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MODELING THE EFFECTS OF VEGETATION ON MEDITERRANEAN CLIMATE DURING THE ROMAN CLASSICAL PERIOD. PART I: CLIMATE HISTORY AND MODEL SENSITIVITY[1]

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Abstract

This is the first of a two-part study to construct a vegetation map around the Mediterranean Sea that is an accurate representation of conditions two millennia ago, and to use this data in general circulation model experiments, to better understand historical climate and climate change. Particularly, we want to evaluate the sensitivity of the atmospheric circulation around the Mediterranean Sea to changed land surface conditions. The idea that 2000 yBP, during the Roman Classical Period (RCP), northern Africa and the Mediterranean countries were moister than today is widely acknowledged but has not been discussed within a scientific framework until a few decades ago.

Archeological and historical documents provide some qualitative agreement that moister conditions prevailed during Roman times, and interdisciplinary scientific research provides some confidence through proxies that the Mediterranean has been experiencing a trend towards drier conditions.

The first step of this work is the multidisciplinary task of organizing all the available information coming from historical and archeological sources, together with what is known from scientific methods, into a coherent history of climate and vegetation.

The second step is to run a 25 year GCM experiment, with a forcing that represents an idealized RCP vegetation distribution. The forcing produces a noticeable effect on the climate, namely a northward shift of the intertropical convergence zone during summer over the African continent.

1 Introduction

The study of past climate variations is important to better understand the current climate system. Climate history can be investigated across different time-frames, ranging from the geological to the historical past. The former involves time-scales of $10^4 - 10^5 yr$ or more, the latter deals with the last $10^2 - 10^3 yr$, and is significant because these data could reveal human impact. In fact, beyond the relatively recent and quite controversial issue of a human-induced global warming, there is another, far more ancient way through which humans have been interacting with the climate system: land surface usage.

Farming, cattle grazing and demand for wood had required, since the onset of the Mesolithic Age ($10,000\ yBP$), an alteration of land surface properties. The role played by land surface changes in climate change is universally accepted and actively studied in the climate community (e.g., Charney et al, 1977; Dickinson, 1983; Shukla et al., 1990; Xue and Shukla, 1993; Polcher, 1995). Most Land Surface Process (LSP) studies of the impact on climate of land cover change have been performed over the tropics. The mid-latitudes have been neglected, mostly because of the prevailing effect of baroclinic instability, which was thought to dominate the atmospheric dynamics. However, some of the largest and most ancient clearings performed by early civilizations occurred in the mid-latitudes, particularly around the Mediterranean basin. The study of climatic effects of vegetation change around the Mediterranean thus becomes quite relevant.

There is a large historical record of grain production in Roman Africa, which was probably the most productive and thriving part of the Roman World for several centuries (Jones, 1964; Cornell and Matthews, 1982; Rees, 1987; Raven, 1993). It has been generally accepted that 2000 years ago northern Africa was moister than today (Grove, 1972) and that the wealthy agricultural economy of pre-Roman and Roman Africa in the areas of present northern Morocco and Algeria, Tunisia and Egypt, was possible because of a different climate than present day. But the assumption of moister conditions 2000 years ago has never been investigated within a scientific framework until recently.

In the last 30 years, the rise of disciplines like palynology (study of fossil pollens embedded in sediments), sedimentology and lymnology (study of sedimentation processes in lakes) has allowed scientists to infer climate variables in absence of real meteorological measurements (i.e., using proxies). Many authors have come to the conclusion that, since classical times, the Mediterranean has been experiencing a continuous trend towards a drier kind of vegetation (i.e., less water demanding). Noteworthy are the symposium on the “Desertification of Europe” (Fantechi and Margaris, 1986), and the multinational collection of “Case studies on desertification” promoted by UNESCO (Mabbutt and Floret, 1980), in which, among others, a thorough analysis of a highly representative Tunisian region is presented (Floret et al., 1980).

There is general agreement that a tremendous amount of deforestation has occurred, and consequently there has been soil erosion, caused by heavy winter rainfall and steep orography.

In Spain, Southern Italy, Greece, Turkey, the Middle East and Northern Africa, large areas of the landscape can be defined as "desert-like" (Mensching, 1986). However, a further step is needed. In fact, the change in the landscape is itself an indication, not a proof of drier climate: landscape can change as a purely geological and mechanical consequence of clearing, without any concurrent change in precipitation. Less water demanding species can better adapt better to degraded landscape and poorer soil. So, the questions that arises is: if the soil had not been eroded, could the preexisting vegetation be supported by the present climate? And did the changes in lansdcape (which involves changes in albedo, roughness, fluxes, etc.) affect the climate?

To investigate the issue, the information coming from all possible proxies are used to design a low-resolution general circulation model (GCM) experiment, conceived as a pilot test for a higher resolution experiment, to be described in the Part II of this paper.

Our experiments focus on the Mediterranean, during the so-called Roman Classical Period (RCP), which corresponds approximately to the first century B.C., and is referred as the "Golden Age" of Latin Literature. There are several reasons for choosing this area and this period.

- The amount of historical and geographical information available is much larger for the RCP, if compared to 10 centuries before or after, and the area has been thoroughly investigated from the palynological perspective. The possibility of interesting cross-comparison between scientific and historical information is expected.

- Despite the fact that the Mediterranean is a mid-latitude area, the prevailing atmospheric dynamics that dominates during summer are mostly unaffected by baroclinic systems, and are likely to be strongly sensitive to local boundary conditions such as changes in vegetation. In this way the Mediterranean summer is sub-tropical in nature.

- There is an indication of climate change occurring between the so called Greek Classical Period (GCP) in the 5th century B.C., and the Late Roman Period (LRP) in the 5th century A.D., in terms of a gradual warming (Lamb, 1977; 1982). The 5th century B.C. climate appears to have been colder than the present climate, whereas the 5th century A.D. climate appears to have been warmer. But the RCP climate does not appear to be a significantly warmer or colder phase, so the main difference that has to be investigated is rainfall distribution.

- There is a clear indication that the human induced clearings and land depletion began 8-10,000 yr BP, but intensified only after the first century A.D.: they were enhanced by the political crises of the 3rd and 5th centuries A.D. and they became stronger in the Middle Ages because of the large scale expansion of sheep and goat herding, which replaced the previous agricultural economy, and because of the absence of any organized agricultural policy throughout the Middle Ages (Raven, 1993). In other words, the largest landscape change occurred after the RCP, and the previous clearings had been relatively minor until that time. So the RCP vegetation can be considered a close approximation to what the vegetation might be in present times if it had not been destroyed by human action.

This work requires a multi-disciplinary approach, and it starts with a brief review of information coming from classical literature and archeology, mostly to justify the general belief in conditions moister than present around the Mediterranean during Roman times. The development of paleoclimatology and the need for organizing all the possibles proxies in a general, widely accepted climate history led several authors to describe a sequence of climate events. Among them Lamb (1977; 1982), assembled all the historical and scientific information available, and in his works presents a large amount of evidence supporting the traditional idea of a moister climate in historical times throughout the Mediterranean, but particularly in northern Africa.

The second step is to design a GCM experiment to test the sensitivity of the Mediterranean to changes in surface conditions. A simplified but reasonable vegetation map, resembling the RCP vegetation (which will be discussed in a greater detail in the Part II) is used to force the climate. Two low-resolution integrations of 25 years each are performed. By comparing the GCM integrations, started with the same initial conditions but one forced with the modern vegetation and the other with the RCP vegetation, the impacts on climate are compared. With this experiment, we demonstrate that changes of albedo can be effective in changing climate far from the tropics; so a higher resolution and more realistic experiment is justified. The higher resolution experiment is described in Part II.

2 Classical Historical, Geographical and Archeological Sources

2.1 Classical literature

The vegetation that is used as a forcing in the climate model experiments is inferred primarily from pollen maps. However, an overview of the historical, geographical and archeological sources can provide us with a higher degree of confidence, because of the agreement found with palynology.

During the almost 1000 years that separate the Greek Classical Period (GCP, 5th century B.C.) from the Late Roman Period (LRP, 5th century A.D.), when the western Roman Empire collapsed, a large number of documents were written. Until the beginning of the 20th century, before the rise of scientific methods, these documents were the basis on which statements on environmental changes around the Mediterranean were made. Even in more recent times, Lamb (1977) stressed the importance of this information, stating that “texts from Italy in Classical Times not only record isolated years with extreme winters or heat and drought in summer, but seem also to trace a gradual climatic change”.

The writings of at least 13 classical authors provide information about climate, vegetation, land surface usage and agriculture in classical times. A larger text collection related to weather and climate issues is in Panessa, (1991). All of the authors we selected are published in the Loeb Classical Library. General information about the authors and the texts are from Ferrari et al., (1993) or from the authors themselves.

We could separate 10 of these authors in two main groups: works dealing with History or Geography, which have some geographical digressions of marginal relevance to our study, and works dealing with agriculture. The remaining 3 authors, Teophrastos, Pliny the Elder and Ptolemy need a separate account, and they will be discussed later.

Works dealing with History and Geography We can start with Herodotus (484-430 B.C.), Greek historian: he wrote the "Histories" *(Historiai),* in which interesting geographical information about the Middle East, Persia, Greece, Egypt and southern Italy is provided. We then can mention Polybios (200 - 120 B.C.), Greek historian; in 146 B.C., during a military expedition for Scipio, he explored the coast of Africa to the west of Carthage. In the 34th book of the "Histories" (his 40 books masterwork), geographical subjects are addressed, and a description of the northern coast of Africa is given. Julius Caesar (100-44 B.C.), Roman general, statesman and historian, provides general geographical information through his works ("Gallic War", *De Bello Gallico;* "Civil War", *De Bello Civili;* "Hispanic War", *De Bello Hispaniensi;* "Alexandrinian War", *De Bello Alexandrino;* and "African War", *De Bello Africo;* the latter normally attributed to him although of uncertain authorship). In particular, the Alexandrinian and African Wars provide detailed descriptions of Northern African geography and agriculture and confirm the presence of wooded areas in present Tunisia and Libya. General information on some weather extreme events, climate and wind patterns are also recorded, providing the impression of stormier weather during the warm semester in the Mediterranean. Sallust (86-34 B.C.), Roman historian, wrote, among other works, the "War with Jugurtha" *(Bellum Iugurthinum),* which describes the war between the king Jugurtha and Rome (111-105 B.C.). Two wide digressions on African geography are useful for our study. Strabo (64 B.C - A.D. 21), Greek geographer and historian, wrote the "Geography" in 17 books, in which there is some significant information about the lands in which the vineyard and olive could be sustained. To Strabo, the southern parts of Roman Libya were the northern border of the desert (Lamb, 1977). Livy (59 B.C. - A.D. 17), Roman historian devoted his life to write the huge "Roman History", *(Historiae).* Although not dealing directly with geographical subjects, this work provides some useful information for our study. For example, the use of elephants in various wars, evidence of a very different climate over northern Africa and the Middle East, is documented by Livy. Tacitus (A.D. 55-120). Roman historian: his "Annals" *Annales* are a superb source of historical information of his century and provide some information for this study about climate and agricultural prosperity of various regions. Ammianus Marcellinus (A.D. 330-392). Latin historian of Greek origin: His primary concerns were history, ethnography and a psychological analysis of characters, but with respect to this study, some information about the date of the grain harvest in approximately A.D. 350. Lamb (1977) quotes him reporting that the grain harvest in Gaul (modern France) took place earlier than it does today. Some valuable geographic information about the areas on the border between the Roman Empire and the Sassanid Persian Empire is provided.

