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Modeling the effects of vegetation on Mediterranean climate during the Roman Classical Period
Part I: Climate history and model sensitivity

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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 years BP, 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Archeological and historical documents provide some qualitative agreement that moister conditions prevailed during Roman times, and interdisciplinary scientific research provides some confidence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 general circulation model (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.

Keywords: climate history; deforestation; desertification; land–atmosphere interaction; climate sensitivity

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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 to 10^5 years or more, the latter deals with the last 10^2 to 10^3 years, 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

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more ancient way through which humans have been interacting with the climate system: land surface usage.

Farming, cattle grazing and demand for wood have required, since the onset of the Mesolithic Age (10,000 years BP), 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; Dirmeyer and Shukla, 1996). Most Land Surface Process (LSP) studies of the impact on climate of land cover change have been performed in 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 it is 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, sedimentology and lymnology has allowed scientists to infer climate variables through proxies, in absence of real meteorological measurements. 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 to degraded landscape and poorer soil. So, the questions that arise are as follows. If the soil had not been eroded, could the preexisting vegetation be supported by the present climate? And did the changes in landscape (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 1st century BC, 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 during summer are dominated by the northward part of the descending branch of the Hadley cell, 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 BC, and the Late Roman Period (LRP) in the 5th century AD, in terms of a gradual warming (Lamb, 1977, 1982). The 5th century BC climate appears to have been colder than the present climate, whereas the 5th century AD 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 8,000–10,000 years BP, but intensified only after the 1st century AD: they were enhanced by the political crises of the 3rd and 5th centuries AD 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 that conditions were moister than present around the Mediterranean during Roman times. The development of paleoclimatology and the need for organizing all the possible proxies in a general, widely accepted climate history led several authors to describe a sequence of climate events. Among these, Lamb (1977, 1982) assembled all the historical and scientific information available, and in his works present 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 climate to changes in surface conditions. A simplified but reasonable vegetation map, resembling the RCP vegetation (which will be discussed in a greater detail in Part II of this paper) 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 (IC) but forced with different vegetation — modern and RCP — the impacts on climate are evaluated. 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 GCP (5th century BC) from the LRP (5th century AD) — 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. Panessa (1991) contains a larger text collection related to weather and climate issues. All of the authors we selected are published in the Loeb Classical Library. General information about the authors and the texts are taken from Ferrari et al. (1993) or from the authors themselves.

We could separate these authors into main groups: works dealing with History or Geography, which have some geographical digression of marginal relevance to our study, works dealing with agriculture, and works with some explicit reference to vegetation or climate.

2.1.1. Works dealing with history and geography

Herodotus (484–430 BC), Greek historian, wrote the ''Histories'' (*Historiai*), in which interesting geographical information about the Middle East, Persia, Greece, Egypt and southern Italy is provided. Polybios (200–120 BC), Greek historian, explored the coast of Africa to the west of Carthage in 146 BC, during a military expedition. In the 34th book of his 40 books ''Histories'', geographical subjects are addressed, and a description of the northern coast of Africa is given. Julius Caesar (100–44 BC), 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*, normally attributed to him although of uncertain authorship). In particular, the Alexandrinian and African Wars provide descriptions of Northern African geography and agriculture and confirm the presence of wooded areas in present Tunisia and Libya. General information on some extreme weather events, climate and wind patterns are also recorded, providing the impression of stormier weather during the warm semester in the Mediterranean. Sallust (86–34 BC), Roman historian, wrote, among other works, the ''War with Jugurtha'' (*Bellum Iugurthinum*), which describes the war between the king Jugurtha and Rome (111–105 BC). Two wide digressions on African geography are useful for our study. Strabo (64 BC–AD 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 BC–AD 17), Roman historian, although not dealing directly with geographical subjects, provides in his huge ''Roman History'' (*Historiae*) some useful information for our study. For example, the abundance of elephants (evidence of moister conditions than today), used by King Pyrrhus of Epyrus in 275 BC, by the Carthaginians during the second Punic War (218–202 BC), and by King Anthiocus in 190 BC, is documented.

Tacitus (AD 55–120), Roman historian, wrote the ''Annals'' (*Annales*), in which some information about climate and agricultural prosperity of various regions is given. Ammianus Marcellinus (AD 330–392), Latin historian of Greek origin, was primarily concerned with history, ethnography and analysis of characters, but with respect to this study, he provides some information on agriculture. Lamb (1977) quotes him reporting that the grain harvest in Gaul (modern France), in the middle of the 4th century AD, 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 also provided.

2.1.2. Works on agriculture

Cato the Elder (234–149 BC), 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 crops must be alternated to allow the soil to recover. The Roman author Varro (116–27 BC) describes in his work ''On Agriculture'' (*De re rustica*) the agricultural techniques and policies of the RCP. From the 1st century AD, 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). The Roman writer Columella (AD 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.

2.1.3. Works with some explicit reference to vegetation or climate.

The Greek author Teophrastos (371–288 BC) wrote two important treatises on plants. Particularly, his ''On causes of plants'', is a six-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 (AD 23–79), author, among other works, of a monumental ''Natural History'' (*Historia Naturalis*) in 37 books. The parts relevant to this study are books two and three, which deal with geography, and books 12–19, which pertain to botany. According to Pliny, during the 4th century BC, the beech tree grew almost at the sea level along the river Tiber, whereas in the 1st century AD, 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 5th century BC 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 desert. Lamb (1977) also noted that the elephants died out in the 3rd century AD, probably because of the increased aridity.

