An Intercomparison of General Circulation Models
over Africa:
Implications for Future Climatic Change

by

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1993 Summer Employment Program

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The National Center for Atmospheric Research is sponsored by the National Science Foundation
To my parents
for encouraging my curiosity
Photographs made available by the Environmental and Social Impacts Group
National Center for Atmospheric Research

All photographs depict Sahel Drought conditions in 1973
ACKNOWLEDGEMENTS

I am sincerely grateful to Dr. Gregory S. Jenkins for the confidence he showed in me by allowing me to work with him. He shared with me his deep love for Atmospheric Science and a readiness to be of assistance to me. His efforts have helped me to appreciate the intimate relationship between science and society. For this, I am eternally grateful. Thank you Greg, for not only being my advisor, but for also being a friend.

I would like to show my appreciation to Anna Reyna-Arcos for the enormous amount resourcefulness she put into making my stay in Boulder so complete. I can never thank you enough. My thanks also extends to Chyrl Brunner and everyone at UCAR's Human Resources Department. I appreciate your willingness to address my many concerns. I will always remember your kindness.

The editing of my paper would never have been complete without the suggestions provided by several sincere and dedicated individuals. To Joann, Harvey, and Mary, of RDD Consultants; a very big thank you.

Furthermore, I would like to thank Barb McDonald and Judy Miller, of the Advanced Study Program for their assistance in providing everything I needed to make this paper complete. Thank you both for always being there. I would also like to thank Darrell Holley of the Super Computing Division, for providing assistance with various aspects of NCAR's computing facilities. Thanks to all the people of SCD and CGD who were there to provide answers to my technical questions.

Finally, I would like to thank the National Science Foundation for their willingness to sponsor the Summer Employment Program. I have found my experience with NCAR to be both fulfilling and challenging. It was a source of great pleasure that my job remained simultaneously exciting and exacting.

And to all those individuals who have provided assistance in just as many ways.

Thank you.
INTRODUCTION

Background

The delicate balance of gases that constitute the earth's atmosphere has allowed humankind to flourish over the ages. Certain gases (CO₂, CH₄, N₂O, and a variety of CFCs) trap longwave radiation in the atmosphere. For this reason, these gases have been collectively termed "greenhouse gases". A lot of concern has justifiably been attached to increased CO₂ scenarios produced by climate models. Although water vapor is the largest single contributor to the greenhouse effect, its concentration in the atmosphere remains unchanged by the actions of people. Carbon dioxide is the single largest greenhouse factor that is governed by human activities. According to the Intergovernmental Panel on Climate Change (IPCC) Scientific Assessment, CO₂ is responsible for over half of the enhanced greenhouse effect, and is likely to remain so in the future. The level of CO₂ has risen from its pre-industrial concentration of 280 ppm to the present-day concentration of about 358 ppm. If current emission levels are maintained, it is expected that the concentration of CO₂ in the atmosphere will approach a level of 560 ppm by the year 2030 (Ominde 1991).

The magnitude of an increased concentration of CO₂ in the atmosphere can be appreciated if the nature of the greenhouse effect is understood. As mentioned earlier greenhouse gases deter the emission of long-wave radiation in the atmosphere. High-frequency solar radiation filters through the atmosphere quite easily, and most of it is absorbed by the earth's surface which subsequently warms up. The warming of the earth's surface leads to the emission of infra-red radiation which, because of its low-frequency, is easily absorbed and re-emitted by gases in the atmosphere. The higher the concentration of greenhouse gases in the atmosphere, the more difficult it is for long-wave radiation to escape. For instance, Venus with a 90% concentration of CO₂ in its atmosphere has an observed temperature of 523°C. Based on a comparison of the degree of sunlight entering Venus' atmosphere and satellite measurements of the planet's emitted radiation, it has been shown that there is an absorption of heat due to greenhouse gases. Assuming the reflectivity of its surface remains constant, Venus would have a surface temperature of -46°C in the absence of a greenhouse effect. Similarly, researchers have shown that the surface
temperature of the earth is about 33°C warmer than it would otherwise have been without the presence of natural greenhouse gases.

The presence of observational posts around the earth’s surface assist in documenting climatic fluctuations. A directional trend in climatic variations, coupled with the increasing amount of greenhouse gases, confirms a relationship between the two. As people become more aware of the growing impact of increased concentrations of greenhouse gases, it becomes increasingly necessary that we all act to ensure our future on this planet. However, in order to be certain of the implications of future climate changes, the accuracy of climate models must first be measured and dealt with.