Works on Agriculture Cato the Elder (234-149 B.C.), Roman author, provides through his relevant work "On Agriculture" *(De agricultura)* important information about the agriculture of his times, based on small farms and personal ownership of land. Great care is advocated to preserve the productivity of land in order to avoid overexploitation of agricultural resources. Cato describes in a detailed way how the various cultivars must be alternated to allow the soil to recover to its capabilities. From the first century A. D., this kind of "environmentally concerned" approach started to be replaced by *latifundium* (fewer owners with extremely large estates), which may have contributed to agricultural damage (Rees, 1987), triggering a process of land depletion that was enhanced during the civil wars of the 3rd century A.D., and even more so during the barbaric invasions of the 5th century A.D. The Roman author Varro (116-27 B.C.) describes in his work "On Agriculture" *(De re rustica)* the agricultural techniques and policies of the RCP. The Roman writer Columella (A.D. 30-60) wrote a systematic treaty on Agriculture in 12 books, completely preserved, in which he described the agricultural techniques of his time in a very detailed way. From our perspective, it is very interesting that he laments about the decline in productivity of the land in his time, compared with the past. He warns farmers to use more sophisticated criteria on the land, in order to allow the soil to recover its original capabilities. Lamb (1977) reports that Columella notices a a "change in climate" occurred between his time and the times of a a previous Roman writer Sasernas, whose books are lost.

Teophrastos, Pliny and Ptolemy The Greek author Teophrastos (371-288 B.C.) deserves a separate account. His most important surviving works are two treatises on plants. Particularly, his "On causes of plants", is a 6-book work describing plant physiology and the climate constraints which allow different species of plants to grow. Based on this work, Lamb (1977) reports that in Teophrastos' time there were beech trees in the vicinity of Rome. Today the beech tree grows at about 1000 m above sea level in the Apennines.

From our perspective, probably the most interesting information comes from the Roman writer and historian Pliny the Elder (A.D. 23-79). He wrote, among other things, a monumental "Natural History" *(Historia Naturalis)* in 37 books. This work is a sort of ancient Encyclopedia, which tries to put together the knowledge of his time. More than 500 authors are quoted, and the first book consists entirely of the quoted works and an index. The relevant books to this study are nos. 2 and 3, which deal with geography, and books 12 to 19, which pertain to botany. According to Pliny, during the 4th century B.C. the beech tree grew almost at the sea level along the river Tiber, whereas in the 1st century A.D., when Pliny was writing, that tree was regarded as a mountain tree. (Lamb, 1977). This fact is consistent with Teophrastos' report. Pliny also gives us much information about the northernmost land in which a vineyard could be established, during different phases of Roman history. The hints of a climatic change since the fifth century B.C. were very evident to Pliny. Another useful source of information from the climate perspective is the distribution of elephants in North Africa during Pliny's time. Pliny indicated that the extensive area at the southern foot of the Atlas Mountains were populated by elephants at that time. He writes that elephants used to live in forests, and emerge from them in wintertime to roam over rich pastures. Today, these areas are completely deserts. Lamb (1977), who reports this information, also tells us that the elephants died out in the third century A.D., probably because of the increased aridity. The presence of elephants in classical history is widely documented. Elephants were used in wartime against the Romans: by the King of Epyrus (modern Albania), Pyrrhus, in 275 B.C.; by the Carthaginians during the second Punic War (218-202 B.C.), and by King Anthiocus in Asia Minor (modern Turkey) in 190 B.C. The extensive use of elephants testifies to their abundance in North Africa and the Middle East and provides a clear indication of much more moist conditions than today.

Finally the great Alexandrian astronomer and geographer Claudius Ptolomaeus (A.D. 100-170) wrote about astronomy in his most important work, but through additional minor works he provides a large contribution to the past climate study. In fact, his weather diary, written in Alexandria during the summer of A.D. 120, reports a clear indication of frequent convective activity and summer precipitation. Today there is no precipitation at all during summer in Alexandria.

2.2 Archeological evidence

In addition to texts, archeological remains also provide an account of differences in climate that may have existed in the past. For example, cities with a certain number of inhabitants must require a certain daily amount of water. If the amount of water that could be collected today with the original aqueduct network built by the Romans is not sufficient, this is some evidence that different hydrological resources were available, and possibly that a different climate existed. Baths, aqueducts from sources that do not exist today and bridges over rivers that are now dry are all examples of possible climatic changes. All the information discussed in this section and in the previous one is summarized in Figure **??**: some qualitative, general agreement on past moister conditions over parts of northern Africa and the Mediterranean countries can be seen.

During the entire millennium between the GCP and the LRP, the areas of northern Africa had been, with alternate phases, among the richest and most prosperous areas of the western world. The notion of northern Africa as the "granary of Rome" is widely accepted by historians. Particularly, towards the end of the RCP, the agricultural policy of the Roman Empire (see next section) placed the role of leading production of grain and olives in the regions of northern

Africa. As evidence of the prosperity of this area, it is interesting to note that 600 cities existed over northern Africa during the RCP and following centuries, versus only 60 in Gaul (modern France). Among them, we can mention:

- Leptis Magna. Situated in modern Libya, the city was founded in approximately the 5th century B.C., and was extremely prosperous and rich during the RCP. The city entered a period of decline in the 4th century A.D., when continuous invasions of desert tribes occurred. The decline continued during the Vandals' domination, and when the Byzantines conquered the area in the 6th century, the city was already abandoned. From the agricultural perspective, the city was able to support a tax of three million pounds of olive oil during Julius Caesar's time (Cornell and Matthews, 1982). Now it is a subdesert area.

- Carthage. The Roman Carthage, built after the third Punic War (146 B.C.), received its water from a source more than 50 kilometers away, through a magnificent aqueduct, that is still visible today (Cornell a nd Matthews, 1982). The source for this aqueduct could not provide water for such a city today.

- Thugga (modern Dougga). Situated in modern day Tunisia, 90 kilometers southeast of Carthage, Thugga was an extremely rich city due to the agriculture of the neighboring plains (Cornell and Matthews, 1982).

- Cuicul (modern Djemila) and Thamugadi (modern Timgad). These cities are currently in Algeria, and both were extremely prosperous. According to Cornell and Matthews (1982), the prosperity of Cuicul was due to agricultural resources, and it is noteworthy for our purpose that the city of Thamugadi had no less than 14 thermal baths, which provide proof of a significant amount of fresh water.

- Cyrenaica (northeast of Libya). It was an area particularly productive, where a set of five cities called "Pentapolys" developed due to the relative abundance of water from the coastal mountain, Gebel el Achar (Cornell and Matthews, 1982). In all those cities thermal baths are still recognizable, proof of the availability of fresh water.

Some other relevant archeological remains of the Middle East offer also evidence of moister past conditions:

- Palmyra (in modern Syria). During the Roman Empire the prosperity of "the city of the palms" was spectacular. Destroyed towards the end of the third century A.D., it never recovered its original wealth (Cornell and Mathews, 1982). The archeological site is currently desert (Lamb, 1977).

- Heliopolis (modern Baalbeck, in Lebanon) and Petra (currently in Jordan), both extremely prosperous, and now in desert areas. Even now the archeological evidence of a large network of aqueducts and thermal baths is a striking indication of the previous availability of large amounts of fresh water.

- Arabian bridges: Crown (1973) reports that the astronomer and geographer Claudius Ptolomaeus described Roman bridges of the 2nd century A.D. across Arabian rivers that now are dry.

2.3 Population distribution

Population can be inferred and estimated mainly through burial sites and artefacts since prehistorical times, thus providing a definition of a possible Sahara desert border. Various civilizations contemporary to Rome flourished to the south of Egypt, along the Nile: Nubian, Meroitic and Ethiopian. They were located mostly in modern Sudan and the extreme northwestern part of modern Ethiopia, and developed with alternating phases intense commercial relations with Rome, in terms of spices and other agricultural products. According to McEvedy Colin (1980), about A.D. 200 8.5 million people were living in Roman Africa or very close to the Roman borders, 4 million people were living in Nubia, Meroe and ancient Ethiopia, and 5 million people were living to the south of the Sahara in western Sahel (in the area that centuries later would have become the Benin Empire), but nobody seemed to live between Roman Africa, the west of the Nile and the north of the Sahel. The distribution of the population, perfectly bordering the desert to its northern, eastern and southern flanks, indicates where large human settlings were possible at that time, and supports the idea of a smaller Sahara than at present.

2.4 Ancient agriculture evolution and land management strategies

On the basis of the huge amount of historical information left from Greek and Roman History, the crucial phases of agricultural history in the Mediterranean can be outlined. It is possible that changes in agricultural strategies affected the impact on land surface properties.

Throughout the entire Roman period, agriculture was the most important source of state income: taxes from land properties were used to cover state and public expenses (Rees, 1987). At the same time, agricultural income was the most stable and reliable form of investment (Jones, 1964) for a citizen of the Roman world. But the way in which agriculture was performed through the centuries changed between the GCP, that in Italy corresponds to the Roman Archaic Period (RAP) and the RCP. Huge historical and political changes occurred over the Mediterranean world, affecting land management and agricultural demand.

- During the 5th century B.C., which is the GCP for Greece, or the RAP for Rome, the Mediterranean area was divided into several areas of influence: Greek, Egyptian, Phoenician-Carthaginian, Etruscan and Roman. All these political entities were developing their agriculture. Northern Africa and the entire Mediterranean area were more moist than today. However, agricultural activity was not very heavy over northern Africa and the Middle East, and at least over Italy conservation principles for agricultural use were applied until the first century B.C., (which is essentially the RCP), so that severe degradation of land quality had not occurred. Moreover, there was no place with a monopoly in one particular kind of agricultural product.

- By the first century A.D., when the entire Mediterranean region was under Roman control, a change in agricultural techniques started to take place: the small estates that had characterized Roman agriculture since its beginning started to be replaced by large estates *(latifundium).* The owner of a small plot of land, on which he was applying the rules of crop rotation in order to allow the natural recovery of nutrients, was gradually replaced by the large scale farmer (Rees, 1987), who frequently used monocultural techniques. This tendency started in the second century B.C. and increased during the second century A.D., possibly causing some damage to land resources.

  In addition, another significant change occurred: the increase in demand, which increased dramatically because of the higher standard of living and because the population was two to three times larger than five centuries before. So, the protectionist approach of defending the interests of Italian agriculture with respect to the agriculture of various provinces, became economically unacceptable. For example, the emperor Augustus (27 B.C. - A.D. 14) lifted the ban on oil and wine production outside Italy (Rees, 1987); as a consequence, northern Africa reeived a very strong push towards agricultural development and large areas were devoted to intensive agricultural production. Only 2 centuries earlier, in Carthaginian times (before the third Punic War, in 146 B.C.), northern Africa was not very intensively cultivated. Carthaginians were getting most of the grain they needed from Sardinia and Sicily, which were Carthaginian colonies. After Romanization, northern Africa became the most important source of grain and cereals for the Roman world (Rees, 1987). Massive irrigation systems were constructed, and vast areas were devoted to cultivation. After being permitted to establish oil plantations outside Italy, northern African provinces also became the most productive in terms of olive oil (Rees, 1987). Therefore, vast areas originally covered by Mediterranean forest or Mediterranean shrub were converted into grain plantations or olive orchards.

- During the the third century A.D., which is considered by some to be the beginning of the "Decline of the Roman Empire", many of the areas devoted to intense agricultural exploitation were abandoned, and therefore both irrigation and land control ended. Civil wars and invasions were coupled with a severe agricultural crisis particularly in northern Africa. Even though the Roman Empire made a strong recovery during the 4th century A.D. the crisis that affected northern Africa was never completely solved. In fact, during the LRP the amount of abandoned land was estimated to be about 30% (Rees, 1987), forcing several emperors to legislate in order to provide economic support for farmers willing to recover deserted fields *(agri deserti).* Still, some concern for the land productivity and maintenance prevented severe damage until the Vandals' invasion of the fifth century A.D., after which essentially any form of agriculture policy and land control ended throughout most of Northern Africa.

