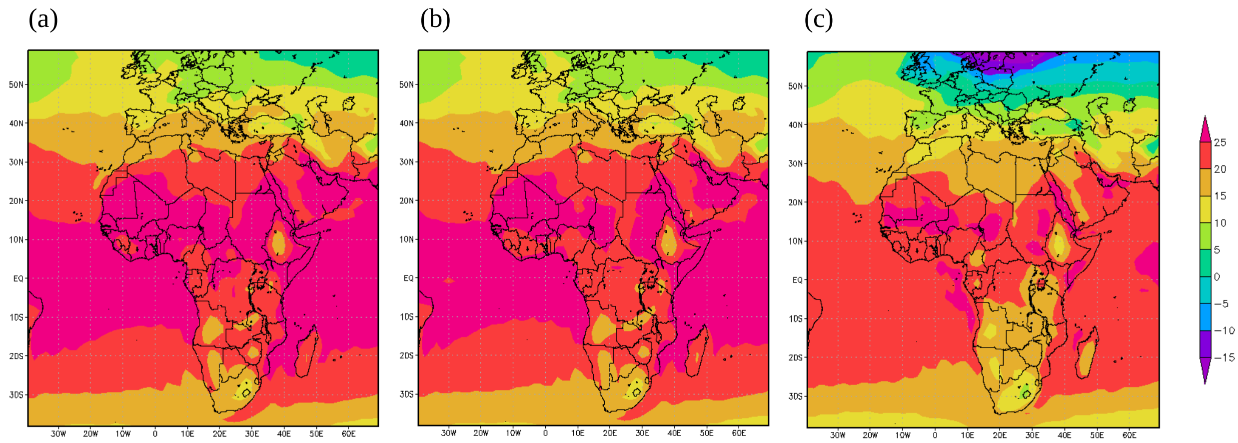

Fig. 4.3 Temperature values in Africa as deduced from (a) the Historical Data, (b) the mid-Holocene and (c) the LGM. The scale on the right depicts the mean temperature in degree Celsius.

The mean temperature modelled for Africa shows similar patterns for the temperature in the Historical and mid-Holocene periods (figure 4.3). The temperature values during the Historical and mid-Holocene range from about 10 °C to values equal or greater than 25 °C in

Africa as a whole. Areas of much cooler temperatures are modelled northwards of North Africa (i.e. from parts of the European continent). In case of the LGM, the modelled temperatures also range from about 10 °C to values equal or greater than 25 °C. In areas around Namibia (southern Africa) the temperature ranges between 5 and 10 °C. The model also showed temperature values ranging from 5 to 10 °C in areas north of North Africa and even much lower temperature of less than or equal to -15 °C to about 0 °C in higher latitudinal areas of Europe reaching towards the Mediterranean Sea as well as parts of North Africa.

Change in mean temperature in Africa (°C)

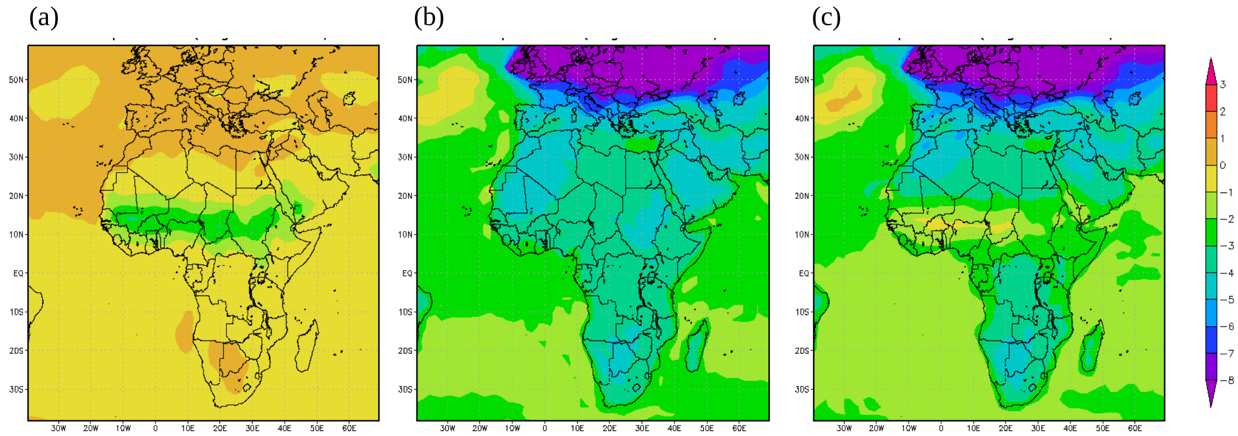

Fig. 4.4 Change in African mean temperature (a) between mid-Holocene and Historical Data, (b) between LGM and Historical Data, (c) between the LGM and mid-Holocene periods. The scale on the right depicts the change in the rate of temperature in degree Celsius.

The results for the mean change in temperature for Africa are presented in figure 4.4. They are presented on the basis of the mean changes between mid-Holocene and Historical, the LGM and Historical as well as the LGM and mid-Holocene periods.

In the case of the mid-Holocene and Historical periods (figure 4.4a), the mean change in temperature for regions between 8 °N and 32 °S as well as 20 °N and 34 °N is less than in the region between 8 °N and 20 °N where the change in mean temperature is greater. Thus, with the exception of the cooler conditions in the Sahel and southern Sahara regions, where the change in mean temperature was greater, other regions of Africa are relatively warmer.

The change in mean temperature between the LGM and Historical periods (figure 4.4b), as observed by the model, shows that the whole of Africa was colder with a decreasing mean temperature change (between -3 and -5 °C) than the prevailing Historical temperature in Africa. On the other hand, the change in mean temperature between the LGM and mid-Holocene periods (figure 4.4c) as provided by the model, shows that regions between latitudes 8 °N and 32 °N as well as 18 °N and 34 °N decreased more in temperature than regions between latitudes 8 °N and 18 °N. Therefore, regions within the central part of Africa stayed relatively warmer than southern and northern regions of Africa.

Precipitation in North Africa (mm/day)