Africa: the region

Nowhere is the threat of global warming better illustrated than in sub-Saharan Africa. Even though the underdeveloped nations of the world contribute only 20% of the total CO₂ emission, they are more likely to be impacted by global warming (Ominde 1991). Most African nations possess fragile economies that are riddled with debt. In a bid to solve the continent’s economic woes, a significant portion of Africa’s natural forests are felled annually. In general, African countries continually strive to increase their production of cash crops, only to increase their net import of staple foods that could be grown domestically. Ironically, there has been a corresponding decrease in demand for African exports. For instance, Sierra Leone used to export considerable amounts of piassava fiber for the production brushes and brooms. Nowadays, piassava has been replaced by synthetic imitations that are much cheaper to produce. However, the present socio-economic structure in most African countries is but an enhanced reflection of socio-economic structures imposed by colonialisms parasitic nature. A vice-president of the World Bank once commented that international aid organizations had failed Africa drastically:

We have not fully understood the problems. We have not always designed our projects to fit the agroclimatic conditions of Africa, and the social, cultural, and political framework of African countries. (Walsh 1980)

Two other problems, conflict and famine, have served to strengthen Africa’s economic woes. This study investigates scientific methods to curtailing the latter problem, as the former is often based on prevailing economic conditions. During
the period from 1968 - 1974, much of the Sahel region of Africa was affected by a full-scale drought. The Sahel is a climatic belt across Africa which represents a blend between the Sahara in the north and the savanna grasslands in the south. The effect of the Sahel Drought, in both material and human terms, were far reaching. A good agricultural harvest in Mali, entailed grain productions of about 850,000 tons. An issue of the Washington Post revealed that only 450,000 tons were harvested during that year (Franke 1980). In 1974, Mauritania had 600,000 head of cattle from an estimate of 2.5 million before the drought. Displaced people, where also seen roaming the countryside all around West Africa. Tuaregs from Niger and Mauritania could be found as far south as Kumasi and Lagos, as they struggled hard to make a living. The weak had no choice but to remain in famine-plagued areas, scrounging for the dry remains of dead cattle (US Senate hearing 1974). The inevitable result of all this was disease. Entire villages around Lake Chad were wiped out by diphtheria. In Niger alone, the incidence of documented child measles cases went up from 2,880 in 1971 to 35,000 in 1973 and the death rate went up tenfold. And the cycle continued: the inescapable ecological relationship between people, animals, plants, and climate, was set into motion.

Yet the question remains, could the full implications of the Sahel Drought have been known, could it have been prevented, could such a drought be stopped from occurring again? It is these questions that this intercomparison seeks to answer.

The latter part of this study focuses on West Africa in particular. For the purpose of this paper, West Africa is defined as the region west of longitude 20°E, falling between the equator and latitude 25°N. Since climate patterns neither follow strict parallels nor clear-cut political boundaries, this definition of West Africa is not restrictive. Features of interest, occurring around West African region, will also be noted. Of particular interest, will be regions that were severely hit by the Sahel Drought. West Africa is an excellent choice for study because it possesses a broad range of climatic features which provides an appropriate representation of the entire continent. There is the gradual variation in climate from the fringes of the Sahara, to regions of dense vegetation near the equator. West Africa also has a notably higher population density than the rest of Africa as well as a high rate of population increase. Therefore, it is imperative that the full implications of
climate change be known. In this light, it is hoped that this study of West Africa during the growing season may prove useful to policy makers in the region.

**Climate Models: the tools**

The technique that was used to simulate the climate of West Africa makes use of several general circulation models (GCMs). Such models are able to make climatic predictions based on parameters which imitate the laws of nature. This paper applies estimates of the present-day climate generated by GCMs and validates them against observation. The data used in this study are based on rhomboidal 15 (R15) truncations (which implies that climatic measurements are estimated at grid spacings of 4.5° latitude by 7.5° longitude). Also, the models are three-dimensional in nature, not only collecting data from specified longitudes and latitudes, but also at definite intervals above and below sea level. The first part of this study will validate the mean annual climate generated by five different GCMs over the entire continent of Africa. These models, which are all versions of the Community Climate Model (CCM), have been investigated by the Model Evaluation Consortium for Climate Assessment (MECCA). A principal focus of MECCA is to increase the understanding of the uncertainties of numerical climate model predictions. The MECCA Phase I investigators of these models are 1) A. Henderson-Sellers et al., 2) Robert Oglesby el al., 3) D. Pollard and S. Thompson, 4) W. Washington and G. Meehl, and 5) Wei-Chi Wang et al. This study will serve to reinforce or contradict previous model-observation comparisons. Once some idea has been obtained of how well the generated climate of a GCM compares to observation, then any climate change scenarios generated by GCMs will be seen in the proper perspective.

In the second part of this study, the growing season of West Africa (May-September) is also validated against observations. It was determined whether R15 truncations provided an an appropriate interpretation of West African climate. If the models are in good agreement with observation the a technique that nests a limited area model within the GCM can be used in an attempt to extract more accurate climatic information. Nesting produces high resolution climate model with grid spacing of about 80km squared (which is finer than a T106 resolution). However, if the models are not in good agreement with observation, then nesting merely intensifies the imprecision.
METHODS

Controls

Averaged annual values of precipitation and temperature over Africa were taken into account. The study of the growing season in West Africa includes an intercomparison of monthly averages of precipitation, temperature, wind, sea level pressure, outgoing long-wave radiation (OLR), and the total cloud fraction. The observational data sets are described below.

