FACULTAT DE CIÈNCIES

Secció de Ciències Ambientals

Climate change in the Atlantic Ocean since the 1940's and the effects on the global climate

-MEMÒRIA DEL PROJECTE-

Environmental Science project
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Author: Aida Pintó Biescas
Director: Carlos Roberto Mechoso
Tutors: Cristina Palet Ballús i Josep Enric Llebot Rabagliati

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ABSTRACT

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In this paper we have investigated the consistency between SST changes in the Atlantic Ocean and the changes in the atmospheric circulation in the XX century , concretely two periods of study have been analyzed; the first period from 1940 to 1960 and the second period from 1980 to 2000).

Special interest was put on the SST anomalies in the tropical Atlantic regions and their possible links with changes in the other variables studied and analyzed, and the connection with the main climate changes observed and predicted.

For the study a set of experiments have been carried out using the UCLA-AGCM model and the results obtained have been analyzed in form of plots and figures for the variables of study.

Furthermore a comparison between our results and those obtained in other works and research on the subject has been done.

The results obtained are extensive and can have several interpretations. Nevertheless some of the conclusions found are: The strongest difference between fields simulated by the UCLA ACCM for the two periods considered are in the northern winter months and over the tropics specially over north parts of south America and north Africa with changes in rainfall patterns.

Also a northward shift in the Inter Tropical Convergence zone is observed and it can be due to the anomalous cross-equatorial SST gradient.

However, for a definitive discussion and conclusions on the experiment results a larger study will be required.

AKNOWLEDGMENTS

I would especially like to thank my mentor/advisor at UCLA Professor Roberto Mechoso who has demonstrated a high interest in my work since the beginning of the project, and who has put a big effort in supporting my actual work.

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Finally I want to thank my family and friends for supporting my research at all times, for their patience and for their help in the last days.

1. INTRODUCTION

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The record of sea surface temperatures (SSTs) in North America during the last 100 years shows relative minima around 1910 and the mid-1970s (Baines and Follan 2007). This feature is thought to result from a natural oscillation of the climate system, which is associated with variability in the thermohaline circulation in the North Atlantic (**Robert B. Gagosian 2003**). This thermohaline circulation, referred to as the "Ocean Conveyor," brings warm, saline waters from the Tropical Atlantic into high northern latitudes where they cool and sink, forming cold, deep currents, which return to the south. While there is no direct oceanographic evidence such an oscillation has been actually happening over the past 100 years, various numerical climate models indicate that when the thermohaline circulation is strong, the North Atlantic is warm and vice versa.

Over the last 30 years, the North Atlantic has been at a warm peak in its cycle, and SSTs have increased substantially.

These variations in Atlantic SST are important because they have been linked to significant impacts on climate in many regions: The Americas, Africa, and Eurasian continent (Wang et al. 2004). Some impacts for which there is specific evidence include changing of rainfall patterns over the north African continent and the North-east of Brazil, influences on the summertime climate of north America, also influences in the genesis of Atlantic Hurricanes (Sutton and Hodson 2005, 2007) and changing patterns of rainfall over European continent linked with the warming trend of the SST of the tropical Atlantic region (Losada et Al 2007).

Other important aspects of the natural variability in the North Atlantic that have been studied in many papers are the North Atlantic Oscillation (NAO), the Atlantic Meridional overturning circulation (AMOC), and a possibly potentially predictable Atlantic Multidecadal Oscillation (AMO) (Rotstayan and Lohnman 2002).

To get insights in some of the effects above referred this work is based on a set of experiments done with an AGCM model and the data obtained from its different runs during the period 1940-60 and 1980-2000 over the Atlantic region.

The report is organized as follows. The first part is a review of a large body of information from different sources of research of relevance to success with the principal objectives of this project. The review includes some background concepts; important for the understanding of the issue treated in the work. Since there is a large amount of information with a variety of different objectives and hypotheses, to collect the most recent and reliable works which can also provide guidance to the interpretation of results found in the present work. The second part of the project document is an introduction to the general circulation models and its different variables, and also the model used for the experiments technical information. A description of the variables of study is also provided in this part. The third part of the report presents the results of the experiments done with the general circulation model of the atmosphere (AGCM) here used and developed at the Department of Atmospheric Sciences, University of California Los Angeles (UCLA). These results are presented in the form of figures and plots accompanied by a discussion.

The last part of the report contrasts some of results with others in the literature, and conclusions.

2. OBJECTIVES

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The main goal of this research is to study the possible relations and impacts between the SST fluctuations in the Atlantic Ocean since the 1940's on the global atmospheric circulation and other climate and weather anomalies that have been observed during that period. The specific objectives of the research are:

- The rainfall anomalies over the Western Europe region due the variations in SST in the North Atlantic Ocean.
- The SST anomalies in the Atlantic mid latitudes and their influence on the variability of the European climate
- The sensitivity of the wind system (trade wind) due to changes in the tropical SSTs.
- Which can be the possible cause of the climate shift: The paper of the natural variability phenomena's and the anthropogenic contribution to the changes?

3. Section 1: BACKGROUND CONCEPTS

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This section reviews some important concepts of relevance to this work. These include, for example, natural variability phenomena like the NAO oscillation and *El Niño* Southern Oscillation (ENSO). I also review the climate shift that happened in the late 1970s, since its study and understanding is part of the objectives of this research.

A short description of the current models used for the study and prediction of climate (the GCM's models), the different variables, and the methodology used for extracting the data for the goal of research of this project is here presented.

3.1. THE CLIMATE SHIFT IN THE LATE 1970'S[1]

A climate shift is a change between two identifiable "before and after" states. The Earth's climate goes through changes that affect every region simultaneously. The most recent global climate change was in the early 1940s and mid-1970s. Many studies show that a number of important characteristics of the global atmospheric circulation and climate changed over the decade centered on the late 1960s and early 1970's (Baines and Folland 2007). These changes were largest in tropical regions, the Southern Hemisphere, and the Atlantic sector of the Northern Hemisphere.

The North Atlantic Ocean has experienced a climate change. Some papers suggest that the change coincides with frequent El Niño events in the Pacific and a strong global warming trend.

Many studies have shown statistically that climate features like El Niño and the North Atlantic Oscillation (NAO), affect weather patterns across some parts of Europe. These studies demonstrate that some of these features were synchronized for a few decades, before the links abruptly break down and a new pattern emerged this is called for some authors the "synchronized chaos" (Tsonis, A. A., K. Swanson, and S. Kravtsov, 2007).

Recent modeling studies have shown the action is always driven from the North Atlantic. However some studies argued that accelerated global warming since the 1970s could be due partly to a natural climate shift (Swanson, K.L., and A.A. Tsonis, 2009).

Some of the changes observed and described for Baines and Follan (2007) in the mid-1970 include:

[1] Most of concepts and data exposed in this part come from a research of different sources specified in the bibliography and are not from own source.

- The decrease in rainfall in the African Sahel: As we can see in the **figure 1** below, the amounts of precipitation in that region started a negative trend since the 1960's. In the early 1970's negative precipitation and drought in the entire region prevailed for several years. Some works show a correlation between the Atlantic SST anomalies (colder SST in North Atlantic) and the rainfall patterns in the Sahel.

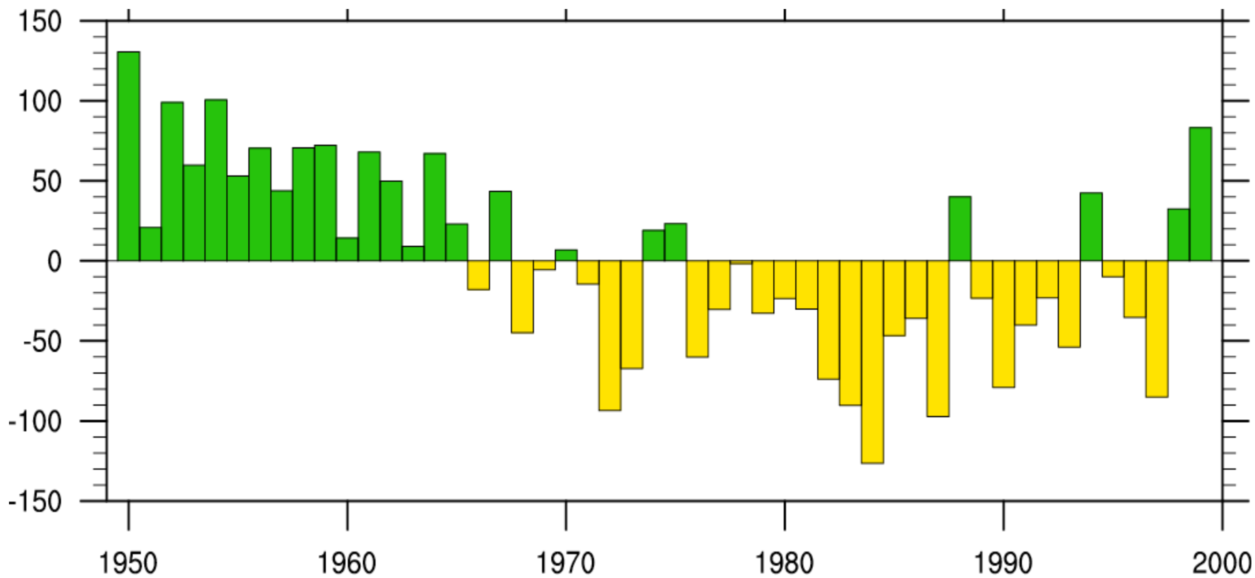


***Figure 1**: Rainfall patterns in African Sahel. Source: Baines and Follan 2007*

- Anomaly patterns of tropical rainfall in the Amazon basin, and northeast Brazil;
- Anomalies in pressure and SST in the tropical North Atlantic and the west and central Pacific;
- Various branches of the southern Hadley circulation and the southern subtropical jet stream;
- Anomalies in the summer North Atlantic Oscillation: In the North Atlantic sector there is a signature of this change in the sign of the summer North Atlantic Oscillation (NAO) pattern with anomalies of pressure at mean sea level (Hurrell and Folland 2002). This phenomenon occurs mainly between northern Europe and the high Arctic in boreal summer
- Anomalies in the Southern Hemisphere storm track;
- Other effects all around the Atlantic region and its surroundings.
- Other possible large effect over the globe.

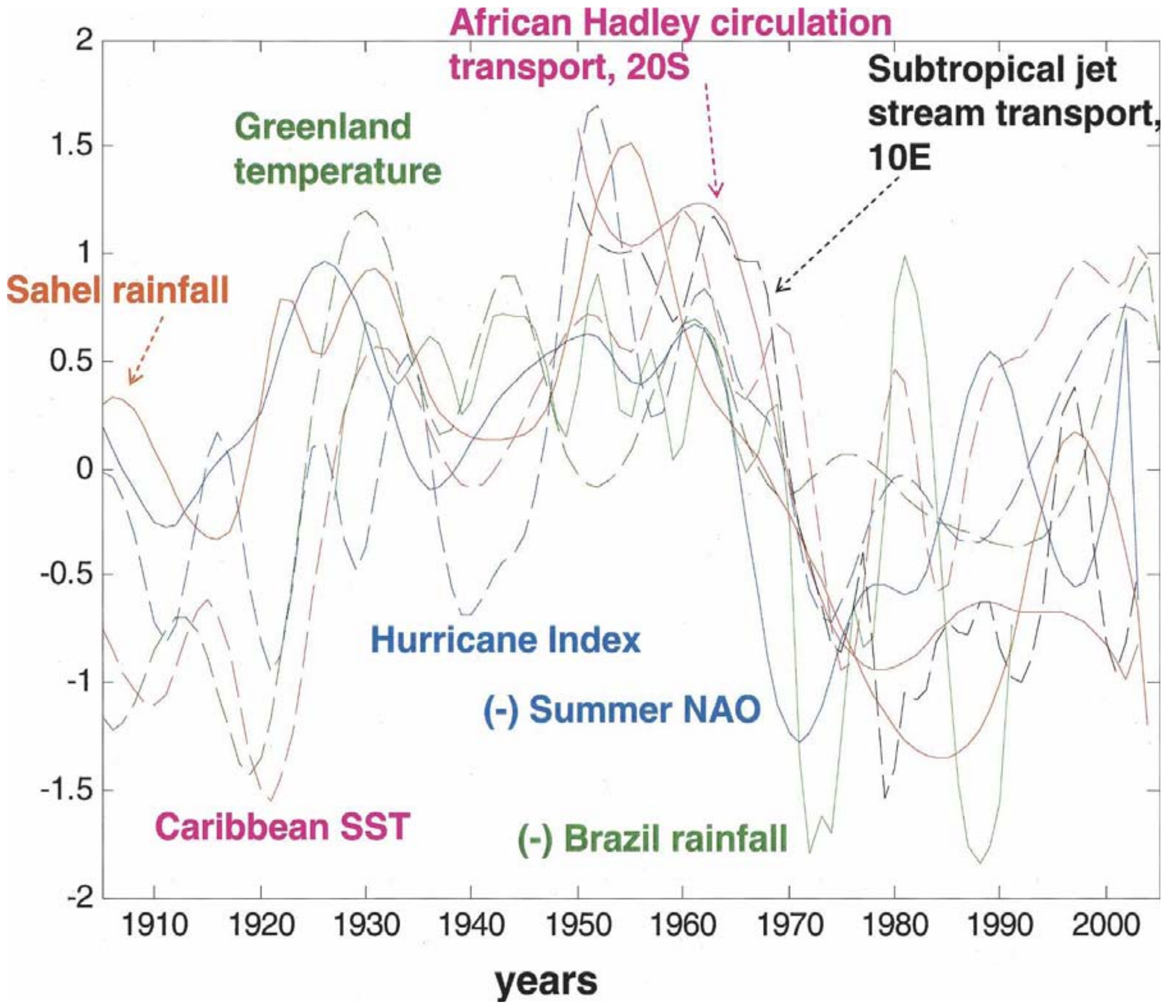


***Figure 2**: (from Baines and Folland, 2007): Low-frequency variability of some of the principal variables that show the late 1960s climate shift for June–August. Details: Sahel rainfall (red)source : Hadley Centre data, 10°–20°N, 10°W–25°E; Brazilian rainfall (green): University East Anglia data, 0°– 10°S, east of 60°W; southern node of summer NAO in July and August (blue): Hadley Centre sea level pressure data (Ansell et al. 2006); African Hadley circulation transport at 20°S (magenta): NCEP data, 20°W–20°E, 500–100 hPa; southern subtropical jet stream transport at 10°E (black dashed): NCEP data, 20°–40°S, 500–100 hPa; south Greenland (south of 65°N) coastal temperature (land and adjacent sea surface; dark green dashed) taken from HadCRUT3 (Brohan et al. 2006); SST over the south Caribbean (magenta dashed) taken from HadSST2 (Rayner et al. 2006), based on evidence given in Knaff (1997); and an index of intense hurricane activity over the North Atlantic (blue dashed) updated from Landsea et al. (1999).*

In **Figure 2** the changes in the principal variables described above by Baines and Folland are presented. The interest variables are the Brazil rainfall and Sahel rainfall and the Caribbean SST. Also the summer NAO anomalies must be take in account. Other variables are not matter of research for this work.[2]

[2] Figure 2 was obtained from a pdf source, which was not possible to modify and variables with no interest for the study of present work are also presented (Greenland temperature, the jet stream transport and the Hadley circulation transport)

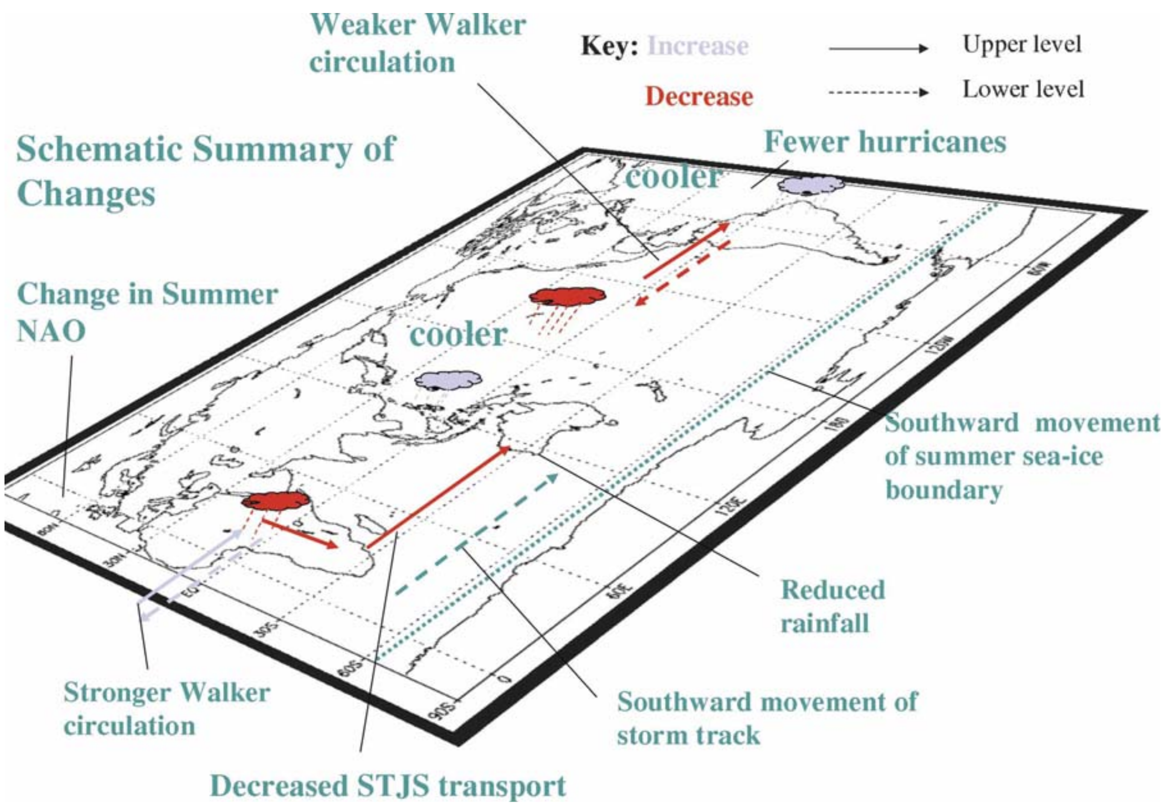
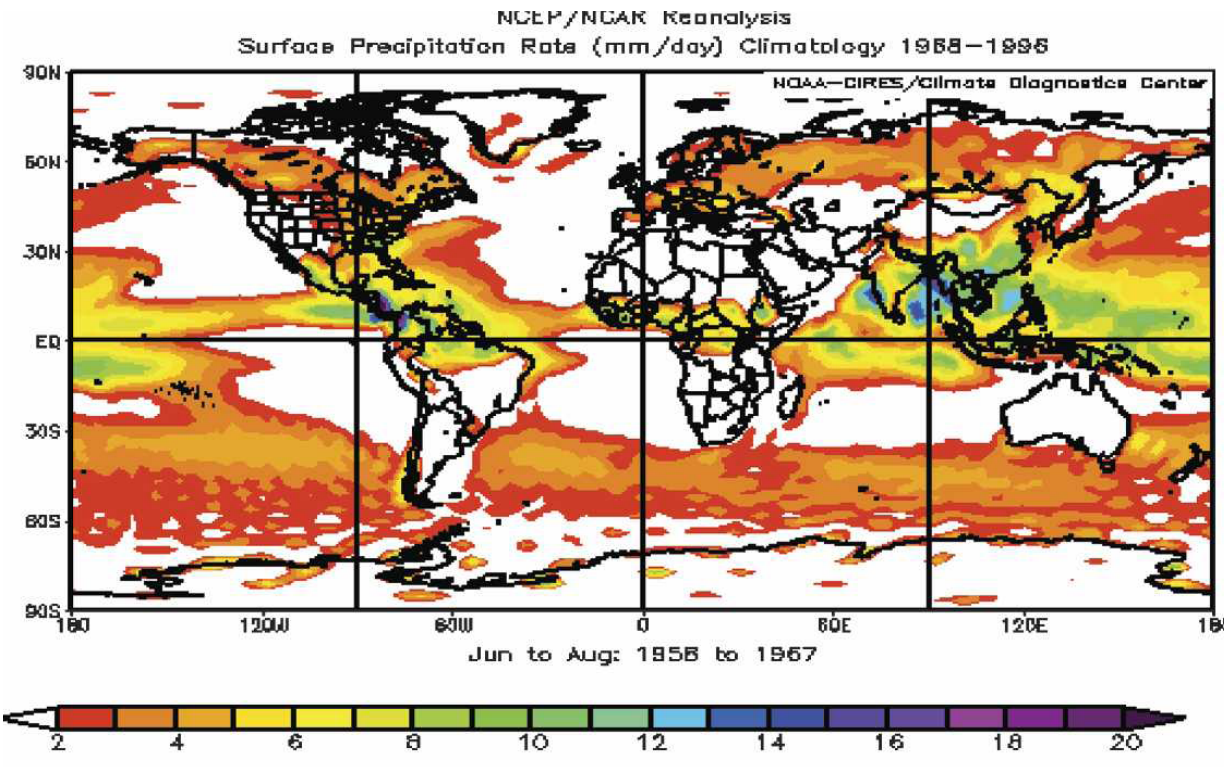