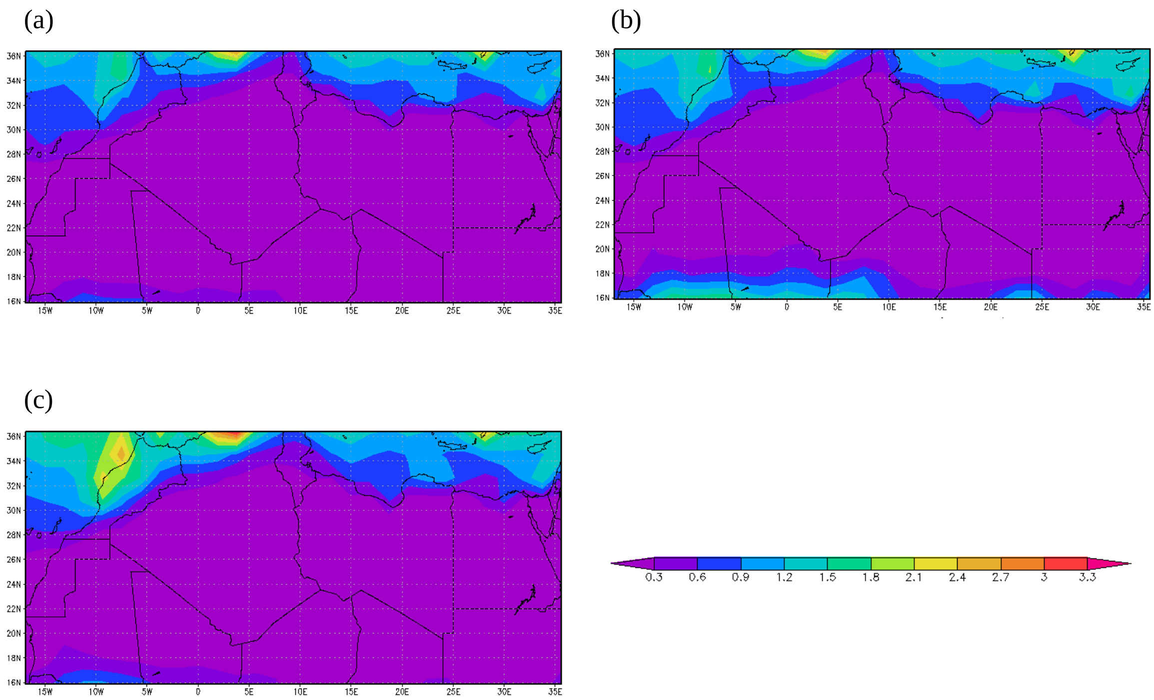

Fig. 4.5 Precipitation in North Africa as deduced from (a) Historical Data, (b) mid-Holocene and (c) LGM. The scale depicts the mean precipitation in millimetres per day.

As observed from figure 4.5, precipitation for North Africa shows subtle differences during Historical, mid-Holocene and the LGM periods. In the Historical period, the rate of precipitation ranges from less than 0.3 mm/day to about 2.1 mm/day. The rates of precipitation in regions within latitude 16 °N and 34 °N ranges from low to moderate while coastal areas of the Mediterranean and North Atlantic have higher precipitation rates. This increase could be attributed to the cyclonic processes within this region.

In the case of the mid-Holocene period, the rate of precipitation in the northern parts of North Africa stays the same as in the Historical model but there seem to be more areas covered by precipitation in the southern parts (between 16 °N and 19 °N) of North Africa. This could be attributed to a displacement of the ITCZ northwards during the mid-Holocene period.

In the LGM, the precipitation shows wetter conditions for the northern parts of North Africa, with the rate of precipitation reaching about 2.7 mm/day. This increase along the coastline of North Africa may be due to mid-latitude cyclogenesis that initiates winter precipitation. In the southern parts of North Africa, there is a fall in the extent and distribution of precipitation, leading to dryer conditions.

Change in mean precipitation in North Africa (mm/day)

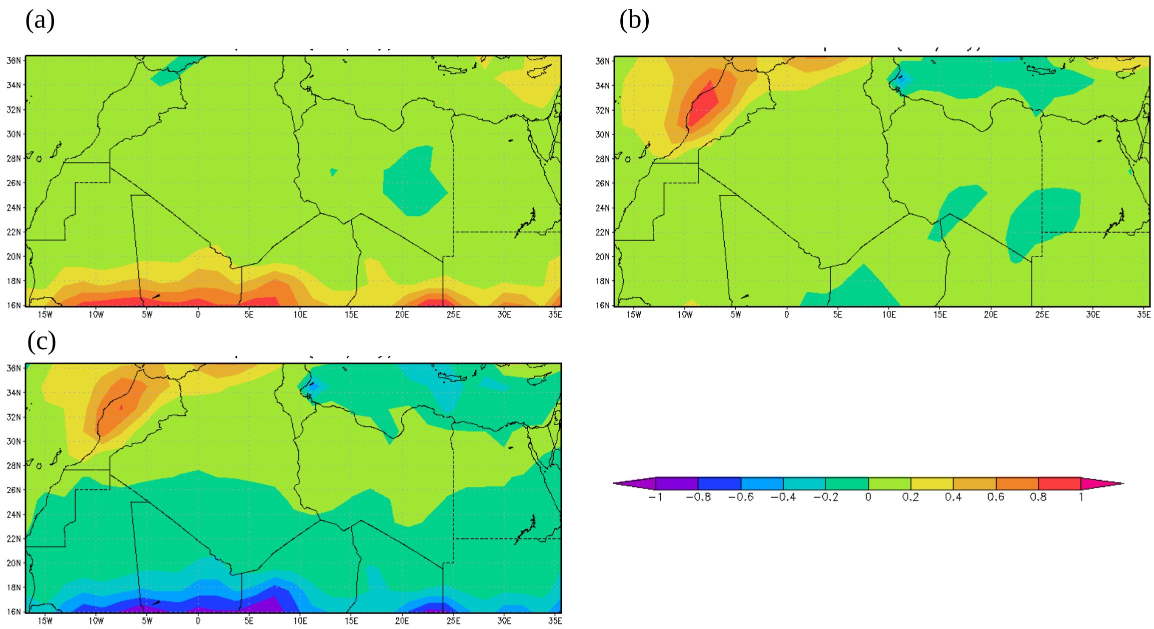

Fig. 4.6 Change in North African mean precipitation (a) between the mid-Holocene and Historical periods, (b) between the LGM and Historical periods, (c) between the LGM and mid-Holocene periods. The scale depicts the change in the rate of precipitation in millimetres per day.

The differences in the North African mean precipitation as given in figure 4.6 vary between periods and its distribution from one region to the other. In the case of mid-Holocene and Historical, the mean change in precipitation shows an increase in most areas of North Africa. However, in regions between 16 °N and 20 °N and extending from west to east of North Africa, there seems to be a positive change in mean precipitation from about 0.2 to 1 mm/day. The humid conditions experienced in these regions may be a result of the weakening of the north-eastern trade winds which favours the penetration of the ITCZ northwards.

Areas around the Atlas Mountains (e.g. Morocco and Algeria), the highlands or massif of northeast and southeast of Libya show practically no change in mean precipitation. It is very likely that the same rates of precipitation are being modelled in the Historical as they were in the mid-Holocene. In the north-eastern Mediterranean Sea, a change from 0.2 to 0.4 mm/day was modelled, thus, there is an increase in wetness.

In the LGM and Historical periods, there is a low to high rate of change in North Africa. The change in mean precipitation is between -0.2 to 0.2 and 0.2 to 1mm/day. That means a lower precipitation rate in some regions (e.g. southern part of North Africa, southern Libya, the south-eastern part of Libya and south-western parts of Egypt as well as in parts of north-eastern Mediterranean) during the LGM than during Historical while most parts of North Africa (especially north-western parts of the Mediterranean) have higher precipitation rate during the LGM than during the Historical.

For the difference between the LGM and mid-Holocene periods, there is a positive change in mean precipitation around the northern parts of North Africa (between the north-western and north-eastern parts), indicating higher precipitation during the LGM for that area. On the other hand, the southern parts of North Africa as modelled show a negative change in mean precipitation, reflecting lower precipitation for the area during the LGM.

Positive changes in northern areas of North Africa during the LGM are attributed to climatic patterns associated with mid-latitude processes as well as cyclonic processes induced by many factors, among which is the gradient in pressure between the Azores High and the Icelandic Low that influences the North Atlantic Ocean storm track. This induces precipitation from the Mediterranean regions onward to the northern parts of North Africa. In the southern parts of North Africa, the negative change in mean precipitation during the LGM may be due to strengthening of north-eastern trade winds that inhibit the northward penetration of the ITCZ.