Temperature data compiled by D.R. Legates and C.J. Willmott were used. These data sets are based on archives of shelter-height air temperatures as compiled by Wernstedt (1972), Willmott et al. (1981), and NCAR (Spangler and Jenne, 1984). Redundant terms were either eliminated or averaged, depending on the degree of uncertainty in the data. In a bid to remove potential coding errors, each data set was compared with nearby stations, and checked for accuracy when the interpolated monthly value exceeded 5K. After editing, the Legates and Willmott study included 17,986 independent station records between the dates 1920 and 1980. In this study we compared temperatures at the first atmospheric level.

For precipitation, the gauge-uncorrected values compiled by Legates and Willmott were used as controls. Although measurements taken directly from rain gauges do incorporate systematic errors, it was found that the uncorrected data is sufficiently close to observation. The following is an equation that has been posed to estimate values of corrected precipitation (Sevruk and Hamon, 1984):

$$P' = k(P + \Delta P_w + \Delta P_s) \pm \Delta P_b \pm \Delta P_r.$$  (1)

where $P'$ is the corrected gauge precipitation, $P$ is the gauge measurement, $\Delta P_w$ is the correction for wetting loss on the internal walls of the gauge, $\Delta P_s$ is the correction due to the splashing, $\Delta P_b$ is the correction for the blowing of snow, $\Delta P_r$ is the correction due to random errors and $k$ is the wind correction factor ($k \geq 1$). The R.M.O. Mk I rain gauge (elevated at 30cm) is frequently used by former British colonies (Kurtyka 1953), including many countries in Africa. The Hellman gauge (elevated at an average height of 1m) remains the dominant type throughout Africa (Sevruk 1982). Both of these gauges are sufficiently elevated to nullify splashing. Furthermore, any effect due to
snow can be assumed to be negligible over the entire continent of Africa. For a sufficiently long period of time, random errors even out causing only minute errors in regard to guage readings. A reduced form of equation (1) over the continent of Africa can then be written as:

\[ P' = k(P + \Delta P_w + \Delta P_e) \quad (2) \]

Sevruk (1979) noted that wetting losses cause an underestimate of 2.6%, and Sevruk and Hamon (1984) showed that evaporation causes a decrease of 0.5% in globally averaged precipitation. Despite these corrections for wetting loss and evaporation, we found the uncorrected data over Africa to be in better agreement with expectation than the corrected version for precipitation. This may suggest that inadequate values of \( \Delta P_w \) and \( \Delta P_e \) were used in the compilation of the corrected data. The period studied was from 1920 - 1980.

The Legates and Willmott study of precipitation includes 24,635 spatially independent terrestrial station records. Developed nations of the northern hemisphere are particularly rich in data. In the desert regions of Africa, the sparseness of data does introduce a degree of error. This error is mainly evident in temperature measurements; the presence of only a limited amount of rainfall over the desert ensures that there is very little error in precipitation.

Legates and Willmott's data were compared, at triangular wavenumber 42 (T42) truncations, with two other precipitation data sets (Jaeger and Shea), and three data sets for air temperatures (Crutcher, Oort and Shea). The Legates and Willmott data sets show a slightly wet and warm bias over Africa when compared to the other annual averages. Overall, the data from Legates and Willmott is in good agreement with the other data sets, and it was used in our study of West Africa during the growing season.

To compare the effect of outgoing longwave radiation (OLR), we used the data sets from the Nimbus-7 satellite as a reference. The Nimbus-7 mission is presently the most important satellite source of experimental results relating to atmospheric processes (NASA/ TN-1215). From a vantage point of 955 km above the Earth's surface, a given point on the Earth is viewed twice every 24-hour period (once during the day and once at night). The Earth Radiation Budget (ERB) instrument aboard the Nimbus-7 was used to read measurements of outgoing radiation. We used compilations of these
The results from the MECCA Phase I investigators were compared to the observed data sets mentioned above. All the models are CCM derived. Washington and Meehl's version is a CCMOA climate model, and all the others are derivations of CCM1 models. The Phase I investigators emphasized the importance of sensitivity in their experiments. The parameters taken into account by each investigator's model are listed below. This information is based on responses to a November 1992 questionnaire produced by the MECCA Project Manager. All model scenarios are based on R15 resolutions and 50m mixed layer oceans.