Finally, the great Alexandrian astronomer and geographer Claudius Ptolomaeus (AD 100–170) wrote mostly about astronomy, but in additional minor works (e.g., his weather diary, written in Alexandria during the summer of AD 120), reported a clear indication of frequent convective activity and 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 Fig. 1: 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. 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, vs. only 60 in Gaul (modern France). Among them, we can mention the following:

- *Leptis Magna*. Situated in modern Libya, the city was founded in approximately the 5th century BC, and was extremely prosperous and rich during the RCP. The city entered a period of decline in the 4th century AD, 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 semi-desert area.
- *Carthage*. The Roman Carthage, built after the third Punic War (146 BC), received its water from a

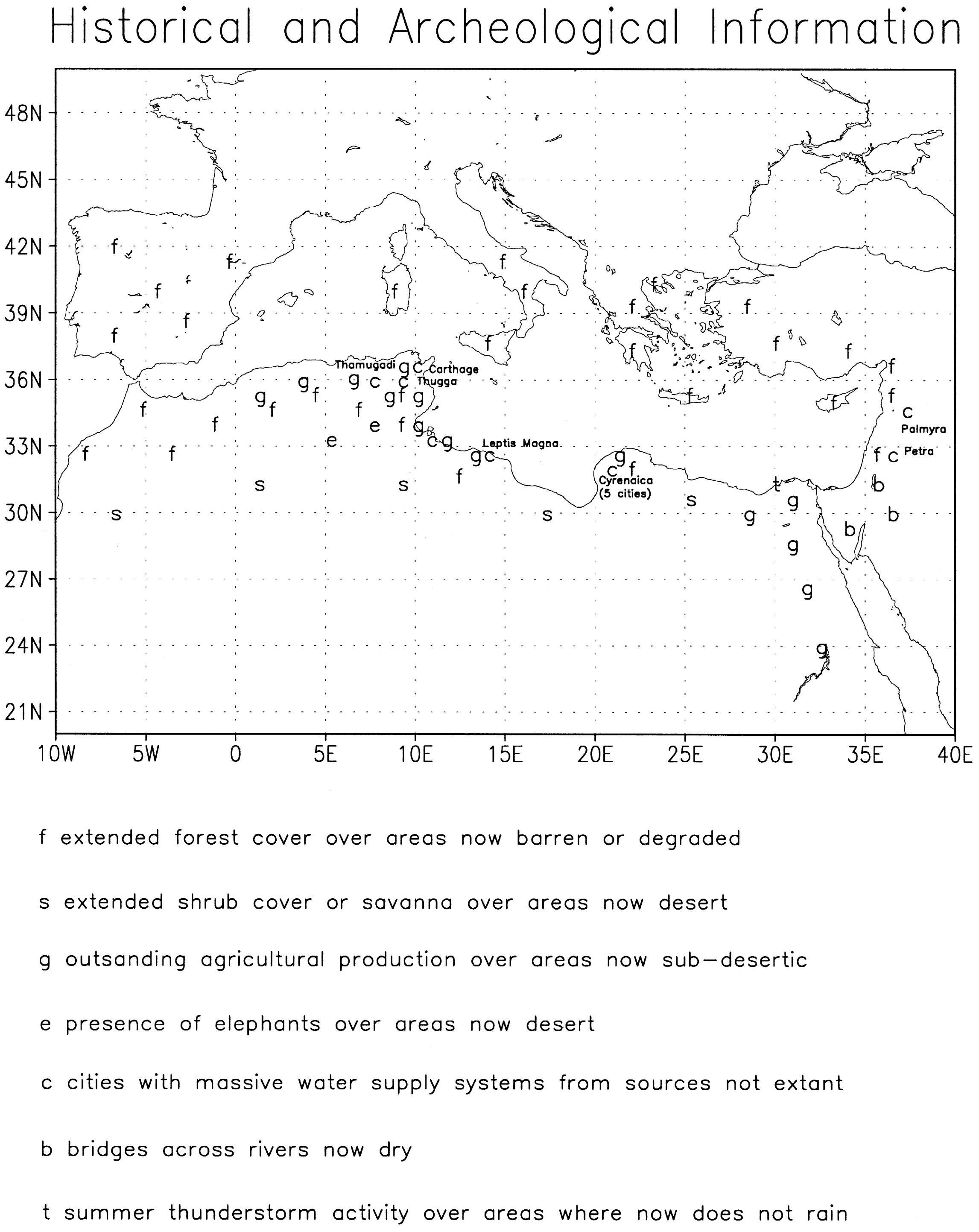


Fig. 1. Qualitative information on climate and/or landscape change that can be deduced from classical literature sources and archeology.

source more than 50 km away, through a magnificent aqueduct that is still visible today (Cornell and 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 km 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 and they include the following.

· *Palmyra* (in modern Syria). During the Roman Empire the prosperity of ''the city of the palms'' was spectacular. Destroyed towards the end of the 3rd century AD, 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 AD across Arabian rivers that now are dry.

2.3. Population distribution

Population can be inferred and estimated mainly through burial sites and artifacts since prehistoric 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 (1980), about AD 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 settlements 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 large amount of historical information left from Greek and Roman Histories, 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 BC — which is the GCP for Greece or the RAP for Rome — the Mediterranean area was divided into several areas of influence: among them Greek, Egyptian, Phoenician–

Carthaginian, Etruscan and Roman. The entire Mediterranean area were moister than today and agricultural activity was not very heavy in northern Africa: Carthaginians were getting most of the grain they needed from Sardinia and Sicily. In Italy, the conservation principles for agricultural use were applied until the 1st century BC (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 1st century AD, 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.

In addition, another significant change occurred: the increase in demand, due to the higher standard of living and caused by a population two to three times larger than 5 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 BC–AD 14) lifted the ban on oil and wine production outside Italy (Rees, 1987).

Northern Africa soon became the most important source of olive oil (Rees, 1987), grain and cereals for the Roman world. Massive irrigation systems were constructed, and vast areas originally covered by Mediterranean forest or Mediterranean shrub were converted into grain plantations or olive orchards.

• During the 3rd century AD, which is considered by some to be the beginning of the ‘‘Decline of the Roman Empire’’, many of the northern African areas devoted to agriculture were abandoned, and therefore, both irrigation and land control ended. Even though the Roman Empire made a strong recovery by the end of the 3rd century AD, 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*).