Temperature in North Africa (°C)

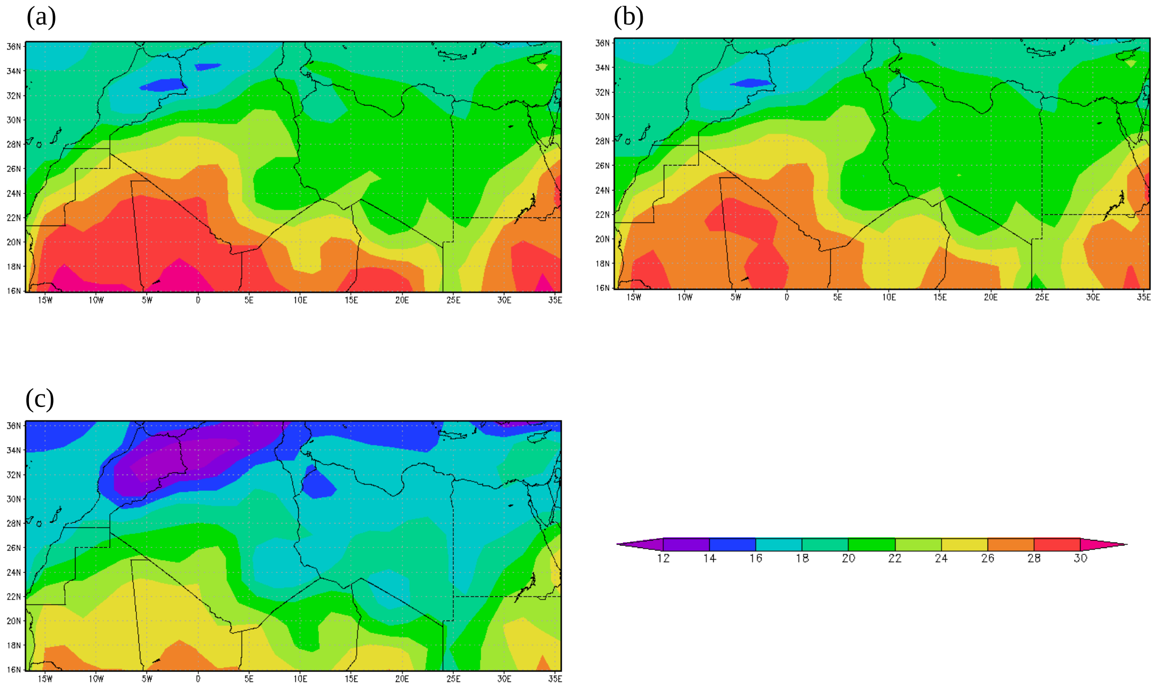

Fig. 4.7 Temperature values in North Africa as deduced from (a) the Historical Data, (b) the mid-Holocene and (c) the LGM. The scale depicts the mean temperature in degree Celsius.

As observed from figure 4.7, the temperature values during the Historical, mid-Holocene and the LGM in North Africa vary marginally between the Historical and mid-Holocene, while during the LGM the variability is greater. In the Historical period, regions between 25 °N and 34 °N are cooler, while regions within 16 °N and 25 °N have moderate to warm temperatures. In the mid-Holocene, an almost similar temperature profile as in the Historical is modelled. However, there is a slight difference in the distribution of temperature in southern parts of North Africa when compared to the Historical. In the LGM, moderate to warm temperatures occur within regions of 16 °N and 25 °N, while regions between 25 °N and 34 °N show cooler temperatures.

Change in mean temperature in North Africa (°C)

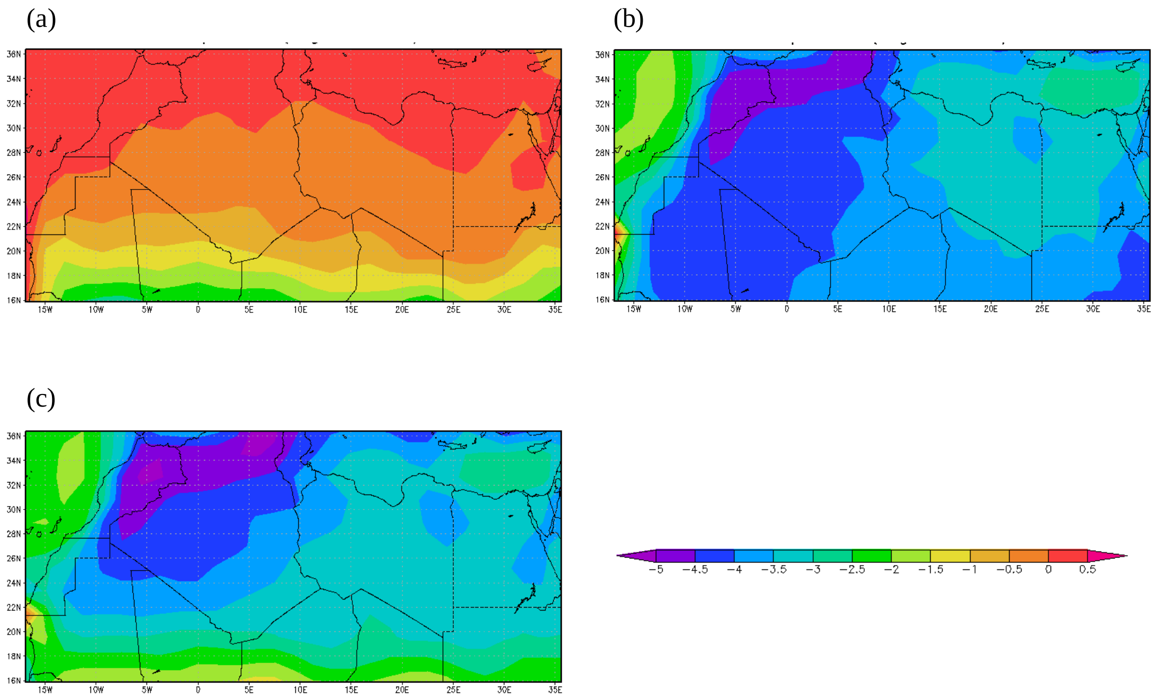

Fig. 4.8 Change in North African mean temperature (a) between the mid-Holocene and Historical periods, (b) between the LGM and Historical periods, (c) between the LGM and mid-Holocene periods. The scale depicts the change in the rate of temperature in degree Celsius.

As shown in figure 4.8, the mean changes in North African temperature vary between the considered periods. In the case of the mean difference in temperature between the mid-Holocene and the Historical, the model shows both negative and positive changes between 24 °N to 36 °N. However, within latitudes 16 °N to 22 °N denoting the southern parts of North Africa, the mean change in temperature decreased further during the mid-Holocene than during the Historical. Therefore, there is an increase in warming as deduced from the temperature in the Historical when compared with the mid-Holocene.

The changes in mean temperature between the LGM and Historical show that the mean changes vary from the north-western to the north-eastern regions of North Africa. The regions of relatively greater change in mean temperature is between 27 °N to 36 °N. These are north-western North Atlantic (off the coast of Morocco), central Morocco and eastwards, including northern Algeria where the changes in mean temperature decrease. Similarly, areas within continental North Africa also show decreases in mean temperature change. Thus, the whole of North Africa was much cooler than the Historical.

The mean changes in temperature between the LGM and mid-Holocene show relatively similar conditions to those observed between the LGM and Historical. Most areas in North Africa have a decreased change in mean temperature. Therefore, the results indicate that the mean changes in temperature during the LGM were relatively higher than in the mid-Holocene for North Africa, and that the LGM was much cooler than the mid-Holocene.