1) Group Name: Climatic Impacts Center (CIC), Macquarie University, Australia
Investigators: A. Henderson-Sellers, T.B. Durbridge, K. McGuffie (University of Technology, Australia), A.J. Pitman
Model Name: CCM1-Oz\(^1\) (put footnotes to reference model details)

Year of Model Version: 1990

Horizontal Resolution: R15
Number of Vertical Layers: 12
Seasonal Cycle: yes
Diurnal Cycle: yes
Convection: Moist Convective Adjustment (MCA)
Cloud: Relative Humidity (RH)
Ocean: mixed layer, 50m deep
Q-flux: yes
Horizontal Ocean Resolution: R15

\(^1\)Specific references to model details:
Dickenson et al. (1986). Biosphere-Atmosphere Transfer Scheme (BATS) for the NCAR Community Climate Model. NCAR/ TN-275+STR. (Update, 1992)
Henderson-Sellers et al. (1993). Tropical Deforestation: Modelling and Regional-Scale Climate Change. JGR.
Vertical Ocean Resolution: n/a
Sea Ice: 3 layer thermodynamic
Land-Surface: Biosphere-Atmosphere Transfer Scheme (BATS)
Land-Surface Horizontal Resolution: same as atmosphere
Roughness Length: same for energy, heat, momentum
Continental Runoff Tracked to Ocean: no

2) Group Name: GCM Sensitivity to Atmospheric CO2 Changes
Investigators: Barry Saltzman (Yale University); Robert Oglesby (Purdue University); Susan Marshall (Colorado State University)
Model Name: variation of the NCAR CCM1

Year of Model Version: 1987, with subsequent updates
Modifications since: programming adjustments to run under UNICOS (originally developed to run under COS); 1989, implementation of the Covey-Thompson slab ocean mixed-layer model; 1990, 1993, modifications to snow hydrology; recent implementation of the Martinson's true mixed-layer/dynamic sea-ice model.

Horizontal Resolution: R15
Number of Vertical Layers: 12
Seasonal Cycle: yes
Diurnal Cycle: no
Convection: MCA
Cloud: RH
Cloud Properties: fixed
Ocean: slab ocean (standard version); genuine mixed-layer (new version)
Q-flux: only Covey-Thompson "1/2 Q-flux used for a few experiments
Horizontal Ocean Resolution: R15
Vertical Ocean Resolution: same as atmosphere
Sea Ice: Semtner's 3-layer thermodynamic,mixed-layer version also used
Land-Surface: bucket scheme, implementation of Marshall snow hydrology

2) specific references to model details:
Land-Surface Resolution: same as atmosphere
Roughness Length: same for sensible heat, latent heat, and momentum
Continental Runoff Tracked to Ocean: no

3) Group Name: NCAR
Investigators: Starley L. Thompson, David Pollard, Jon C. Bergengren
Model Name: GENESIS version 1.02

Year of Model Version: 1992
Modifications Since: none released

Horizontal Resolution: R15 for atmospheric model, 2x2 degrees for surface models
Number of Vertical Layers: 12
Seasonal Cycle: yes
Diurnal Cycle: yes
Convection: penetrative convection, simplified sub-grid plume type
Cloud: stratus clouds based on RH, convective clouds based on plume-model
Cloud Properties: fixed
Ocean: 50m mixed layer
Q-flux: yes
Horizontal Ocean Resolution: 2x2 degrees
Vertical Ocean Resolution: 1 layer, 50m slab
Sea-Ice: 6-layer thermodynamic, cavitating-fluid dynamics
Land-Surface: SVAT Land-Surface Transfer Scheme (LSX)
Land-Surface Horizontal Resolution: 2x2 degrees
Roughness Length: calculated from Canopy Aerodynamic Equations,
same for sensible heat, water vapor, and momentum

3 Specific references to model details:
Continental Runoff Tracked to Ocean: yes, globally averaged and uniformly given to mixed layer at each time step

4) Group Name: State University of New York at Albany
Investigators: Wei-Chyung Wang, Xin-Zhong Liang, and Mike Dudek
Model Name: CCM1 with trace gases

Year of Model Version: 1987
Modifications Since: updated since for longwave scheme, absorption of trace gases (CH4, N2O, CFC-11, CFC-12)

Horizontal Resolution: R15
Number of Vertical Layers: 12
Seasonal Cycle: yes
Diurnal Cycle: no
Convection: MCA
Cloud: Slingo-based scheme; stratus, convective and anvil cirrus can form depending on the relative humidity and precipitation rate
Cloud Properties: specified emissivity and albedo
Ocean: mixed layer with fixed thickness
Q-Flux: flux correction is applied for water and ice covered oceans
Horizontal Ocean Resolution: same as atmosphere
Vertical Ocean Resolution: one layer of 50m thickness
Sea-ice: 2 layers
Land-Surface Processes: 3 layer snow and 1 layer soil
Land-Surface Horizontal Resolution: same as atmosphere
Roughness Length: 10cm for land and a few tenths for the ocean
Continental Runoff Tracked to Ocean: no

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4 Specific reference to model details:
Wang et al. (Ozone climatology and simulation of the effect). In preparation?
5) Group Name: NCAR
Investigators: Warren Washington and Gerald Meehl
Model Name: Dynamical Framework CCMOA