- The damage to land resources became even larger after the fall of the Roman Empire. The barbaric invasions of the Vandals and the Visigoths, which destroyed most of the cities of northern Africa, brought about the end of agriculture in this region. By the 6th century, when for a brief period the Eastern Roman emperor Justinian reconquered northern Africa, none of those cities could be recovered from the decline. Together with a generally drier climate, the native vegetation could not naturally recover.
- The depletion continued for the entire Middle Ages, eventually becoming dramatic because of the large scale unorganized sheep and goat herding.
- Currently, most of the areas of pre-Roman and Roman agricultural activities are desert in North Africa and through much of the Middle East. Areas of southern Spain, Sicily, Greece and Turkey have also to be considered sub-desert (Mensching, 1986). The hydrological and geological mechanisms that lead to land degradation, erosion and eventually desertification are related to torrential winter rainfall and steep orography. The poorly consolidated texture of the Neogene rocks of the geologically young relief are subject to strong erosion. Therefore, extensive clearing and cereal cultivation in the steep areas of the Mediterreanean region began a process of ecological degradation, the first step towards desertification (Mensching, 1986).

3 Climate History through proxies.

3.1 A brief history of hlimate from classical times

In the absence of meteorological observations, it is necessary to define other criteria to infer climatic features of the past. The term "proxy" has been extensively used to refer to any line of evidence that provides an indirect measurement of former climate environments (Ingram et al., 1981). Pollen studies, lake level measurements and geological analyses of river and glacier sediments allow to delineate the climate changes with respect of precipitation and temperature. The reconstruction of environmental change during the last few thousands of years involves analysis ranging on different spatial and temporal scales. Several scientific works have sought to describe the changes in climate through the geological and historical past: among them we can mention Brooks (1970), Lamb (1977), Bell and Walker (1982), Budyko (1982), Lamb (1982) and Flohn and Fantechi (1984). For our purpose, the most useful work is the one performed by Lamb (1977), who extensively investigated the period between 2500 B.C. and the present: his work, although somewhat dated, is still unsurpassed. By coupling the very large amount of proxies with any kind of historical and archeological reports with climatic implications, a generally accepted "history of climate" is outlined:

- 500 B.C to A.D. 500: There is evidence of a general warming from the 5th century B.C., to the 5th century A.D. Moreover, the overall average of the climate in the RCP shows that a wetter climate regime was occurring then (Lamb, 1982). Today, the Mediterranean Sea is characterized by a long, persistent drought condition during the entire summer. Quoting a weather diary written in Alexandria (Egypt) by Claudius Ptolomaeus in about A.D. 120, Lamb (1982) reports the occurrence of rain in every month of the year except August and of thunder in every summer month. Today rain does not occur there during the entire warm semester. Lamb (1977), in a comparative study between reports of occurrences in floods of the river Tiber in Italy, states that from the year A.D. 174 to A.D. 489 only two floods occurred, compared to the 22 floods that occurred between 200 B.C. and A.D. 174, confirming a tendency towards drier conditions.

  Van Overloop (1986) reports that the analysis of fossil pollen in the sediments of Greece contemporary to the Roman Period (1st century B.C. - 5th century A.D.) reveals a continuous decay of vegetation from tree pollen (Pine, Rosaceae trees, Oleaceae) typical of the so called Mediterranean Forest, towards steppe pollen. Van Overloop declares that the original vegetation could never recover, and the corresponding agriculture shows an analogous kind of decay. Brooks (1970) examined the phases of Roman history classified as prosperous or declining, and he found a very strong correlation between agricultural productivity (and therefore higher civilization and luxury) and rainfall, from 450 B.C. to A.D. 200. According to Brooks, most of the events of decline, famine and pestilence in Roman history could be explained by drought events. Particularly, the entire process of the "Decline and Fall of the Roman Empire" that took place between the 3rd and 5th century A.D. could be correlated with a long and continuous drift towards drier conditions. In agreement with these authors, Paepe (1986) reports that a dry phase occurred during the Middle to Late Roman Period (i.e., from the 2nd to the 5th century A.D.) in Greece. Paepe's analysis is based on the geological analysis of river sediments.

- A.D. 500 to A.D. 1300: The warming tendency, although the historical information from the early Middle Ages is less accurate, may have continued until the 9th century. The period between A.D. 900 and A.D. 1300 or later, is considered to be a period of relatively higher temperatures and a lesser extent of ice cover (Flohn and Fantechi, 1984). Precipitation does not seem to follow the same regular pattern. Most of the authors seem to agree that dry and wet phases alternated, with each period lasting about 300 or 400 years. From an analysis of occurrences of Tiber river flood in Italy, Lamb (1977) writes that after the fifth century A.D., Italy again experienced some recurring wet situations, with one dry phase in about A.D. 1000. The same tendency is confirmed in other flood reports from

France, Germany and England. Paepe (1986) reports that the Middle Byzantine Period (i.e., about A.D. 1000) was a dry phase also in Greece.

- A.D. 1500 to present: The period 1550-1850 was characterized by a general reversal of the warming tendency. Therefore it has been defined as the Little Ice Age. It is likely that the ice extent of that time was the greatest of any time since the Ice Age. After that, a general warming trend was experienced, particularly during the present century. With respect to precipitation, both Lamb (1977) and Paepe (1986) consider the present phase to be a dry one.

The trends in temperature and precipitation around the Mediterranean Sea are shown in Figure ??.

4 Hypotheses and Experiment Design

4.1 Land Surface Processes into GCMs and deforestation experiments

It is quite clear that even widely documented and exhaustive works like Lamb's, that try to put together the evidence of climate change in a unifying vision through proxies and historical information, are still mostly qualitative.

Palynology, despite providing an immense contribution to the understanding of past climates and environments, cannot yet quantify all the variables involved in such a complex system as climate. Palynology can state if an environment was warmer or colder, but cannot make any statement on the atmospheric dynamics involved, and certainly cannot provide possible explanations of climatic changes. Therefore, the idea of using a powerful tool like a GCM to evaluate the sensitivity of climate to changed surface conditions over the area of our interest becomes appealing.

Since the introduction of Land Surface Processes (LSPs) into GCMs, the variety of possible climate sensitivity experiments has been increasing dramatically. Biosphere models such as the Biosphere-Atmosphere Transfer Scheme (BATS), based on Dickinson's work (1986), or the Simple Biosphere Model (SiB; Sellers et al., 1986) and its later version Simplified SiB (SSiB; Xue et al., (1991), provide a very powerful tool with which to investigate the impact on climate of human activities such as deforestation and desertification.

The land surface acts on the atmosphere in three ways: exchange of momentum, heat and water vapor. The interface between land and atmosphere is substantially regulated by the biosphere, and therefore a biosphere model such as SiB, that includes all of these exchanges and can realistically simulate the fluxes between land and atmosphere, is an appropriate tool to study the sensitivity of climate to changes in vegetation. Significant experiments of this kind have been performed using SiB for Amazonian deforestation, in order to evaluate a scenario in which most of the tropical rainforest was destroyed (Shukla et al., 1990; Nobre et al., 1991;

Dirmeyer and Shukla, 1994). For these studies, the vegetation category of tropical forest was replaced with degraded grassland. The results of the experiments showed that precipitation and evapotranspiration decrease, while temperature increases. Climate change appear to depend strongly on albedo, rather than on morphology and physiology of vegetation (Dirmeyer, 1992). Therefore, the change in albedo due to the difference between rainforest and degraded grassland is the most important factor in the decrease in precipitation. Plant physiology affects evapotranspiration, causing it to decrease, but this effect is somewhat balanced by an increase in moisture convergence (Dirmeyer and Shukla, 1994). Most of the studies on climate sensitivity to changes in LSPs have been performed for the tropics. There are several reasons for this choice. Because of the relatively low values of the Coriolis parameter in the tropics, small changes in surface temperature can induce significant changes in convergence, with consequent changes in the vertical motion. In other words, a decrease in surface albedo can generate an increase in surface temperature that causes sea level pressure to fall and convergence to increase. In fact, because of the relatively small values of the Coriolis parameter, the ageostrophic component of the flow is quite large and convergence increase at the surface can be relatively large too. Consequently, upward motion and deep convection can be triggered (or inhibited) by albedo decrease (or increase) in the tropics. Therefore, low level convergence in the tropics is controlled by latent heat release associated with areas of convection. In the mid-latitudes, low-level convergence is driven mainly by baroclinic instability, which has its main cause in the meridional gradient of potential vorticity, does not depend on land surface properties and is so powerful that it dominates most mid-latitude atmospheric events.

Nonetheless, Dirmeyer (1994) demonstrated that changes in land surface properties at mid-latitudes can also affect climate during the summer, when the baroclinic activity is weak, and convective conditions could be enhanced by changes in the surface fluxes. Therefore the low level ageostrophic flow, (the cause for convergence to occur), can be still strong enough to generate an increase (decrease) of convection as a consequence of a decrease (increase) in albedo.

In present times, the Mediterranean is dominated during the warm semester by a strong high pressure system, linked with the Atlantic high, causing several months of a lack of precipitation. In other words, the descending branch of the Hadley cell reaches the Mediterranean, even if its center of action is, of course, the Sahara desert. The Inter-Tropical Convergence Zone (ITCZ) is confined 20^0 to the south of the Mediterranean, so the only rainfall that can occur in present times over most of the Mediterranean countries in summer is related with sporadic baroclinic events.

In contrast, palynological evidence (Ritchie and Haynes, 1987) suggests that, during the “climatical optimum” (6000 yBP), the ITCZ was advancing much further north, given the strong evidence of a much moister climate over the area that now is the Sahara desert, and particularly over its eastern side.

Furthermore, there is some suggestion of the sensitivity of the ITCZ position to albedo changes over the Sahel, which is the northernmost boundary between the areas reached by summer tropical convection and the Sahara desert (Charney, 1975; Charney et al., 1977. Xue et al., 1991). The question that arises is if and how much the position of the ITCZ is sensitive to changes in albedo that take place to the North of the Sahara. In other words, would the ITCZ be affected by changes in land surface properties occurring much further north than its usual northernmost limit?

4.2 The present and the RCP vegetation

To perform a GCM experiment suitable for our purpose, it is necessary to compare two climates generated by the same model, but having different forcing boundary conditions. To this end, we integrate the atmospherici GCM with the present day vegetation (Control) and with the RCP vegetation (experiment).

First, the RCP vegetation map must be constructed. During the RCP, the vegetated areas around the Mediterranean covered an appreciable part of the northern shore of Africa, as well as most of southern Europe. Today, almost the entire forest cover is replaced by farmland, the Sahara comes up to the sea and much of southern Europe is subarid. The vegetation assumed for the RCP period, mostly inferred from pollen maps, geographical information and relict vegetation, is described in detail by Reale (1996), and in Part II of this article.

Next, we converted the RCP vegetation map in terms of the 12 vegetation types allowed by SSiB (table **??**) for the present vegetation. As all the vegetation associations characterizing the RCP and described above are still in existence, but just shifted or reduced in size, no introduction of different vegetation types is necessary. It is interesting to note that the so-called Mediterranean forest, a vegetational environment dominated by evergreen oaks like the *Quercus ilex* is essentially a broadleaf evergreen forest similar to the tropical forests. In fact, the albedo over the few areas in which patches of Mediterranean forest are extant is the same of a tropical forest. Therefore, in the SSiB classification, the Mediterranean forest, being broad leaf evergreen with very low albedo, is regarded the same as tropical forest.