Precipitation in the Maghreb (mm/day)

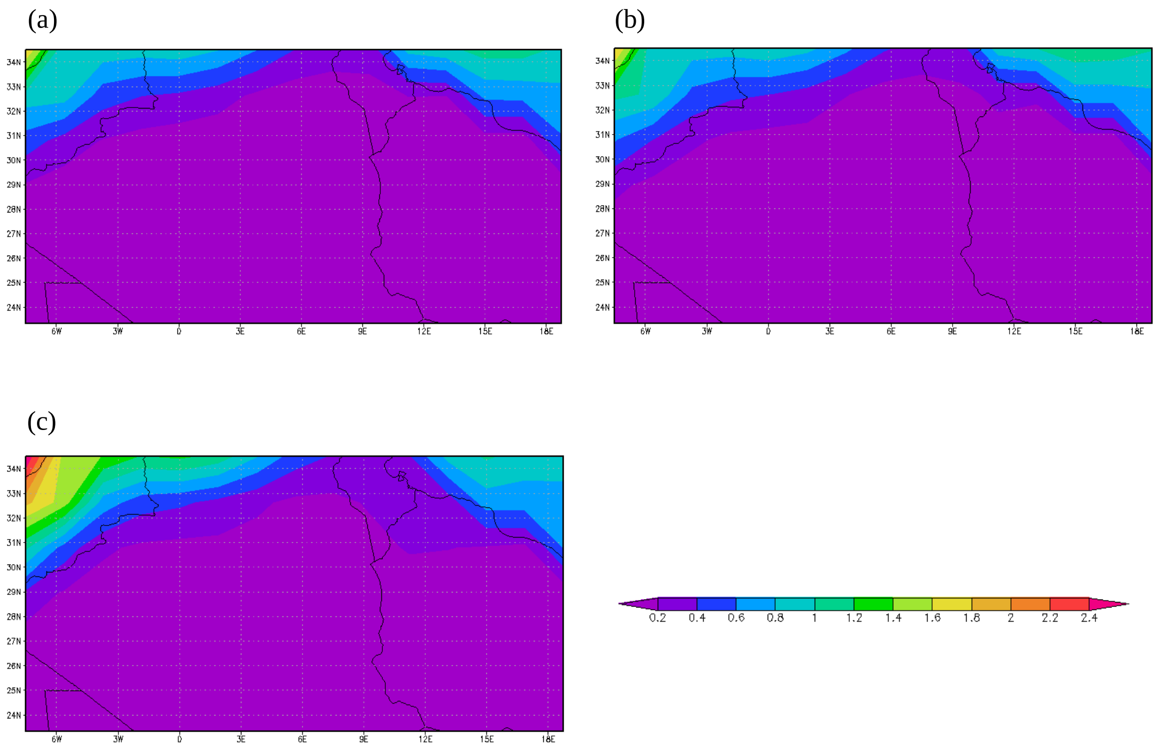

Fig. 4.9 Precipitation in the Maghreb as deduced from (a) the Historical Data, (b) the mid-Holocene and (c) the LGM. The scale depicts the mean precipitation in millimetres per day.

The precipitation rates during Historical, mid-Holocene and the LGM periods for the Maghreb are shown in figure 4.9. Similar rates of precipitation were modelled for the Historical and mid-Holocene periods. It shows that regions between 23.5 °N and 30 °N (e.g. central and southern Algeria, Tunisia and Libya) have low rates of precipitation while those between 30 °N and 34 °N (e.g. Morocco, northern Algeria) have low-to-moderate and high precipitation rates.

The LGM also shows a similar pattern as modelled during the Historical and mid-Holocene periods. However, the rates of precipitation in Morocco are relatively higher than during Historical and mid-Holocene periods.

Temperature in the Maghreb (°C)

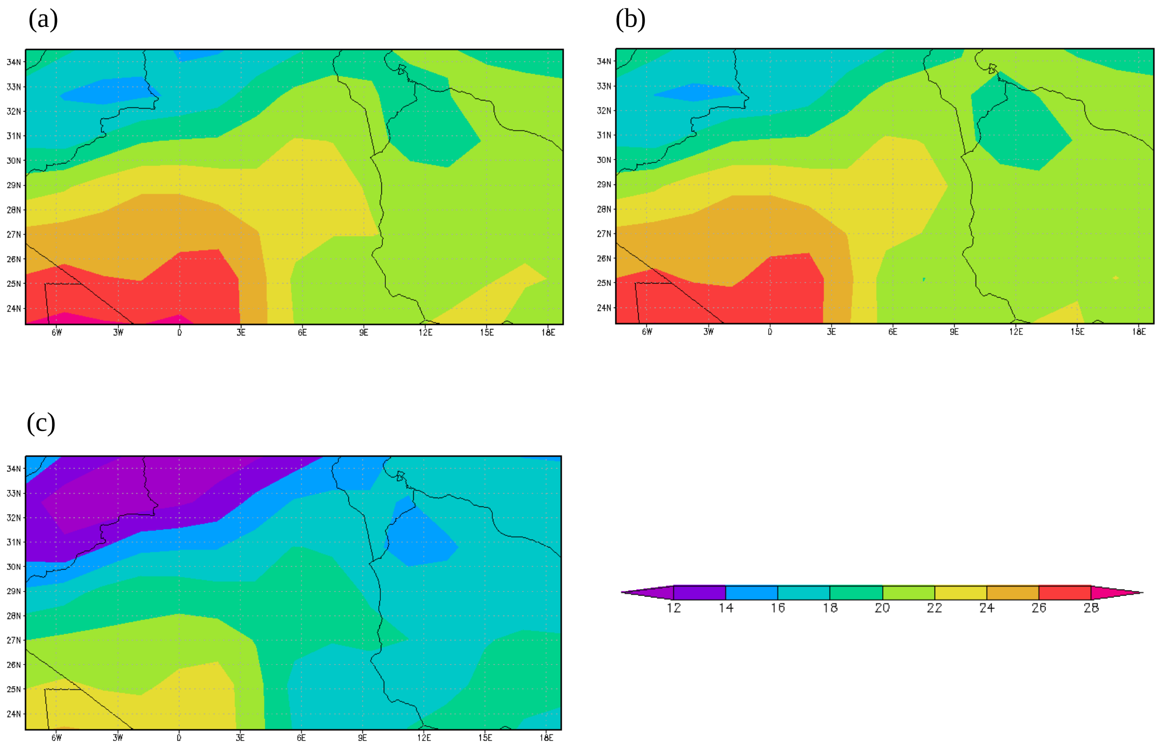

Fig. 4.10 Temperature values in the Maghreb as deduced from (a) the Historical Data, (b) the mid-Holocene and (c) the LGM. The scale depicts the mean temperature in degree Celsius.

As seen in the modelled temperature for the Maghreb (figure 4.10), there is similarity in the temperature distribution for the Historical and mid-Holocene periods. During both periods, the temperature is warm in the southern areas and cool in the northern areas. However, the LGM shows a cool temperature in the southern areas and cooler temperature in the northern areas.