• The damage to land resources became 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 — any form of agricultural policy and concern for land maintenance ended. By the 6th century, when — for a brief period — the Eastern Roman emperor Justinian reconquered northern Africa, none of those cities could recover from the decline. 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 throughout much of the Middle East. Areas of southern Spain, Sicily, Greece and Turkey have also to be considered semi-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, agriculture and herding in the steep areas of the Mediterranean 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 climate 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 delineation of the climate changes with respect to precipitation and temperature. The reconstruction of environmental change during the last few thousand years involves analysis ranging over 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 (1977,1982), Bell and Walker (1982), Budyko (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 BC 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 BC–AD 500*: There is evidence of a general warming from the 5th century BC, to the 5th century AD. 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 AD 120, Lamb (1982) reports the occurrence of rain in 11 months of the year and of thunder in every summer month. Lamb (1977), in a comparative study of reports of occurrences in floods of the river Tiber in Italy, states that from the year AD 174–489, only two floods occurred, compared to the 22 floods that occurred between 200 BC and AD 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 BC–5th century AD) 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 BC to AD 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 AD 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 LRP (i.e., from the 2nd to the 5th century AD) in Greece. Paepe's analysis is based on the geological analysis of river sediments.
- *AD 500–1300*: 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 AD 900 and AD 1300 or later, is considered to be a period of relatively higher temperatures and a lesser extent of Alpine ice cover (Flohn and Fantechi, 1984). Precipitation does not seem to follow the same regular pattern. Most of the authors 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 5th century AD, Italy again experienced some recurring wet situations, with one dry phase in about AD 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 AD 1000) was a dry phase also in Greece.
- *AD 1500 to present*: The period 1550–1850, often referred to as ''the little Ice Age'' was characterized by a general reversal of the warming tendency. 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.

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, which 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 usually determine 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 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 appears to depend strongly on albedo, more so 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 in the 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, a lack of precipitation for several months. 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 to 20° 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, palynology (Ritchie and Haynes, 1987) suggests that, during the ''climatical optimum'' (6000 years BP), the ITCZ was advancing much further north, given 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: 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 atmospheric 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 semi-arid. 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 expressed the RCP vegetation map in terms of the 12 vegetation types allowed by SSiB (Table 1) for the present vegetation. As all the vegetation associations characterizing the RCP and those described above are still in existence — but just shifted or reduced in size — no introduction on the different vegetation types is necessary. It is interesting to notice that the so-called Mediterranean forest, a vegetational environment dominated by evergreen oaks like the *Quercus ilex* and dwarf palms, is a broadleaf evergreen forest. Due to its mean climatological values of albedo (10–15%), surface roughness length (1–1.5 m) and its very low values of summer stomatal resistance (25–50 $s\ m^{-1}$, it is classified the same as tropical forest in the SiB map (Dorman and Sellers, 1989). The largest extant patch of Mediterranean forest is over western Morocco.

Table 1
Vegetation types in SSiB

1. Broadleaf–evergreen trees (tropical or Mediterranean forest)
2. Broadleaf–deciduous trees
3. Broadleaf and needle-leaf trees (mixed forest)
4. Needle-leaf–evergreen trees
5. Needle-leaf–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)

However, because of the relatively poor resolution of the R15 experiment, a simplification has to be made with respect to the much more detailed information obtained from pollen maps. Essentially, the R15 RCP vegetation map — with respect to the present one — expands the areas of vegetation types 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, three gridpoints of vegetation type 8 (groundcover with shrubs) replace vegetation type 9 (bare soil with shrubs). Two gridpoints of Mediterranean forest (vegetation type 1) replace vegetation 9, one gridpoint of Mediterranean forest replaces type 7, and two gridpoints of type 6 (savanna) replace vegetation type 9 over northwestern Africa. In the Middle East, two gridpoints of vegetation type 9 are replaced by vegetation type 7 (grassland) and four gridpoints of vegetation type 3 replace the remaining relatively higher elevation areas, currently classified as vegetation types 12, 7 and 8. Overall, 25 gridpoints were changed to create the R15 RCP vegetation map.

In Fig. 2, 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 1.