However, because of the relatively poor resolution of the R15 experiment, a simplification has to be made with respect of the much more detailed information obtained from pollen maps. Essentially, the R15 RCP vegetation map, with respect to the present one, expands vegetation types number 1 (Mediterranean forest), 2 (oak forest), 3 (mixed oak and pine forest), 4 (spruce, fir and pine forest) at the expenses of 12 (farmland) over Europe. Over northeastern Africa, 3 gridpoints of vegetation type 8 (groundcover with shrubs) replace vegetation type 9 (bare soil with shrubs). 2 gridpoints of Mediterranean forest (vegetation type 1) replace vegetation 9, 1 gridpoint of Mediterranean forest replaces no 7, and two gridpoints of number 6 (savanna) replace vegetation type 6 over northwestern Africa. In the Middle East, two gripoints of vegetation type 9 are replaced by vegetation type 7 (grassland) and 4 gridpoints of vegetation type 3 replace the remaining relatively higher elevetion areas, currently classified as vegetation types 12, 7 and 8.

Overall, 25 gridpoints were changed to create the R15 RCP vegetation map.

In figure **??**, the R15 control and RCP vegetation maps are displayed. In both maps, the shaded area represent the gridboxes where RCP vegetation is different from the control vegetation. Vegetation types are listed in Table **??**.

4.3 The model

The model used is the Center for Ocean Land Atmosphere Studies (COLA) GCM, implemented with SSiB. The model uses the hydrodynamics described by Sela (1980), which is the core of the National Center for Environmental Predictions (NCEP) medium range forecast model. The COLA GCM is a climate oriented research version of the latter, described by Kinter et al. (1988) and Schneider and Kinter (1994). The version used here has a rhomboidal truncation at wavenumber 15. The corresponding gaussian grid is approximately 7.5^0 longitude and 4.5^0 latitude. The model is implemented with a biosphere model derived from SiB (Sellers et al., 1986). After Dorman and Sellers (1989) a set of 12 types of vegetation has been adopted to represent the entire planet. Xue et al. (1991) provided a simplified version of SiB, called SSiB, that provided a computational gain of almost 50%. The main difference between SiB and SSiB is the reduction from two to one vegetation layer. SiB and SSiB have been widely used in a variety of climate sensitivity experiments related with deforestation and desertification.

4.4 Design of the experiments

A 25 year GCM control integration with with present vegetation and an experiment integration with RCP vegetation were conducted, starting from the same initial conditions. This low resolution experiment, although not having detailed geography, does provide a useful tool to test the sensitivity to vegetation in the Mediterranean scenario on a relatively long time-scale, without being too computationally expensive. In fact, the essential features of Mediterranean geography are roughly present. There is a relatively warm internal sea that covers 11 gridboxes, placed between Europe, Asia and Africa. Italy is not resolved at R15 resolution, but the basic shape of northern Africa, Iberia, the Balkanic peninsula, Turkey and the Black Sea are represented. The essential geographic features are therefore present. The main goal of the R15 experiment is to test for gross sensitivity to vegetation change. Positive results will encourage further investigation at higher resolution.

The integrations are started with the initial conditions (IC) of 1 January 1990, obtained from a one month integration starting from the observed IC of 1 December, 1989. The use of present time initial and boundary conditions (including the soil wetness), instead of presumed conditions of 2000 yBP), is done to avoid the superposition of the climate response. We wanted to attribute any signal exclusively to the vegetation change. For the same reason, we did not consider any change in either the solar constant or in the solar zenith angle. In other words, the experiments represent the modern day climate forced with modern vegetation everywhere, except around the

Mediterranean, where we replaced the modern vegetation with the RCP vegetation.

All the fields displayed are averaged over the last 20 years of the integrations, because of a trend in the experiment's precipitation field, which was a consequence of a slow adjustment in the soil moisture fields in semi-arid regions during the first five years.

5 Results of the experiment

5.1 Analysis of results

The 25 year control precipitation is displayed in Figure ??, together with the anomaly (RCP-Control) precipitation field. It is important to notice that the largest area of contiguous positive anomaly appears to be over the central part of Northern Africa, and most of it occurs over areas in which the control precipitation is less than 1 $mm\ d^{-1}$.

The statistical significance test provides a clearer picture. In Figure ??a, we can see the t-test performed at 99% significance level, showing a clear and well defined area in which there is a statistically very significant response of climate. The gridpoint t-test is calculated for the mean annual precipitation (Preisendorfer and Barnett, 1983), by scaling the anomaly field with the pooled standard deviation estimated from the two runs. In Figure ??b the percentage departure is plotted, and we can see that the only large area with a precipitation increase of more than 20% is over northeastern Africa. The reason why the amplitude of the precipitation anomaly looks small in Figure ??, is because we are dealing with a desert area, with very low mean rainfall.

In fact, looking at the regional picture on Figure ??, we can see that southwestern Egypt gets less than 0.25 $mm\ d^{-1}$ of rainfall in the control run, whereas in the RCP run the precipitation increases more than 0.1 $mm\ d^{-1}$, a substantial fraction of the entire value. It is important to stress that the effect of this precipitation increase is not only statistical, but has large environmental implications. In fact, the 100 mmy^{-1} line, which approximately corresponds to the 0.3 $mm\ d^{-1}$ line, is defined by many authors as the desert border (e.g., Floret et al., 1980). Therefore, it becomes quite clear that many areas would shift from a desert climate to a sub-desert one. Moreover, the steep precipitation gradient that characterizes the Sahel, which is a sharp transition from a savanna-like environment to desert, is affected too, with some environmental implications: all the critical limits like the savanna-shrub limit (400 mmy^{-1}) or the groundcover line limit, (250 mmy^{-1} separates groundcover with shrubs from bare soil with shrubs) would be shifted northward. The negative values over part of the Mediterranean are not statistically significant and occur over gridboxes representing water. However, Figure ??b suggests that the Mediterranean could act like a source of moisture for northern Africa, thus explaining the negative precipitation anomaly.

The clearest picture arises when observing the time structure of the precipitation in the experiment: the only significant response arises in the summer months, and it is particularly strong in August. In Figure ?? we can see the control July, August and September (JAS) precipitation and the corresponding precipitation anomaly. August only is displayed in Figure **??** and a strong indication of a shift and strengthening of the ITCZ over the African continent is evident. Note the change in contour intervals between Figure **??**b and Figure **??**b. Moreover, the increase of precipitation over southern Egypt and Sudan in the RCP run supports the idea of a moister climate over the Nile countries, with important ecological and historical implications.

Interestingly, an increase appears also over Europe. The increase is strongest during August, but is also evident in the JAS mean, and is related with a large positive evapotranspiration anomaly that begins to appear during May, and lasts throughout the summer, peaking during August. This is an area where agricultural land is replaced by forest, thus increaseing the potential for transpiration. It appears that during late summer, southern Europe may be sufficiently unaffected by baroclinic activity that a direct feedback between evaporation and precipitation can be established locally.

In Figure **??**, the time series of precipitation averaged over a wide area between longitudes 4^0E and 45^0E and latitudes 13^0N to 24^0N (including the upper Nile countries and most of the eastern Sahel) shows a clear response related with summer ITCZ activity. It is interesting to notice that the RCP precipitation has less interannual variability.

The northward shift of the ITCZ is evident in Figure **??**, where the 900 mb wind in terms of streamlines is displayed, especially between $10W$ and $30E$. The anomaly RCP-Control wind is southwesterly over the entire Sahara, meaning as a result of the RCP experiment, a weakening of the northeasterly flow to the north of the ITCZ and a strengthening of the southwesterly flow to the south of the ITCZ.

In Figure **??**a, the vertical profile of the JAS divergence, averaged over the same rectangular box used to calculate the time series of precipitation, shows convergence below 800 mb and mid-tropospheric divergence, mostly between 700 and 600 mb. The RCP-Control departure of the same quantity, shows an increase in the low level convergence. We can also see increase in upper level divergence, which provides the picture of a deeper atmospheric overturning, suggesting "deep" instead of "shallow" convection.

Overall, the basic expected result is that the RCP vegetation in the R15 experiment does provide a response and therefore is a good starting point to design a more realistic R40 experiment.

6 Conclusions

In this paper we address a problem that is widely discussed in modern times, whether the Mediterranean area is experiencing or not a desertification trend. The information obtainable from archeology to the classical geographical documents of antiquity suggest that the climate might have been moister in Roman times around the Mediterranean. The wide-spread presence of aqueducts, bridges and thermal baths, built around 2000 years ago in areas which are currently desert, and the historical documents written by many Greek and Roman authors (providing general qualitative descriptions of the Mediterranean countries, and particularly northern Africa as vegetated or forested lands), support this hypothesis. Modern works of history confirm that the Roman Africa was an agricultural productive and wealthy part of the ancient world, and was the main source of grain for the Roman world.

Wooded areas or shrublands have been replaced by farmland since ancient times throughout the Mediterranean. The steep orography of much of the Mediterranean landscape, helped by the rainy winter season, triggered the process of land erosion and soil depletion. Economies based mainly on large scale goat and sheep herding rather than agriculture, and the lack of any land management strategy, characterized most of the Middle Ages, continuing the process of land depletion.

We then described the evolution of the climate history as offered by the pioneer works by Lamb (1977, 1982), that organized all the proxies into a coherent frame, providing substantial evidence about much moister conditions around the Mediterranean during Roman times.

After having shown the general agreement of proxies with the historical works written in classical times, we realize that quantitative results are needed. To this end, we use a GCM to evaluate the general role that vegetation change could play around the Mediterranean. Then, the following question was addressed:

Can land surface processes changes be effective in modifying climate in a mid-latitude area like the Mediterranean? In order to perform a vegetation change experiment around the Mediterranean we needed first an RCP vegetation map, mainly constructed from palynological information. The vegetation map that can be obtained with this approach, to be discussed in the Part II of the article, has a much higher resolution that what needed by the simple R15 geography. Therefore, after having build a simplified RCP vegetation map, one 25 year experiment was performed, at R15 resolution.

In this experiment we reproduced conditions that do not include any changes in the solar constant or orbital parameters, because we wanted to isolate the climatic effect, if any, produced by land surface changes around the Mediterranean.

Changes in albedo and land surface properties, between a situation roughly comparable with the RCP one and the present day, produce a strong measurable and statistically significant signal into the GCM climate. This change consists of a northward shift of the ITCZ, towards the Sahara desert, particularly over northeastern Africa. Although with the limitation of the very simple R15 geography, we can state that northeastern Africa, which receives almost no rain during the summer season in the control run (and in the observations), shifted to a substantially moister climate in the experiment. The relatively long integration time allows us to speculate that the model reached an equilibrium, and that the climate conditions found are reasonably steady with respect of the RCP vegetation map introduced in the model.

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1	Broadleaf-evergreen trees (tropical or Mediterranean forest)
2	Broadleaf-deciduous trees
3	Broadleaf and needleleaf trees (mixed forest)
4	Needleleaf-evergreen trees
5	Needleleaf-deciduous trees (larch)
6	Broadleaf trees with groundcover (savanna)
7	Groundcover only (perennial)
8	Broadleaf shrubs with perennial groundcover
9	Broadleaf shrubs with bare soil
10	Dwarf trees and shrubs with groundcover (tundra)
11	Bare soil
12	Winter wheat and broadleaf-deciduous trees (cultivated)

Table 1: Vegetation Types in SSiB

Figure 1: Qualitative information on climate and/or landscape change which can be deduced from classical literature sources and archeology.

Figure 2: Qualitative precipitation and temperature trends in Mediterranean climate.

Figure 3: Vegetation Map at R15 Resolution. The numbers correspond to the vegetation types and are listed in table **??**. Panel a: Control. Panel b: RCP. Shading indicates gridboxes where modern and RCP vegetation differ.

Figure 4: Mean annual precipitation. Control (panel a), RCP-Control (panel b). Contour interval is 1 $mm\ d^{-1}$ in panel (a) and at $+/-0.4, 0.2$ and 0.1 $mm\ d^{-1}$ in panel (b). In the darker (lighter) shaded areas the RCP-Control precipitation is greater (less) than $+/-0.1$ $mm\ d^{-1}$.