Precipitation in the Nile Valley (mm/day)

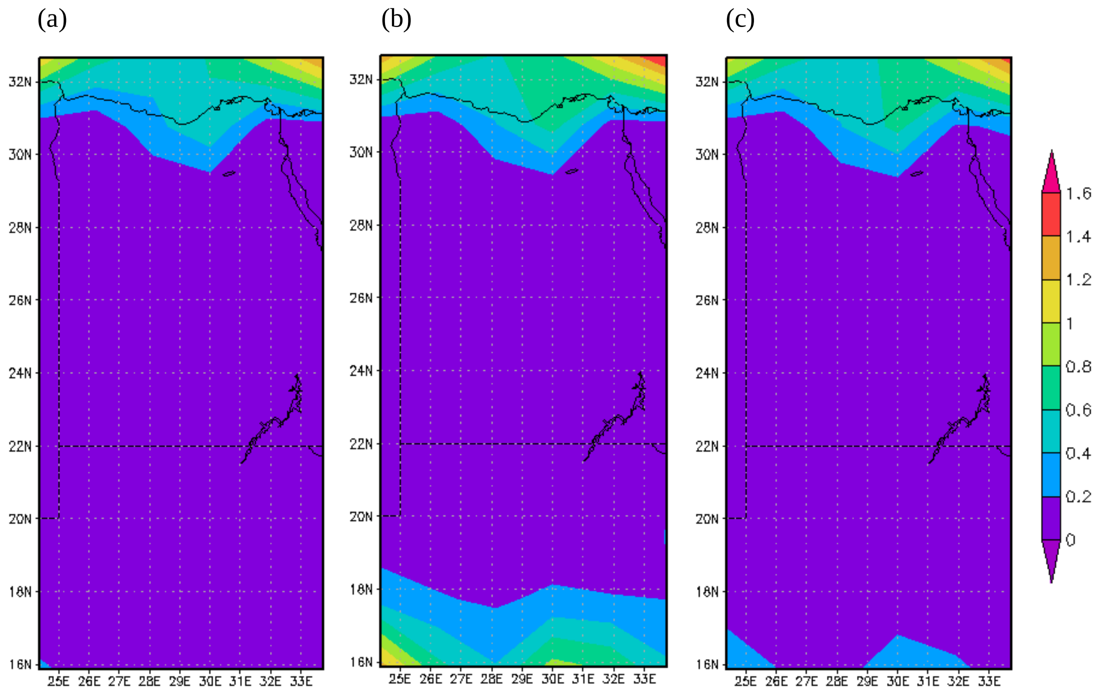

Fig. 4.11 Precipitation in the Nile Valley as deduced from (a) the Historical Data, (b) the mid-Holocene and (c) the LGM. The scale depicts the mean precipitation in millimetres per day.

The most noticeable change in the modelled precipitation for the Nile Valley (figure 4.11) during the Historical, mid-Holocene and the periods, occurred between 16 °N and 18.5 °N (e.g. south of Sudan). In contrast to that, areas between 18.5 °N and 30 °N (e.g. central and northern Sudan, south and central Egypt) as well as between 30 °N and 32.5 °N (e.g. northern Egypt and parts of south-eastern Mediterranean) show relatively similar precipitation results for all periods.

In the Historical period, areas between 16 °N and 30 °N show decreased rates of precipitation while areas between 30 °N and 32.5 °N show increased rates of precipitation. The mid-Holocene period shows increased rates of precipitation in areas between 16 °N and 18.5 °N, and in areas between 30 °N and 32.5 °N. While there is a decrease in precipitation rates for areas between 18.5 °N and 30 °N. In the LGM, there is a mild increase in precipitation rates within some areas around 16 °N and 17 °N. Areas between 17 °N and 30 °N showed decreased rates of precipitation while areas between 30 °N and 32.5 °N shows an increase in precipitation rates.

Temperature in the Nile Valley (°C)

(a) (b) (c)

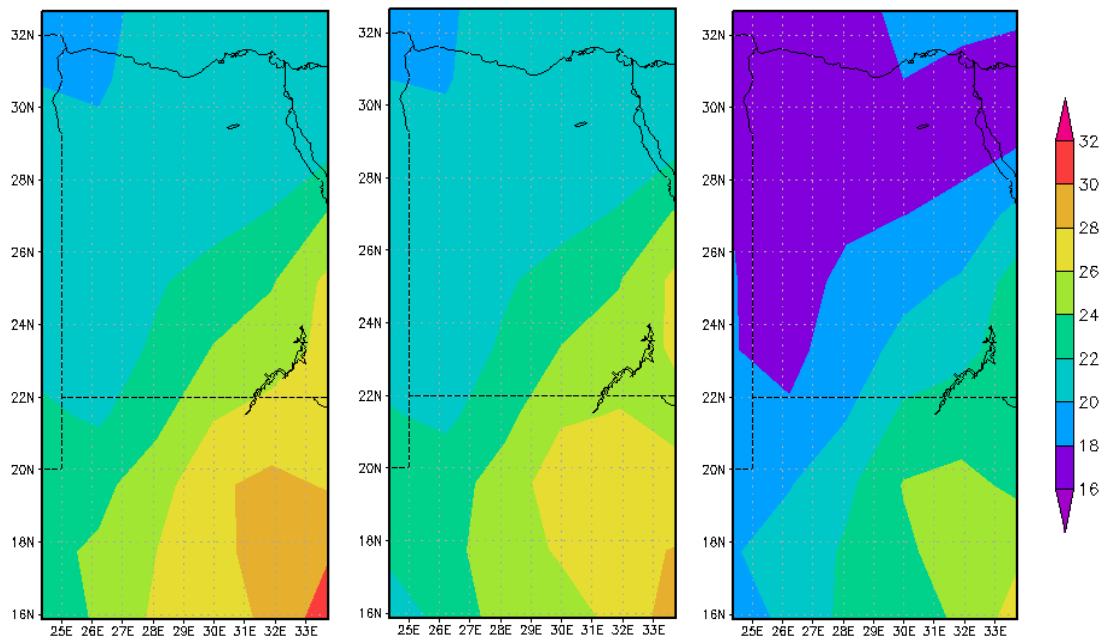

Fig. 4.12 Temperature values in the Nile Valley as deduced from (a) the Historical Data, (b) the mid-Holocene, (c) the LGM. The scale depicts the mean temperature in degree Celsius.

As seen in the modelled temperature for the Nile Valley (figure 4.12), there is relative similarity in temperature distribution between the Historical and mid-Holocene periods. However, during the LGM, there is an exception in temperature distribution.

Historical and mid-Holocene periods show warmer to warm conditions between 16 °N and 27 °N. Nevertheless, there are some areas within this range of latitude that have relatively cool conditions. The rest of the northern areas, between 27 °N and 32.5 °N, are relatively cooler.

The conditions during the LGM are much colder in all areas of the Nile Valley except in south-eastern Sudan where some areas experience warmer conditions.

5: COMPARISON OF PROXY DATA WITH PMIP3 SIMULATIONS

5.1. Introduction

This chapter attempts to compare the MPI-ESM simulations in North Africa, particularly the Maghreb and Nile Valley, with the two aforementioned sediment proxies (see chapter 3), namely, palygorskite and k/cl ratio. We recall that the palygorskite is used to compare model results for the Maghreb while the k/cl ratio is used to compare model results for the Nile Valley region.

This is done by evaluating if the modelled precipitation during the periods of the LGM (21 kyr ago) and the mid-Holocene (6 kyr ago), permits or prevents the presence of the described sediment proxies. Areas where there is a likelihood of such a sediment proxy being present, given the right geological and atmospheric conditions and in agreement with model results, will be described as a positive correlation. Areas where there is no agreement with model results are described as a negative correlation.

The results of the PMIP3 model for temperature will only be used as additional evidence for this thesis, supporting the parameter of precipitation without being compared to a specific proxy for temperature.