Figure 3 *from Baines and Follan 2007 is a Schematic depicription of some of the major changes occurring in June–August in the late 1960s. Red (blue) clouds denote decreased (increased) rainfall. Red (blue) arrows denote decreased (increased) winds, with solid arrows denoting upper-tropospheric winds and dashed arrows denoting lower-tropospheric winds; "cooler" refers to SST. STJS refers to storm track June September transport.*

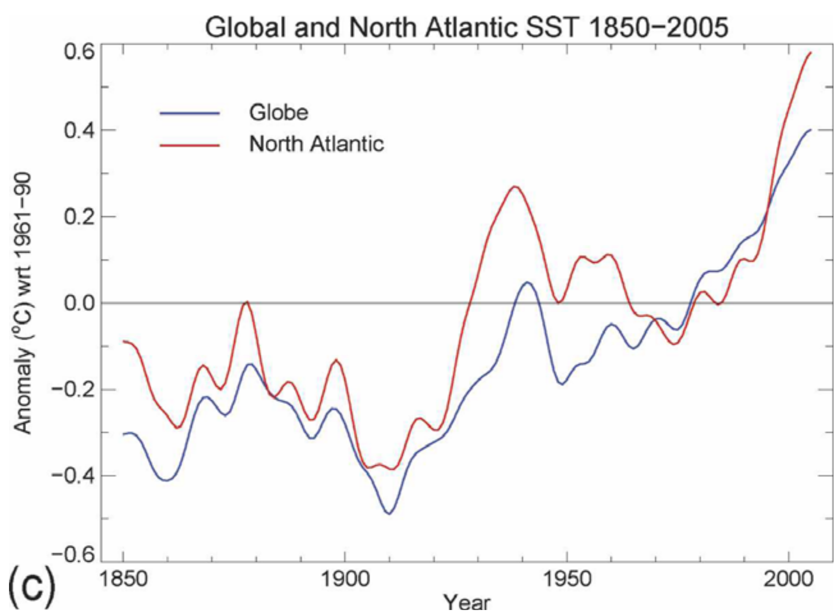
Figure 3 present major changes all over the globe with special focus over the pacific and Indic ocean. For the present work the interest of this figure is on the global effects of these changes and the positive value of summer NAO and the increased hurricane activity.

Figure 3 demonstrates that the changes are often strongest in the June-August season while changes occur between the months December-February but are generally smaller. In Greenland, the annual mean temperature seems to be strongly affected in SST throughout the year in the higher latitudes of the North Atlantic. Possible causes for these coordinated changes are a reduction in the northward oceanic heat flux associated with the North Atlantic thermohaline circulation in the 1950s to 1970s, which was nearly in phase with a rapid increase in anthropogenic aerosol emissions during the 1950s and 1960s, particularly over Europe and North America

A very important aspect studied is the patterns of change in rainfall as can be seen in the **figure4.**



<u>Figure 4</u> *shows Mean rainfall (mm day_1) for the 10-yr period 1958–67 for the season June–August from the NCEP–NCAR reanalysis. This is before the shift in 1970. Source: Baines and Follan 2007.*



<u>Figure 5:</u> *from Baines and Follan 2007:* North Atlantic compared to global mean SST, calculated over the period 1850–2005 using the HadSST2 dataset (Rayner et al. 2006). The data are filtered using a 21-point binomial low-pass filter, suppressing fluctuations with periods less than about a decade. *The period of interest, the 1970's shows a negative trend with a post warming trend in the SST.*

The data show that there was a major change in the global pattern of rainfall in June–August centered on the late 1960s, which tended to persist throughout the year. This major change is approximately coincident with the well-known rainfall decrease in the African Sahel, but the pattern contains major changes in other regions of the Tropics. This coordinated change was unique in its magnitude and large-scale structure over the past 50 years.

Possible causes of the changes:

Various factors have been examined and proposed as possible contributions to the climate changes in the late 1960's. Some are unlikely to be correlated but others are still under investigation. The following factors are frequently disputed:

- **Solar variability:**
  This is very unlikely to be a cause. There is also no evidence of an isolated abrupt change in solar output at this time. The year 1970 coincided with a maximum in the "solar constant" in the 11-yr cycle of total solar irradiance, and dominates the reconstructed solar radiation record of the past 50 years (Lean et al. 1995; Ramaswamy et al. 2001). This periodicity is not evident in the variables studied in recent studies.

- **Increasing amount in the atmosphere of Greenhouse gases:**
  Greenhouse gases are one of the main causes of the recent global warming and the increase of temperatures, however in the case of the climate shift in the late 1960's most of the studies publicized do not show any strong correlation between the trend of the increasing GHG and the changes experimented in the period of study.

- **Variability of ozone:**
  There is no evidence for this to be a significant factor in the 1960s to early 1970s. Ozone is a possible cause of tropospheric atmospheric circulation changes at high southern latitudes, but these are primarily in the 1980s, coinciding with the deepening of the ozone hole. Also stratospheric influences on the troposphere are mostly confined to the period November—February and associated with the seasonal breakup of the stratospheric vortex, which has negligible signature in June–August. (Sexton 2001; Thompson and Solomon 2002)

- **Desertification:**

  This can be a possible cause of the long-term drought in the African Sahel. The prevailing evidence now supports the thesis that it is largely caused by several SST patterns. Also a role for land surface processes is still likely, for example, perhaps through deforestation to the south. However, the observed behavior in the Amazon basin is the opposite of that in the Sahel: the rainfall there has increased in spite of cumulative land clearing (Fearnside 2005) over the past several decades. Although land surface changes are capable of causing changes in rainfall and climate, they are regional and seem unlikely to contribute to the collective global phenomena.

- **Internal variability of the coupled ocean–atmosphere system:**

  It is suggested that the changes of the 1960s may be largely due to a reduction in the strength of the global thermohaline circulation. The importance of natural variations in the global thermohaline circulation is shown by Knight et al. (2005, 2006). A repeated warming of the North Atlantic region relative to the South Atlantic region on the multidecadal time scale is consistent with evidence from four centuries of proxy temperature data as shown by the observational and modeling studies of Delworth and Mann (2000), and a very persistent climate fluctuation on the same time scale affecting Scotland as shown by Proctor et al. (2002).

  There is a considerable amount of climate prediction research using many climate models which suggest the weakening of thermohaline circulation as consequence of global warming. Studies from Bryden et al. (2005) have detected a recent slowdown of the thermohaline circulation from sparsely sampled oceanographic data. However, Knight et al. (2005), based on model results and recent observed SST changes and after allowing for anthropogenic effects on SST, argue in favor of an increase in the thermohaline circulation strength associated with the recent sharp warming of North Atlantic SST. This conclusion is supported by Latif et al. (2006).

  Also Baines and Folland (2007) conclude that there is no convincing evidence of a slowing effect on the thermohaline circulation due to anthropogenic effects on climate. However, a sharp decline in the thermohaline circulation in the next few decades due to a combination of natural and anthropogenic effects is suggested by some studies.

- **Effect of anthropogenic sulfate aerosols:**

  It is well known that anthropogenic aerosols affect radiation reaching the surface both directly and indirectly (Haywood and Boucher 2000; Houghton et al. 2001). The indirect effect occurs because aerosols act as cloud condensation nuclei and thereby increase cloud albedo in its own lifetime. Consequently, they may also suppress rainfall (Rosenfeld 2000; Ramanathan et al. 2001) and alter the distribution of latent heat release. The direct effect causes solar radiation to scatter into space resulting in surface cooling. The magnitudes of these effects (particularly the indirect effects) and the temporal and spatial distribution of the various types of aerosols are all still uncertain, but there is some evidence that they are significant in global terms.

  Also recent modeling studies from Swanson, K.L., and A.A. Tsonis, 2009 suggest that aerosol-forced changes in atmospheric circulation may have large impacts on rainfall in tropical and subtropical regions. The observed distribution of aerosols in space and time is consistent with the observed changes in sea surface temperature (SST), which cause the observed changes in rainfall and the atmospheric circulation changes. It is also consistent with the observed decrease in surface temperature from 1945 to 1970, which was almost entirely concentrated in the Northern Hemisphere. Moreover, with the observation that the late 1960s changes are strongest in the season June–August, the sunlight is strongest in the Northern Hemisphere and the global radioactive impact of aerosols is largest.

Some recent studies propose that both the shift a significant part of the variability in the 20th century is intrinsic, but they do not exclude the possibility that these shifts are superimposed on an anthropogenic trend. An explanation made for the post-1970s warming is that human emissions of greenhouse gases have had a warming influence on global climate. (Swanson, K.L., and A.A. Tsonis, 2009)

3.2. THE NAO (NORTH ATLANTIC OSCILLATION)

The North Atlantic Oscillation (NAO) must be explained and understood because it is often affected by the changes and anomalies in the Atlantic Ocean. The NAO is a meridional oscillation in atmospheric mass with centers of action near Iceland and over the subtropical Atlantic from the Azores across the Iberian Peninsula. Westerly winds blowing across the Atlantic bring moist air into Europe. In years when westerly are strong, summers are cool, winters are mild, and rain is frequent. If westerly are suppressed, the temperature is more extreme in summer and winter leading to heat waves, deep freezes, and reduced rainfall.

A permanent low-pressure system over Iceland (the Icelandic Low) and a permanent high-pressure system over the Azores (the Azores High) control the direction and strength of westerly winds into Europe. The relative strengths and positions of these systems vary from year to year and this variation is known as the NAO index. A large difference in the pressure at the two situations is denoted as NAO+ or positive phase NAO. During this phase there are increased westerly and, consequently, cool summers and mild and wet winters in Central Europe and its Atlantic façade are found. In contrast, if the index is low NAO-, westerly are suppressed and these areas suffer cold winters and storms track southerly toward the Mediterranean Sea. This brings increased storm activity and rainfall to southern Europe and North Africa.

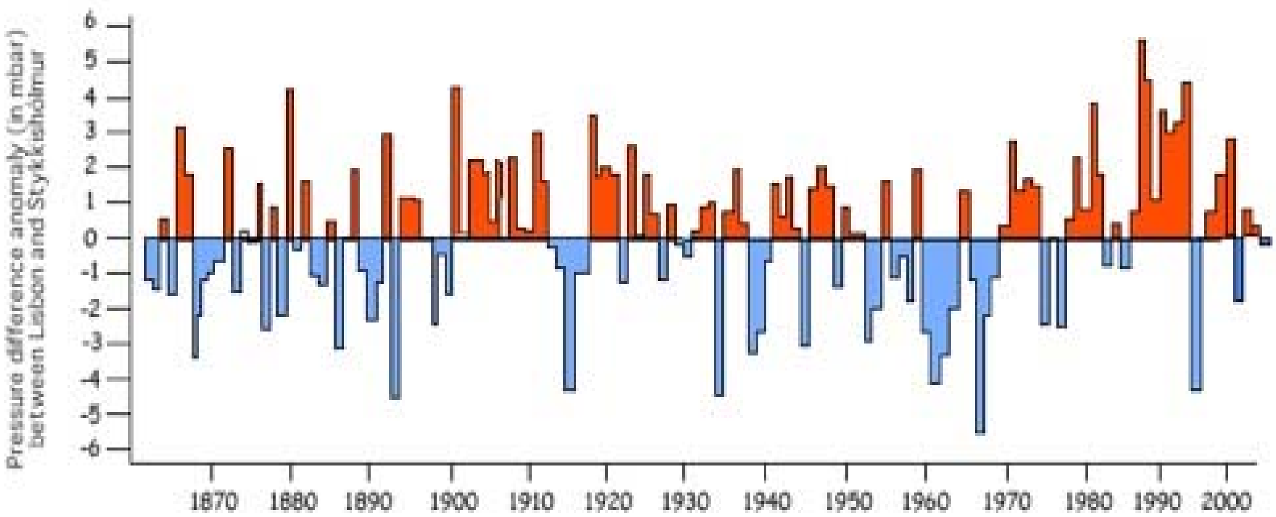


Figure 6. *NAO (North Atlantic Oscillation) index from 1864 to 2005, The NAO index is defined as the anomalous difference between the polar low and the subtropical high during the winter season (December through March). Source: http://web.me.com/uriarte/Earths_Climate/North_Atlantic_Oscillation.html*

The NAO is especially important during northern hemisphere winter months (from November to April) because it is responsible for much of the variability of weather in the North Atlantic region; it affects wind speed and wind direction changes, changes in temperature and moisture distribution, as well as the intensity, number and track of storms.

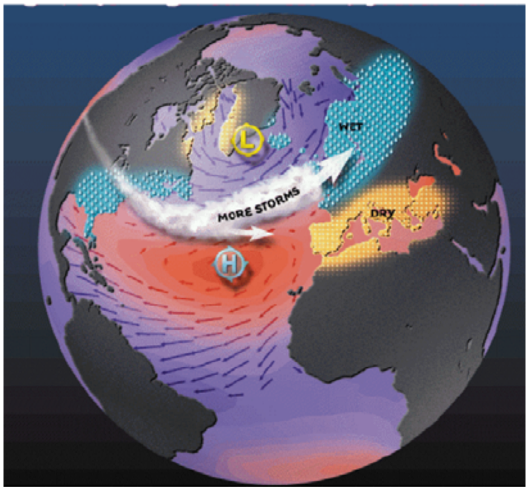


Figure 7. *Positive NAO*

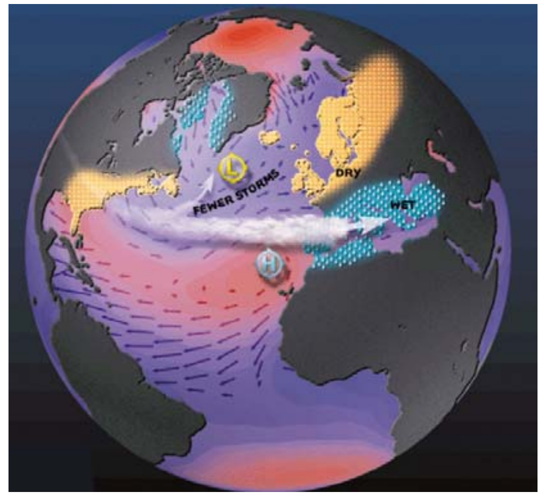


Figure 8. *Negative NAO*

Source of the figures: **http://www.Ideo.columbia.edu/res/pi/NAO**

A remarkable feature of the NAO that has motivated much recent study is its trend toward a more positive phase over the past 30 years. The most pronounced anomalies have occurred since the winter of 1989 (Hurrell 1995a; Walsh et al. 1996; Thompson and Wallace 1998; Watanabe and Nitta 1999) when record positive values of an index of the NAO were recorded. Also, the trend in the NAO have been said to be recently connected with several remarkable changes in the climate and weather over the middle and high latitudes of the Northern Hemisphere, as well as in marine and terrestrial ecosystems.

Much research has been dedicated to finding the effects and teleconnections of weather and climate variability's at various locations over Europe and North Africa. These findings suggest that there is still much uncertainty about the possibility that anthropogenic climate change might influence modes of natural variability, perhaps making it more likely that one phase or another of the NAO be preferred over the other phase (Palmer 1999; Corti et al. 1999).

In conclusion, the understanding of the physical mechanisms that govern the NAO, its intraseasonal-to-interdecadal variability, and how modes of natural variability such as the NAO may be influenced by anthropogenic climate change is still under research.

3.3. *EL NIÑO* PHENOMENONA

It is also important to describe the *El Niño* phenomena because of its global effects and possible connection with the changes in the Atlantic Ocean. A great amount of investigation and research has been committed to understanding how the changes in the Atlantic Ocean in the past decades have influenced in the occurrence of this phenomenon. Although I will not further discuss this area of research, we must refer to *El Niño* due to its global effects.