Figure 5: t-test (panel a) and percentage departure (panel b) on mean annual precipitation. In the darker (lighter) shaded areas the precipitation RCP-Control is greater (less) than zero at 99% significance (panel a). In the darker (lighter) shaded areas the RCP-Control percentage departure from Control is greater (less) than $+/-20\%$ (panel b). Contour interval is at 20%.

Figure 6: Regional view of mean annual precipitation. Control (panel a), RCP-Control (panel b). In pabel a, the contour interval is 1 $mm\ d^{-1}$ (for $p_{Control} > 1\ mm\ d^{-1}$), 0.5 $mm\ d^{-1}$ (for $p_{Control}:\ 0.5\ mm\ d^{-1} < p_{Control} < 1\ mm\ d^{-1}$) and 0.25 $mm\ d^{-1}$ (for $p_{Control} < 0.5\ mm\ d^{-1}$). In panel b, the contour interval is 0.1 $mm\ d^{-1}$. In the darker (lighter) shaded areas the RCP-Control precipitation is greater (less) than 0.1 $mm\ d^{-1}$.

Figure 7: Regional view of JAS precipitation. Control (a), RCP-Control (b). In panel a, the contour interval is 1 $mm\ d^{-1}$ (for $p_{Control} > 1\ mm\ d^{-1}$), 0.5 $mm\ d^{-1}$ (for $p_{Control}:\ 0.5\ mm\ d^{-1} < p_{Control} < 1\ mm\ d^{-1}$) and 0.25 $mm\ d^{-1}$ (for $p_{Control} < 0.5\ mm\ d^{-1}$). In panel b, the contour interval is 0.25 $mm\ d^{-1}$. In the darker (lighter) shaded areas the RCP-Control precipitation is greater (less) than 0.25 $mm\ d^{-1}$.

Figure 8: Regional view of August precipitation. Control (panel a), RCP-Control (panel b). In panel a, the contour interval is 1 $mm\ d^{-1}$ (for $p_{Control} > 2\ mm\ d^{-1}$), 0.5 $mm\ d^{-1}$ (for $p_{Control}:\ 0.5\ mm\ d^{-1} < p_{Control} < 1\ mm\ d^{-1}$) and 0.25 $mm\ d^{-1}$ (for $p_{Control} < 0.5\ mm\ d^{-1}$). In panel b, the contour interval is 0.25 $mm\ d^{-1}$. In the darker (lighter) shaded areas the RCP-Control precipitation is greater (less) than 0.25 $mm\ d^{-1}$.

Figure 9: Time series of precipitation, in $mm\ d^{-1}$,averaged over a box between lon 4^0 and 45^0E, and lat 13^0 and 24^0N (Sahel and south Sahara), from the January of the 6th year to the Dec of the 25th year. The A.D. year numbering is fictitious. Control (a), RCP (cent.) and RCP-Control (b)

Figure 10: JAS wind at 900 mb, displayed with streamlines, to enhance the ITCZ position and shift. Control (a), RCP (cent.) and RCP-Control (b)

Figure 11: JAS Divergence profile, Sahel and south Sahara, averaged over the same box of figure **??**. Units in $10^{-5}s^{-1}$, and ordinates in mb.

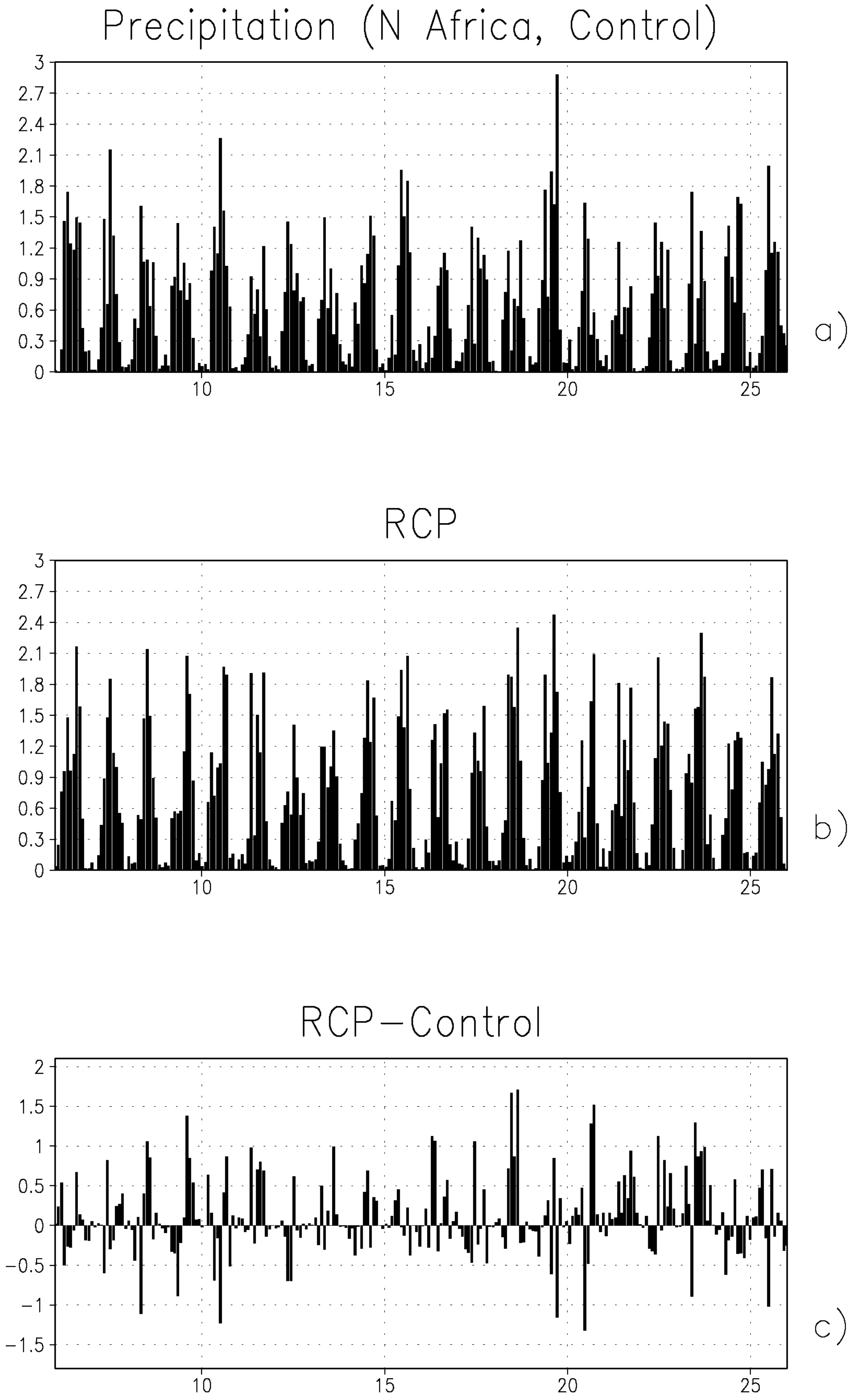

Precipitation (N Africa, Control)
3
2.7
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0
10
15
20
25
a)
RCP
3
2.7
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0
10
15
20
25
b)
RCP−Control
2
1.5
1
0.5
0
−0.5
−1
−1.5
10
15
20
25
c)

Figure 9

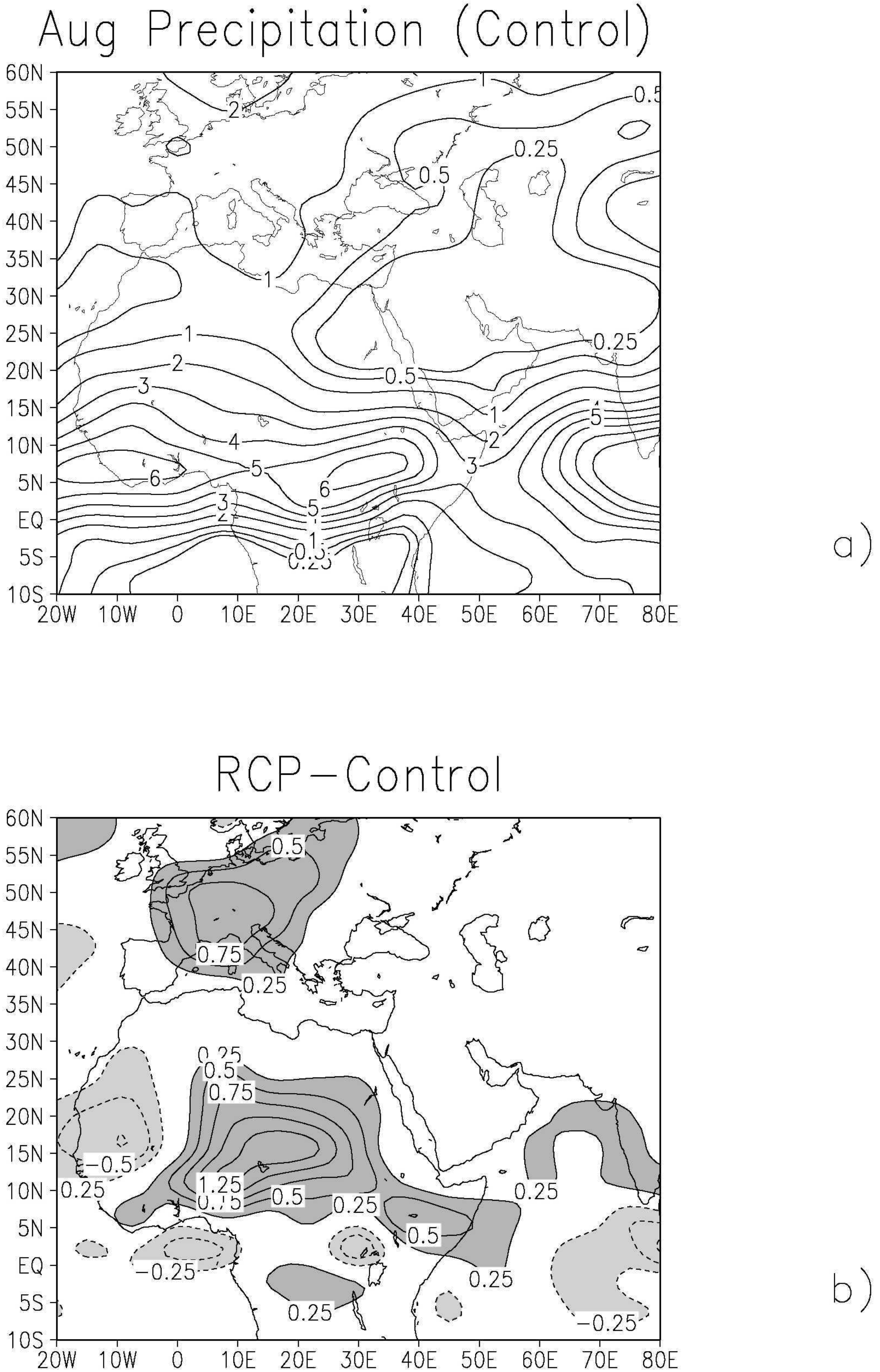

Aug Precipitation (Control)
60N
55N
50N
45N
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
20W
10W
0
10E
20E
30E
40E
50E
60E
70E
80E
1
2
3
4
5
6
0.5
0.25
a)
RCP−Control
60N
55N
50N
45N
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
20W
10W
0
10E
20E
30E
40E
50E
60E
70E
80E
0.5
0.75
0.25
1.25
−0.5
−0.25
b)