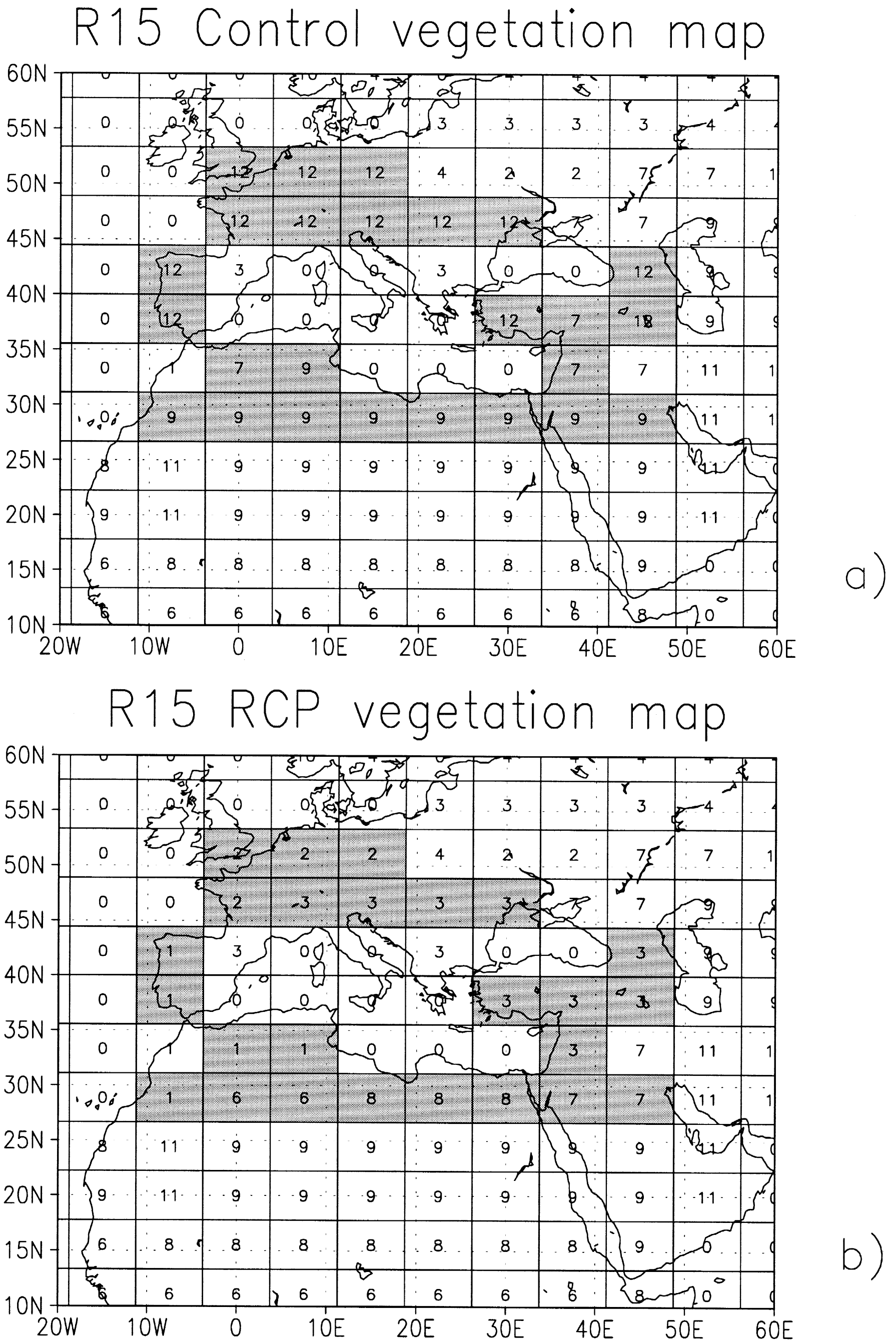


Fig. 2. Vegetation map at R15 solution. The numbers correspond to the vegetation types and are listed in Table 1. Panel a: Control. Panel b: RCP. Shading indicates grid boxes where modern and RCP vegetation differ.

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° longitude and 4.5° latitude. The model is implemented with a biosphere model derived from SiB (Sellers et al., 1986). Based on Dorman and Sellers (1989), a set of 12 types of vegetation has been adopted to represent the entire planet. Xue et al. (1991) developed SSiB, which provided a computational gain of almost 50%. SiB and SSiB have been widely used in a variety of climate sensitivity experiments related to deforestation and desertification.

4.4. Design of the experiments

A 25-year GCM control integration with present vegetation and an experiment integration with RCP vegetation were conducted, starting from the same ICs. This low-resolution experiment, although without detailed geography, provides a useful tool to test the sensitivity to vegetation change in the Mediterranean 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 the R15 truncation, 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 integrations were started with the IC of 1 January 1990, obtained from a 1-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 years BP — is done to avoid the superposition of the climate response. Climatological sea surface temperatures (SSTs) are used. It is recognized that this is a limitation since the climate of the Sahel is sensitive to the variability of the observed seasonal Atlantic SSTs, but 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. 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. The main goal is not a realistic experiment, but to test for gross sensitivity to vegetation change. Positive results will encourage further investigation at higher resolutions. All the fields displayed are averaged over the last 20 years of the integration 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 5 years.

5. Results of the experiment

5.1. Analysis of results

The 20-year control precipitation is displayed in Fig. 3, 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 Fig. 4a, the *t*-test performed at 99% significance level shows a clear and well-defined area in which there is a statistically significant response of climate. However, because of the temporal and spatial correlations that exist in a field of data points, local samples are not statistically independent and local *t*-tests are not definitive. In Fig. 4b, 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 Fig. 3 is because we are dealing with a desert area, with very low mean rainfall.

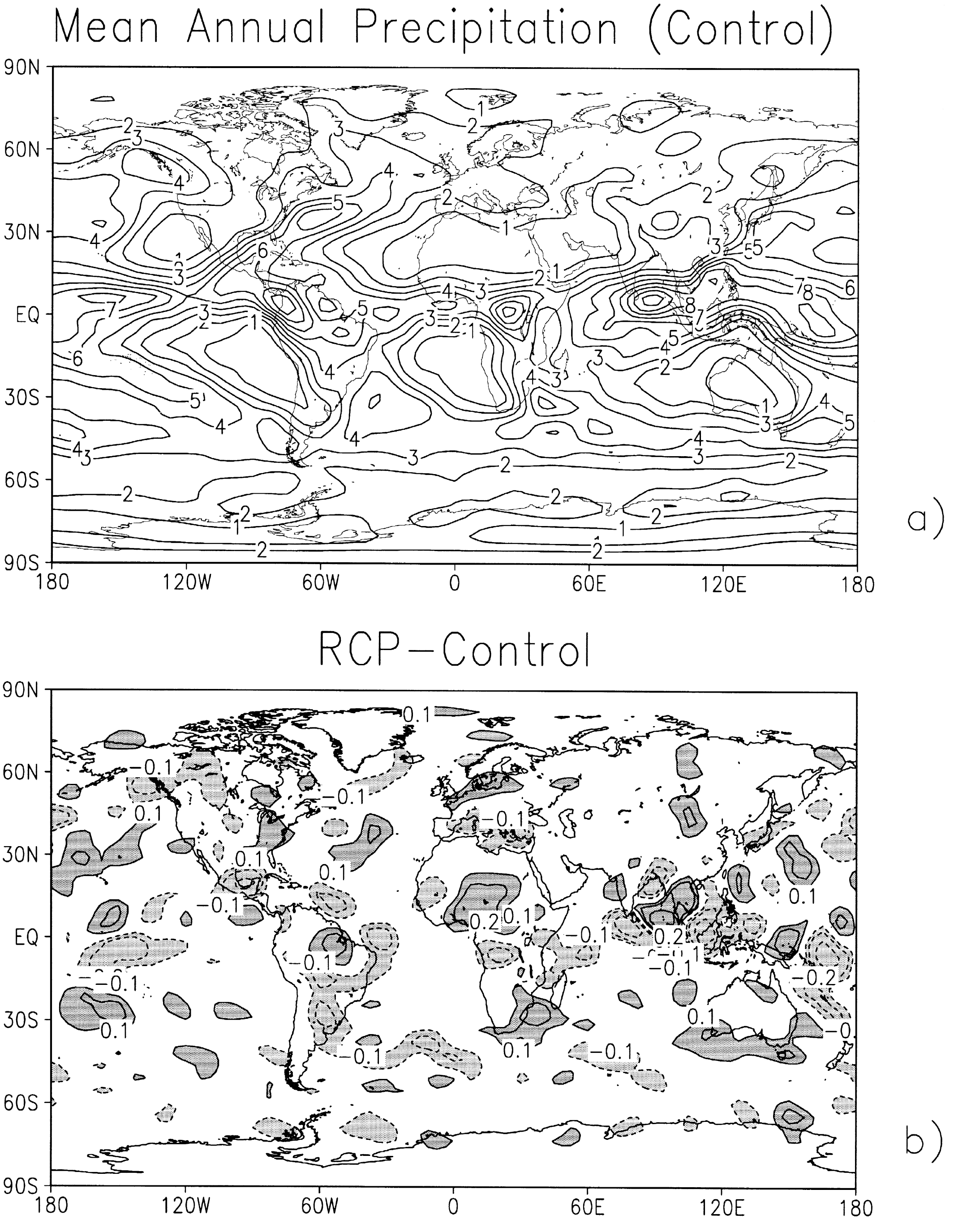


Fig. 3. Mean annual precipitation. Control (panel a), RCP–Control (panel b). Contour interval is 1 mm d^{-1} in panel (a) and at ±0.4, 0.2 and 0.1 mm d^{-1} b in panel (b). In the darker (lighter) shaded areas, the RCP–Control precipitation is greater (less) than ±0.1 mm d^{-1}.