El Niño/Southern Oscillation (ENSO) is a periodic change in the atmosphere and ocean of the tropical Pacific region. It is manifested in the atmosphere by changes in the pressure difference between Tahiti and Darwin, Australia and in the ocean by warming or cooling of surface waters of the tropical Eastern Pacific Ocean. *El Niño* is the name given to the period when water in tropical Pacific region is warmer than normal while La Niña is the period when the water there is colder than normal. The oscillation does not have a fixed period, but normally occurs every three to eight years. The mechanisms that sustain the *El Niño* - La Niña cycle remain a matter of research.

ENSO is associated with floods, droughts and is linked to other weather disturbances in many locations around the world. El Niño's effects in the Atlantic Ocean lag behind those in the Pacific by 12 to 18 months. Developing countries dependent upon agricultural and fishing are especially affected. *El Niño's* effects on weather vary with each event. Recent research suggests that treating ocean warming in the eastern tropical Pacific separately from that in the central tropical Pacific may help explain some of these variations. (Wu, L., F. He and Z. Liu (2005)

El Niño and its connection with the Atlantic Ocean[3]:

An effect similar to El Niño sometimes takes place in the Atlantic Ocean where water along equatorial Africa's Gulf of Guinea becomes warmer and eastern Brazil becomes cooler and drier. This is related to El Niño's effect on the Walker circulation over South America, which causes the easterly trade winds in the western Atlantic Ocean region to strengthen. Study of climate records has found that about half of the summers after an El Niño have unusual warming in the Western Hemisphere Warm Pool (WHWP). This affects weather in the area and seems to be related to the North Atlantic Oscillation. Cases of El Niño-type events in both oceans simultaneously have been linked to severe famines related to the extended failure of monsoon rains.

[3] Information source: Sutton et al. 2005; Rowan, Sutton and Hudson 2005.

Also this atmospheric signal from the Pacific *El Niño* is the same phenomenon that causes the Atlantic to experience fewer hurricanes during El Niño years. The result of that "teleconnection" is the tropical Atlantic usually experiences a smaller but anomalous warming several seasons after the maximum warming in the Pacific (which usually occurs in December).

There is another “Atlantic *El Niño*" effect but is a non-synchronous and non-periodic warming that occurs along the equator, entirely due to internal Atlantic dynamics. It is only similar to *El Niño* in the sense that those dynamics are similar to the Pacific case, but it has no correlation with Pacific events. Moreover, the magnitude of the warming is much smaller, as is the typical period between events. Hence, it does not have a strong impact and should probably not be called *"El Niño"*, because this would create unnecessary confusion.

4. Section 2: TECHNICAL CONCEPTS

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4.1. GENERAL CIRCULATION MODELS

The climate of the planet is governed by the fundamental laws of physics which express basic relations between the variables usually associated with atmosphere and ocean behaviour, such as wind and velocity of ocean currents, air pressure, atmospheric water vapor content, cloud cover, and atmosphere and ocean water temperature.

It is useful to convert these governing equations for the climate variables into a form from which they may be used by modern high-speed computers. Thus this system of equations leads to deterministic solutions (at least in an average sense) that have led to a massive worldwide effort to implement a program in climate modeling. The modeling of climate is very complicated; it requires very fast computers with large storage capacities. Also, there must be a balanced program of observations featuring a merge of studies of individual processes such as tropical storms involving localized aircraft measurements to a program of satellites looking down on the planet and providing global coverage.

The first version of climate models made were the models based upon energy balance. Energy flows into and out of the system in the form of electromagnetic radiation in two streams: 1) solar radiation, which warms the earth by the rate of its absorption in the atmosphere and in the surface features, and 2) terrestrial radiation, which flows from the top of the atmosphere out to space, cooling the planet.

Energy balanced models made use of the balanced energy streams for individual latitude belts. In order to relate the energy streams to climate it was necessary to connect the outgoing radiation to the surface temperature through simple mathematical formulas. In addition, there must be provision for heat to be transported from one region to its neighbors. Energy balance modelers applied simple rules based upon flows of heat proportional to the temperature differences between neighboring regions. Using these simple rules the problem was put into the form of an equation, and the surface temperature could be solved for as a function of position at the earth's surface. With very little adjustment in the empirical coefficients in the model, the agreement to the observed values of the temperature field was remarkable.

From time to time these models were perfected and feedback mechanisms were included in the climate models (ice cap feedback, water vapor feedback, the clouds effects, etc). While energy balance models have become very sophisticated in their mathematical formulation and in the insight they have provided, there are some features of climate they cannot simulate faithfully: the details of the transport of heat and material in the atmosphere and oceans. These features can only be incorporated in the mathematical formulation by including the flow of wind and ocean currents. And this requires several orders of magnitude of computational resources and large teams of scientists.

The principal energy source for the general circulation is solar radiation, which influences the atmosphere primarily by heating at the Earth's surface. The various heat components in the atmosphere (and in the climate system) are produced by complex interactions among these processes. Also GCMs include formulations of most or all of the physical processes; the quality of the simulations depends crucially on those formulations.

- **AGCM's**:

Atmospheric general circulation models (AGCMs) simulate the evolution, maintenance and variations of the general circulation of the atmosphere. AGCMs are based on the equations of fluid motion, conservation of water and other substances, the laws of thermodynamics, and detailed physics of radiation transfer in the atmosphere. For numerical predictions, those equations are replaced by a finite number of algebraic equations suitable for a high-speed computer.

An AGCM works in some ways like the energy balance model, but many more variables are accounted for and the sizes of sub-domains (computational cells) are much finer. **Figure 9** is a schematic diagram indicating a single box-shaped region with arrows indicating the flow of heat horizontally out of the box. The vertical flows are not shown due to the radiation heating and cooling.

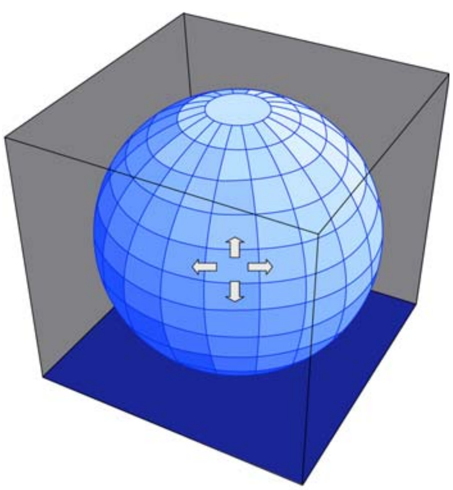


Figure 9: *Schematic diagram of the planetary surface divided into rectangular cells. The arrows indicate the net flow of heat from one cell to its four neighbors through transport by winds and ocean currents. In more realistic models the cells are stacked vertically as well with flows of momentum, air, water vapor and radiation as well. Source :*

The GCMs have two primary applications: weather and climate prediction, and investigations oriented to the increasing understanding of the climate system. AGCMs are applied to both climate and weather prediction. For weather prediction the cell size required is smaller and the time needed to compute the results are only a fraction than the required for climate modeling. Climate studies may require AGCM computations running for hundreds of simulated years. Contemporary AGCMs for climate studies use cells that are of the order of 100 kilometers in each horizontal direction and perhaps one kilometer in the vertical direction. This comes to about 1 million cells to cover the atmospheric envelope, and there are about 10 variables to keep up with in each cell. Hence, it follows that research in climate modeling requires very powerful computers.

- **OGCM's:**

The Ocean general circulation models (OGCMs) model the currents, temperature and salinity fields of the world oceans. They have been developed in parallel with AGCMs. In some ways the oceans are simpler (no clouds, shallow penetration of radiation, no water vapor complications, nearly constant density, etc) but in other ways they are as or even more convoluted:

The conditions at the ocean surface are crucial, but are controlled by different parameters which must be either prescribed from observational data or provided by an interacting atmospheric model. These fields are difficult to obtain directly over the oceans, and depend on the quality of the atmospheric model. In addition, the way this stress (horizontal force per unit area) is transmitted to the ocean is itself hard to characterize in a model.

The requirements on model resolution are very strict: Because of density profile differences between ocean and atmosphere, the ocean cells need to be of the order of tens of kilometers as opposed to hundreds for the atmosphere. So the ocean model requires very small numerical cells in the solution. Finally, the boundary conditions of the ocean are very difficult to model and represent, like the bottom of the ocean surface, the sea ice and it's interaction with clouds, etc.

Another important problem is the lack of reliable observational data. The lack of routine observations on a dense mesh over the planet is more serious for oceanic than for atmospheric studies. Furthermore, the ocean is very inaccessible, and we have only been able to map major current systems in the most recent decades. Hence, we hardly know the present state of the ocean, and its more detailed properties such as its variability over centuries. Although with all of these difficulties OGCMs have been improved since last year and most of these issues have been resolved. Also the lack of reliable data has been solved in part with satellite observation networks and with more accurate and sophisticated instruments available nowadays.

Even with these improvements in observation capabilities we will only be able to sample the oceans over a very small interval compared to some of the longer time scales expected to be exhibited in long term ocean behavior. This short record of observational data means that long-term climate simulations will always be faced with uncertainty associated with the lack of testing of the ocean component at the longer time periods.

- **COUPLED AOGCM'S:**

The need of climate simulations over longer periods in the last decades has lead to the development of models that consider both atmospheric and oceanic processes. The latter are ultimately crucial since the oceans have profound effects on the time dependent response of the surface climate over periods of a few years to decades, but especially centuries – the time scale of primary concern in the global warming problem.

Therefore global climate model were built by coupling AGCMs to OCGMs. Here "coupling" means that conditions required by one model at its interface with the other are produced by the latter using values from both. In the current configuration of coupled atmosphere-ocean models (AOGCMs), the AGCM provides the OGCM with the fluxes of momentum (surface wind stress), heat, and important species such as fresh water through the difference between precipitation and evaporation, and pressure at sea level. In turn, the OGCM produces the sea surface temperature, roughness characteristics, etc. The fields exchanged are among the most challenging to model accurately.

But nowadays these models are not sufficiently for the complicated prediction of climate and weather and also they must include more components than just the atmosphere and the oceans like land surface, sea ice and carbon contents.

So the progress and improvement of the models continues year to year. However despite all this progression our ability to predict future climates precisely remains limited. There are about a dozen climate models around the world that are capable of doing simulations over many centuries. These models are tuned to imitate the present climate and do so with reasonable fidelity. Although there will always be an uncertainty component because of the complicated and changing components of the climate.

4.2. DESCRIPTION OF THE VARIABLES

The variables which will be studied in this project are described below, most of them are included in the Essential Climate Variables that currently feasible for global implementation, and have a high impact. They are of key importance for understanding and monitoring the global climate system.

Domain	Essential Climate Variables	
Atmospheric (over land, sea and ice)	**Surface:**	Air temperature, Precipitation, Air pressure, Surface radiation budget, Wind speed and direction, Water vapour.
	Upper-air:	Earth radiation budget (including solar irradiance), Upper-air temperature (including MSU radiances), Wind speed and direction, Water vapour, Cloud properties.
	Composition:	Carbon dioxide, Methane, Ozone, Other long-lived greenhouse gases[12], Aerosol properties.
Oceanic	**Surface:**	Sea-surface temperature, Sea-surface salinity, Sea level, Sea state, Sea ice, Current, Ocean colour (for biological activity), Carbon dioxide partial pressure.
	Sub-surface:	Temperature, Salinity, Current, Nutrients, Carbon, Ocean tracers, Phytoplankton.
Terrestrial[13]	River discharge, Water use, Ground water, Lake levels, Snow cover, Glaciers and ice caps, Permafrost and seasonally-frozen ground, Albedo, Land cover (including vegetation type), Fraction of absorbed photosynthetically active radiation (fAPAR), Leaf area index (LAI), Biomass, Fire disturbance.	

***Table 1:* Essential climate variables defined by the Global climate observing system .** *12: Includes nitrous oxide (N_2O), chlorofluorocarbons (CFCs), hydro chlorofluorocarbons (HCFCs), hydro fluorocarbons (HFCs), sulphur hexafluoride (SF_6), and per fluorocarbons (PFCs). 13: Includes runoff ($m^3\ s^{-1}$), ground water extraction rates ($m^3\ yr^{-1}$) and location, snow cover extent (km^2) and duration, snow depth (cm), glacier/ice cap inventory and mass balance ($kg\ m^{-2}\ yr^{-1}$), glacier* length (m), ice sheet mass balance ($kg\ m^{-2}\ yr^{-1}$) and extent (km^2), permafrost extent (km^2), temperature profiles and active layer thickness, above ground biomass (t/ha), burnt area (ha), date and location of active fire, burn efficiency (%vegetation burned/unit area).

Source: Global climate observing system panel: http://www.wmo.int/pages/prog/gcos/index.php?name=EssentialClimateVariables

The variables analyzed and studied in this project are:

- **<u>Sea Surface temperature</u>:**

Is the water temperature close to the surface of the ocean?

It is very important to know the SST because it controls the ocean atmosphere heat transfer, and more heat reaches the atmosphere from Earth's surface than from direct Solar Heating so ocean-atmosphere heat transfer have a very important paper in driving our weather and climate. Also SST is an important indicator of Climate Change and is classified as an essential climate variable because any warming trend in the ocean (natural or otherwise) is indicative of a climate system in transition to a warmer world. And any small change in SST, related to changes in land surface temperatures can be important because the ocean have a higher heat capacity of water

The SST variability can have numerous consequences on the environment. For example, SST changes have important biological implications for living conditions for many organisms including species of plankton, sea grasses, shellfish, fish and mammals.

The SST data are used for different aspects:

- For process monitoring: Tracer for major current systems (Gulf Stream, Aghulas, Malvinas, KuroShio etc), Detection of major anomalies or periodic events (el Niño, Somali upwelling etc), Detection and monitoring of long-term changes, etc.

- For climate and meteorology monitoring: On a smaller scale, ocean temperatures influence the development of tropical cyclones (hurricanes and typhoons), which draw energy from warm ocean waters to form and intensify. And on a large scale SST have a large influence on natural process like ENSO, NAO, etc.

- For measure the ocean-atmosphere heat transfer.

There are different ways of measuring SST, through direct in situ measurement - from ships, buoys or float – or indirect (from the ocean radiation in -mostly- infrared but also microwave wavelengths) measurements by satellites.

- For the goal of this project the SST were obtained from earth observing satellites by using remote sensing techniques. (For more information consult NCAR reanalysis web page:

http://www.cdc.noaa.gov/data/reanalysis/reanalysis.shtml)

The observational SST measurements obtained from the NCAR reanalysis have been introduced into the UCLA-AGCM model for doing the simulations. The model data is used to create the plots of the Atlantic zone and analyze the trend of SST in the past years and its influence in other climate variables and in global climate patterns as well.

Wind Stress

A better understanding of wind stress (drag) over the ocean is central to many facets of air-sea interaction, which in turn is vital for models of weather prediction and climate modeling.

Wind stress refers to the horizontal force of the wind on the sea surface. That is, wind stress is the tangential force per unit area exerted on the surface of the Earth or ocean by the adjacent layer of moving air. The ocean the production of waves on the water surfaces is one of its manifestations.

Surface wind stress determines the exchange of momentum between the Earth and the atmosphere and exerts a strong influence on the typical variation of wind through the lowest levels of the atmosphere. The values of the surface wind stress depend on the nature of the surface and the character of the adjacent airflow.

Wind stress T can calculate from wind speed using a drag coefficient:

$$T = \tilde{n} \cdot C_D \, U^2_{10}$$

Where $\tilde{n}$= 1.3k g/m^3 is the density of air, U_{10} is wind speed at 10 meters, and C_D is the drag coefficient. Fast response instruments measure wind fluctuations within 10-20 m of the sea surface, from which T is directly calculated.

The drag coefficient over the sea is an important quantity in both meteorology and oceanography because it relates the wind speed to the drag, which generates ocean waves, drives the ocean currents, and sets the scale of the atmospheric turbulence that transfers water vapor and heat from the ocean to the atmosphere to provide the energy for clouds and weather systems. The drag coefficient of the sea surface depends on the wave field and on the turbulent structure of the flow in the air and the water

Wind vectors, Velocity Potential and Divergent Wind

Wind is a vector quantity, which indicates direction and intensity of the wind. The vectors point in the direction to which the wind is blowing. The Intensity of the wind is conveyed through the size of the vector. The longer the arrows, the stronger the win it is.

Wind vectors are also useful in finding regions of upper level convergence and divergence, which indicate regions of upward and downward motion. Upward motion is typically associated with clouds and precipitation

Divergent winds flow from regions of low velocity potential to regions of high velocity potential, opposite of the way that the pressure gradient force does (from areas of high pressure to areas of low pressure).

Moreover the stronger the gradient of velocity potential, the stronger the divergent wind—much like pressure gradient force is stronger when the height gradient is stronger.

These variables are important to analyze because some tropical weather features are more easily seen and identified in the wind velocity potential than in other atmospheric variables. And also Velocity potential and stream function are defined and useful on the equator.

For this work plots with divergent wind vectors plotted over velocity potential has been made with the UCLA-AGCM model. Figures are presented in results in section 4.

- **Sensible and latent heat flux**

In general terms the Heat that causes a change in temperature in an object is called sensible heat. In this project we refer to sensible heat as the heat transmitted from the ocean to the atmosphere by a conduction process. Sensible heat transfer depends on the temperature differences between two objects.

Latent heat is associated with the phase changes of atmospheric water vapor, mostly vaporization and condensation.

Latent heat flux from the Earth's surface to the atmosphere is given by evaporation or transpiration of water at the surface and subsequent condensation of water vapor in the troposphere. It is an important component of Earth's surface energy budget.

It is common to express both variables in W/m2.

In this work fields calculated from the UCLA-AGCM 1940-2000 runs for the sensible and latent heat flux are presented in form of plots.

o **Precipitation**

As we know precipitation is any product of the condensation of atmospheric water vapor that is deposited on the Earth's surface. The main forms of precipitation include rain, snow, ice pellets, and graupel. It occurs when the atmosphere, a large gaseous solution, becomes saturated with water vapor and the water condenses, falling out of solution so it precipitates.