Year of Model Version: 1983
Modifications Since: 1990, updated for physical properties such as surface albedo and penetrative convection

Horizontal Resolution: R15
Number of Vertical Layers: 9
Seasonal Cycle: yes
Diurnal Cycle: no
Convection: penetrative convection, albrecht hybrid type
Cloud: RH
Cloud Properties: fixed, except if SST > 303K and deep convection present, then cirrus albedos increase
Ocean: 50m mixed layer
Q-flux: no
Horizontal Ocean Resolution: R15
Vertical Ocean Resolution: 1 layer, 50m deep
Sea Ice: 1 layer, thermodynamic
Land-Surface: bucket
Land-Surface Horizontal Resolution: same as atmosphere
Roughness Length: simple drag coefficient $C_D = 1 \times 10^{-3}$ ocean and $C_D = 4 \times 10^{-3}$ for land
Continental Runoff tracked to Ocean: no

**Averaging Techniques**

The NCAR processor was used in order to process the mean annual values of observed precipitation from twelve long-term monthly values supplied by Legates and Willmott. We then took the last five years of data from the MECCA Phase I investigators and

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used them for our annual and monthly analysis of the growing season. The last 5-year runs of the GCMs were used in general. However, in the case of Oglesby, we used years 16 - 20 of his 100-year controlled climate integration. The fields that were used in the annual cases were temperature and precipitation. We used the first atmospheric level GCM temperatures for all the Phase I investigators (therefore, these temperatures are taken at level that are higher than shelter-height).
RESULTS

Abbreviations used to identify investigators: 

HS = Henderson-Sellers  
OP = Ogleby et al.  
PT = Pollard and Thompson  
WG = Wang et al.  
WM = Washington and Meehl

Abbreviations used to identify controls: 

LW = Legates and Willmott, controls for temperature and precipitation

Other acronyms are obvious and have already been defined

Part One: Intercomparisons of Annual Scenarios over Africa

Temperatures

Observation shows maximum temperature levels over the Sahel. The same levels of warmth are maintained over southern West Africa (extending into central Africa), and over the mid-Sahara. Desert temperatures (over the Sahara and Kalahari) show significantly cool temperatures over all. These values represent a mean between the hot extremes during the day, and the very cold extremes at night. The coolest temperatures are located over South Africa.

WM shows a warm bias all over West Africa. In fact, a warm bias of over 3K is displayed over approximately 70% of the continent. WM indicates biases of over 12K in parts of northern Ethiopia. OG's model indicates a strong cold bias which is especially evident in northern Africa. HS and PT's model scenario shows a slight cold bias over all. In WG's scenario, there are indications of a cold bias in the northern hemisphere.

The interesting feature in all the model scenarios is that they all show a strong warm bias over western Angola. Furthermore, all scenarios show warm biases over central Ethiopia and along the western sea-board of sub-Saharan Africa. Over all, it seems that HS's model does the best job of limiting the uncertainty on either side of the temperature scale.

Precipitation
Observation shows maximum amounts of precipitation over Sierra Leone. Further rainfall highs may also be recorded around Sierra Leone and in Central Africa. Significant levels of precipitation may be found over northern Mozambique. Rainfall lows are recorded over both the Kalahari and Sahara deserts.

All the models significantly distort the recognized high temperature areas over the Sahara. All models, with the exception of HS's model, show a wet bias. Although HS's model succeeds in duplicating the rainfall patterns over the deserts the model fails to do the same in regions of maximum rainfall. PT's scenario shows the most extreme wet bias. In fact, only PT's model does not show an extensive underestimation of rainfall over Sierra Leone. This underestimation uniformly exceeds 6 mm/day. Overall, it seems that WG shows the best estimate of annual precipitation values.

**Part Two: Intercomparisons of Summer Scenarios over West Africa**

**Temperatures**

Legates and Willmott observed temperature plots were used as controls. These data sets recorded a gradual temperature gradient throughout the summer months, with maxima typically observed in the north and minima observed within the southern latitudes.

During the month of May, observation showed a marked maximum of over 308K around the mid-point of the Mali-Mauritania border. In comparison to this, WM's model shows an extremely warm bias, revealing temperatures of >308K over much of West Africa. The precision in HS's model is better appreciated, but it still remains far from observation. The models by PT, OG, WG do not detect any maxima over 308K. Temperature minima in West Africa may be detected along the southern limits of the region.

In June, the region of maximum temperature broadens considerably and extends into central Algeria. However, the entire warm belt shifts notably northward, leaving equatorial West Africa with a temperature reduction of about 4K. This cooling effect is to be expected as heavy monsoonal winds are blown in by the easterlies. All the model simulations also produce this slight northward trend in warm temperatures. There is a
recognized minima over central Cameroon. This minima may be attributed to the cool air rising from the Gulf of Guinea. All the model scenarios, however, fail to pick up these minima.