5.2 The Maghreb

In this part of the comparison, palygorskite is the chosen parameter for comparison of sediment proxies with palaeoclimate model data during the LGM and mid-Holocene epochs in the Maghreb. To achieve this, the records and fluctuations of palygorskite of the last 50 kyr (see figure 3.3a in chapter 3) are used as a reference.

As observed from figure 3.3a, the percentage of palygorskite during the LGM lies between 6% and 8% while in the mid-Holocene, the percentage is between 3% and 4%. Based on these percentages, there is evidence that there was higher deposition of palygorskite during the period of the LGM than during the mid-Holocene.

Analyses of the rate of precipitation (see chapter 4 and figure 4.9) as presented in tables 5.1 and 5.2 show the overview of averaged daily as well as yearly precipitation during the LGM and mid-Holocene epochs respectively.

Table 5.1 Overview of precipitation during the LGM

Latitude	Description	mm/day	mm/annum
23.32 – 28 °N	Areas from mid-Algeria-Libya southwards	0.01 – 0.11	3.7 - 40
28 – 31.5 °N	Areas from mid-Algeria to mid northern Algeria, south of Morocco, mid-Libya to north of Libya	0.06 – 1.03	22 – 376
31.5 – 34.5 °N	Areas of central Morocco northwards, northern Algeria, mid-Tunisia northwards and northern Libya	0.16 – 1.86	58 – 679

Table 5.2 Overview of precipitation during the mid-Holocene

Latitude	Description	mm/day	mm/annum
23.32 - 28 °N	Areas from mid-Algeria-Libya southwards	0.01 - 0.12	3.7 - 44
28 – 31.5 °N	Areas from mid-Algeria to mid northern Algeria, south of Morocco, mid-Libya to north of Libya	0.05 – 0.65	18 – 237
31.5 – 34.5 °N	Areas of central Morocco northwards, northern Algeria, mid-Tunisia northwards and northern Libya	0.11 – 1.05	40 – 383

5.2.1 The LGM

The relative higher percentage of palygorskite during the LGM implies that the palaeoclimate of the source region (i.e. the Maghreb) during the LGM was most likely semi-arid or arid and dominated by aeolian transportation that was not hindered by vegetation. In addition, the climate was relatively cool in most parts of the Maghreb. This is in line with the general downward trend in temperature prevailing in the region during the LGM.

Palygorskite according to Bout-Roumazeilles et al. (2007) is representative of the sub-arid belt of the northern hemisphere. In the Maghreb, palygorskite is usually restricted to the potential source areas of western Morocco, northern Algeria, central Algeria, southern Sahara (see chapter 3). The association of Argania pollen (see chapter 3) with palygorskite can also be used to explain the provenance of palygorskite, the nature of the palaeoclimate and the most probable amount of precipitation expected for such an area. Argania pollen usually thrives in an environment of low precipitation, between 200 and 400 mm. Since it is typical for southern Morocco, it has been used as evidence supporting the southern origin of the dust (see Bout-Roumazeilles et al., 2007).

Following the range of precipitation most suitable for the occurrence of Argania pollen, the regions beneath latitude 28 °N (see table 5.1 and figure 4.9) have extremely low precipitation values based on model results. These regions are arid and may be good locations for palygorskite transport. Areas between 28 °N and 31.5 °N are also characterized in some parts by low precipitation (described as arid) while other areas show moderate rates of precipitation (described as semi-arid). These areas with semi-aridity are in agreement with the range of precipitation for the occurrence of Argania pollen, dust origin and palygorskite transportation (e.g. southern Morocco). Areas between 31.5 °N and 34.5 °N also show variable climatic patterns ranging from a low amount of precipitation to areas of a relatively high amount of precipitation. This implies a transition from arid to semi-arid and humid areas.

Furthermore, it also indicates that there are locations that could be dry and prone to aeolian activities and as such are possible sources of dust by which palygorskite can be transported. Areas with higher amounts of precipitation are unfavourable for dust sources as well as palygorskite transport.

Climatologically, the relative palygorskite abundance in the core sediment examined by Bout-Roumazeilles et al. (2007) is connected to the nature of the prevailing climate in the source region. During the LGM there was a strengthening of the wind system over northern North

Africa. According to Bout-Roumazeilles et al. (2007) this may be attributed to the strong high-pressure cells that develop over the tropical Atlantic (Azores High) as well as over the North African continent (North African High), and also due to the Westerlies, which may have shifted northwards.

The model results show that areas south of 31.5 °N satisfy the requirement for the transport of palygorskite. The rate of precipitation is generally low to moderate. Areas north of 31.5 °N show patches of low precipitation but in general, they show relatively higher precipitation values that may not be suitable for dust origin or palygorskite transport. Therefore, on the basis of the model results of distribution of precipitation and corroborative evidence from palygorskite, there is a positive correlation between the model results in the Maghreb and the sediment proxy for the LGM.

5.2.2 The mid-Holocene

The observed percentage of palygorskite during the mid-Holocene, which is about 3% to 4%, as well as in the other epochs preceding the mid-Holocene (except for the last millennium), shows gradual increases in the proportion of palygorskite (see figure 3.3a). This slight increase may imply that the palaeoclimate of the source region changed from humid towards arid and thus provides a dryer environment for dust dispersal.

Furthermore, the above assumption is strengthened by the argument of Bout-Roumazeilles et al. (2007), which claim that palygorskite cannot survive transportation in a fluvial medium (e.g. rivers). Therefore, in North Africa, palygorskite transportation will arise in areas exposed to aeolian activities as well as areas of less precipitation.

Another reason for the slight increase in the percentage of palygorskite could be due to the increased availability of erodible materials or dust sources. Erodible materials are usually transported by fluvial mediums during wet climates to different places of convergence such as basins. In dry climates however, the deposits become arid and prone to transportation by aeolian activities.

Therefore, it is possible that the wetter conditions which prevailed during the Holocene for most parts of the southern Sahara and some parts of the northern Sahara reduced the source areas for dust. The subsequent retreat of vegetation in most parts of the Sahara during the mid-Holocene until recent times may have favoured the increase of source areas for dust and hence the increase in the proportion of palygorskite as observed in the figure 3.3a.

The opinion of this thesis is derived from the reasons given above, proposing that the palaeoclimate in the Maghreb region may have shifted from humid to relative aridity, therefore accounting for the slight increase in palygorskite during the mid-Holocene epoch.

On the basis of the model results for precipitation as presented in table 5.2 the region between 23.32 °N and 28 °N exhibits low precipitation and is thus most likely arid. The region between 28 °N and 31.5 °N exhibits precipitation that is low in some parts and relatively moderate in some other parts of the defined region. The region of the extreme northern parts of the Maghreb (i.e. between 31.5 °N and 34.5 °N) exhibits areas with both low amounts of precipitation and areas of relatively high precipitation values.

The precipitation records imply that areas south of 31.5 °N are mostly dry and may have been suitable sources of dust and palygorskite transport, while some other areas within this latitudinal window additionally satisfy the precipitation requirement for the existence of Argania pollen (see above). The areas north of 31.5 °N are predominantly wet and thus are unfavourable locations for dust sources. However, there are patches of dry areas within this region that might also be sources of dust as well as palygorskite transport.

The work of Nicholson, and Flohn, (1980) agrees with the model in terms of its low and high amounts of precipitation regime during this period. They suggest that the north-western parts of North Africa were characterized by aridity while areas in the north-eastern sector such as eastern Algeria, Tunisia and areas further east were relatively humid. They also propose that there was increased rainfall in the semi-arid subtropics south of the Sahara, while the north-western sector of North Africa and the northern fringes of the Sahara were characterized by arid conditions.