Precipitation is a major component of the water cycle, and is responsible for depositing most of the fresh water on the planet. Approximately 505,000 km^3 of water falls as precipitation each year, 398,000 km^3 (95,000 cu mi) of it over the oceans

Global warming has a big effect in global precipitation patterns and especially the increasing in temperature has lead to more evaporation which in some regions has increased the amount of precipitation. As average global temperatures have risen, average global precipitation has also increased. Precipitation generally increased over land north of 30°N from 1900 through 2005 but has declined over the tropics since the 1970s.

Globally there has been no statistically significant overall trend in precipitation over the past century, although trends have varied widely by region and over time

Changes in SST can result in changes in precipitation and evaporation over the oceans and also remotely over the land. It is also suggested by the decreased salinity of mid- and high-latitude waters (implying more precipitation), along with increased salinity in lower latitudes (implying less precipitation and/or more evaporation). For example over United States, total annual precipitation increased at an average rate of 6.1 percent per century since 1900,

Global precipitation patterns:

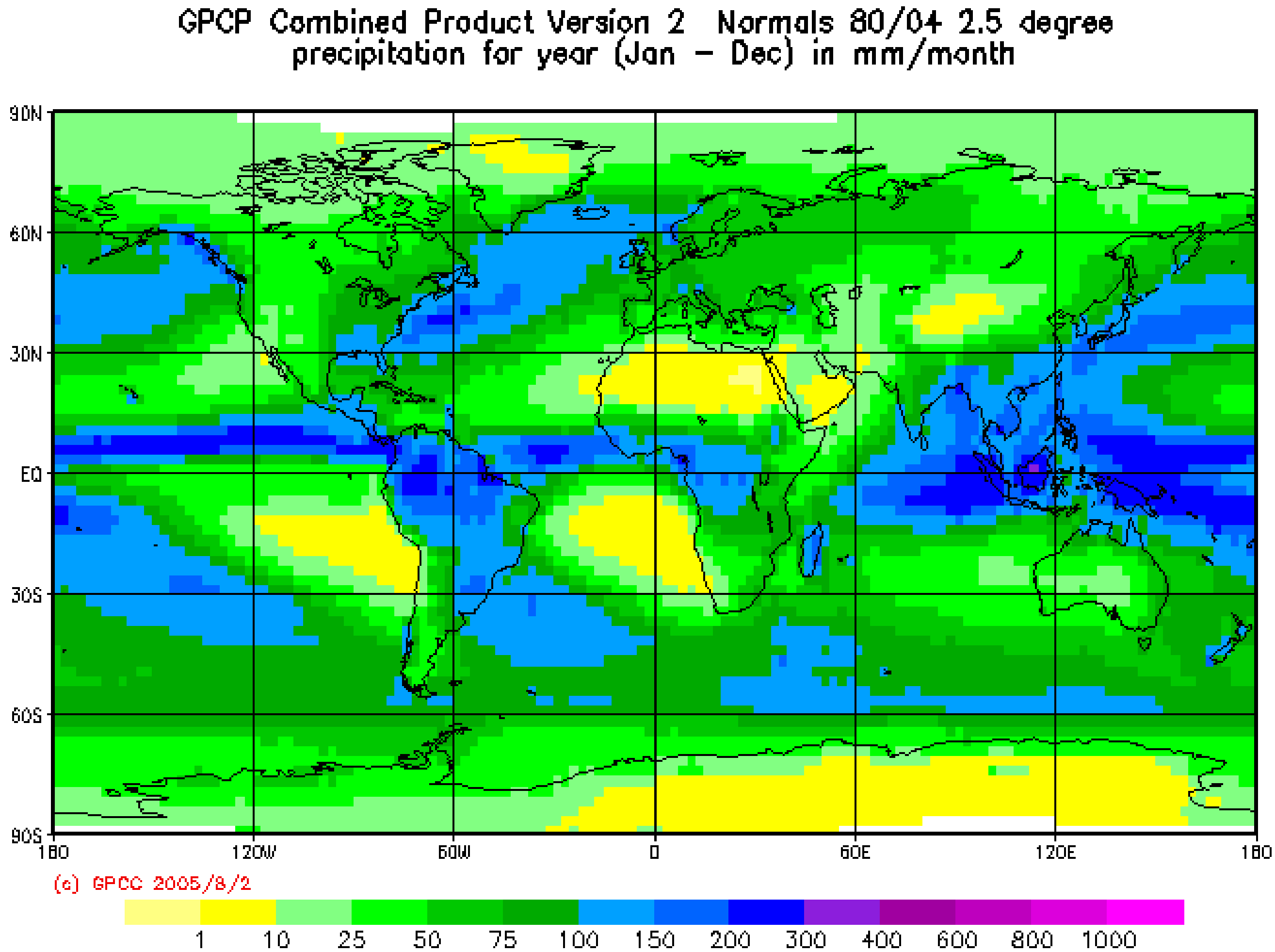


Figure10:: *Mean annual global precipitation 1980-2004. Precipitation plays a major role in determining the climate of an area. Rainfall is critical, in particular, for it replenishes ground water and supplies both natural watershed systems and irrigation channels. Worldwide rainfall averages vary greatly from region to region, as shown here. Areas that receive less than 250 mm (10 in) of rain each year are considered deserts, while regions receiving more than 2000 mm (80 in) are usually termed equatorial or tropic. Average rainfall is determined by the depth of water falling on a flat surface and is measured by a rain gauge.*

Source: http://www.eoearth.org/article/Global_distribution_of_precipitation>

4.3. MATERIALS AND METHODS

- **Data base, protocol for collecting data:**

The method for research in this project consists of a detailed comparison of the atmospheric circulation during a period around the middle of the last century (Period 1: 1940-1960), and another recent period (Period 2: 1980-2000). The atmospheric fields will be obtained from two sources. The first corresponds to the observations in the form of NCEP-NCAR Reanalysis[4]. The second source corresponds to simulations with an atmospheric general circulation model (the UCLA AGCM).

Observational data records from different sources were collected for contrasting the observed patterns and the results obtained by the computing model.

Description of the UCLA AGCM:

The UCLA atmospheric GCM is a state of the art grid point model of the global atmosphere extending from the Earth's surface to a height of 50 km. The model predicts the horizontal wind, potential temperature, water vapor mixing ratio, cloud water and cloud ice mixing ratios, planetary boundary layer (PBL) depth and the surface pressure, as well as the surface temperature and snow depth over land. In view of the goals of this project only some variables (as specified in the Introduction) will be analyzed.

[4] The NCEP/NCAR Reanalysis Project is a joint project between the National Centers for Environmental Prediction (NCEP, formerly "NMC") and the National Center for Atmospheric Research (NCAR). The goal of this joint effort is to produce new atmospheric analyses using historical data (1948 onwards) and as well to produce analyses of the current atmospheric state (Climate Data Assimilation System, CDAS).

Until recently, the meteorological community has had to use analyses that supported the real-time weather forecasting. These analyses are very inhomogeneous in time as there have been big improvements in the data assimilation systems. This played havoc with climate monitoring as these improvements were often produced changes in the apparent "climate". Even fundamental quantities such as the strength of the Hadley cell have changed over the years as a result of the changes in the data assimilation systems.

Technical parameter[5]s:

The horizontal finite differencing of the primitive equations is done on a staggered Arakawa "C" grid and is based on a fourth order version of the scheme of Arakawa and Lamb (1981) that conserves the potential entropy and energy when applied to the shallow water equations (Takano and Wurtele 1982). The differencing of the thermodynamic energy and water vapor advection equations is also based on a fourth-order scheme. The vertical coordinate used is the modified sigma-coordinate of Suarez et al. (1983). In this coordinate, the lowest model layer is the planetary boundary layer. The vertical finite differencing is performed on a Lorenz-type grid following Arakawa and Lamb (1977) above 100 mb and Arakawa and Suarez (1983) below. This differencing is of second order accuracy and is designed to conserve the global mass integrals of potential temperature and total energy for adiabatic, frictionless flows.

For the integration in time of the momentum, thermodynamic energy and water vapor and cloud water/ice advection equations, a leapfrog time-differencing scheme is used with a Matsuno step regularly inserted. To avoid the use of the extremely short time step necessary to satisfy the CFL condition near the poles, a longitudinal averaging (which takes the form of a Fourier filter) is performed on selected terms in the prognostic equations to increase the effective longitudinal grid size. The filter acts poleward of 45 degrees latitude and its strength is gradually increased towards the pole by increasing the number of affected zonal wave numbers and the amount by which they are damped (Arakawa and Lamb 1977). A more localized spatial filter is applied to the predicted PBL depths (Suarez et al. 1983) everywhere. A nonlinear horizontal diffusion of momentum is included following Smagorinsky (1963). The coefficient used is one order of magnitude smaller than that used by Smagorinsky. The diffusion is applied at each time step, using a forward time differencing scheme. In layers where an unstable stratification develops (potential temperature decreasing with height), we assume that sub grid-scale dry convection occurs and that the prognostic variables (horizontal momentum, potential temperature and water vapor mixing ratio) in the layers involved are mixed completely.

Planetary boundary layer processes are parameterized using the mixed-layer approach of Suarez et al. (1983). In this parameterization, surface fluxes are calculated following the bulk formula proposed by

[5] Technical explanation of the model UCLA-AGCM is extracted from **http://www.atmos.ucla.edu/~mechoso/esm** . These explanations have a very technical and complicated component but all explained above is necessary for understanding its technical function and for these reasons the description of the model has been copied exactly as it can be found in the web.

Deardorff (1972). The formulation of moist processes in the PBL and moisture exchange with the layer above has been recently revised (Li et al. 1999, Li et al. 2002), resulting in an improved simulation of the geographical distribution and optical properties of PBL stratocumulus clouds. Parameterization of cumulus convection, including its interaction with the PBL, follows the prognostic version of Arakawa and Schubert (1974) presented by Pan and Randall (1998). The effects of convective downdrafts and vertical momentum and rainwater budgets are included in the cumulus parameterization (Cheng and Arakawa 1997). The current model version also includes an implementation of the prediction scheme for cloud liquid water and ice from Köhler (1999). Parameterization of cumulus convection, including its interaction with the PBL, follows Arakawa and Schubert (1974) and Lord et al. (1982), with a relaxed adjustment time scale for the cloud work function as described in Cheng and Arakawa (1994)> and Ma et al. (1994). The parameterization of both long and shortwave radioactive heating follows Harshvardhan et al. (1987, 1989). The ozone mixing ratios used in the radiation calculations are prescribed as a function of latitude, height and time based on values from a monthly UGAMP climatology (Li and Shine 1995). The cloud optical properties are specified following Harshvardhan et al. (1989). The geographical distribution of sea surface temperature is prescribed using climatologically or yearly varying values from the Reynolds (1998) dataset; sea ice thickness and extents are prescribed following Alexander and Mobley (1976). Surface albedo and roughness lengths are specified following Dorman and Sellers (1989), in which roughness lengths over land vary according to the vegetation type. Daily values of these surface conditions (as well as sea ice thickness) are determined from the monthly mean values by linear interpolation.

The version of the model used for doing the experiments is the most recent version the UCLA-AGCM 7.3. However like all climate models it has an uncertainty component that must be take in account when analyzing the results.

The specific technical description of the runs used for data collection is given in the Appendix. Four different runs were made of which only two were used for making the analysis described here.

<u>The program used to plot the data:</u>

The program used for manipulate and visualization the data generated by the UCLA-AGCM model was the Grid *Analysis and Display System* (GrADS) . This interactive desktop tool can use the data in either binary, GRIB, NetCDF, or HDF-SDS (Scientific Data Sets) format.

It uses a 4-Dimensional data environment: longitude, latitude, vertical level, and time. Data sets are placed within the 4-D space by use of a data descriptor file. GrADS interprets station data as well as gridded data, and the grids may be regular, non-linearly spaced, Gaussian, or of variable resolution.

The data from different data sets may be graphically overlaid, with correct spatial and time registration. Operations are executed interactively by entering FORTRAN-like expressions at the command line.

A set of built-in functions are provided by the program, but users may also add their own functions as external routines written in any programming language.

Data may be displayed using a variety of graphical techniques: line and bar graphs, scatter plots, smoothed contours, shaded contours, streamlines, wind vectors, grid boxes, shaded grid boxes, and station model plots. Graphics may be output in PostScript or image formats.

It also has a programmable interface (which may be used with scripting language) that allows for sophisticated analysis and display applications.

The program in the manipulation and visualization of data for doing this project the basic functions of Grads were used, with a prefixed vertical level for all the plots.

For all the variables two different type of plots will be made:

- One for studying the climatology , which is the long term average of a given variable, in this case the average from the last 20 year period (from 1960-1980)
- The anomaly, which is the difference between the observed value and the value given by the model run in some cases and it's climatologically value.

With all the plots done a posterior analysis and comparison with other research results will be made with the objective to try to solve and to answer some of the main objectives and questions of this work.

o <u>Description of the study site, geographical situation:</u>

Our principal interest is in the Atlantic Ocean, specifically conditions at the surface will be studied and only the upper atmosphere over it will be studied for analyzing the velocity wind potential.

Specially focus will be put in the North Atlantic and tropical North Atlantic area because of the impact of sea surface temperature (SST) anomalies on the atmospheric circulation over the North Atlantic and

Western Europe (impacts on precipitation over the Iberian Peninsula and northern Africa , rainfall and other weather patterns anomalies, etc).

For the rainfall and the wind patterns we present global plots because of its general effects over all the regions, so for this parameters plots from 180 west to 180 east has been made.
For the other variables just the Atlantic part is analyzed with a longitude from 100º west to 20º est.
The latitude plotted for all variables are from 60º south to 80º north.

- ## How the data is going to be analyzed:

The results will concentrate on the differences between the Atlantic climate during the Period 1 (1940-1960) and Period 2 (1970-2000). The differences will be determined in the annual mean and seasonal means. The results will be represented as plots of the differences between the two periods together with the corresponding figures for Period 2. The following variables will be plotted using Grids software and after analyzed:

- Latitude-longitude plots of zonal mean difference between the two periods for wind stress (wsx and wsy) and for velocity potential at 200mb.

- Latitude-longitude plots of precipitation:
    - Global mean for the second period (1980-2000)
    - Global mean difference between two periods

- Latitude-longitude plots of sensible and latent heat flux

-Latitude-longitude and global plots for SST:
    - Seasonal mean differences and annual mean difference between two periods.
    - Seasonal means for first period
    - Time series graphs for SST in Atlantic region for latitudes between 80S and 80 N.

5. Section 3: RESULTS AND DISCUSSION

5. Section 3: RESULTS AND DISCUSSION

We start by presenting the model results in form of plots for the different variables analyzed. The plots representing climatological aspects and global means of the SST precipitation distributions are shown below.

In the second part of this section the figures and plots of the anomalies for each variable of study are shown and described. These anomalies were calculated from the difference between the two periods of study (first period is from 1940-1960 and second period is from 1980-2000). For the SST, precipitation and wind parameters global anomalies have been calculated because of its possible global impact effects and connections. For other variables just the anomalies for the Atlantic zone has been calculated.

In both parts the results presented are in form of seasonal plots for a better interpretation because of the changing component of most of the variables between seasons.

All the figures presented in this section are from own design using the data generated by the UCLA-AGCM model and plotted with the Grads program (described in section 2).

5.1. GLOBAL MEANS AND CLIMATOLOGIES

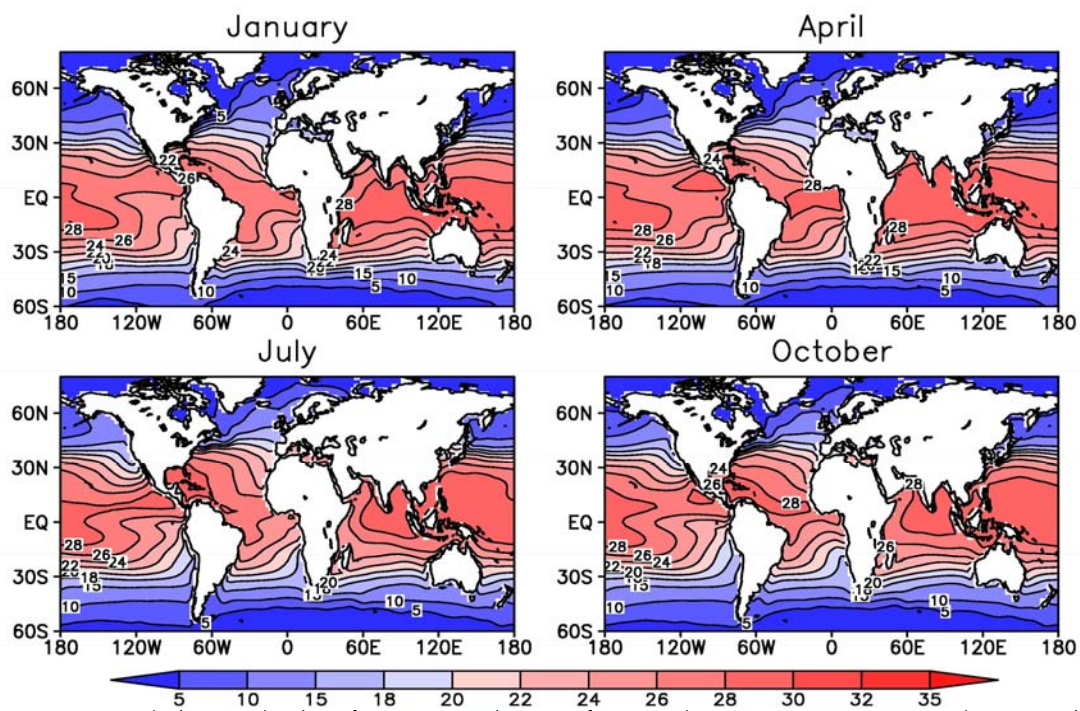
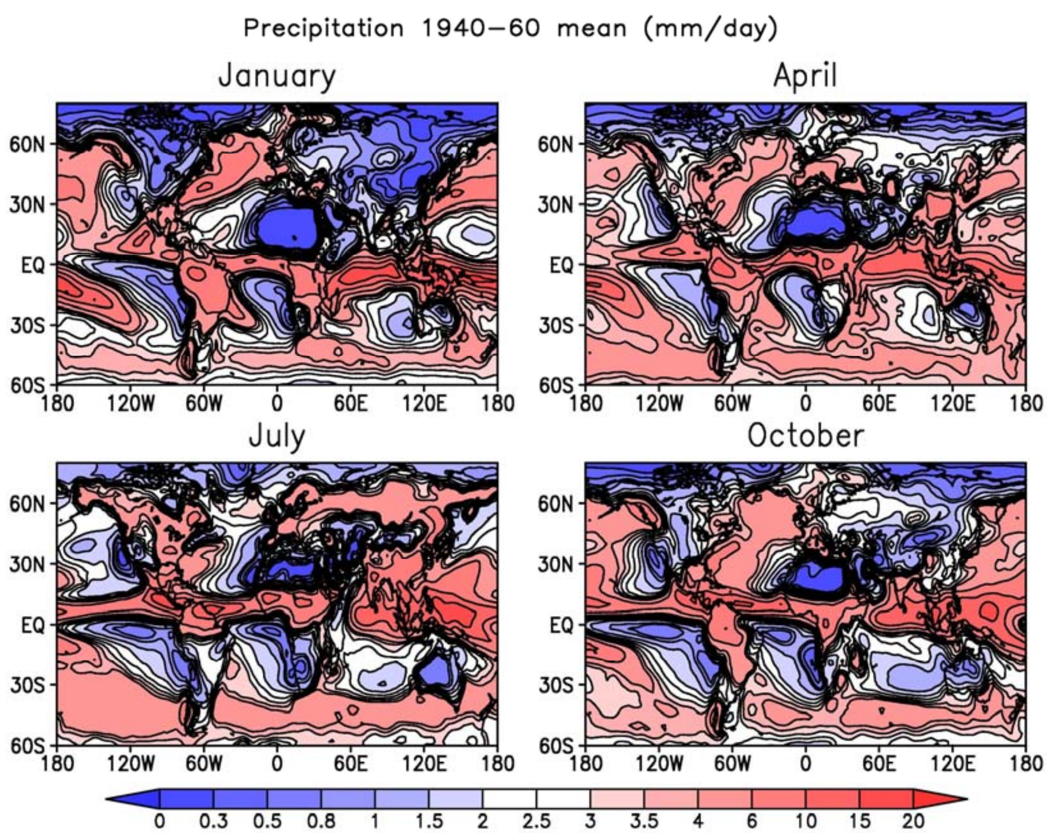


Figure 11: *Latitude-longitude plot of SST seasonal means for period 1940-1960. Units are in degrees Celsius ºC.*

Figure 11 shows the SST means for the 4 most representing months (seasonal means) of the first period corresponding to 1940-1960. No important anomalies can be observed from this figure

The patterns of SST show a latitudinal component with tropics warmer all year round, with a maximum temperatures round the equators and with a decreasing trend towards poles (North and South). Seasonally, SST is warmer in summer months in north hemisphere and colder in winter months. Reverse pattern is found in southern hemisphere. These tendency explained above just verify the normal patterns of SST with no important anomalies observed.