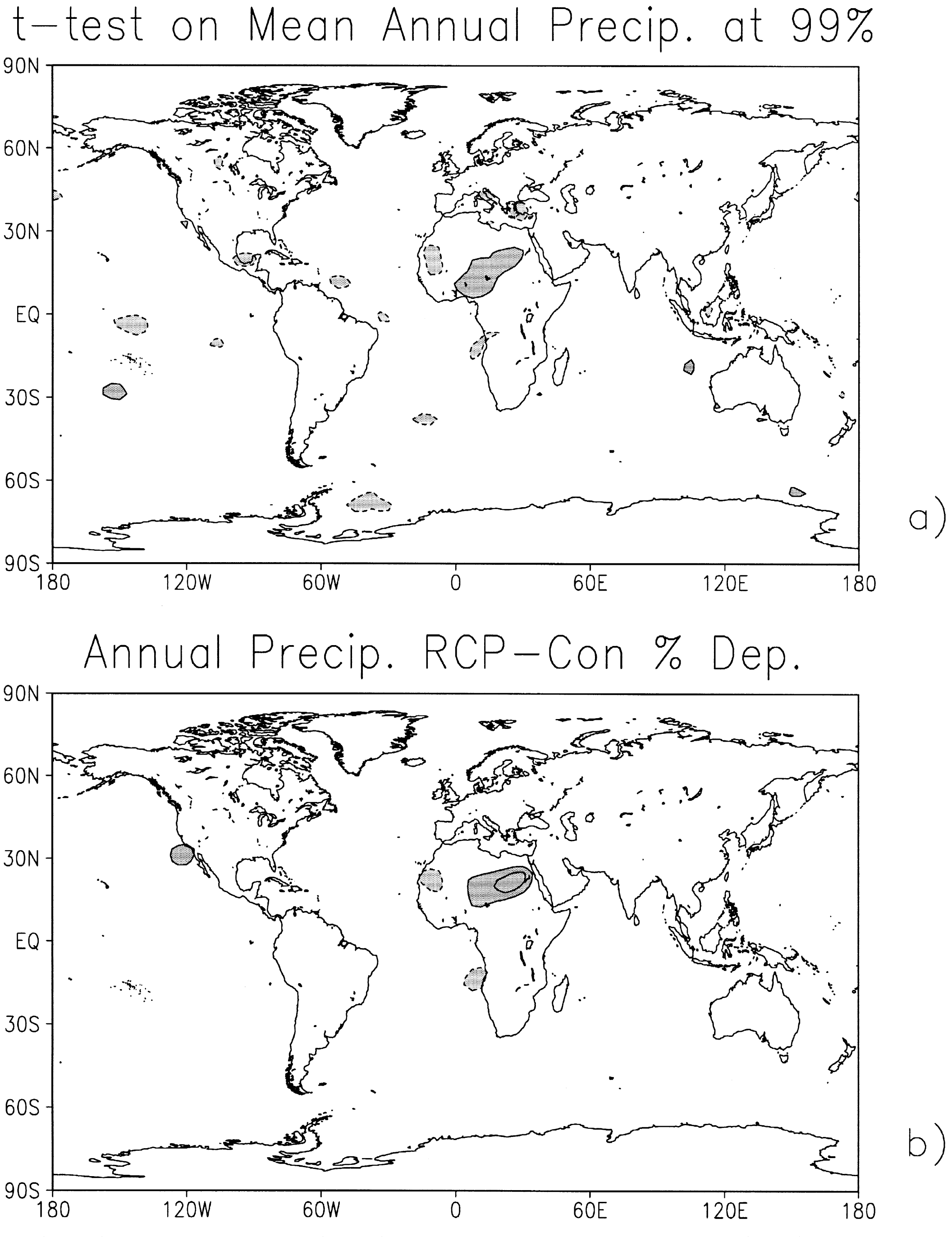


Fig. 4. *t*-Test (panel a) and percentage departure (panel b) on mean annual precipitation. In the darker (lighter) shaded areas, precipitation RCP−Control is greater (less) than zero at 1% significance (panel a). In the darker- (lighter-) shaded areas, the RCP−Control percentage departure from Control is greater (less) than ±20% (panel b). Control interval is at 20%.