Therefore, it is most probable that most of the southern Sahara and parts of the northern Sahara may have been more humid and wet due to the changing climatic pattern, favouring a northward shift of the ITCZ prior to the mid-Holocene epoch. We recall that the northward advancement of the ITCZ during the Holocene epoch led to the shrinking of the Sahara desert belt, which resulted in less aridity and consequently a reduction of the source areas for dust (e.g. Hoelzmann et al., 2004; Nicholson, and Flohn, (1980)).

In addition, the model results for the mid-Holocene temperature shows non-uniformity in the distribution of temperature within the region. According to the model, some areas exhibit a cool to mild climate, which may influence low precipitation while other parts of the region have a relatively warmer climate, which may also be the precursor of higher precipitation.

Marret and Turon, (1993) also agree that the mid-Holocene period in the Maghreb is most influenced by the following factors among others: the seasonal northward movement of the ITCZ, the winter precipitation and the atmospheric circulation that is driven by the north-eastern trade winds.

In the light of the palygorskite evidence, the model results and the distribution of precipitation patterns in the Maghreb, there is a correlation between the perceived relative increase in palygorskite and the areas of low precipitation which are possible sources for dust. The results of the thesis show that there is a positive correlation between the model results on the basis of precipitation and the sediment proxy.

5.3. The Nile Valley

The reconstruction of the palaeoclimate during the LGM and mid-Holocene in the Nile Valley is based on the k/cl ratio (a sediment proxy) with respect to figure 3.5c of chapter 3. This figure serves for interpretation and comparison. From figure 3.5c, it is observed that the ratio of kaolinite is about 1.0 during the time of the LGM, while in the time of the mid-Holocene it varies between 0.9 and 0.8.

As explained in chapter 3, the increase of the k/cl ratio towards 1.0 indicates high kaolinite abundance and dry conditions. This implies that erosion was not hindered by vegetation and there was intense wind activity. On the other hand, a decrease of the ratio towards 0.6 indicates low abundance of kaolinite and reflects humid conditions in the Nile Valley. It could also indicate the existence of a vegetation cover that prevents wind erosion, and therefore a limited aeolian transport.

Analyses of the precipitation rate (see chapter 4 and figure 4.11) as presented in tables 5.3 and 5.4 give an overview of the variability of the results according to different regions during the LGM and mid-Holocene epochs respectively.

Table 5.3 Overview of precipitation during the LGM

Latitude	**Description**	**mm/day**	**mm/annum**
15.85 - 17 °N	South of southern Sudan	0.11 – 0.40	40 – 146
17 °N – 30 °N	Between south of Sudan and northern Egypt	0.01 – 0.09	3.7 – 33
30 – 32.64°N	North of northern Egypt	0.06 – 0.66	22 – 241

Table 5.4 Overview of precipitation during the mid-Holocene

Latitude	**Description**	**mm/day**	**mm/annum**
15.85 - 18.5 °N	South of southern Sudan	0.17 – 1.28	62 – 467
18.5 to 30 °N	Between south of Sudan and northern Egypt	0.01 – 0.21	3.7 – 77
30 – 32.64°N	North of northern Egypt	0.06 – 0.69	22 – 252

As mentioned by Ehrmann et al., 2013 (see chapter 3), dust sources are mostly restricted to areas of average wind velocity exceeding 8 m/s, together with less than 200 to 250 mm annual rainfall. In connection with the above listed values of precipitation, areas of less than 200 to 250 mm annual precipitation qualify as viable sources of dust.

5.3.1. The LGM

The Mediterranean is characterized by a wetter condition during the LGM. This condition is due to the southward shift in the position of the mid-latitude Westerlies and as a consequence a shift of winter extra tropical rainfall towards southern regions of the Mediterranean. In addition, the large scale atmospheric circulation in the entire Mediterranean and North Atlantic region also induces wetter conditions in the Mediterranean Basin. The circulation is strongly influenced by the semi-permanent North Atlantic high (Azores high) and low pressure (Icelandic low) systems. The pressure difference exhibits strong seasonal contrast, thereby controlling the position and distribution of the Westerlies air streams patterns (e.g. Nicholson, and Flohn, 1980; Nash, and Meadows, 2012; Rognon, 1987).

Furthermore, the pressure difference is pronounced during winter and summer. During winter, the pressure difference strengthens and influences the southward shift of the Westerlies, leading to wetter conditions southwards of the Mediterranean. Similarly, interactions between the westerly winds and outbreaks of cold winds from the mountain ranges along the Mediterranean induce the occurrence of cyclones over the western Mediterranean Basin. These cyclones move eastward and bring about enhanced precipitation over the eastern parts during winter. However, during summer, the pressure difference weakens and shifts the Westerlies northwards. This accounts for the dry and hot climatic conditions in the areas surrounding the Mediterranean (e.g. Ehrmann et al., 2013).

However, the modelled precipitation results during the LGM indicate aridity in the hinterlands and at the coastal areas of the Nile Valley (see table 5.3 and figure 4.11c). The arid condition is thereby in contrast to the discussed wetter conditions for the Mediterranean region. The contrast is also acknowledged by Nash, and Meadows, (2012) who argued that the acclaimed “pluvial” scenario (after Butzer, 1957) characterizing most parts of the southern Mediterranean region during the LGM does not extend to the Mediterranean hinterlands.

It is likely that arid conditions in the hinterlands of the Nile Valley during the LGM may be additionally influenced by the strengthening of the north-eastern trade winds. The north-eastern trade winds are boosted in strength during winter due to the aforementioned disparity in pressure, as a result enhancing aridity in the hinterland areas. Furthermore, palaeovegetation evidence from the Nile Valley also corroborates the arid conditions of the hinterlands. They indicate semi desert-like conditions that are dominated by the presence of steppe. Steppe, a type of grassland or shrubland, is usually associated with semi-desert conditions during the LGM (e.g. Elenga et al., 2000).

Therefore, results obtained from modelled precipitation for the Nile Valley during the LGM verify the above mentioned arguments on the basis of climatology. In line with that, the kaolinite proxy which documents aridity and aeolian transport shows a net increase that hints at arid conditions in the Nile Valley. On the basis of temperature, conditions during the LGM are relatively much colder in all areas of the Nile Valley except in south-eastern Sudan where some areas experienced warmer conditions. On the basis of precipitation, the entire Nile Valley is a probable source of dust originating during the LGM. This is because the whole region shows low precipitation rates which fit the thresholds of dust as defined by Ehrmann et al. (2013). In conclusion, there is a positive correlation between proxy and PMIP3 simulation during the LGM.

5.3.2. The mid-Holocene

For the mid-Holocene, the analysis of the precipitation rate (see Table 5.4) shows values similar to those of the LGM between the south of Sudan and north of Egypt as well as beyond northern Egypt. However, there are huge differences in distribution as well as in the amount of precipitation (between 62 and 467 mm/annum) for the areas south of southern Sudan.

Applying the thresholds by Ehrmann et al. (2012), it implies that some areas are unfavourable dust sources while other areas are favourable dust sources. This is supported by the drop in the kaolinite ratio from about 0.9 to about 0.8 (see figure 3.5c). All other areas north of 18.5 °N are suitable locations for potential dust sources.