Over the Atlantic Ocean, a warm area in the equator and subtropics is found, with a rapidly cooling trend of



SST while the latitude is increased. For seasonal patterns the same trends described above are found.

Figure 12: *Latitude-longitude plot of Precipitation seasonal means for first period 1940-1960. Units are in mm/day .Source: Generated with results obtained from the UCLA-AGCM model.*

Related to SST patterns are the precipitation means, as we see in **figure 12**, which represents precipitation means for the first period, in a seasonal basis analysis.

The precipitation patterns shows clear high values over the storm tracks (in the tropics) and very low values over deserts and dry lands, which is logically. Seasonally the value seems to be higher in southern hemisphere during northern hemisphere winter, and also this is correlated with warmer SST over these regions in that period. Inversely during northern hemisphere the ITCZ[6] zones seems to moves north.

Can be observed that over Sahara desert the dry zones are larger during winter months, and it can have a correlation with the colder SST of Atlantic Ocean during this period[7].

In conclusion the climatology simulated by the AGCM for the period of analysis is realistic. In the next part we examine the differences for each variable between both periods (1940-60 minus 1980-2000).

[6] The Intertropical Convergence Zone is a term that is used to describe the North-East and South-East trade wind convergence. For more specific explanations about it see appendices.

[7] For this work all the correlations and similitude between figures and plots are based in observed results and any statistical technique have been used to analyze it.

5.2. ANOMALIES

- **SST anomalies between 1940-60 and 1980-2000**

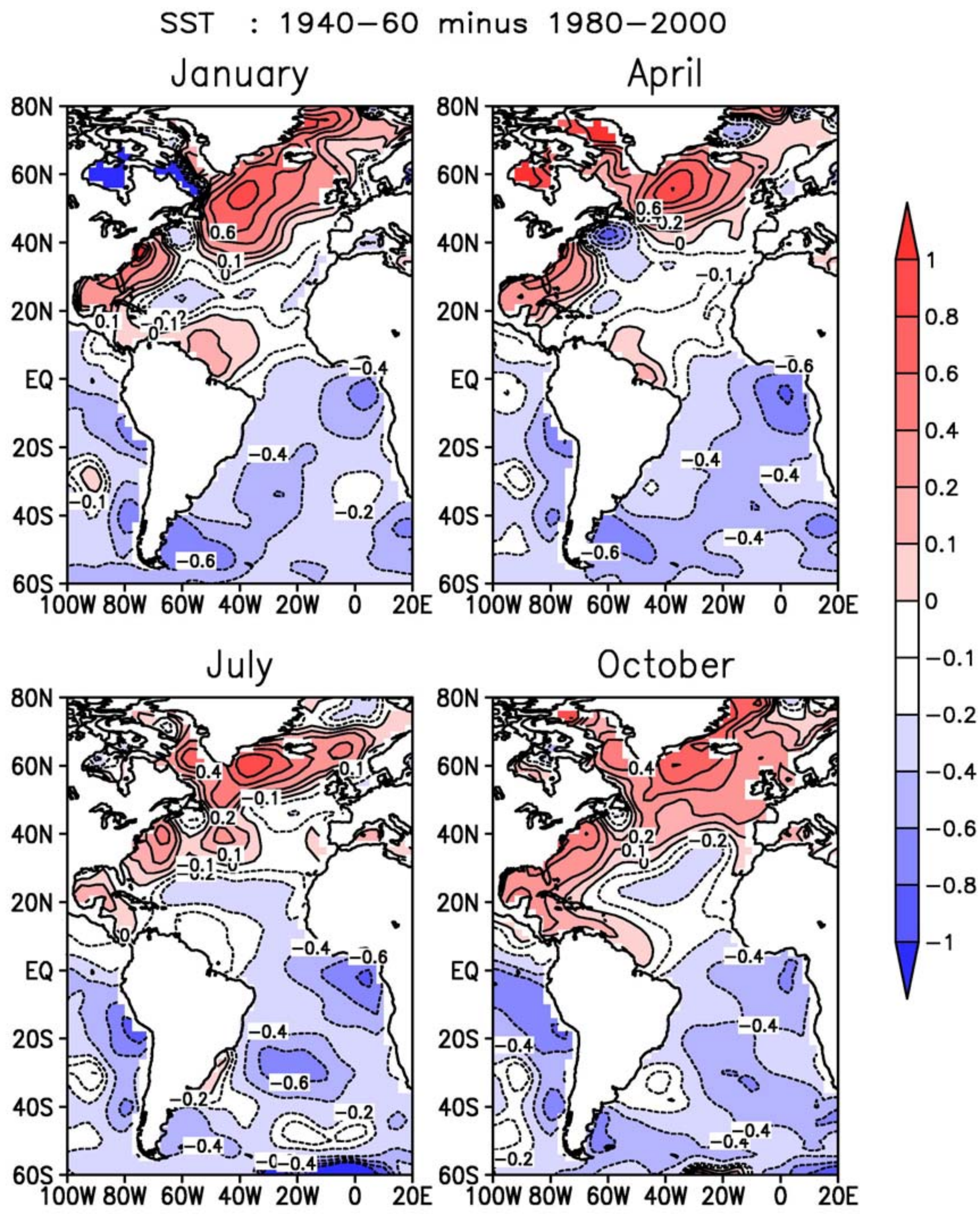
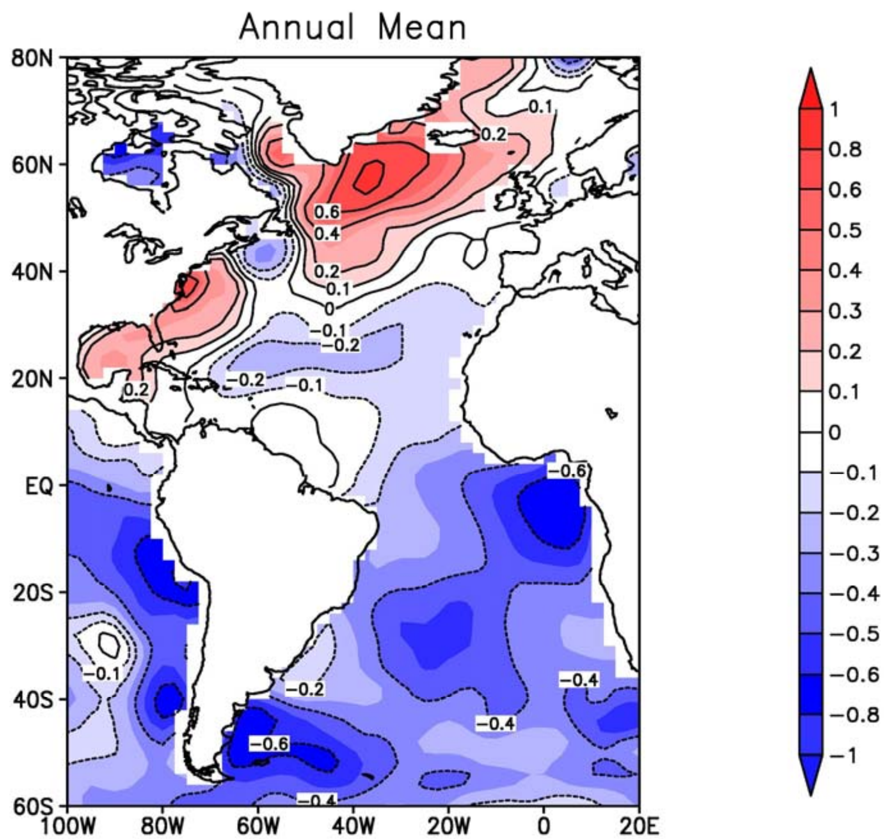


Figure 13: *Latitude-longitude plot of SST anomalies: Differences between the first period (1940-60) seasonal means minus the second period(1980-2000) seasonal means. Source: Figure generated using NCAR/reanalysis observational SST data and plotted with Grads.*

Figure 13 shows SST season anomalies between the two periods represented. Positive values means that the first period had higher SST than second period thus the ocean has cooled. And negative values means that the second period have higher SST temperatures thus the ocean has warmed up.



*<u>**Figure 14**</u>: Latitude-longitude plot of SST annual mean anomalies between two periods: 1940-60 minus 1980-2000. Temperatures are measured in degrees Celsius (Cº). Source: Figure generated using NCAR/reanalysis observational SST data and plotted with Grads.*

Figure 14 shows the anomalies in an annual mean, here the large scale dipole structure between north and south Atlantic regions can be clearly observed. Also a cross equatorial SST gradient can be observed.

More specifically, some observations of the figures are exposed below:

- North Atlantic tends to warm up, particularly near Greenland and Iceland during winter-early spring period, while south Atlantic tends to have colder SST in the same period. Also higher differences are found for north hemisphere summer in South Atlantic Ocean and in north hemisphere winter in North Atlantic Ocean.

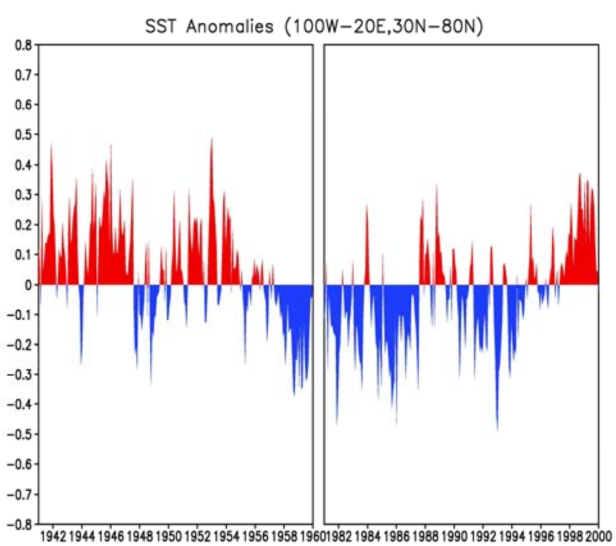
- In the tropics weaker differences are shown (smaller tropical amplitude), we find weaker warming along the coast of Brazil, with more high values in January (summer months in south hemisphere).

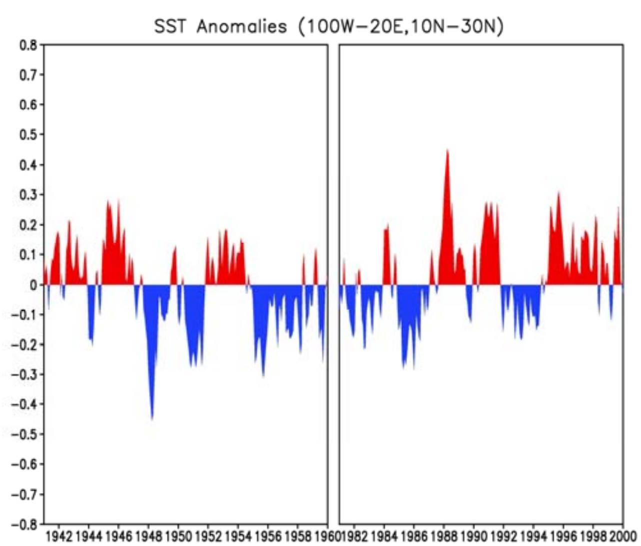
- The Gulf of Guinea has warmed up in the last period, with no season differences.

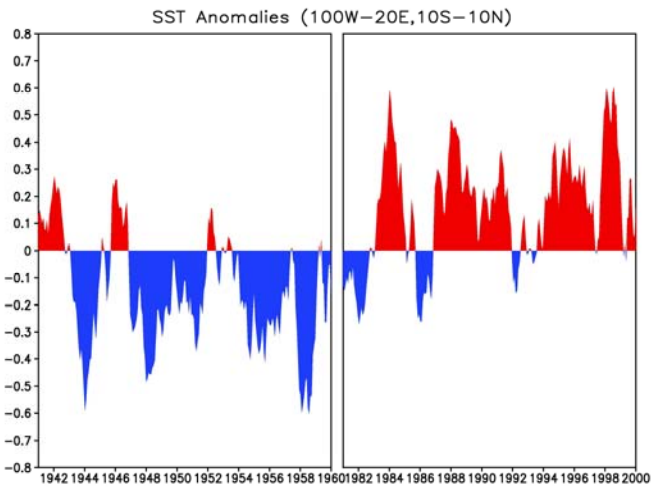
- In South Atlantic Ocean we find a negative value which means that the second period had higher SST than the first, thus a warming trend. This is more relevant in South America east coast during January-April months (south hemisphere summer months).

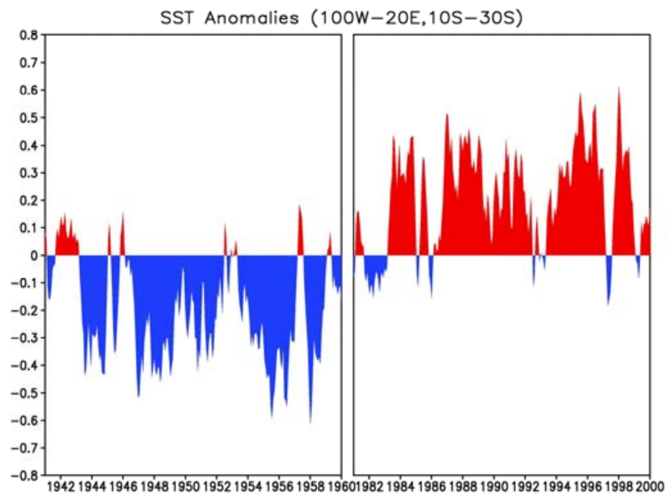
- In almost all plots an SST gradient between the tropical North Atlantic and the tropical South Atlantic can be observed. Some authors (Robertson AW et al 2000) explains these gradient as an atmospheric meridional circulation cell in which the air rises over the warm SST anomaly region, flows toward the cold SST anomaly region aloft, sinks in the cold SST anomaly region, and then crosses the equator toward the warm SST region in the lower troposphere. This anomalies are linked with the years of high NAO index when the atmospheric Ferrel and Hadley circulations are strengthened, and also with surface westerly and easterly wind anomalies in the North Atlantic and in the middle to tropical Atlantic, respectively (see wind anomalies **figures 24-26**)

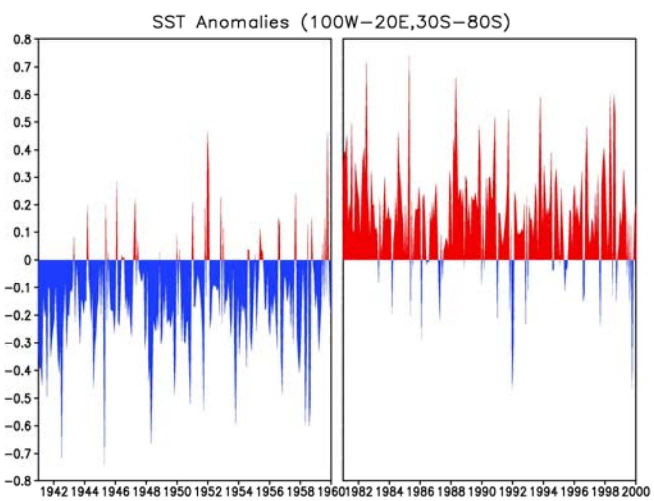
For a better discussion of the results obtained in the plots a Time series have been calculated for the SST anomalies between both periods. For a better interpretation five different latitudinal zones are shown.











__Figures 15-19:__ *SST anomalies time series for periods 1940:1960 - 1980:2000. A) North Atlantic Ocean 30-80 N B) Subtropical north Atlantic ocean 10-30 N C) Tropical Atlantic ocean 10S-10N D) Subtropical south Atlantic Ocean 10-30S E) South Atlantic Ocean 30-80S.*

Figures generated with data obtained from the UCLA-AGCM model and the NCAR reanalysis and plotted with Grads.

In both north and south high latitudes the signal of anomalies seems to be the response to a climate natural variability (Atlantic Multidecadal Oscillation is one of the hypothesis for some of the Atlantic changes observed in the last century, Robertson, Mechoso and Kim 2000) and with also a dipole between north Atlantic and South Atlantic Ocean.