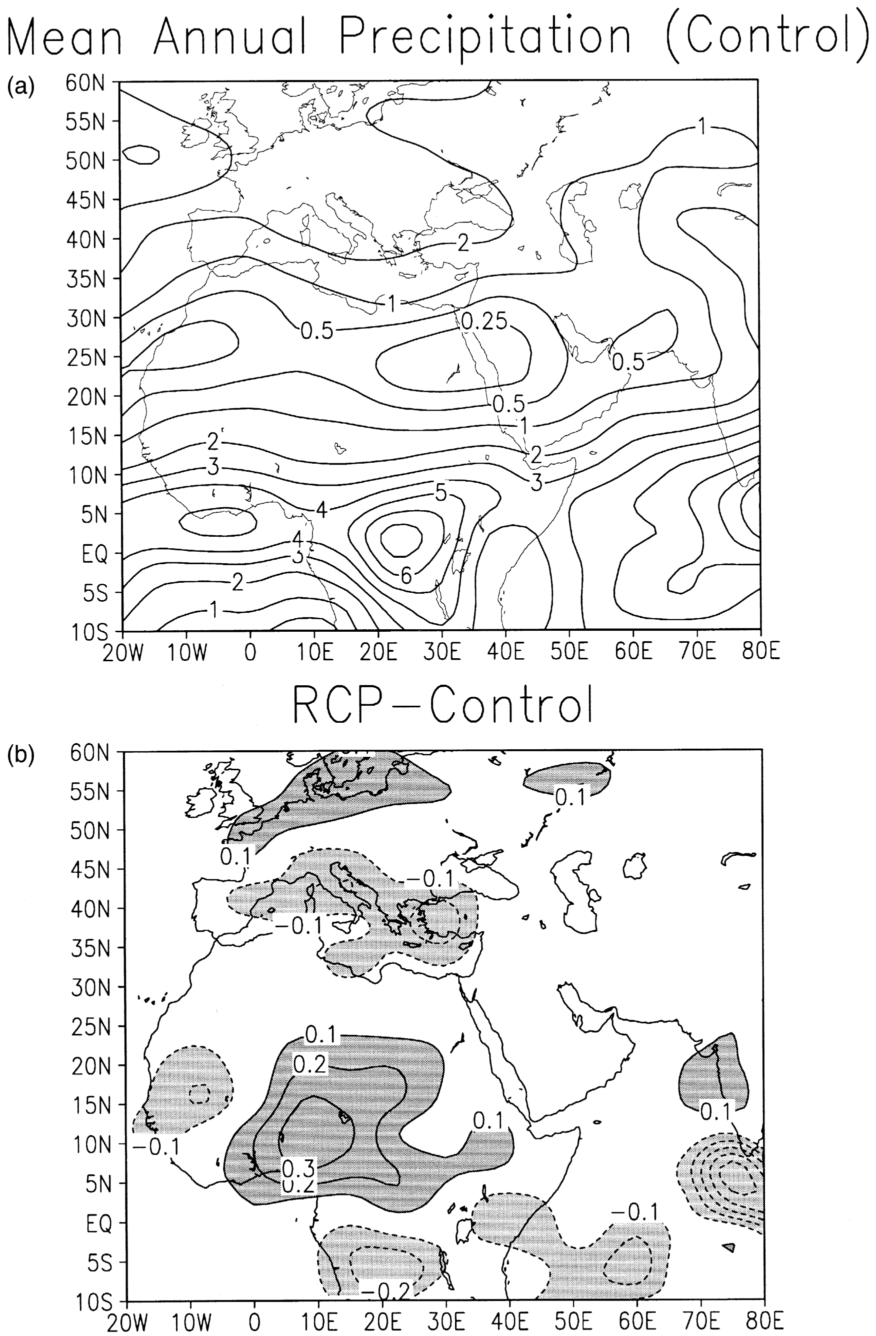
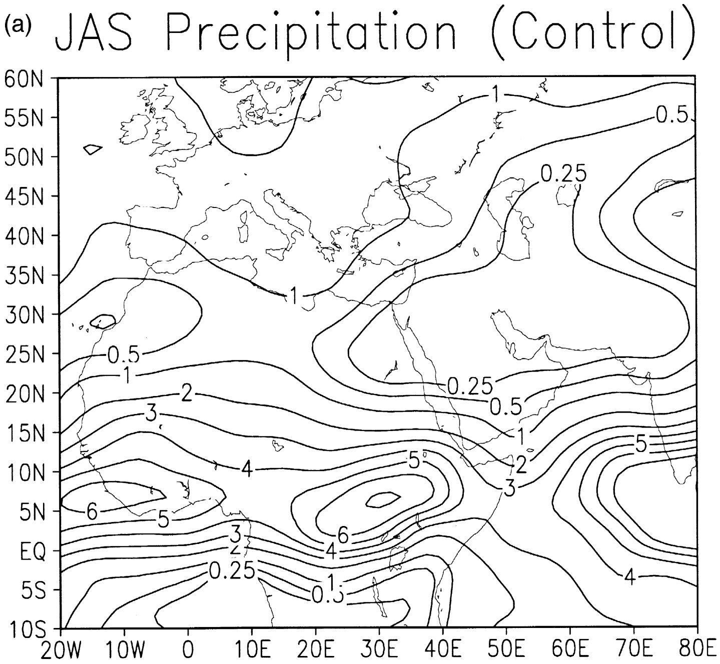


Fig. 5. Regional view of mean annual precipitation. Control (panel a), RCP–Control (panel b). In panel (a), the contour interval is 1 mm d^{-1} (for $p_{\mathrm{Control}} > 1$ mm d^{-1}), 0.5 mm d^{-1} (for 0.5 mm $d^{-1} < p_{\mathrm{Control}} < 1$ mm d^{-1}) and 0.25 mm d^{-1} (for $p_{\mathrm{Control}} < 0.5$ 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}.



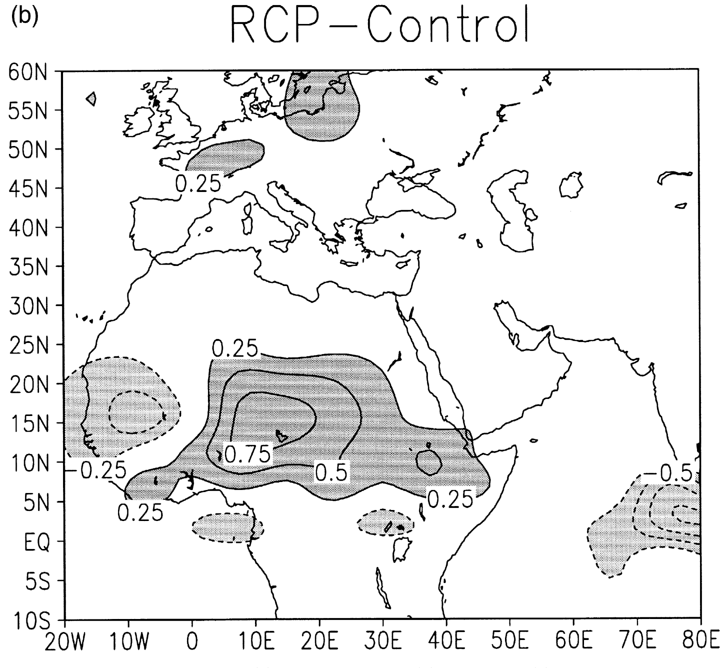


Fig. 6. Regional view of the JAS precipitation. Control (a), RCP–Control (b). In panel (a), the contour is 1 mm d^{-1} (for $p_{\mathrm{Control}} > 1$ mm d^{-1}), 0.5 mm d^{-1}(for 0.5 mm d^{-1} $< p_{\mathrm{Control}} <$ 1 mm d^{-1}) and 0.25 mm d^{-1} (for $p_{\mathrm{Control}} <$ 0.5 mm d^{-1}). In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