Figure 8

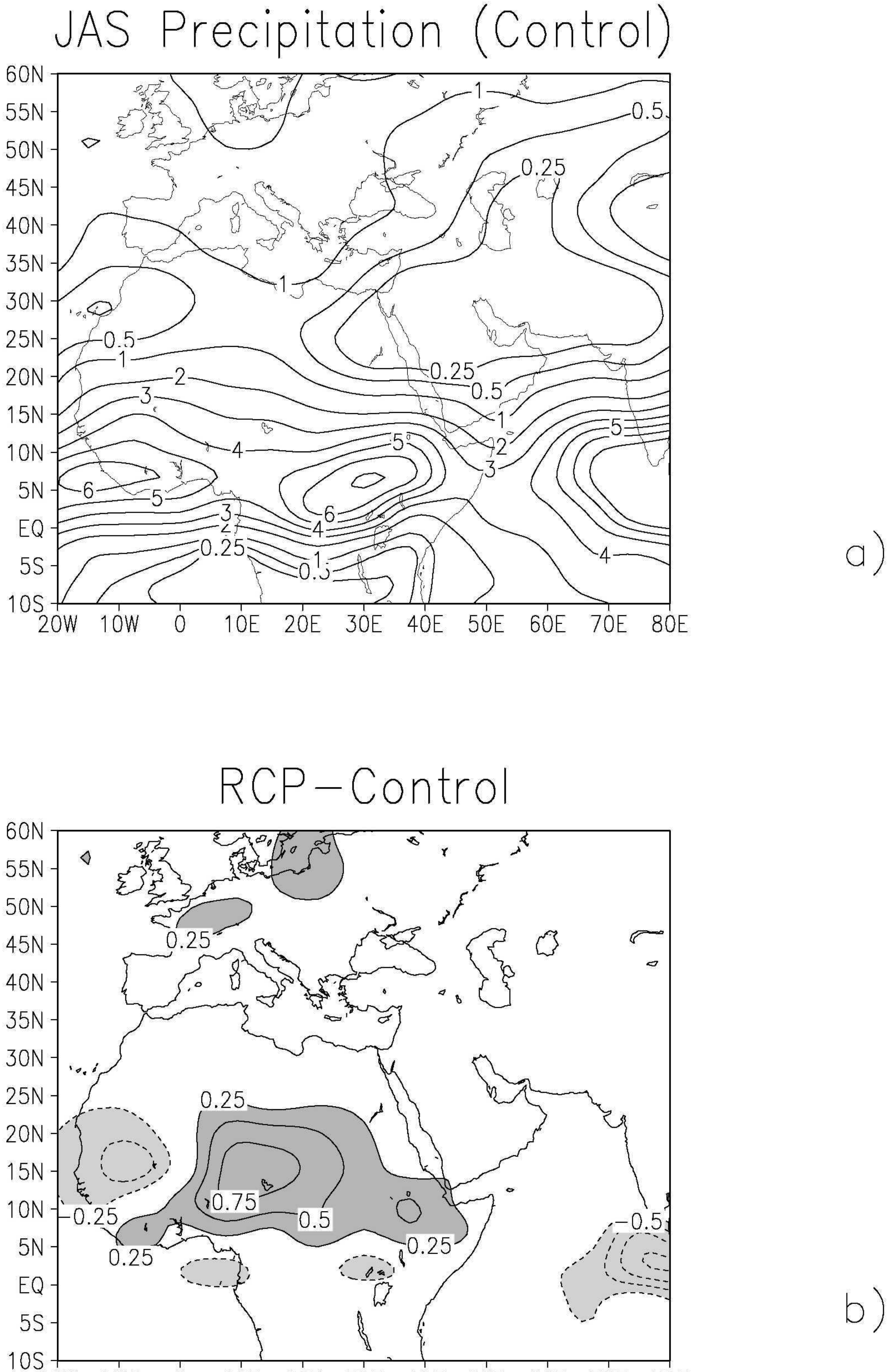

JAS Precipitation (Control)
a)
RCP–Control
b)
60N
55N
50N
45N
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
20W
10W
0
10E
20E
30E
40E
50E
60E
70E
80E
0.25
0.5
1
2
3
4
5
6
0.75
–0.25
–0.5

Figure 7

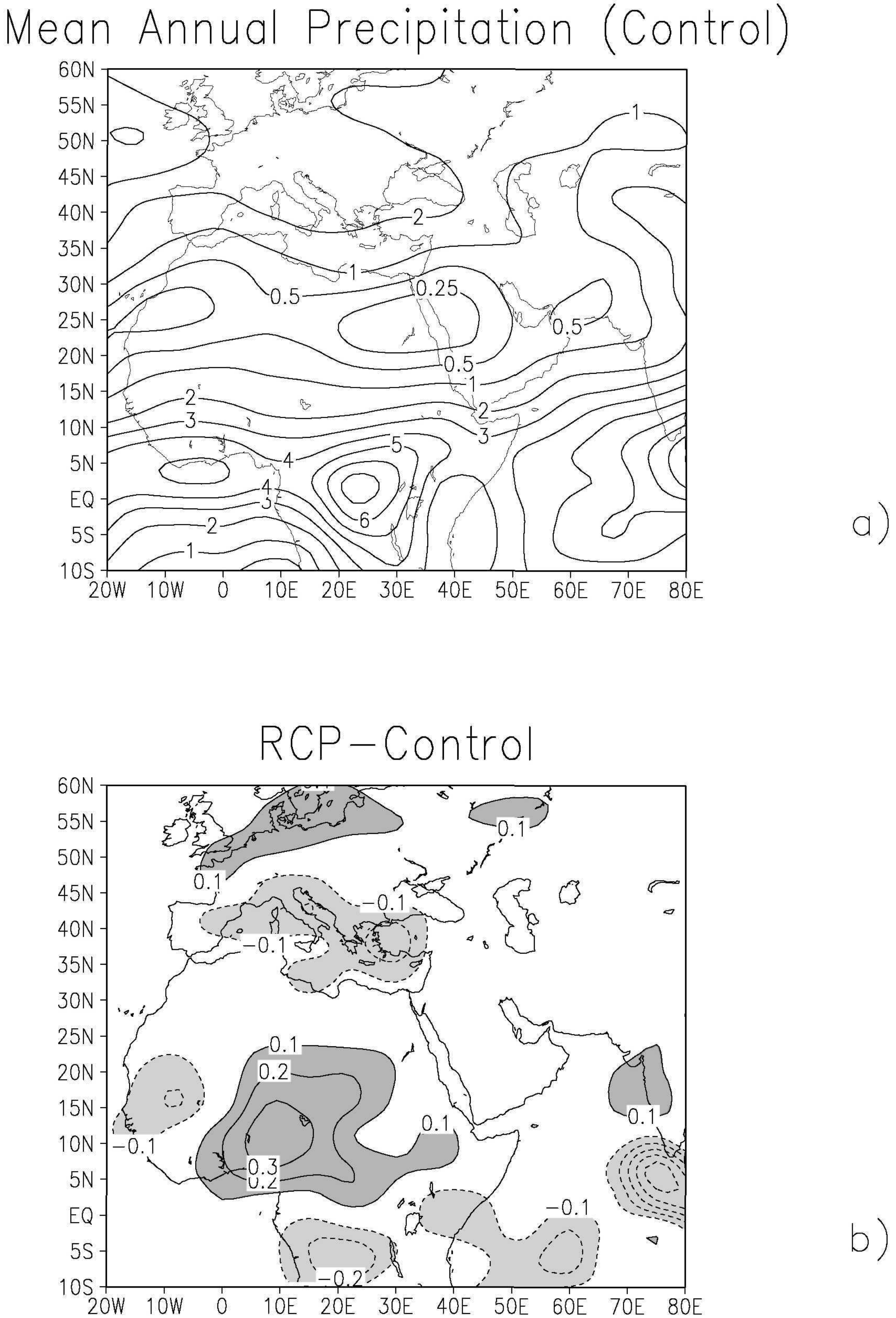

Mean Annual Precipitation (Control)
60N
55N
50N
45N
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
20W
10W
0
10E
20E
30E
40E
50E
60E
70E
80E
1
2
1
0.5
0.25
0.5
0.5
1
2
3
2
3
4
5
4
3
6
2
1
a)
RCP–Control
0.1
0.1
−0.1
−0.1
0.1
0.2
0.1
0.1
−0.1
0.3
0.2
−0.1
−0.2
b)

Figure 6

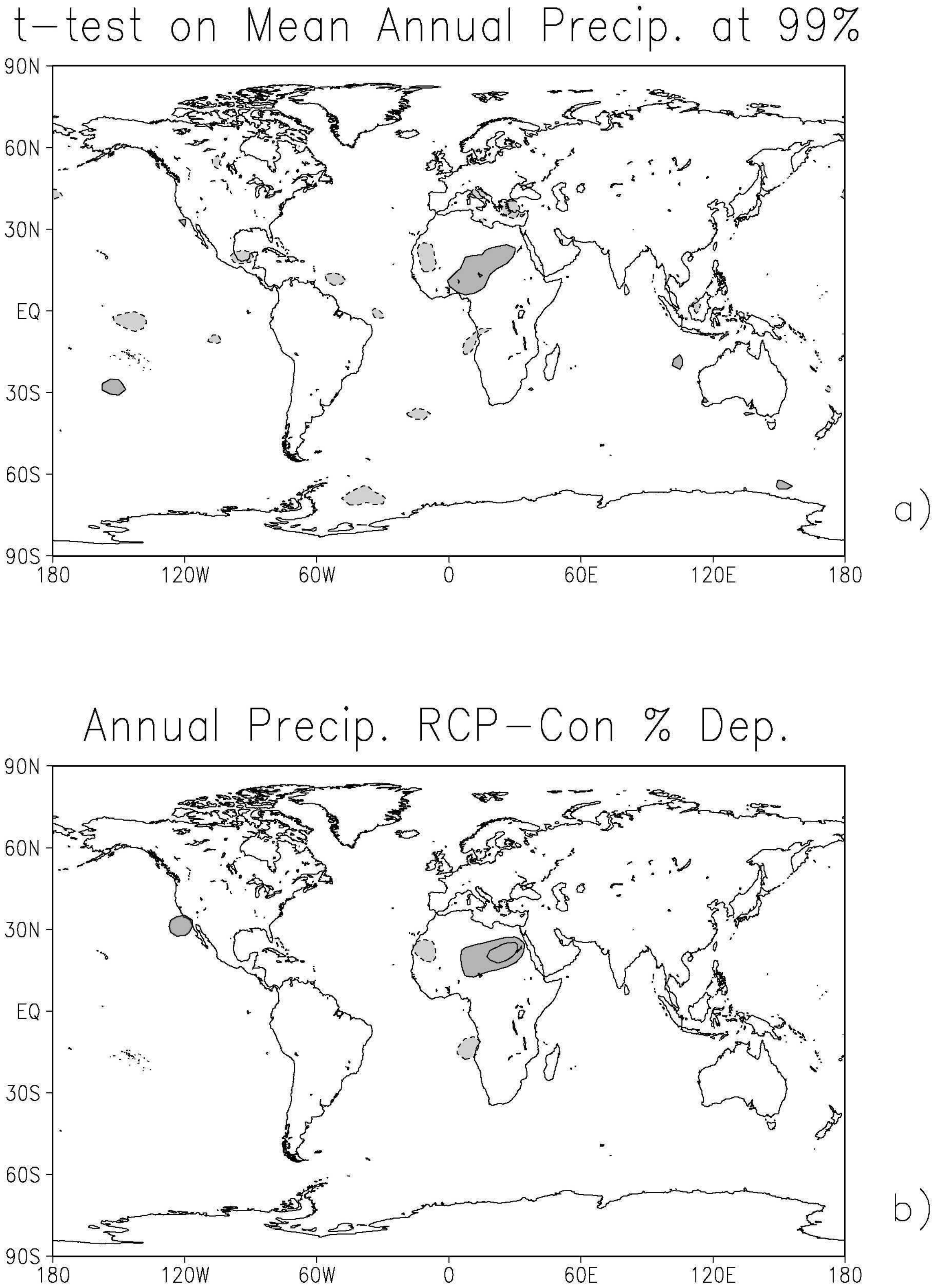
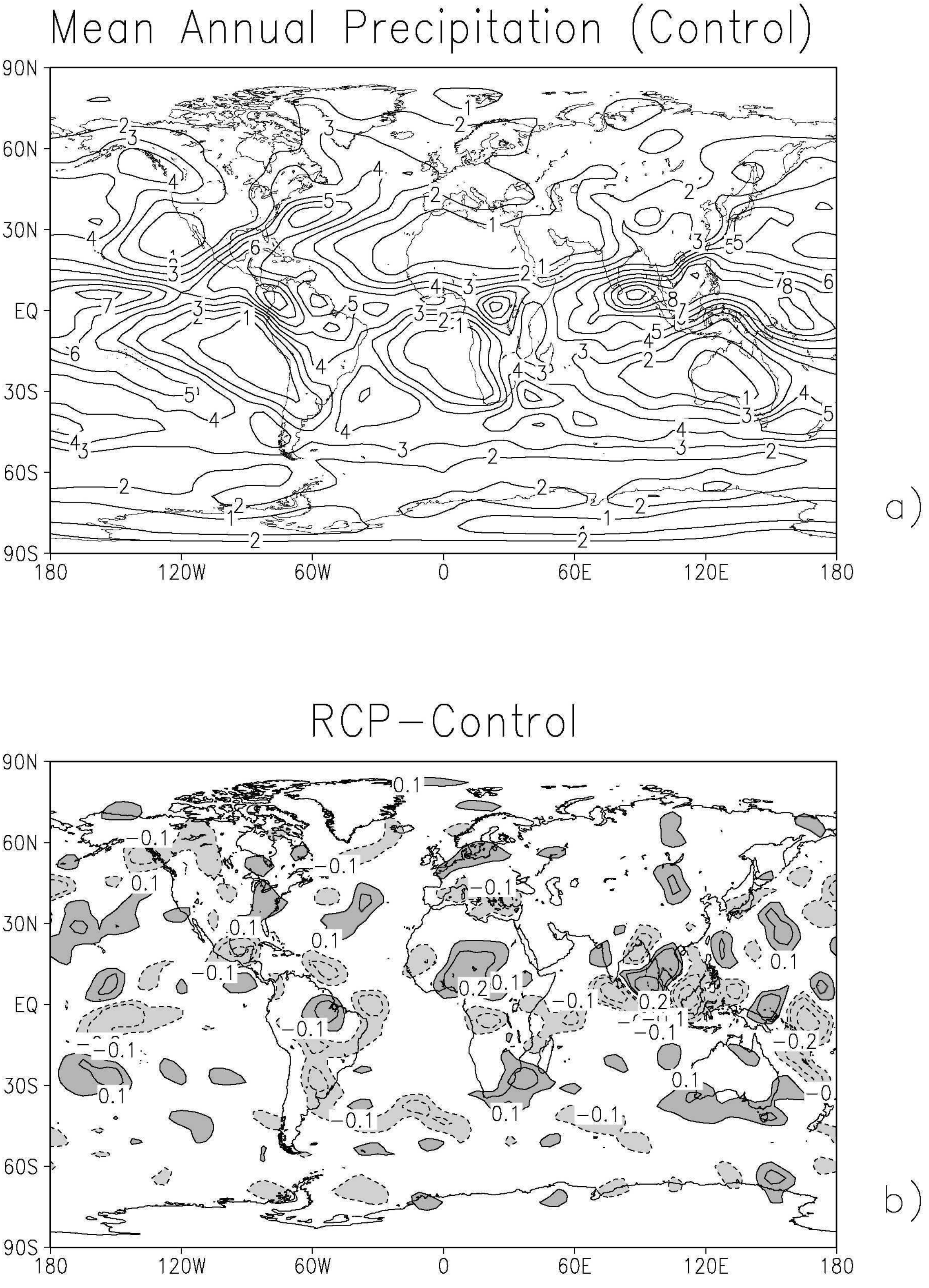