In subtropics the time series shows a kind of different pattern, with more irregular variability. In northern latitudes (figure B) anomalies are weaken compared with southern latitudes (figure D) with a higher anomalies between two periods, and also a warming trend tendency is shown.

In the tropics is where more irregular and higher anomalies are found, and also big differences between two periods with a higher values in second period compared with the first.

o **Precipitation**

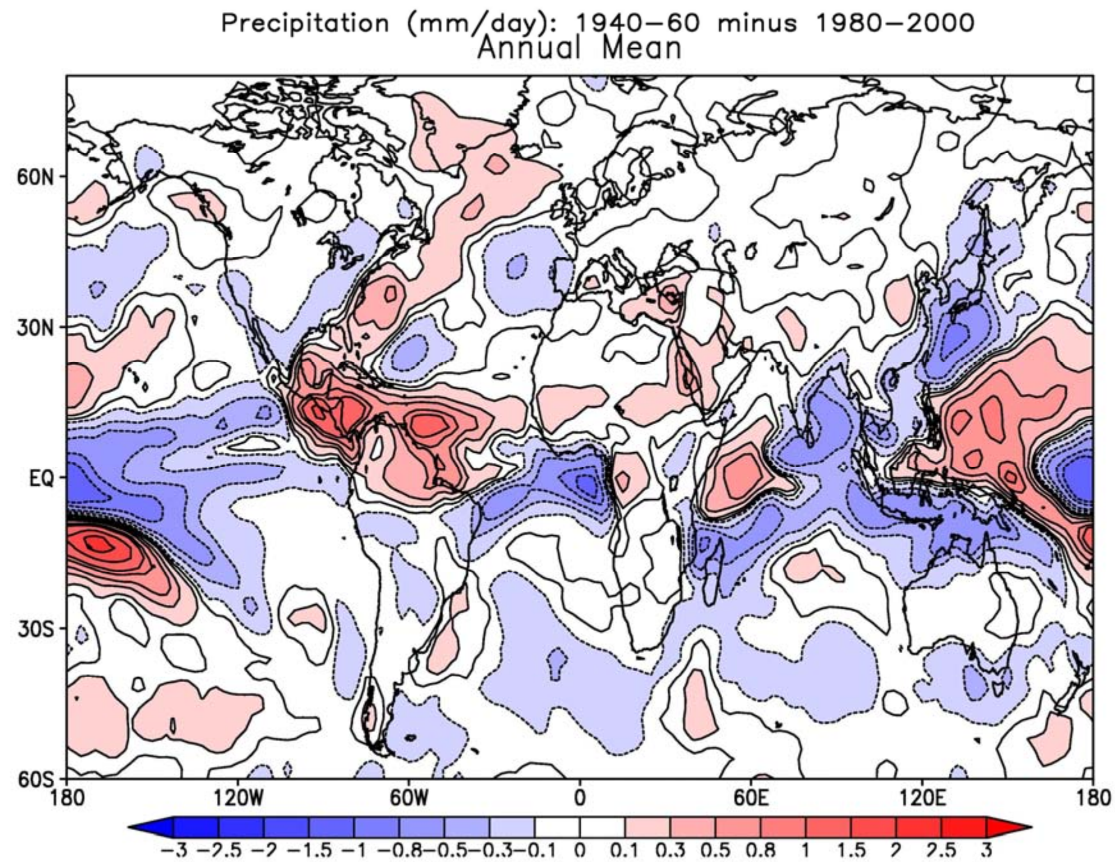
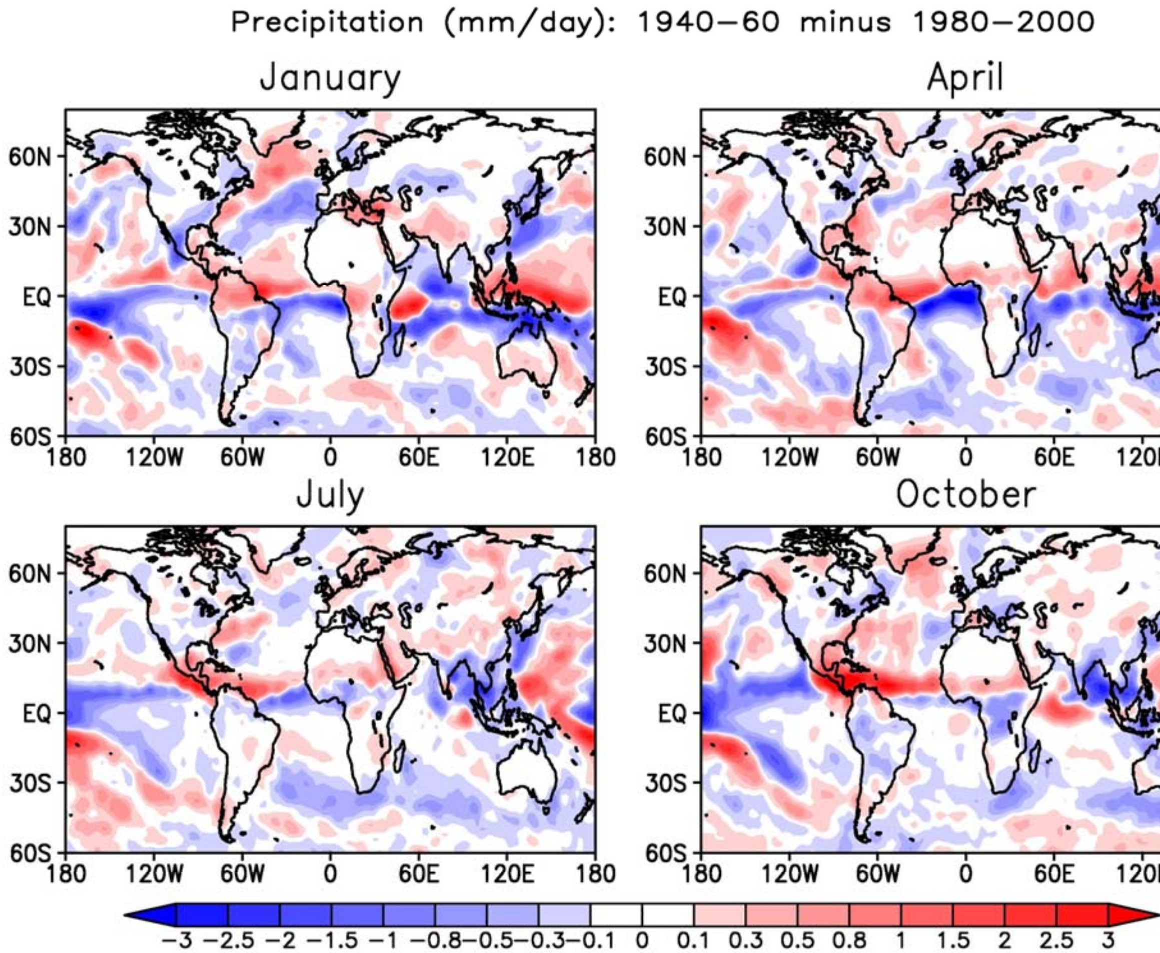


Figure 20: *Latitude-longitude global plot of Precipitation annual mean anomalies between two periods (1940:1960 - 1980:2000), measured in mm/day .Source: Figure generated with results obtained from UCLA-AGCM model.*



<u>Figure 21:</u> *Latitude-longitude global plots of Precipitation seasonal mean anomalies between two periods (1940:1960 - 1980:2000), measured in mm/day . Source: Figure generated with results obtained from UCLA-AGCM model*

Precipitation trends are highly related with SST anomalies, especially over determined regions of the continent. We also find a clear dipole between different regions of the Atlantic Ocean. In north latitudes positive values means that rainfall has decreased in the second period, especially over the North America east coast in winter months.

In subtropical latitudes and in North West Europe negative values means and increasing in rainfall in these regions. Although in North Africa and south Europe more dry trends can be observed.

A clear cross equator dipole is shown, all the year round which also can be related with the position of the Inter tropical convergence zone (ITCZ) and also with some SST forcing. Some observations of anomalies that can be deduced from the figures are:

- More rain over Gulf of Guinea especially in summer hemisphere months is observed.
- In South America anomalies in precipitation are stronger in summer months with a reduced rainfall in northern parts of the continent and with an increased trend over center and south of the continent.
- Out of Atlantic Ocean there some anomalies and a dipole structure over Indian ocean can be observed(specially in the equator zones where increased rainfall with little seasonal change is seen)
- Significant rainfall anomalies over parts of northern South America especially in January and April were a reduced trend in precipitation can be observed.

Some rainfall anomalies in the tropics can be explained by the great SST gradient between North and South Atlantic Ocean.

Must be said here that AGCM traditionally have some difficulties with regional features in the distribution of precipitation, particularly over continents, which could be contrasted with more detail with observed pattern figures from same periods. Even though, this is not the goal of the present research work, so we will not go indeep.

The latent and sensible heat fluxes are much correlated with the precipitation and also with the SST, as shown in **figures 22 and 23.**

o **Latent and sensible heat flux**

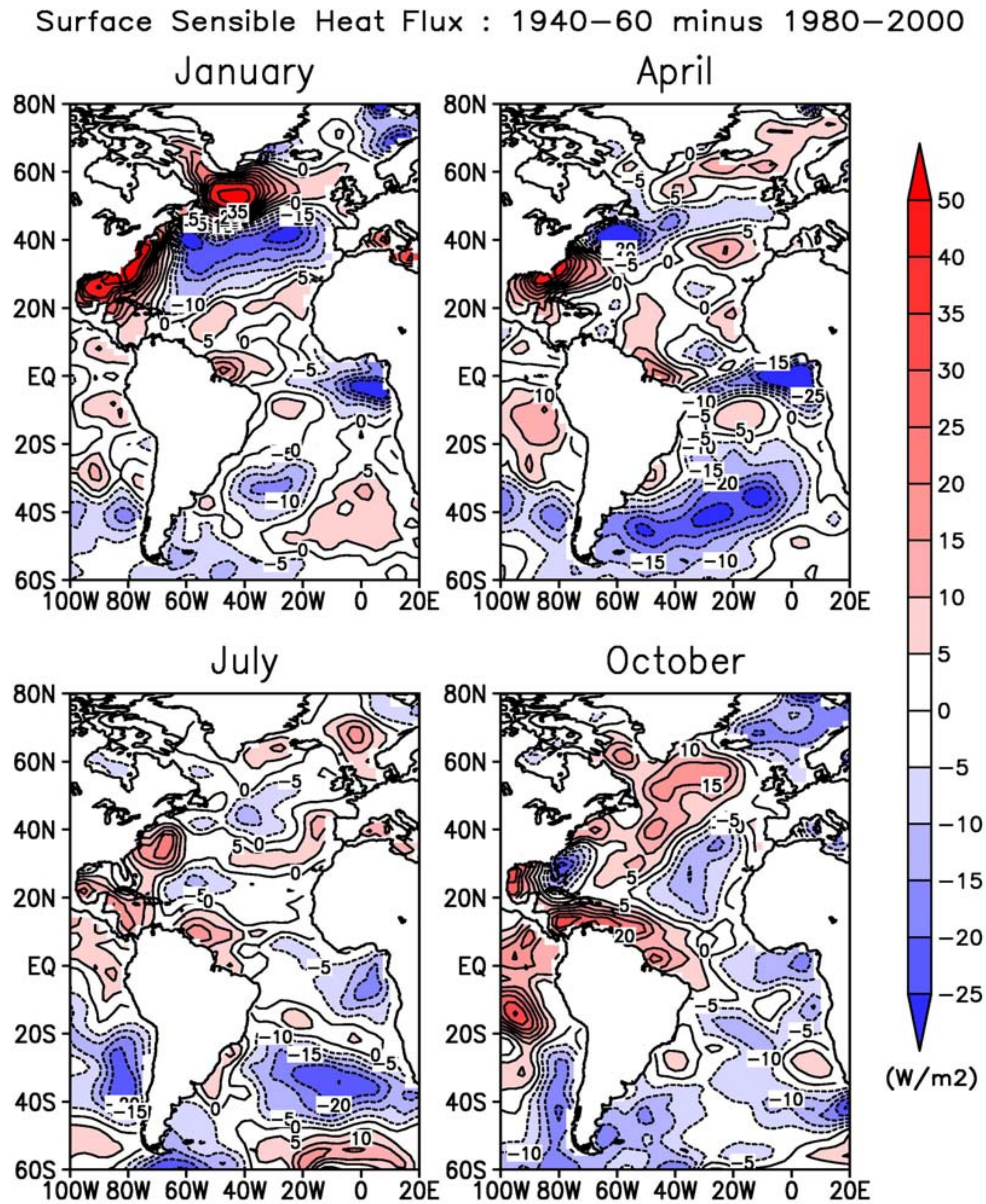


***Figure 22**: Latitude-longitude plots of Surface sensible heat flux anomalies for periods (1940:1960 - 1980:2000) ,units are in w/m2. Source: Figure generated with results obtained from UCLA-AGCM model*

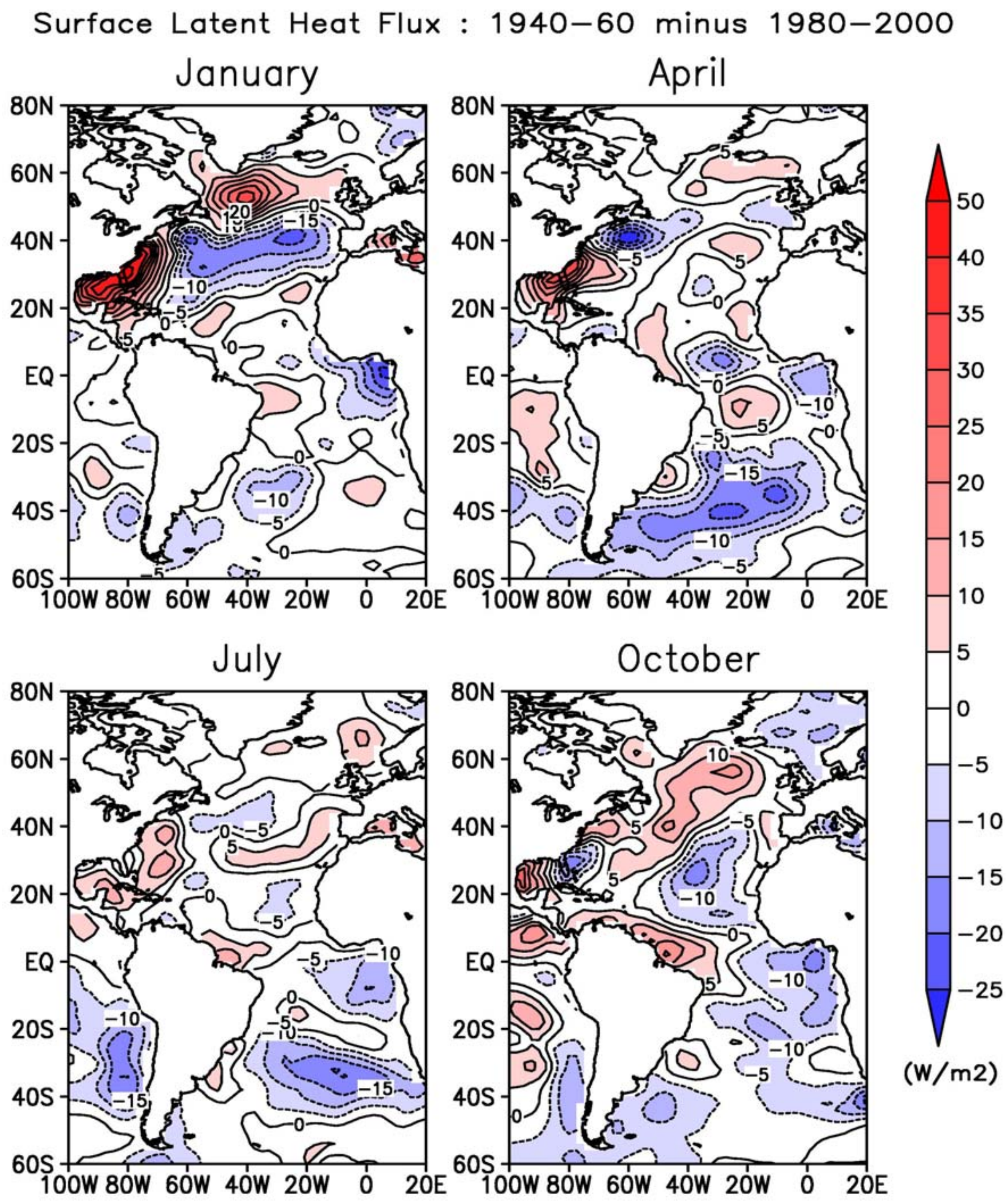


***Figure 23**: Latitude-longitude plots of Surface latent heat flux anomalies for periods (1940:1960 - 1980:2000), units are in w/m2. Source: Figure generated with results obtained from UCLA-AGCM model*

Both figures show strong anomalies over North Atlantic Ocean, with a strong dipole structure especially for winter months. This is correlated with the SST anomalies over the same region and period, where we find warmer SST positive sensible and heat fluxes (this is for the northern latitudes, over Greenland, Iceland), but strong negative values are seen in subtropical north Atlantic regions (especially from20-40 N). Also this values are correlated with the colder SST temperatures found here for the same seasons.

In summer season the anomalies weak, with less significant values and with a more shaped structure.

Weaker anomalies are seen in south Atlantic ocean for all year, but also a dipole structure is seen in subtropical south Atlantic (over 20-40 S latitudes) in south hemisphere winter months.