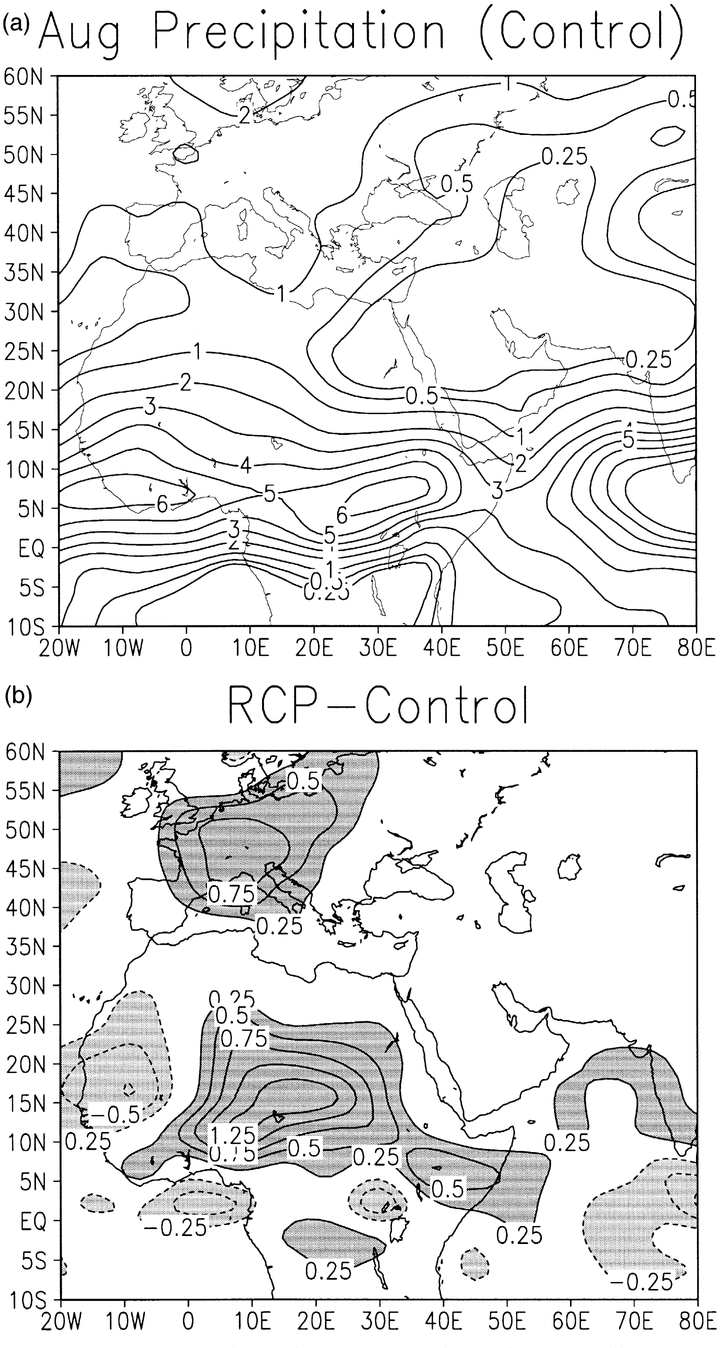


Fig. 7. Regional view of August precipitation. Control (panel a), RCP–Control (panel b). In panel (a), the contour interval is 1 mm d^{-1} (for $p_{\mathrm{Control}} > 2$ mm d^{-1}), 0.5 mm d^{-1} (for 0.5 mm d^{-1} $< p_{\mathrm{Control}} <$ 1 mm d^{-1}) and 0.25 mm d^{-1} (for $p_{\mathrm{Control}} < 0.5$ 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}.

In fact, Fig. 5 shows 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 by more than 0.1 mm d^{-1}, which is a substantial fraction of the entire value. It is important to stress that the effect of this precipitation increase is not only statistically significant, but has environmental implications as well. In fact, the 100 mm $year^{-1}$ 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, in the experiment climate, many areas would shift from a