t-test on Mean Annual Precip. at 99%
90N
60N
30N
EQ
30S
60S
90S
180
120W
60W
0
60E
120E
180
a)
Annual Precip. RCP-Con % Dep.
90N
60N
30N
EQ
30S
60S
90S
180
120W
60W
0
60E
120E
180
b)

Figure 5



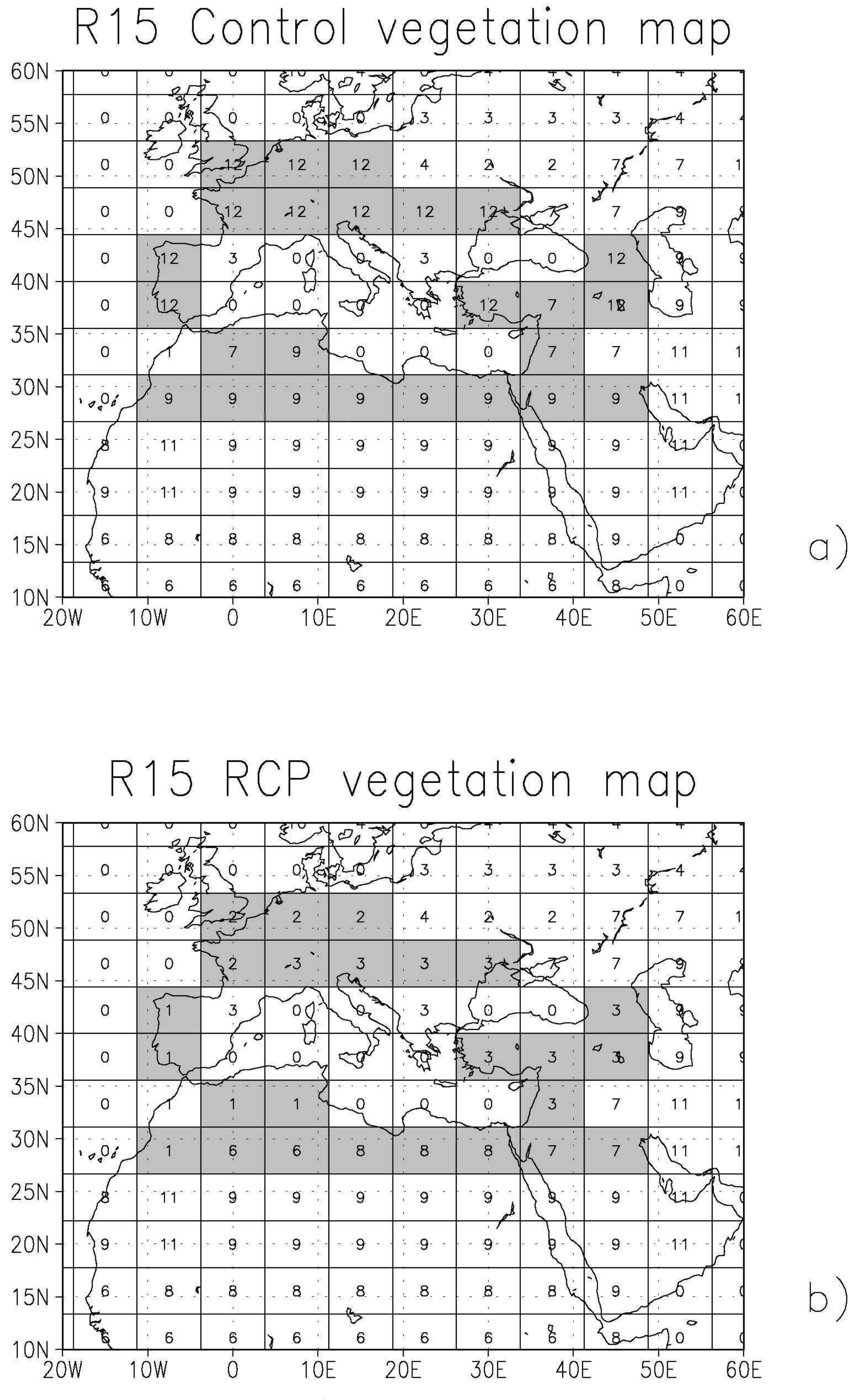
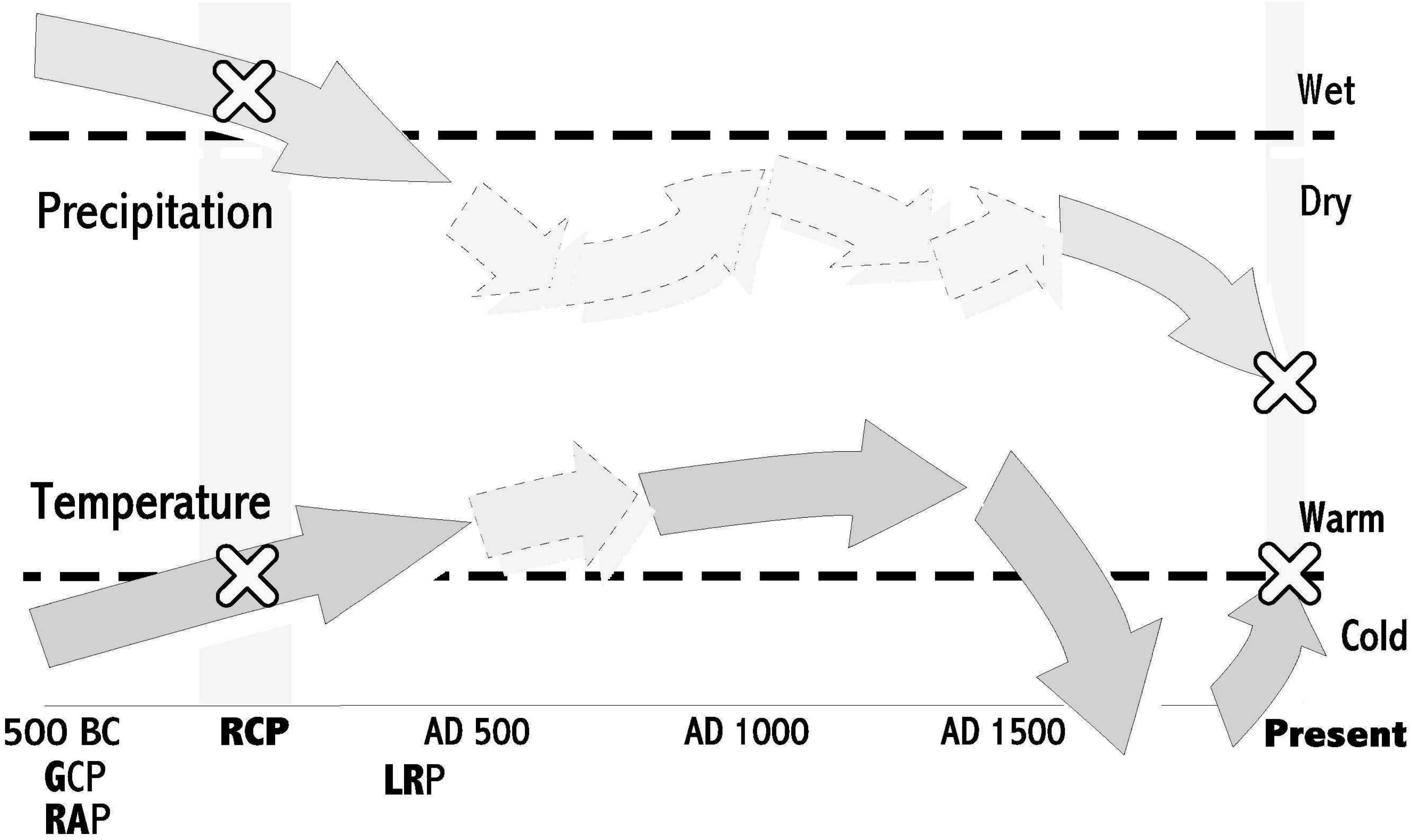

R15 Control vegetation map
60N
55N
50N
45N
40N
35N
30N
25N
20N
15N
10N
20W
10W
0
10E
20E
30E
40E
50E
60E
a)
R15 RCP vegetation map
60N
55N
50N
45N
40N
35N
30N
25N
20N
15N
10N
20W
10W
0
10E
20E
30E
40E
50E
60E
b)