The northward trend continues throughout July. July is when the WM scenario indicates maximum regions of high temperatures. In WM's model, this temperature high is >308K, and spans the cities of Abidjan near the equator, Bissau on the western coast, N'djamena in the east, and also expands northward into southern Algeria. There is also a region of maximum temperature in northern Ethiopia and Sudan. As shown the warmth of this model appears to be quite exaggerated when compared to observation.

It is interesting that the OG, PT, and WG scenarios never show a high of greater than 308K over West Africa. Among these three simulations for temperature, PT and WG simulations keep differences to a minimum.

The observed minima over West Africa does not change much for August which shows a minimum temperature of between 292K and 296K over most of Cameroon and over some of central Nigeria, around the Jos Plateau. None of the models pick up similar estimates of minimum temperatures over West Africa.

In September the self-defined warm front stagnates above coastal West Africa. Crops are prepared for harvest and in a couple of months much of equatorial Africa will be overcome by cool north-easterly winds originating from the Sahara. This corresponds with the recessions of the summer monsoon rains and the end of the growing season.

For temperature scenario's, it is difficult to say which model does the best overall.

*Precipitation*

Using Legates and Willmott values for uncorrected precipitation as a base for the intercomparison, model precipitation plots were observed for May through September. West Africa is heavily dependent on the high levels of rainfall brought in by the south-westerly monsoon winds. It is this rainfall that spawns the beginning of most agricultural projects.
During the month of May, observation shows annual precipitation highs of between 4 and 6 mm/day in southern Sierra Leone and southern Nigeria, extending into central Africa. Precipitation minima of < 1 mm/day can be observed over the Sahara. The wet belt observed extends through West Africa up to a latitude of 13°N. Above this, little or no rainfall occurs. In WM's model, this area is significantly distorted, showing a wet bias in some regions and a dry bias in others. For instance, according to WM's model, southern Sierra Leone now receives less than 2mm/day, while southern Nigeria receives significantly more (between 14 and 18 mm/day of rainfall). In HS's scenario, the entire West African rainbelt is somewhat drier, while significant amounts of rainfall appear over the Sahara which receives between 2 - 4 mm of rainfall per day. In PT's model, the entire scenario shows a wet bias, and the same is true for OG's model. WG's model shows a uniform wet bias all over West Africa. Although the accuracy of WG's model is questionable, the precise degree of error that it entails should definitely be appreciated.

The observational scenario becomes notably wetter during the month of June. A maximum degree of rainfall (between 14 and 18 mm/day) remains over Sierra Leone. The rainfall belt extends northwards to include parts of the Sahel. All areas included in the study have either retained the same degree of moisture or have shifted considerably northward. Most of Niger uniformly shows very little rainfall, yet in all the model diagrams, there is an exaggeration of the degree of moisture received. The most visible exaggeration is shown in WG's model which records between 2 and 4 m daily over Niger.

For July, maximum and minimum precipitation levels are maintained over the same areas. Sierra Leone records over 22 mm/day of rainfall, and this amount decreases most visibly in the northward direction. A rainfall level level of between 2 and 4 mm/day, stretching from Senegal into Chad, is maintained in a belt that spans 4° of latitude. This band is best approximated in HS's scenario, although several area (over Mali, Niger and Burkina Faso) record a wet bias coupled with dry biases over Gambia and Senegal. WM's model shows a precipitation peak of of greater than 18 mm/day over Liberia and Cote d'Ivoire. This is definitely not in accordance to observation, or any of the other data sets. This may be be attributed to the fact that WM used a significantly different CCM version, the CCMOA. PT's model does significantly well in approximating rainfall distribution over West Africa in this scenario. However, at this point WG's model does
very poorly, and it displays significant amount of rainfall (between 8 and 10 mm/day) over the Sahel, with regions of greater than 4 mm/day over the Sahara.

Maximum rainfall levels are recorded for the month of August. Several countries on the western coast (from Gambia to Liberia) exhibit rainfall levels of greater than 22 mm/day. Precipitation levels of up to 2 mm/day can be observed as far as latitude 22°N. All the models show more rainfall over the Sahara than should be expected. It can easily be seen, however, that WM's model does the best job of simulating the overall pattern in Sahara rainfall. Yet, this same scenario displays a wet bias of about 14mm over Cameroon. OG's scenario is drier than necessary over the tropical region. The best August scenario over the Tropics can be observed by PT's model.

In September, rainfall amounts recede. The models all continue to hold their strong and weak points over certain areas, and it is difficult to say which model performs best. Both WM and PT's scenarios show very good rainfall patterns over the Sahara. The rainfall distribution over tropical West Africa is best simulated by PT's model.