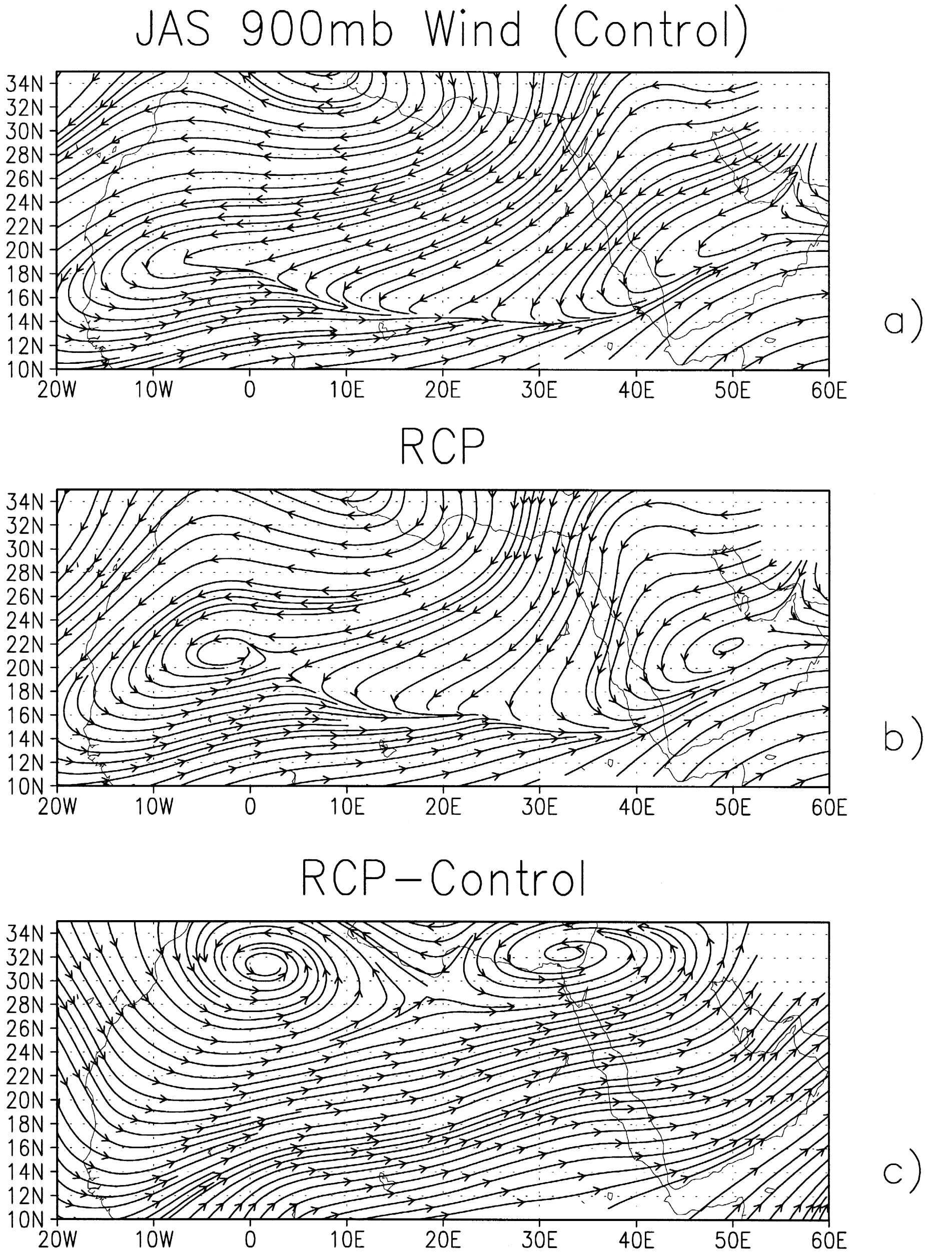


Fig. 8. JAS wind at 900 hPa, displayed with streamlines, to enhance the ITCZ position and shift. Control (a), RCP (b) and RCP−Control (c).

desert climate to a semi-desert. 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 mm year^{-1}) or the groundcover line limit (250 mm y^{-1} separate 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.

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 Fig. 6, the control — July, August and September (JAS) — precipitation and the corresponding precipitation anomaly are shown. Values for the month of August are displayed in Fig. 7 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 Figs. 5b and 7b. 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 to a large positive evapotranspiration anomaly that begins to appear during May and lasts throughout the summer, with peak values occurring in August. This is an area where agricultural land of modern times (i.e., Control experiment) is replaced by forest in the RCP perturbed experiment, thus increasing 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.

The northward shift of the ITCZ is evident in Fig. 8, where the 900-hPa wind streamlines are displayed, especially between 10°W and 30°E. The anomaly RCP–Control wind is southwesterly over the entire Sahara — meaning that, as a result of the RCP experiment, the northeasterly flow to the north of the ITCZ is weakened and the southwesterly flow to the south of the ITCZ is strengthened.

In Fig. 9a, the vertical profile of the JAS divergence, averaged over a wide area between 4°E to 45°E and 13°N to 24°N (including the upper Nile countries and most of the Sahel), shows convergence below 800 hPa and mid-tropospheric divergence, mostly between 700 and 600 hPa. The (RCP–Control) departure of the same quantity, shows an increase in the low level convergence and upper level divergence, providing the picture of a deeper atmospheric overturning and suggesting ‘‘deep’’ instead of ‘‘shallow’’ convection.

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

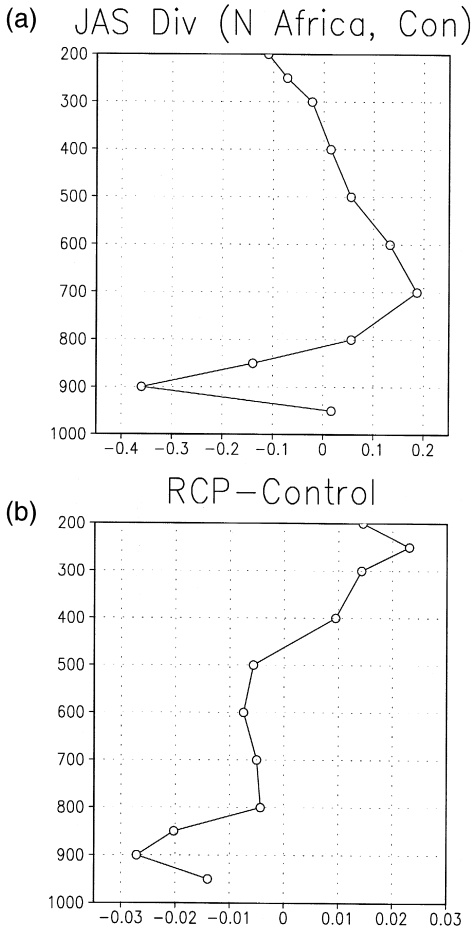


Fig. 9. JAS divergence profile, Sahel and south Sahara, averaged between 4°E to 45°E and 13°N to 24°N. Units are expressed in 10^{-5} s^{-1}, and ordinates in hPa.

6. Conclusions

In this paper, we address a problem that is widely discussed in modern times — whether or not the Mediterranean area is experiencing 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 widespread 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 northern Africa was an agricultural, productive and wealthy part of the ancient world and was the main source of grain for the Roman empire.

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 pioneering works by Lamb (1977, 1982), which 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, which will be discussed in Part II of the article, has a much higher resolution than what is needed by the simple R15 geography. Therefore, after having built a simplified RCP vegetation map, one 25-year experiment was performed at R15 resolution.

In this experiment, we reproduced the 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. For the same reason, we used climatological SSTs.

Changes in albedo and land surface properties — between a situation roughly comparable with the RCP one and the present day — produce a significant signal in the GCM climate. This change consists of a northward shift of the ITCZ — towards the Sahara desert, particularly over northeastern Africa. Within 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 to the RCP vegetation map introduced in the model.

Acknowledgements

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