Climatologically, the mid-Holocene, which is an epoch during the Holocene, is still classified as humid (see chapter 2). Precessional influence is mentioned as one of the causes that changed the global climate at that time to more humid conditions, especially in tropical Africa. If the precession index is at its minimum, the boreal insolation reaches its maximum, which accounts for an enhanced African monsoon, a precursor of wetter conditions in tropical and sub tropical Africa. Precession maxima on the contrary lead to increased regional aridity and dust generation from the Sahara (see Nash, and Meadows, (2012)).

On the basis of the aforementioned climatology, it is possible that the rise in precipitation and its distribution as observed from the model in southern Sudan may have been influenced by internal dynamics (from sub-Saharan Africa) that are associated with boreal insolation maxima. Such dynamics could be convection influences from tropical Africa, leading to the shifting of the ITCZ. It could also be associated to the weakening of the north-eastern trade-winds. Increased rainfall from the Ethiopian highland may have also contributed to the observed increase in precipitation (e.g. Nicholson, and Flohn, (1980)).

Due to the influence of the boreal insolation maxima, there was a more intense movement (in summer) of the ITCZ northwards during the mid-Holocene. This movement is coupled with the weakening of the north-eastern trade winds, which are usually stronger in colder periods and may be responsible for the advancement of the sub-tropical depression towards northern latitudes and the intensification of the tropical rains to reach south of the Sahara. This scenario described above, may have been the trigger that caused an increase in precipitation and distribution as observed in south of southern Sudan.

Nicholson, and Flohn, (1980) conclude that this period was indeed characterized by increased rainfall in the semi-arid subtropics south of the Sahara. They further state that between 6.5 to 4.5 kyr BP, the mid-Holocene is regarded as wetter than the present both in the temperate and tropical margins of the Sahara. This led to a considerable shrinking of the desert belt. A reduction of the desert belt would clearly reduce the source areas of dust during this period. The only viable sources are those of the north of northern Sahara, which have less amounts of precipitation.

In addition, the temperature values (see figure 4.15) in the mid-Holocene show a trend similar to that explained for precipitation above. Higher temperature values were recorded from regions south of southern Sudan while lower temperature values were recorded from regions north of northern Egypt. This could mean that a higher temperature resulting from strong boreal insolation was dominant within sub-Saharan Africa.

Results obtained from the kaolinite proxy verify the above mentioned arguments based on climatology. A reduced k/cl ratio in the proxy represents humid conditions in the Nile Valley. Thus, there is a positive correlation between the proxy result and the PMIP3 simulation during the mid-Holocene.

CONCLUSION

The history of the Earth's changing climate has been investigated in different ways. This thesis presents one of those ways of evaluating the Earth's palaeoclimate conditions by comparing model and proxy data during the periods of the LGM and mid-Holocene in North Africa.

The study area of North Africa is comprised of seven countries and one territory, namely Morocco, Algeria, Tunisia, Libya, Egypt, and Sudan (divided into Sudan and South Sudan) and Western Sahara. On the basis of proxy origin, North Africa is divided into two regional parts, namely the Maghreb and the Nile Valley. The Maghreb consists of the countries in the western part of North Africa (e.g. Morocco, Algeria, Tunisia and Libya). It is characterized by the proxy palygorskite. The Nile Valley consists of the countries in the eastern parts, namely Egypt and Sudan, and it is characterized by the proxy kaolinite/chlorite ratio (k/cl ratio).

From the literature review, there are many other associated factors influencing the global climate and, on a local scale, the internal climate dynamics of North Africa. However, precession is mentioned as being the most influential factor forcing the variability of the North African palaeoclimatic conditions. We recall that the palaeoclimate has often shifted from arid to humid and humid to arid conditions over the years. This change in palaeoclimate conditions is connected with boreal insolation minima (associated with precession index maxima) and boreal insolation maxima (associated with precession index minima).

The boreal insolation minima produce an enhanced aridity of the North African climate and, consequently, an expansion of the desert belt during the period of the LGM. Thus, the climate conditions favour the transportation and distribution of dust. On the other hand, boreal insolation maxima produce an enhanced humidity (e.g. the African humid period, AHP) in North Africa and, consequently, a contraction of the desert belt during the period of the mid-Holocene. This type of climatic condition is unfavourable to the transportation and distribution of dust. This opinion is also confirmed by many other authors such as Nash, and Meadows, 2012; Rossignol-Strick, 1985; Tjallinghi et al., 2008, deMenocal et al. 2000; Hoelzmann et al., 2004; Nicholson, and Flohn, 1980.

The proxy palygorskite, being a clay mineral, was found in the sediment core investigated by Bout-Roumazeilles et al. (2007). The core was extracted from the ODP site 976 in the Alboran Sea, a semi enclosed basin at the westernmost part of the Mediterranean Sea. The Alboran Sea is a receptor of dust particles originating from the Maghreb region of North Africa.

In the Maghreb, deposits of palygorskite abound in western Morocco, northern and central Algeria and southern Sahara. Palygorskite is transported as components of dust. It represents the aeolian contribution to deep-sea sedimentation. Abundance or scarcity of palygorskite in the source region indicates aridity or humidity in the hinterlands respectively. Thus, palygorskite is used to characterize the palaeoclimate conditions in the Maghreb region of North Africa.

The clay minerals kaolinite and chlorite were found in the sediment core investigated by Ehrmann et al. (2013). The sediment core GeoTü SL143 was extracted from the central Aegean Sea. Because the Aegean Sea has a marginal and semi-enclosed shape, it is a good preserver of sedimentary deposits resulting from climate change. The Aegean Sea is located in the northern part of the Eastern Mediterranean Sea. In the Aegean Sea, kaolinite is the defining parameter for palaeoclimate reconstruction because chlorite is ubiquitous and its proportion is relatively constant. The Aegean Sea is also a receptor of dust particles from the Nile Valley region of North Africa.

In the Nile Valley, kaolinite is found in huge deposits in the Mesozoic, Palaeocene and Eocene sediments as well as the lateritic soils in Egypt and the adjacent desert of Egypt. Kaolinite is transported as components of dust to the Aegean Sea. The abundance or scarcity of kaolinite compared to chlorite (i.e. k/cl ratio) indicates aridity or humidity in the hinterlands respectively. Thus, the proxy k/cl ratio is used to characterize the palaeoclimate conditions in the Nile Valley region of North Africa.

The MPI-ESM simulations presented variations in the values for precipitation and temperature conditions in different areas of North Africa. However, only the aspect of precipitation was confirmed by the two sediment proxies of palygorskite and the k/cl ratio during the periods of the LGM and mid-Holocene. This is because no published temperature proxy was found for these periods.

The results of the comparison between model and proxy show that a relatively low rate of precipitation during the LGM correlates with increases in both palygorskite and kaolinite. Based on that, arid to semi-arid conditions are inferred during the LGM for North Africa. In contrast, a relatively high rate of precipitation during the mid-Holocene reflects decreases in both palygorskite and kaolinite. On that basis, humid and wet conditions are inferred during the mid-Holocene for North Africa. Therefore, the outcome of this thesis shows that there is a correlation between MPI-ESM results and considered proxy results on the basis of precipitation for both the Maghreb and Nile Valley regions, during the periods of the LGM and mid-Holocene in North Africa.

Since a temperature proxy was not found for this thesis, temperature was only interpreted on the basis of the modelled results. Further analyses of sediment proxies that are relevant for temperature could additionally help to compare and verify the prevailing temperature conditions of MPI-ESM results for temperature in North Africa.

Furthermore, the use of other PMIP3 – members could be performed to compare and evaluate their analyses and capabilities with proxies for reconstructing palaeoclimate conditions.

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