In a region wherein the degree of moisture is the most important concern of agriculture, it is most important that climate models be able to interpret precipitation levels accurately. Unfortunately, none of the CCM versions is in good agreement with observed precipitation measurements. Most of the models do very well within limited areas of West Africa, but then do poorly in other areas. It is therefore difficult to say which models provide the best interpretation of seasonal precipitation levels. Yet, the implications of poor precipitation scenarios are quite obvious. A moist bias, as observed over much of the Sahel region, would lead to the inability of the model to predict future periods of drought. Even a wet biased scenario would only serve to skew the priorities of many weak Third World economies in anticipation of a drought. Both cases would serve only to lower the confidence in climatic models.

**Outgoing Longwave Radiation (OLR)**

Observation shows minimum amounts of OLR over southern West Africa and maxima over the Sahara. There is a median stretch over the Sahel. Observation shows sharp boundary limits for outgoing longwave radiation.
WM's version displays far less OLR over tropical West Africa than is actually observed and then displays an overestimate of OLR over the Sahara. Furthermore, the boundary limits in WM's scenario are interwoven to produce a gradual OLR trend. The notable difference in WM's scenario may be due to the fact that WM version is based on a significantly different type of CCM, the CCMOA.

All models show greater amounts of OLR over the Sahara than is actually observed. This may be due to the fact that approximations for large amount of dust over the Sahara were not taken into account. Dust would serve to hinder the escape of OLR.

**Cloud Fractions**

Both the Cloud Fraction and the Outgoing Longwave Radiation are closely related. OLR may be affected by a) area of cloud cover, b) altitude of cloud, and c) thickness of the cloud. A large cloud fraction corresponds to a lower degree of cloud cover. This is because the greater the cloud cover, the less likely outgoing longwave radiation is to escape to the outer atmosphere. The thicker a particular type of cloud is the more likely it is to hinder the escape of OLR. Clouds that are higher up in the atmosphere are more likely to block the escape of OLR. Temperature reduces as altitude increases, and by Stefan-Boltzmann relationship, the power of the OLR is reduced also. Therefore, by the time the OLR reaches high altitude clouds, it is easily absorbed and re-emitted into the atmosphere. The results of the previous intercomparison are therefore related to the next one in many ways.

The Cloud Fraction scenario has also been averaged for July and August. All models show maximum cloud fractions over central Africa. This is to be expected as moist monsoon winds well up over equatorial Africa. However, the east-west position of the maxima does not correspond with observations. All scenarios show minimum amounts of cloud cover over dry regions. However, OG's model shows an overestimate of cloud cover over the Sahara, and WM's version indicates an underestimate.

Both WG and PT's model do a sufficiently good job of duplicating the observed scenario over West Africa.

**Zonal Winds**
An intercomparison was made for zonal winds at a pressure of 200mb (this typically occurs at altitudes of about 3km) and 700mb (which usually occur at heights of over 11km).

The 700mb winds are caused by a reverse temperature gradient at the surface. This, in turn, is caused by low equatorial temperatures due to the high cloud cover (Jenkins, personal communication). Over the desert, there are few clouds, therefore average temperatures are higher. Thus by the Thermal Wind Equation, easterly winds should occur. If westerlies or weak easterly winds occur, then a weaker reverse temperature gradient is apparent.

At 200mb pressures, easterly winds extend from southern Asia and weaken when they are over West Africa. They are also caused by a reverse temperature gradient. The coldest temperatures at this level occur at the equatorial tropopause and warmer temperatures are located to the north and south. Therefore, if these winds are weaker than observation, a weaker reverse gradient occurs in the model data.

The shear force between the upper and lower tropospheric winds produces West Africa's infamous line squalls. The ECMWF reference scenario illustrates the presence of the line squalls as the prevalent easterlies are observe at lower altitudes compared to the strong westerlies at upper elevations. Essentially the easterlies and westerlies act in opposite directions with the easterlies conventionally given a negative wind speed (and the westerlies are assigned positive wind speed values).

The ECMWF July wind speed averages at 200mb pressures indicate an easterly trough. The trough extends all the way into northern Africa, covering most of West Africa. There are maximum absolute easterly wind speed of 10m/s. The OG model does not detect this minimum at all, and there is a complete absence of easterly wind flow. Both PT and WG's model detect temperature troughs, but only WM detects a comparable peak in easterly wind speed. According to observation, there is a steep westerly wind speed gradient extending from Morocco and into the Mediterranean Sea. WG's and WM's model detects a similar gradient.

Over the month of August, the zonal wind pattern remains much the same. There is however, an essential difference in WM's model. Observation shows that the tip of the easterly trough is pointed westwards, while in WM's model the tip is in the opposite
direction. However, only WM's model continues to represent a wind speed range similar to that shown by observation.

For the low-altitude 700mb winds, the observed wind speed scenario alters considerably. Wind speeds are known to decrease considerably. It can also be observed that the westerlies are now far back, occupying only parts of North Africa. The easterlies are now extremely dominant.

During July, both the PT and WM scenarios agree quite well with observation. One drawback of the PT model is that the easterly trough covers an area that is about 30% of what is observed. Very little changes are made through the month of August.