Over tropics there are stronger anomalies in north hemisphere winter months, with a trend of higher values over Caribbean that can also be correlated with the warmer SST there.

o **Wind stress and velocity potential anomalies**

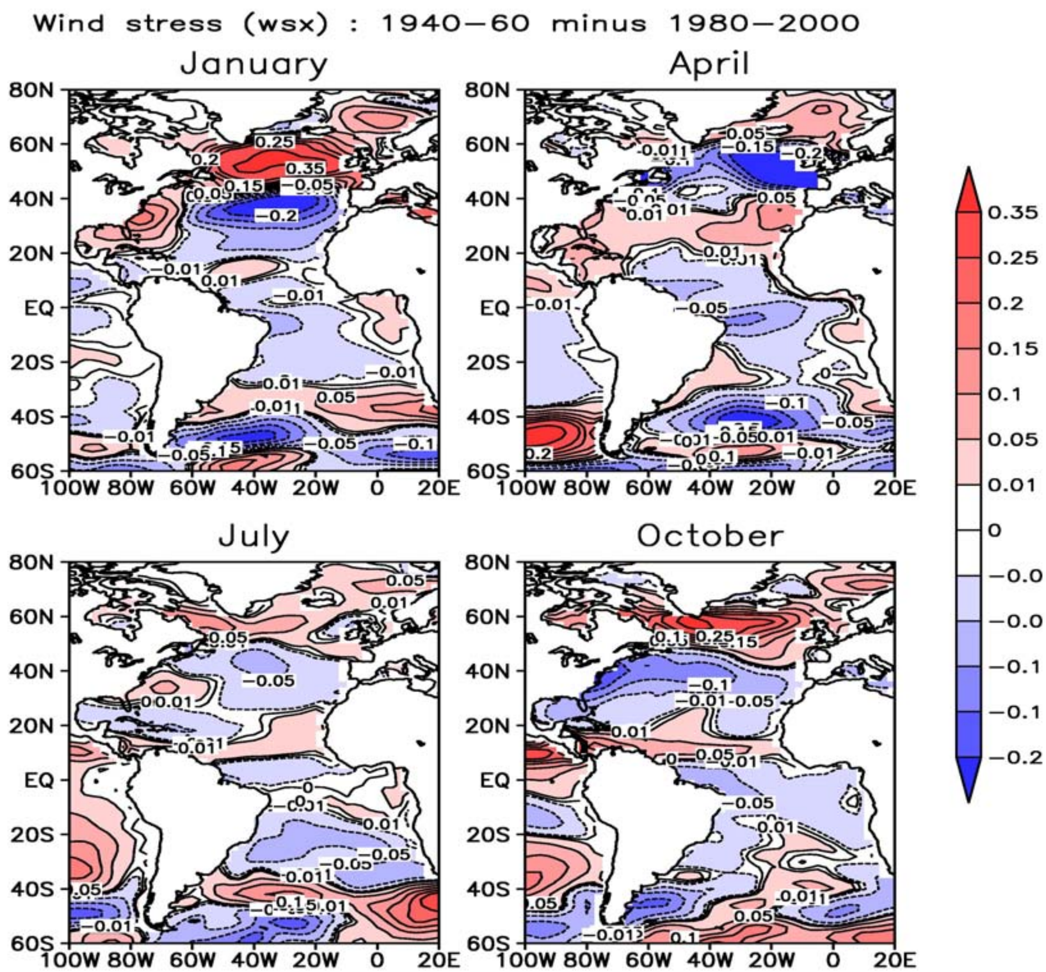


Figure 24: *Latitude-longitude plots of Wind stress anomalies (τ_x) for periods (1940:1960 - 1980:2000) Source: Figure generated with results obtained from UCLA-AGCM model*

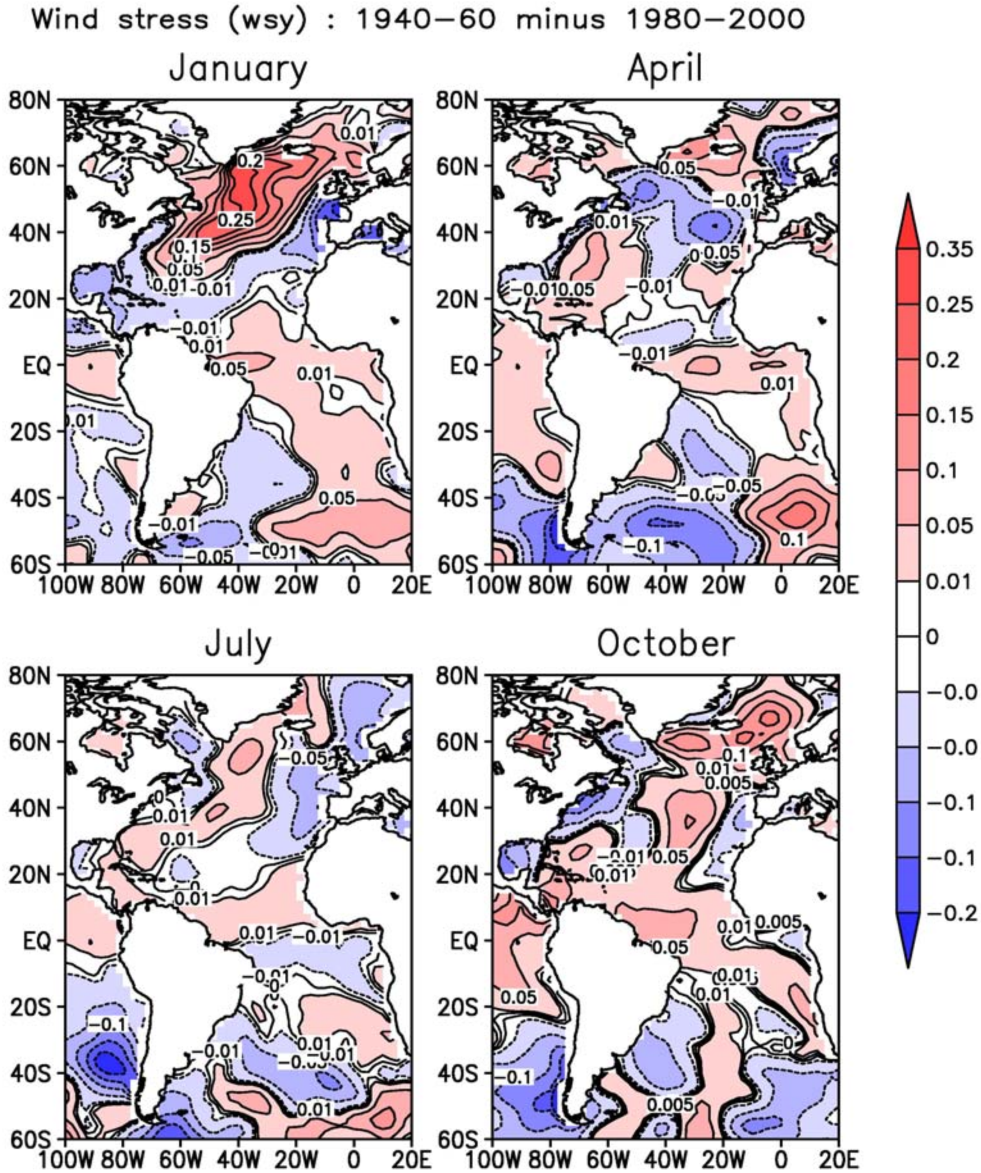


***Figure 25**: Latitude-longitude plots of wind stress anomalies (τ_y component) for periods (1940:1960 - 1980:2000) . Source: Figure generated with results*

In **figures 24-25**[8] we can see weakened trade winds over the warm zone of SST anomalies and enhanced trade winds over cold SST zone. Furthermore the northward SST gradient induces a cross-equatorial southerly wind pattern.

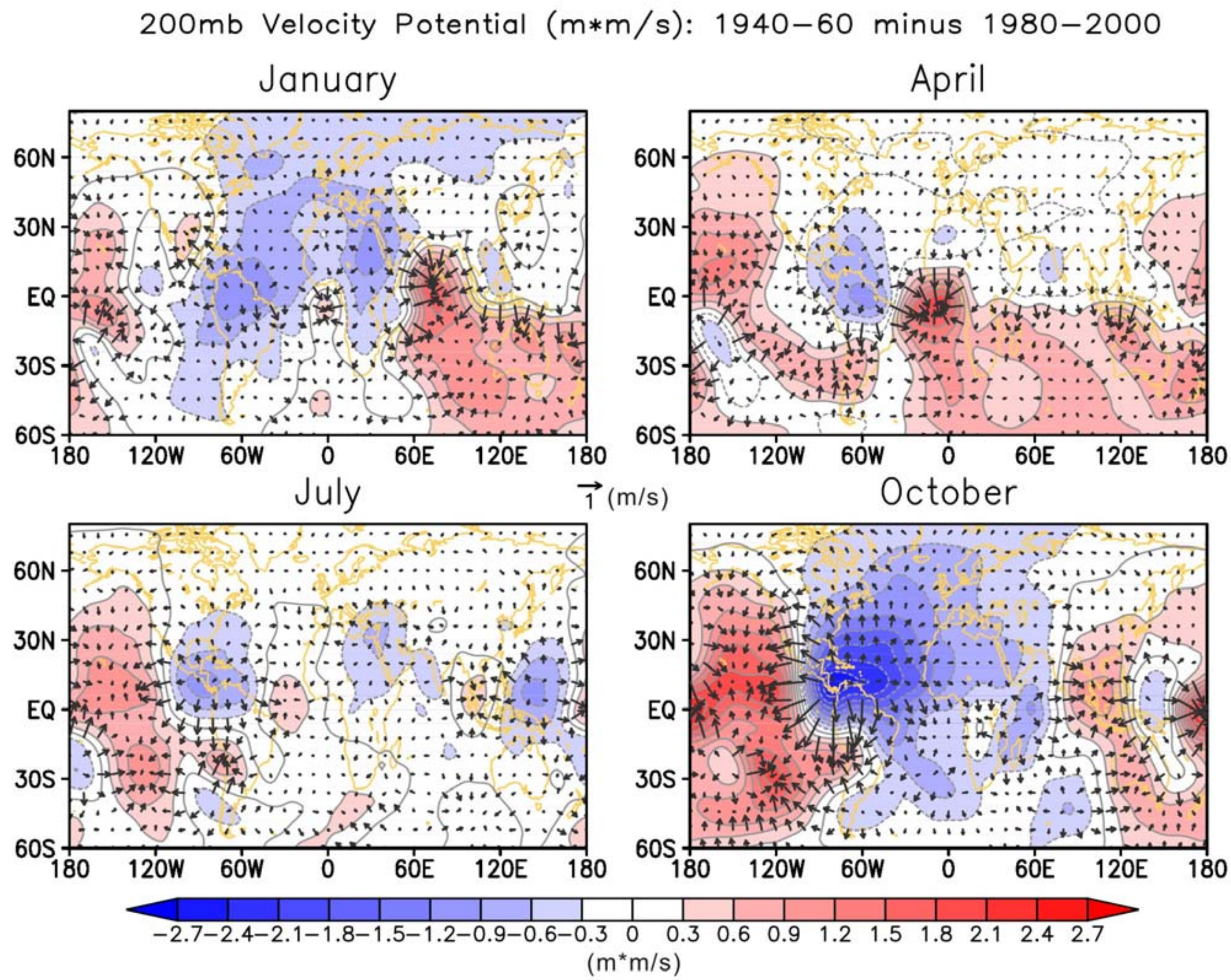


***Figure 26**: Latitude-longitude plots of velocity potential anomalies at 200mb level for periods (1940:1960 - 1980:2000) units are in m*m/s. Source: Figure generated with results obtained from UCLA-AGCM model*

Figures 24 and 25 present a strong dipole structure in the North Atlantic region, especially in winter North Hemisphere months. There a strong dipole over the higher north latitudes with a strong convergence zone in the highest latitudes with a strong divergence zone in mid latitudes. Over the equator a dipole structure is

[8] The wind stress components $\boldsymbol{\tau}_x$ and $\boldsymbol{\tau}_y$ are calculated by the model from the equation $\boldsymbol{\tau} = c_a \rho_a |\mathbf{u}| \mathbf{u}$, where ρ_a = 1.2 kg m_{-3} is the density of air, c_a = 0.0015 a dimensionless drag coefficient, $\mathbf{u}$ the wind speed and $|\mathbf{u}|$ its magnitude.

seen too but weak than in higher latitudes. Another dipole structure and more complicated (with different centers) is seen in south Atlantic multitudes.

When there are higher values in upper levels, which means convergence zones, in lower levels it turns to divergence, and when we find warmer SST convergence at lower levels, so a divergence at upper levels is expected.

Looking at the figures and comparing upper and lower levels with SST anomalies in a season trends what explained above can be verified.

Figure 26 shows the wind velocity potential anomalies for the periods of study at a 200mb level. Divergent wind vectors are plotted over velocity potential.

The regions with negative values (blue colors) for the velocity potential are active convective regions, and the regions with positive values (red colors) are subsidence regions, this is the reason why the arrows which shows the divergent winds flows from blue regions to red regions.

In this figure the difference between first and second period is plotted.

The strongest circulation impacts are in October: Convection is weaker in the second period (1980-2000) comparing to the first period (1940-60) over the western equatorial Atlantic Ocean (since it is 1940-60 minus 1980-2000) with divergent winds flowing to the strong subsidence region over the equatorial Pacific Ocean.

The second strongest circulation changes are in April, when warmer SSTs increased convection over the Gulf of Guinea. The compensatory motion is decreased convection over the Amazon where the South American Monsoon weakens.

With the results obtained it can also be suggested that increase in zonal westerly Atlantic winds (strong NAO index) can cause periods of winter warming over Europe which can be linked with intense precipitation periods in north east of America.

6. Section 4: CONCLUSIONS

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In this project we have investigated the consistency between SST changes during the XX century and the changes in the atmospheric circulation observed during the same period. We focused on the differences between the climates in the twenty-year periods 1940-1960 and 1980-2000. Special interest was placed on the SST changes in the tropical Atlantic and on their links with changes in the other variables studied and analyzed, and on the connection with the main climate changes observed in nature.

The results obtained from the experiments done with the UCLA AGCM are model dependent and have an uncertainty component. Despite the model dependence of the results, the approach based on an AGCM has the great advantage of working in a fully controlled environment. That is, we are certain that the only reason for the differences in the simulated atmospheric circulation between our results for the two periods selected is due to the different distributions of prescribed SSTs. On the other hand, we are positive that changes in the atmosphere are not due to increased concentration of greenhouse gases, since these are constant in the models (although their effect is implicit in the SSTs). In addition, a comparison between our results and those obtained in other works and research on the subject give us more confidence on our findings.

Our conclusions about the main questions and objectives proposed in the beginning of this project are preliminary. The results are extensive and can have several interpretations. First, the climate system is very complex and still poorly understood. Second, a definitive discussion and conclusions on the experiment results will require more detailed analyses which are beyond the goal and scope of this project. Some of the techniques to be applied may be beyond my knowledge and understanding of atmospheric physics and related topics as provided by my own training as an undergraduate student.

Taken into account the results from other research works and my own results with the UCLA AGCM, we can present the following summary and conclusions.

- According to some authors, the abrupt climate shift around the 1960s was associated with a reduction in the northward oceanic heat flux associated with the North Atlantic thermohaline circulation in the 1950s to 1970s, which was nearly in phase with a rapid increase in anthropogenic aerosol emissions during the 1950s and 1960s, particularly over Europe and North America.

- It is still not well understood which parts of the differences before-and-after the climate change were due to global change caused by increase greenhouse gases and which part to oscillations of the climate associated with the natural variability of the system. Our experiments take the SST directly from the observation, which includes both trends and natural oscillations. However, we can certainly say that trends expected from the greenhouse effect contribute to the changes.

- This project cannot, therefore, resolve whether climate differences between is due to change and oscillations of the climate systems associated with the natural variability of the environment. For this, a full climate model with atmosphere, ocean, ice, and other climate variables is needed

- Our strategy allows us to investigate the consistency between changes in the atmosphere and the oceans. It also allows a better understanding of the mechanisms that generated the changes.

We start with a summary of results obtained with the UCLA AGCM. In the tropics of the Atlantic Ocean, the clearest signal is a warming at the south of the equator with largest magnitudes in the Gulf of Guinea. There is also a cooling along the northern coast of South America. This configuration shows an increase of the interhemispheric gradient of SST.

- The major climate differences are found over the tropics in association with changes in rainfall patterns:

- Consistently with interhemispheric differences in the SST patterns, the model shows a northward shift of the Inter-Tropical Convergence zone.

- The rainfall differences obtained by the model in Sahel, northeast of Brazil and Indonesia can be well related with changes in SST. The pattern observed which a tropical Atlantic dipole also displays a large cross-equatorial SST gradient, which is correlated with the precipitation dipole found over the same region.

- The southward displacement of the ITCZ is also simulated over the Pacific Ocean.

- In the North Atlantic subtropics, the model's precipitation increase is consistent with a southward displacement of the storm track. This suggests average precipitation increases over Western Europe. The pattern is consistent with a southward displacement of the Hadley circulation.

- Also in the North Atlantic, evaporation and loss of sensible heat increased in the Gulf of Guinea and the subtropics, and decreased along the northern coast of South America and South of Greenland.

- The most important result of our project is that, although the SSTs changed over the world oceans, ocean basin that influences the atmosphere most depends on the season.

- The strongest circulation impacts (Fig. 26) are in October, when SSTs along the northern coast of South America were associated with a decrease in upper-level divergence (upward motion) over the northwest tropical Atlantic. This was compensated by increased upper-level convergence over the eastern equatorial Pacific. The increased trade wind over the extreme eastern equatorial Atlantic would discourage El Niño events.

- The second strongest circulation changes are in April, when warmer SSTs increased convection over the Gulf of Guinea. The compensatory motion is decreased convection over the Amazon where the South American Monsoon weakens.

Finally the obtained results could the basis for some predictability of future changes, probably originating in ocean and increased by human interaction even though a larger study would be needed.

7. PROJECT PLANNING

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This project was being carried out in the third quarter of the 2008-09 school years. It started on the second week of April 2009 with a literature revision of similar studies, some background research and scientific information research about the topics to be discussed. It continued with the data collection (both from observational sources and computers data output) and with a posterior analysis and discussion of it.