Figure 3

Precipitation and Temperature Trends in Mediterranean Climate



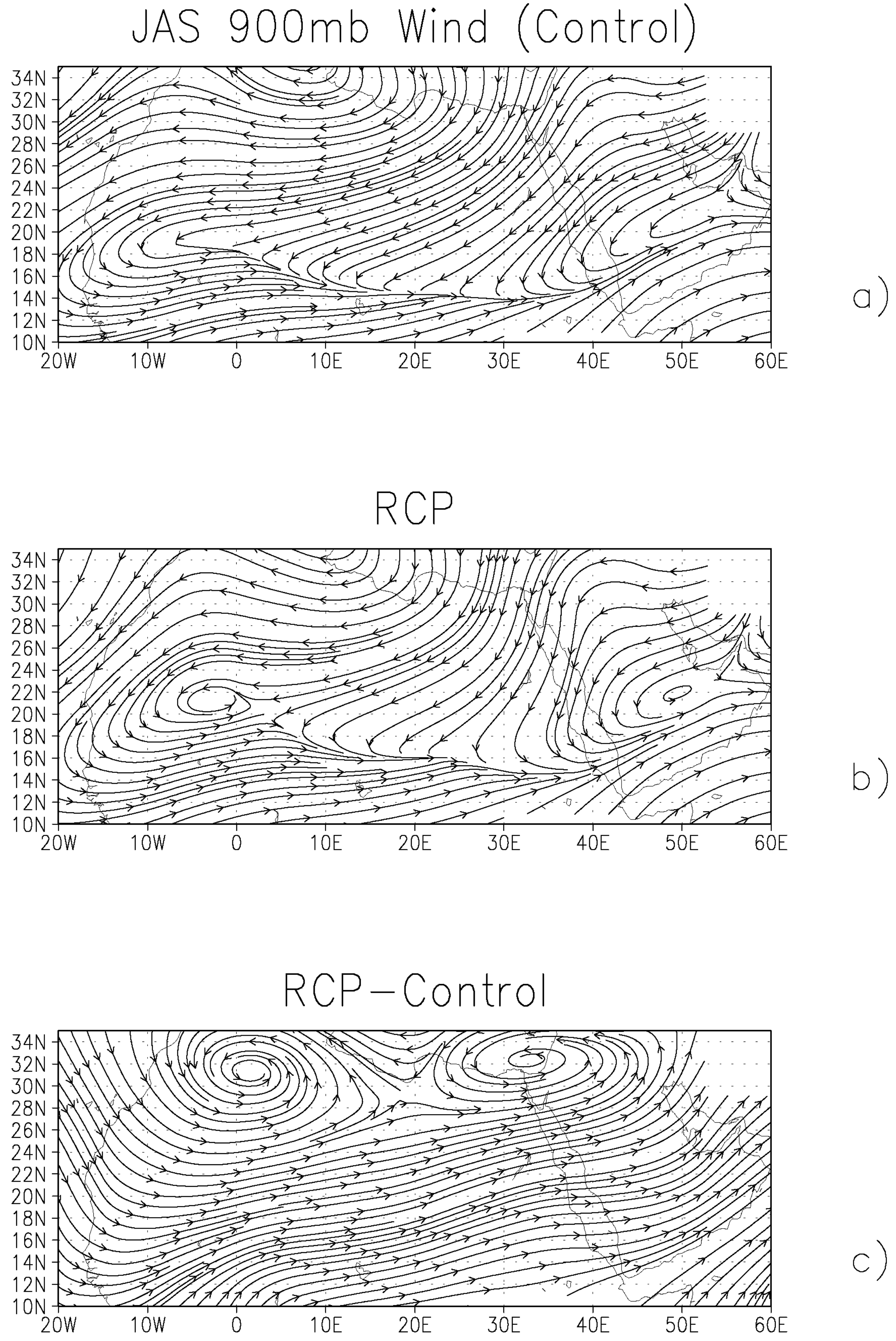

JAS 900mb Wind (Control)
a)
RCP
b)
RCP-Control
c)
34N
32N
30N
28N
26N
24N
22N
20N
18N
16N
14N
12N
10N
20W
10W
0
10E
20E
30E
40E
50E
60E

Figure 10

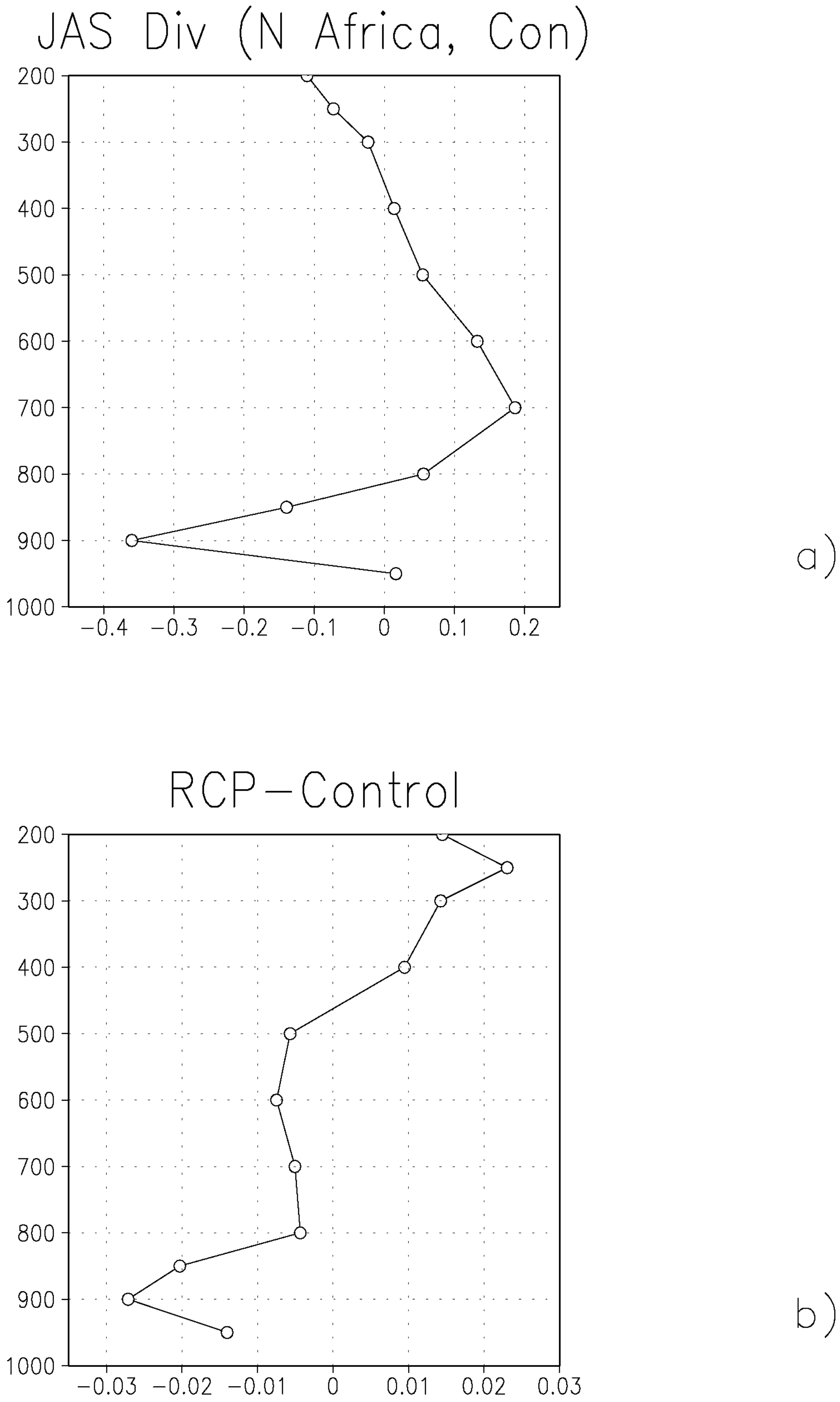
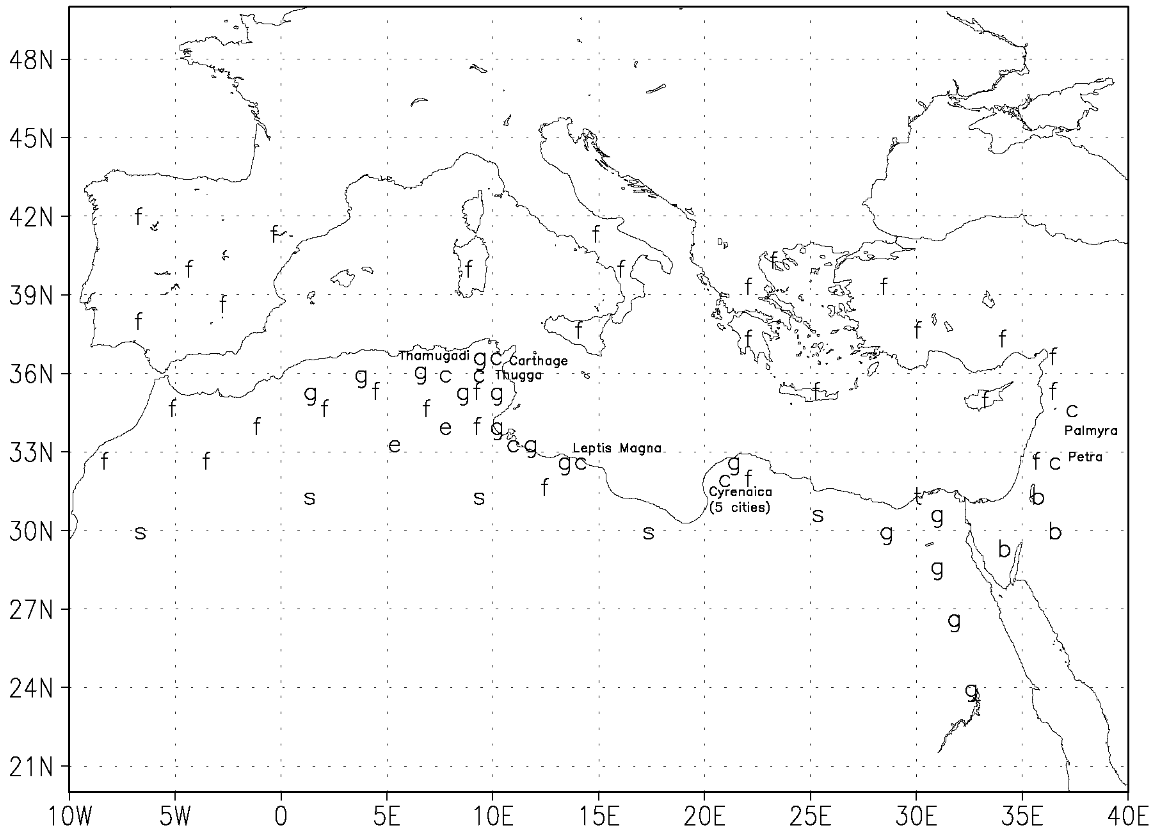

JAS Div (N Africa, Con)
200
300
400
500
600
700
800
900
1000
−0.4
−0.3
−0.2
−0.1
0
0.1
0.2
a)
RCP−Control
200
300
400
500
600
700
800
900
1000
−0.03
−0.02
−0.01
0
0.01
0.02
0.03
b)

Figure 11


Historical and Archeological Information

f extended forest cover over areas now barren or degraded

s extended shrub cover or savanna over areas now desert

g outsanding agricultural production over areas now sub-desertic

e presence of elephants over areas now desert

c cities with massive water supply systems from sources not extant

b bridges across rivers now dry

t summer thunderstorm activity over areas where now does not rain

Figure 1