Both WG's and OG's models produce very poor estimates of wind speeds over Africa. It is interesting to note that although WG's model was the most detailed, and incorporated the effects of most trace gases, it proved quite inefficient with regard to zonal wind speeds. The irony of this is that details, although limiting uncertainty, do not necessarily ensure precision. Overall, WM's model brought forth the best results for upper and lower tropospheric zonal wind speeds.

The implications of zonal wind speeds are quite obvious. A reduced zonal wind speed gradient would correspond to a reduced temperature gradient. This is obviously not the case as observations depict a marked temperature gradient over West Africa, and it is this high temperature gradient that drives the zonal winds. This is one example of how aspects of climate are extremely interdependent.

Furthermore, an accurate prediction of zonal wind patterns will lead to a greater understanding of line squalls and the position of the Intertropical Convergence Zone (ITCZ). The thunderstorms which are a fair indicator of the position of the ITCZ brush through West Africa amazing regularity, at the beginning and end of the growing season. Due to the intimate relationship between various climatic factors, the occurrence of these line squalls may be a gauge for determining future climatic trends.

Sea Level Pressure
Maximum pressure areas naturally flow into lower pressure areas in a bid to reach equilibrium. On a global scale, this causes a perpetual circulation pattern going since pressure varies from region to region.

According to Shea's observed data sets, a maximum pressure region of over 1020mb can be spotted over the mid-Atlantic. This is in contrast to the low pressure (<1008mb) belt located within the Tropic of Cancer, east of the Greenwich Meridian. This scenario represents the mean values over the months of June, July, August. This pattern in sea level pressure is to be expected. The warm pressure region will cause the surge of moist air over sub-Saharan Africa. This graceful, yet complex, flow provides the base for the presence of monsoonal rains throughout the summer months.

All the models do a good job of depicting the overall pattern. WM's model, however, plots a gross overestimation of the low temperature trough. To a lesser extent, PT's model also overestimates area of the trough. HS's scenario shows two peak trough for pressure. This is a good representation of the thinning of the low pressure belt over central West Africa.
CONCLUSIONS

All the models showed both strong and weak points. For instance, all models fail to duplicate the steep temperature gradient over West Africa during the growing season. Yet, these models all do a reasonably good job of showing minimum cloud fractions over the Sahara. In all cases, the resolution is inappropriate for the application of nesting. Although considerable work still needs to be done on climate models, they have demonstrated an ability to simulating general climatic trends. There is a future for GCM's; one that not only involves detecting long-term climatic trends, but also involves predicting sudden fluctuations in climate. By so doing, future droughts may be detected. The lives of people depend on it.
Appendices: Figure Captions

Figures 1a-f: Annual Temperatures

Figures 2a-f: Annual Precipitation

Figures 3a-f: May Temperatures

Figures 4a-f: June Temperatures

Figures 5a-f: July Temperatures

Figures 6a-f: August Temperatures

Figures 7a-f: September Temperatures

Figures 8a-f: May Precipitation

Figures 9a-f: June Precipitation

Figures 10a-f: July Precipitation

Figures 11a-f: August Precipitation

Figures 12a-f: September Precipitation

Figure 13a: JJA OLR

Figure 14a: JJA Cloud Fractions

Figures 15a-b: July - August Zonal Winds, 200mb Pressure

Figures 16a-b: July - August Zonal Winds, 700mb Pressure

Figure 17a: JJA Sea Level Pressures
Appendix

Annual Temperatures
Contour from 284 to 300 by 4
Appendix

Annual Precipitation
Appendix

May Temperatures
Contour from 200 to 300 by 4
Appendix

June Temperatures
Appendix

July Temperatures
Appendix

August Temperatures
Appendix

September Temperatures
CASE:
LEGATES and Willmott Sept. air temperatures

Contour from 296 to 304 by 4

Frame 1.2
08/12/93 15:25:55
Appendix

May Precipitation
Appendix

June Precipitation
Henderson-sellers June Rainfall (mm/day)

Time average for days 1210601.0 to 1250601.0 by

Precm 1000s

Contour from 1 to 5 by 1
Appendix

July Precipitation
Appendix

August Precipitation
Appendix

September Precipitation
Appendix

JJA OLR
CASE: 1  NIMBUS7 ERB
Nimbus 7 ERB JJA OLR
EMITSAT 1000 S

Contour from 250 to 275 by 25

Frame 6.1
08/12/93 08:55:37
TIME AVERAGE FOR DAYS 1210601.0 TO 1210801.0 BY 100.0 FIITP 1000.5

Contour from 275 to 325 by 25
Appendix

JJA Cloud Fractions
CASE 15
Pollard and Thompson JJA CLOUDS
TIME AVERAGE FOR DAYS 1010615.0 TO 1010815.0 BY 100.0 TOTCLD 1000.0
Contour from .1 to .8 by .1
Appendix

Zonal Winds
Appendix

JJA Sea Level Pressures
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