A written report was prepared for UCLA as part of the course work required in the course Atmospheric and Oceanic Sciences 199 (A&O Sic 199) this due in the second week of June 2009. The paper will be turned into a final degree project by the 1st of September at the Autonomous University of Barcelona.
An oral presentation will be scheduled by 17th September 2009 in Barcelona

MONTHLY PLANNING

	April				May				June					July				August				September			
Weeks	1	2	3	4	1	2	3	4	1	2	3	4	5	1	2	3	4	1	2	3	4	1	2	3	4
Choose of Project Topic			■	■																					
Bibliography research					■	■	■	■																	
Data elaboration							■	■	■	■															
Data analisis										■	■	■	■	■											
Elaboration of de Project Memory															■	■	■	■	■	■	■				
Meetings with mentor				■	■		■		■	■						■									
Project presentation																						■	■		

8. PROJECT COSTS

7. PROJECT COSTS

PERSONAL COSTS			
CONCEPT	**NUMBER OF HOURS**	**PAYMENT/HOUR**	**TOTAL**
HOURS/PERSON	400	12€/HOUR	4800€
TRAVELING EXPENSES	64	8€/HOUR	512€
		TOTAL	**5312€**

MATERIAL COSTS			
CONCEPT	**UNITS**	**UNIT PRICE**	**TOTAL**
PRINTING	4	12€	48€
BOOKBINDING	4	5€	20€
CD	3	1.2€	3,6€
		TOTAL	**71,6€**

PROJECT COST	**5383.6€**
IVA 16%	**861.376€**
TOTAL PROJECT COST	**6244.976€**

9. REFERENCES AND LITERATURE CITED

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10. APPENDIX

10. APPENDIX

10.1 OTHER FIGURES NOT USED FOR THE ANALYSIS

Here some figures plotted but not described in the results section of the work are presented:

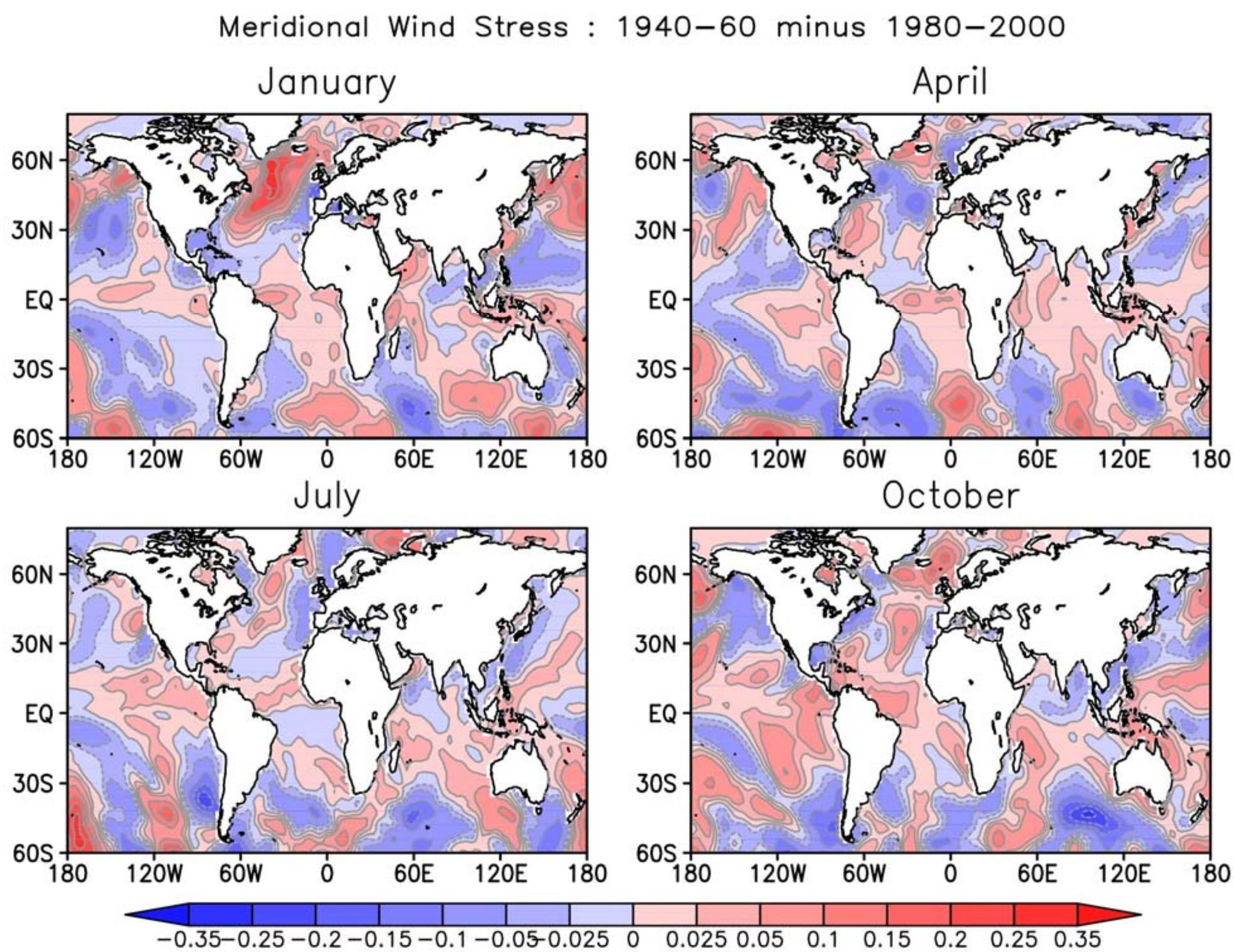
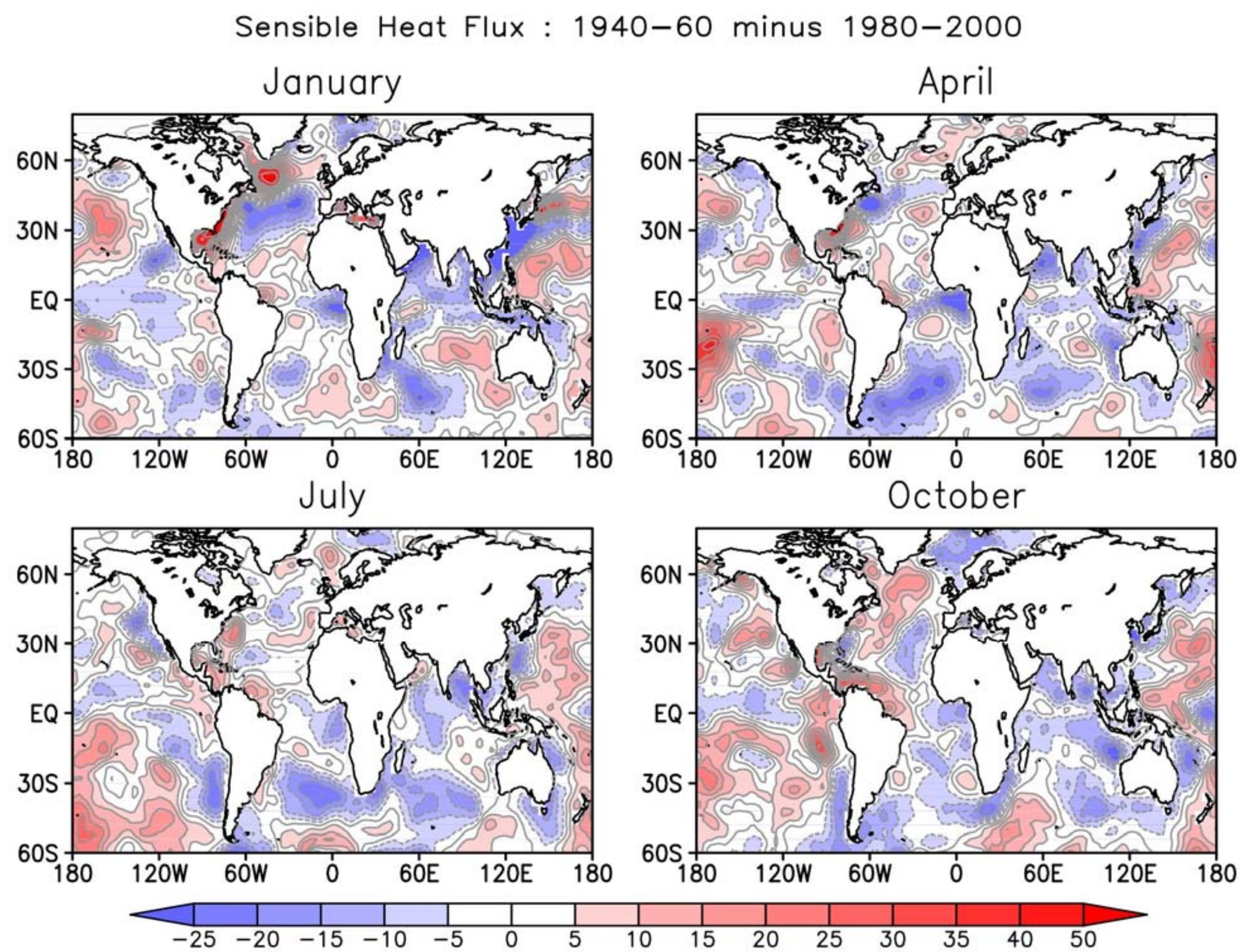


Figure 27: *Longitude-latitude plot of the meridional wind stress difference between the two periods (1940-60 minnus 1980-2000). Figure generated with results obtained from UCLA-AGCM model*



<u>Figure 28:</u> *Longitude-latitude plot of sensible heat flux difference between the two periods (1940-60 minnus 1980-2000). Figure generated with results obtained from UCLA-AGCM model*

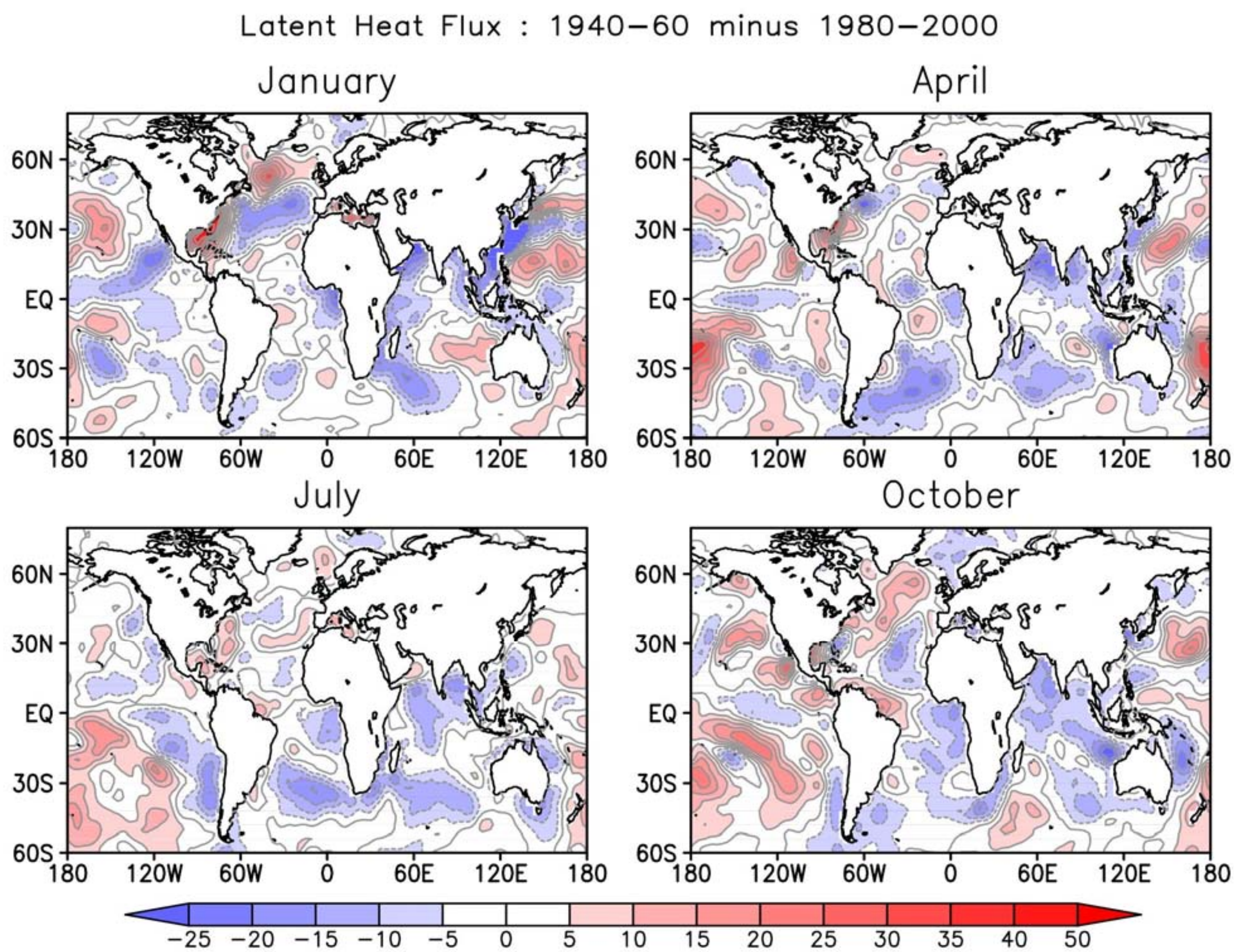


Figure 29: *Longitude-latitude plot of latent heat flux difference between the two periods (1940-60 minus 1980-2000). Figure generated with results obtained from UCLA-AGCM model*

10.2 TECHINCAL PARAMETERS OF THE EXPERIMENT RUNS

Here the technical parameters used for plotting the runs made by the UCLA-AGCM model are presented. The document was generated by Joseph A Spahr. Member of the UCLA atmospheric department and current informatics worker there:

The files from the observed sst run for periods 1940-1960 and 1980-2000 are located in the directory:

/s/spahr/runs_ncar/sst_obs_40-60_80-00

Naming convention:

period 1 period 2

(1940-1960) (1980-2000)

1 e130 e130 _p2

2 e131 e131 _p2

3 e132 e132 _p2

The next 1 or 2 letters described the analysis routine used:

f fields (dynamics on constant pressure surfaces)

ct boundary and pbl variables on sigma surfaces

c3 physic diagnostics variables on sigma surfaces

The next 2 or 3 letters describe the averaging period:

mm: monthly means (240 individual months)

cmm: cumulative monthly means (i.e. all jan averaged) (12 monthly averages)

csm: cumulative seasonal means (i.e. all DJF averaged) (4 seasonal averages)

So, e130ctmm_p2 translate to experiment 130, boundary and pbl variables, monthly means, and for period 2.

Data set are unformatted binary. Each record is a real*4 variable, dimensioned 144 by 89.

The records in the data set are ordered by the following rule:

Files with no name extension:

```
do t=1,number_of_times
do v=1,number_of_variables
do z=1,number_of_levels
write(10) array(:,:,z,v,t)
```

Files with .ztv name extension

```
do v=1,number_of_variables
do t=1,number_of_times
do z=1,number_of_levels
write(10) array(:,:,z,t,v)
```

Variable order:

For f data sets:

16 levels: 1.39,2.68,5.18,10.,19.31,37.28,71.99,100.,150.,200.,300.,400., 500.,600.,700., and 850. mb

'U ' 'm/s ' 'U winds '

'V ' 'm/s ' 'V winds '

'T ' 'K ' 'Temperature '

'SH ' 'g/kg ' 'Specific humidity '

'RH ' 'percent ' 'Relative humidity '

'PHI ' 'm ' 'Geopotential height '

'XI ' 'm*m/s ' 'Velocity potential '

'PSI ' 'm*m/s ' 'Stream Function '`

For ct data sets:

1 level

'ST ' 'C ' 'Surface temperature '

'SLP ' 'mb ' 'Sea level pressure '

'PBL_H ' '? ' 'PBL moist static energy '

'PQ ' 'kg/m^2 ' 'Precipitable water '

For c3 data sets:

1 level:

101 "TOT_PREC" "mm/day " "PHY_DIAG" "AGCM/PD2" "Total Precipitation"

102 "CUMPREC " "mm/day " "PHY_DIAG" "AGCM/PD2" "Cumulus Precipitation"

103 "LSPREC " "mm/day " "PHY_DIAG" "AGCM/PD2" "Grid Scale Precipitation"

104 "CLOUD " "% " "PHY_DIAG" "AGCM/PD2" "Cloudiness"

105 "SHF " "W/m^2 " "PHY_DIAG" "AGCM/PD2" "Net Surface Energy Flux"

106 "SEN_HF " "W/m^2 " "PHY_DIAG" "AGCM/PD2" "Surface Sensible Heat Flux"

107 "FWS " "mm/day " "PHY_DIAG" "AGCM/PD2" "Surface Water Flux"

108 "FHS " "W/m^2 " "PHY_DIAG" "AGCM/PD2" "Surface Heat Flux"

109 "WSX " "dyne/cm2" "PHY_DIAG" "AGCM/PD2" "Zonal Surface Drag"

110 "WSY " "dyne/cm2" "PHY_DIAG" "AGCM/PD2" "Meridional Surface Drag"

111 "RS " "W/m^2 " "PHY_DIAG" "AGCM/PD2" "Net Surface Long Wave"

112 "SS " "W/m^2 " "PHY_DIAG" "AGCM/PD2" "Net Surface Short Wave"

113 "ENTRAN " "mb/hr " "PHY_DIAG" "AGCM/PD2" "PBL Entrainment Rate"

114 "MB " "mb/hr " "PHY_DIAG" "AGCM/PD2" "PBL Cumulus Mass Flux"

115 "STRT_THK" "mb " "PHY_DIAG" "AGCM/PD2" "Stratus Cloud Thickness"

116 "PBLDepth" "mb " "PHY_DIAG" "AGCM/PD2" "PBL Depth"

117 "RH " "% " "PHY_DIAG" "AGCM/PD2" "PBL Relative Humidity"

118 "SWINC " "W/m^2 " "PHY_DIAG" "AGCM/PD2" "TOA Shortwave"

119 "DSWTOP " "W/m^2 " "PHY_DIAG" "AGCM/PD2" "TOA Net Downward Shortwave"

120 "DSWBOT " "W/m^2 " "PHY_DIAG" "AGCM/PD2" "SFC Net Downward Shortwave"

121 "ULWTOP " "W/m^2 " "PHY_DIAG" "AGCM/PD2" "TOA Upward Longwave(OLR)"

122 "ULWBOT " "W/m^2 " "PHY_DIAG" "AGCM/PD2" "SFC Upward Longwave"

123 "DLWBOT " "W/m^2 " "PHY_DIAG" "AGCM/PD2" "SFC Downward Longwave"

124 "HETSW " "K/day " "PHY_DIAG" "AGCM/PD2" "Column Shortwave Heating"

125 "HETLW " "K/day " "PHY_DIAG" "AGCM/PD2" "Column Longwave Heating">126 "DRB " "W/m^2 " "PHY_DIAG" "AGCM/PD2" "PBL Top Longwave jump"

127 "STRT_INC" "% " "PHY_DIAG" "AGCM/PD2" "Stratus Cloud Incidence"

Total number of files when the two experiment are completed: 12 plus 24 derived files (cmm and csm files).